Proceedings of the Annual General Donald R. Keith Memorial Conference
West Point, New York, USA
May 4, 2023
*A Regional Conference of the Society for Industrial and Systems Engineering*

# Value Analysis of Reliability of the ACE and the VTA-903

**Trevor Cosenke, Andy Deniz, Caleb Doyle, Donald Flannery, Phillip Bond, and Jae Kim**

Department of Systems Engineering
United States Military Academy
West Point, New York 10996

Corresponding author's Email: doncflannery@gmail.com

**Author Note:** The views expressed herein are those of the authors and do not reflect the position of the United States Military Academy, the Department of the Army, or the Department of Defense.

**Abstract:** This paper proposes an additive value model of the VTA-903 and the Advanced Combat Engine (ACE) for Program Executive Office Ground Combat Systems (PEO-GCS). Cummins Incorporated (Cummins), paired with the United States Army and Department of Defense, is currently researching a potential transition from the current VTA-903 engine to the new and improved Cummins design: the ACE. The study's analysis of the transition of the VTA-903 to the ACE uses Multi-Objective Decision Analysis to assess the relative value of known/hypothesized aspects of the engines to estimate the minimum reliability of the ACE required to justify its higher procurement costs.

*Keywords:* Advanced Combat Engine (ACE), VTA-903 (VTA)

## 1. Introduction

Army Futures Command (AFC) is a new organizational structure within the Army looking to coordinate modernization. The key modernization initiatives to this project include long-range precision fires, next-generation combat vehicles, and soldier lethality (Bates, 2022). If adopted, the newly developed Army Combat Engine (ACE) would support efforts to improve the lethality and survivability of future generation combat vehicles. The two-stroke opposed piston design is radically different than the current, four-stroke engine, the Cummins VTA-903. Advantages include scalability to meet almost any required power demand, elimination of components within engine subsystems, and a low Brake Specific Fuel Consumption across a broad range of engine speeds and torque conditions.

The Cummins VTA-903 is a common diesel engine, composed of a V-type, 8-cylinder configuration. Cummins has partnered with the United States Army since 1981 implementing the VTA-903 into different ground combat vehicles (Army Guide, 2015). Cummins, aligning with the Army's modernization effort, has developed a cutting-edge engine for the new Optionally Manned Fighting Vehicle (OMFV) that could also be used in a variety of current platforms, such as the M2 Bradley Fighting Vehicle (Bradley), M1 Abrams Tank (M1), Armored Multi-Purpose Vehicle (AMPV), and the Paladin Integrated Management (PIM). The ACE consumes less space than the VTA and can be modified to higher and lower power outputs retaining applicability across multiple vehicles. This study began with the intent to identify the Operation & Sustainment (O&S) costs of the ACE to compare them to the O&S costs of the VTA. However, data availability limited the results to predicting the level of reliability the proposed engine would need to meet the same value as the VTA, given known attributes of each engine. To account for the lack of data within reliability, a Weibull distribution is utilized to predict potential fail rates given hours of use.

## 2. Background

The key distinction between the VTA and the ACE is the placement of the pistons within the cylinder and the stroke required to complete a power cycle. The VTA engine is a common 4-stroke diesel engine with individual pistons firing in each of the eight cylinders. In contrast, the ACE is a two stroke, four-cylinder engine with opposed pistons. An opposed piston engine differs from a common diesel engine in that there are two pistons per cylinder working in opposition of each other. In this two stroke-design, air/fuel/exhaust are all moved via vents in the cylinder walls in 2-stroke engines as opposed to a 4-stroke engine that requires cylinder heads and valves to complete additional strokes to add and exhaust air. The opposed piston, 2-stroke engine has the capability to produce more power, at more efficient fuel consumption rates and the potential to create a longer lifespan due to increased reliability.

For this research, the engine is broken into six main subsystems. The Electronic Controls System is composed of software that controls and operates all systems within the engine. The Fuel System is the pipe/tubing that stores and supplies fuel to the engine for ignition. The Air Handling system, including both the supercharger and turbo charger, regulates the flow of air within the system. The Block/Attachment/Power Cylinder is composed of hardware that oxidizes fuel under controlled conditions and translates chemical energy into mechanical energy. The Lube and Cooling System provides lubrication to all moving parts and transports waste heat out to the system. The Exhaust System removes waste and excess heat from the system as well as providing energy to the turbocharger. Each subsystem has key components that exist in one engine but are void in the other. For example, the ACE has a supercharger and turbochargers while the VTA does not contain a supercharger. Due to the difference in 2-stroke and 4-stroke, the ACE does not have values, cylinder heads, rockers and more. The differences in the number of parts have the potential to improve reliability and decrease overall cost.

The VTA-903 is seen as a reliable engine. One expert, 3rd Infantry Division 1st Armored Brigade Combat Team automotive maintenance Chief Warrant Officer 4, Marchilla Isom even states that it is the most reliable engine he has worked on over the last twenty years. Though generally reliable, CW4 Isom's experience shows that the main factor contributing to engine failure is the pressure timing pump which would no longer exist in the ACE. The ACE also removes additional parts such as crankshafts, valves, and piston heads which add complexity and degrade the reliability of the VTA. Given these changes, the potential exists for increased reliability and a longer engine lifespan. In addition to potential cost savings, one of the major differences in Cummins' new engine is the change in horsepower (hp). The ACE design in consideration generates 1000 hp which is an improvement of 330 hp which could improve system mobility. The increased mobility along with the ability to carry more weapons, ammunition, and armor would have positive effects on lethality and survivability. The ability to deliver this horsepower at half the revolutions per minute (rpm) over a broad range of engine speeds and torque conditions translates to higher reliability and fuel efficiency.

## 3. Methodology

### 3.1 Value Hierarchy

In a previous study conducted by MAJ Courtney Razon (2022), for the Operations Research Center (ORCEN) at the United States Military Academy, a value hierarchy was built to show the value that each engine produced given certain value measures (Figure 1). The value functions used in adjusting the overall score per engine are horsepower, torque, volume, weight, integration burden, nominal fuel consumption, scalability, and reliability. However, reliability was left unknown due to the lack of data. In continuation of this work, this study predicts reliability to model the final value function. To produce values within reliability, this study used a Weibull distribution – with embedded Monte Carlo simulation, to predict failure rates given any number of hours throughout the lifespan of the given engine system. A Weibull distribution is often used to model wear down and breakdowns in engines making it a commonly used and understood model.

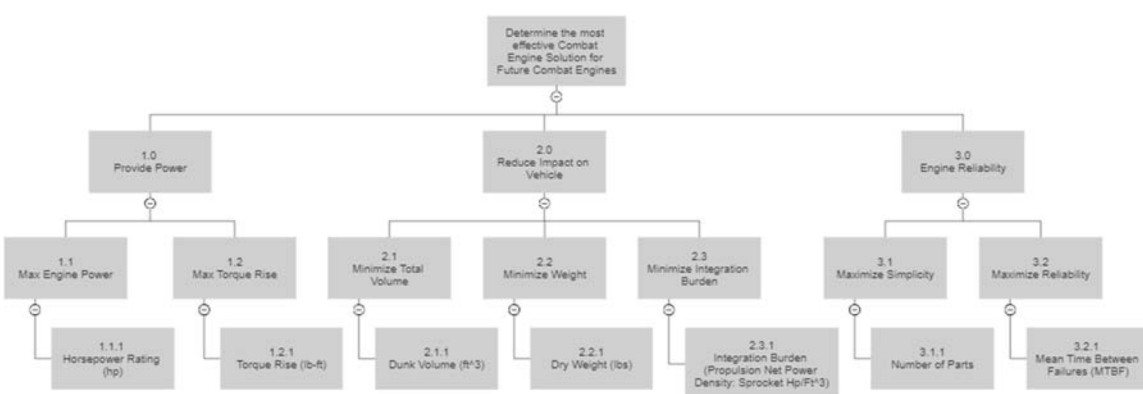


Figure 1. Value Hierarchy

### 3.2 Value Survey

To determine the value of each value measure, we distributed a survey through Master Sergeant Eric Engstrom to the 6/1 CAV. This unit is within an Armored Brigade Combat Team. There are typically one hundred and fifty-two Bradley Fighting Vehicles within a Brigade. The survey was passed down from Master Sergeant Eric Engstrom to senior leaders within the unit. Seventeen key leaders within the 6/1 CAV weighed their values accordingly. The values that were surveyed included, Horsepower Rating, Torque Rating, Dunk Volume, Dry Weight, Integration Burden, Mean Time Between Failure, and Number of Parts. The Bradley Fighting Vehicle currently utilizes Cummins VTA-903 engine and those surveyed generated responses based on experience with the engine. These values were measured on a scale of one to ten. Ten being the highest weighted and one being the lowest. The VTA-903's highest valued value measure was the overall size of the engine (volume) at 15%. The lowest valued value measure was the ease of maintenance (integration burden) at 10%. The results of this survey are directly applied to the value hierarchy.

### 3.3 Qualitative Value Modeling

In Razon's (2022) previous study, ideal candidate engines were identified to compete in total overall value. This study focuses specifically on the VTA-903 675 hp and 760 hp, as well as the ACE. The value functions create a solution for each candidate known as a "value." The values highlight the overall performance of the engine specifications given for each.

### 3.4 Value Functions

The model created shows the performance of each engine based on the values indicated within the Value Survey. This additive value model is shown in Equation 1.

$$v(x) = \sum_{i=1}^{n} w_i v_i(x_i) \qquad (1)$$

Within this equation the v(x) is the total value of the given engine, $i$ =1 to n for the number of value measures, $x_i$ is the score of the given engine on the *i*th value measure, $v_i(x_i)$ is the value of the engine on the *i*th value measure, $w_i$ is the weight measure of the *i*th value measure and the sum of all the weights equal to one. A typical stakeholder view will produce value measures that are not equivalent in weight. In this study, it is seen through the survey with current users that different value measures hold more weight than others. While weights may differ from value measures to value measure, they all must equal 1. Based on the use of the vehicles and interactions with interviewees, the value scores (Table 1) and the respective weights were compiled given their value measure (Table 2).

Table 1. Value Scores

| Horsepower Rating (hp) | | Torque Rise (lb-ft) | | Dunk Volume (ft^3) | | Dry Weight (lbs) | | Integration Burden (Sproket HP/Ft3) | | Nominal Fuel Consumption at Rated Output and Speed (lb/hp-hr) | | Simplicity (Number of Parts) | | 3.1.2 Reliability (MTBF) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Raw Score | Value | Raw Score | Value | Raw Score | Value | Raw Score | Value | Raw Score | Value | Raw Score | Value | Raw Score | Value | Raw Score | Value |
| 500 | 0 | 0.9 | 0 | 120 | 0 | 5200 | 0 | 1 | 0 | 0.3 | 100 | 3250 | 0 | 500 | 0 |
| 600 | 0 | 0.95 | 20 | 80 | 0 | 4500 | 25 | 2 | 20 | 0.325 | 100 | 3000 | 10 | 900 | 30 |
| 700 | 10 | 1 | 40 | 70 | 0 | 4000 | 50 | 3 | 40 | 0.35 | 100 | 2750 | 20 | 1000 | 40 |
| 800 | 45 | 1.05 | 50 | 60 | 20 | 3500 | 80 | 4 | 60 | 0.375 | 85 | 2500 | 30 | 1100 | 50 |
| 900 | 65 | 1.1 | 60 | 50 | 70 | 3000 | 90 | 5 | 80 | 4 | 70 | 2250 | 40 | 1200 | 60 |
| 1000 | 80 | 1.15 | 70 | 40 | 90 | 1000 | 100 | 6 | 100 | 4.5 | 40 | 2000 | 50 | 1300 | 70 |
| 1100 | 88 | 1.2 | 90 | 20 | 100 | | | 7 | 100 | 5 | 0 | 1750 | 60 | 1400 | 80 |
| 1200 | 94 | 1.25 | 95 | | | | | | | | | 1500 | 70 | 1500 | 90 |
| 1300 | 96 | 1.3 | 100 | | | | | | | | | 1250 | 80 | 1600 | 100 |
| 1400 | 98 | | | | | | | | | | | 1000 | 100 | | |
| 1500 | 100 | | | | | | | | | | | | | | |

ISBN: 97819384964-4-8

Table 2. Value Function Weights and Total Scores

| Values Function | Value Function Weight | VTA903E-T675 | VTA903-T760 | ACE-1000 |
|---|---|---|---|---|
| **Horsepower Rating** (hp) | 12.12% | 675 | 760 | 1000 |
| **Torque Rise** (lb-ft) | 12.24% | 1.022820231 | 1.10133483 | 1.2 |
| **Dunk Volume** (ft^3) | 14.80% | 39.7 | 39.7 | 33.4 |
| **Dry Weight** (lbs) | 13.52% | 2580 | 2680 | 3280 |
| **Integration Burden** (Sproket hp/ft3) | 10.08% | 2.881156952 | 3.133721833 | 4.810445 |
| **Nominal Fuel Consumption at Rated Output and Speed** (lb/hp-hr) | 12.88% | 0.36 | 0.36 | 0.315 |
| **Simplicity** (# of parts) | 10.71% | 2250 | 2500 | 2000 |
| **Reliability** (MTBF) | 13.65% | 1600 | 1600 | 4868 |

## 4. Reliability Model

Weibull distributions are the most common reliability model when speaking of engine systems. Given a mean time to failure (MTTF), a shaping parameter, and a varying number of hours of use, Weibull can predict reliability of a system. The U.S. Army Tank Automotive Research Development and Engineering Center lead by Steve Gruenwald, along with Gus Panagos, Brian Harbaugh and Syed Chishti provided a study with life data analysis of the ACE. This came in the form of a Weibull distribution based on a ten-sample test of the ACE. Over the sample, a MTTF and Beta value were created and modeled using Microsoft Excel. To create variance within the model, this study reran the ten-sample test ten thousand times varying the shaping parameter one standard deviation above and below the provided value. Using the results, a new standard deviation was found. This standard deviation was then applied to the Monte Carlo simulation to provide variance within the MTTF of the ACE engine. The Monte Carlo Simulation was run one thousand times with variance to produce an average MTTF and reliability for each given hour of use. The range of hours within the model reaches approximately eleven and a half thousand hours to cover all reliability outcomes to include outliers and complete failure rate.

Mean time to failure (MTTF – $\theta$), the shaping parameter (Beta – $\beta$), and any given number of hours of use (Hours – $t$) are used within an exponential curve create the Weibull distribution that produces a percent reliability per hour $R(t)$ of the system (Equation 2).

$$R(t) = e^{-(\frac{t}{\theta})^{\beta}} \tag{2}$$

The key components that came from this ten-sample test were β =1.9963 and θ = 4868.64. These values were inputted into the Weibull model and run 10,000 times with a standard deviation 1 above and below the MTTF. Then, using the 10,000 samples the study produced a standard deviation that was incorporated into the β and θ to provide variance one standard deviation above and below the mean values. Once this new standard deviation was found, using a Monte Carlo simulation, the model was run 1,000 times producing reliability percentages from 0 to 11325 hours of use.

With the Weibull distribution, the probability density function can be used to predict the reliability of the specific engine over the course of its lifetime. The probability density function is used in multiple practices to define the probability of a continuous random variable adopting a certain value. The area under the curve shaped by the Beta and Theta value for each engine, found by running a simulation 10,000 times, illustrates the probability that failure will happen over the range of time in hours (Figure 2). The probabilities on the Y axis are small due to the wide range of time used to model the lifetime of an engine. The bulk of failures for each engine fall around the midpoint of the curve. This approximate midpoint is the θ, or the MTTF.

When sufficient data is produced for the MTTF for the VTA-903 a direct reliability comparison can be provided to determine the differences between the two. Given a direct comparison of reliability of the VTA and the ACE, there will be a clearer path to where value must be added to continue utilizing the VTA-903 over the ACE (Figure 3).

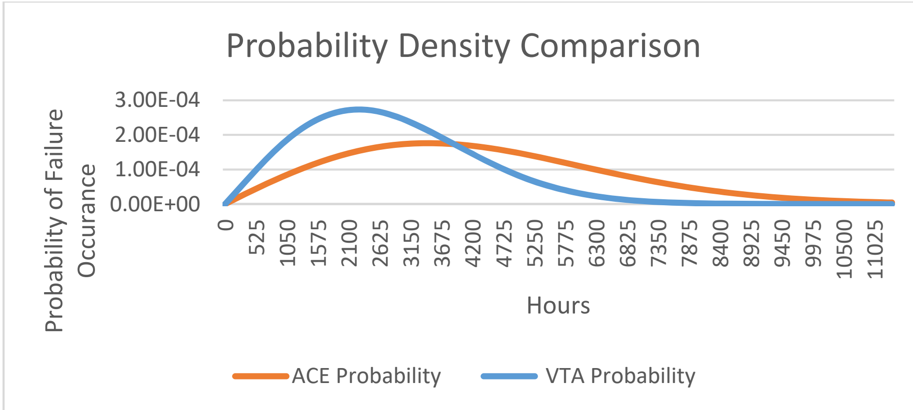


Figure 2. ACE/VTA Probability Density Function Comparison

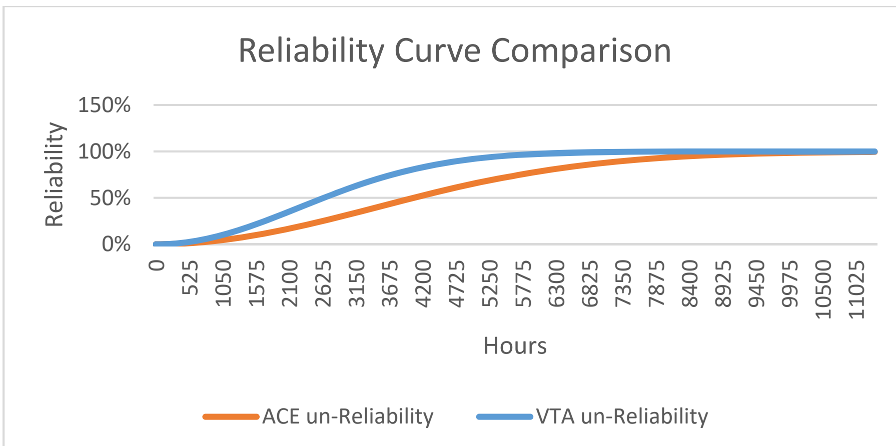


Figure 3. ACE/VTA Reliability Curve Comparison

## 5. Results

### 5.1 Findings

To collect findings on the comparison in value between the two models with insufficient reliability data on the VTA-903, a few key assumptions were made. These assumptions are that the findings in value from MAJ Courtney Razon's are still on pace for the projection of the current VTA-903 and the ACE engine. Given the additional reliability for the ACE engine, the overall value came out to be 69.0 out of 100. This rating of 69 came with a perfect 100 score under the MTTF of 4868 hours. The VTA-903 760 hp came in second and had an overall score of 53.8 out of 100. This came with the assumption that the VTA-903 would receive a perfect 100 score as well. This assumption shows that even with the addition of a perfect reliability score of the VTA-903, the ACE remains the highest value earning alternative. Going forward, if the VTA-903 remains the engine of choice, additional value must be added in terms of hp, torque, dry weight, dunk volume, integration burden, nominal fuel consumption, and overall engine simplicity to reach the breakeven value standard. Without the addition of value in one of these alternative aspects of the engine, the VTA-903 will not produce enough value to be worth continuation and the ACE will be the winning alternative based on these metrics.

### 5.2 Future Work

Using the value model and breaking down the reliability of each engine will allow for a cost and breakeven analysis between the two engine systems in terms of operation and sustainment. To achieve this, future work will require reliability data for VTA-903. Michelle Pentowski, an Organic Industrial Base (OID) Analyst within the US Army Tank-Automotive and Armaments Command (TACOM), was contacted and gave estimates on the operating hours of the VTA-903. However, there is currently no standard, streamlined process for properly reporting engine failures accurately within the Army. This limits how much data from an operational context is available; thus, no reliable mean time to failure value is available. Implementing a standard reporting system across the Army would allow for a more accurate comparison between the two systems and lead to more informed decision from the stakeholders.

## 5.3 Conclusion

Based on the project's research and data, we project that the ACE is significantly more reliable than the VTA-903 due to its simplicity, robustness, and fewer power strokes required to generate power. The current recommendation for PEO-GCS is to continue along with the implementation of the ACE. It provides more value than the current engine despite being in infancy with the potential to provide even more value over time. Since the ACE is still undergoing development, its reliability will increase over time with more research. In addition, the reliability of the VTA will become irrelevant due to its outdated technology. If the ACE's reliability meets that of the ten-test sample that was conducted, the value of the ACE will continue to increase. The ACE's improved value given its higher horsepower, higher reliability, and simplicity, aligns with the Army's values for next-generation combat vehicles. The ACE should be the future engine of the Army unless Cummins develops a 1,000 hp variant of the VTA.

# 6. References

*Advanced Combat Engine the Opposed-Piston Engine for Military and Commercial Applications*. (n.d.). Retrieved November 29, 2022, from (2020, June 23). *Diesel Engine Turbocharger Assemblies*. Central Diesel *Turbodiesel: Diesel Engine Turbocharger Assembly | Central Diesel, Inc.* (n.d.). Central Diesel Inc. https://www.centraldieselinc.com/capabilities/diesel-turbocharger-assemblies/

*Army Guide*. (n.d.). Www.army-Guide.com. Retrieved November 29, 2022, from http://www.army-guide.com/eng/product3948.html

Bates, L. (2022, June 15). *Army Readiness and Modernization in 2022*. Association of the United States Army. https://www.ausa.org/publications/army-readiness-and-modernization-2022#:~:text=Modernization%20of%20the%20Army%20ensures, the%20joint%20force%20and%20allies.

Isom, M. (2023, January 19). *Personal Interview* [Personal communication].

Pangos, G. (September 14, 2022). *West Point Phase II Study (Ace System Breakdown)*

Razon, MAJ C. (2022). *ORCEN GVSC Technical Report.*