Proceedings of the Annual General Donald R. Keith Memorial Conference
West Point, New York, USA
April 28, 2022
A Regional Conference of the Society for Industrial and Systems Engineering

Analyzing and Evaluating Alternatives for the Bradley Fighting Vehicle Powertrain

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Abstract: The United States Army relies on its fleet of combat vehicles to allow for freedom to maneuver on the battlefield. In turn, these vehicles rely on their powertrains, particularly, the engine and transmission, to properly function. This study evaluates the benefits obtained from upgrading the powertrain for the family of medium-tracked vehicles, focusing on the M2A3 Bradley Fighting Vehicle. These benefits are quantified by changes in performance, reliability, and sustainability through the use of a value model. The value model provides an overall score that quantifies for the benefit of upgrading the engine. Vehicle performance is captured through a tractive-effort analysis which converts engine and transmission performance data to vehicle performance measures. Reliability is modeled through a bottom-up component analysis. The study presents a drive-cycle analysis for the M2A3 to estimate the amount of fuel consumption to provide a sustainability metric. The study found that while some improvement can be realized through changing the engine, a much larger benefit can be gained from modifying both the engine and transmission.

Keywords: Vehicle design, reliability, powertrain analysis

1. Introduction

The U.S. Army takes significant pride in its vehicles, many of which have become synonymous with power and performance. Their official song, “The Army Goes Rolling Along,” even praises the maneuverability of these vehicles. Indeed, modern Army doctrine relies heavily on these vehicles to allow soldiers to maneuver across the battlefield. As such, the U.S. Army modernization effort is pushing for longer range, more versatile, and more efficient vehicles. Inherent in this need for improved vehicles is a need for improved powertrains (Raffa, 2005). Although incremental improvements are possible through capitalizing on recent advances in engine technology, the ambitious modernization goals require a revolutionary powertrain.

This study looks at implementing different engine and transmission configurations into the M2A3 Bradley Fighting Vehicle (BFV). The paper presents a value model that quantifies the benefits of the powertrain upgrades in terms of performance, reliability, and sustainability, three metrics that are key for the U.S. Army. The performance is captured through a tractive effort analysis for each powertrain configuration which converts engine and transmission data into vehicle performance parameters. This study uses a bottom-up component analysis to capture the changes in reliability associated with each powertrain alternative. Finally, the study calculates fuel consumption by modeling the engine requirements over a drive-cycle. The results of the analysis provide insight into the benefit for upgrading the engine, transmission, or both.

2. Background

The M2A3 BFV is produced by BAE Systems Land and Armaments and entered service in 1981 (Grummitt, 2021). It is designed to provide transportation and protection to infantry forces. The Bradley has a three-man crew consisting of a commander, gunner, and a driver and can transport 6 passengers and provide protection from small arms fires. The main weapon of the Bradley is a turreted 25 mm chain gun. The Bradley has a wide range of variants suited for specific missions, including variants for cavalry/scout, air defense, and engineer missions. The Bradley originally had a gross weight of 50,000 lb; however, modernization has called for more technology and heavier armor (Jennings, 2015). Operationally, the vehicle will also have a crew, passengers, equipment, and ammunition, which will make the vehicle much heavier.

The powertrain for the M2A3 BFV, consisting of the engine and transmission, had to be upgraded to account for the increasing weight of the vehicle. The original engine was a repurposed commercial diesel engine that produced approximately 300 hp. The engine has undergone numerous upgrades, including turbocharging, and can now produce upwards to 650 hp.

Meanwhile, the transmission underwent upgrades as well to account for the additional power requirements. The M2A3 BFV powertrain has been repurposed for several other applications. The M109A7 Paladin uses the same powertrain as the M2A3 BFV; however, the requirements for the M109A7 Paladin are significantly more extreme given the size of the main gun and the requirement for carrying ammunition. Additionally, the M1283 Armored Multi-Purpose Vehicle (AMPV) is basically an M2A3 BFV without a turret and with minor modifications in the cabin (Feickert, 2016).

The U.S. Army is already designing the replacement to the M2A3 BFV and the M109A7 Paladin; regardless, these vehicles will likely remain in service for many years. The U.S. Army will likely only replace a portion of the vehicle fleet, opting to modernize the rest, as is currently the approach with the Joint Light Tactical Vehicle. Given the increasing demand on the vehicles and their replacements, it is critical to evaluate the use of alternate powertrains. In particular, upgrades to the powertrain can result in increased vehicle performance, more payload, a smaller logistical footprint, and less fuel consumption.

3. Methodology

3.1. Value Model

This study uses a value modeling approach to evaluate the overall value provided to the U.S. Army by adopting modifications to the powertrain. Fundamentally, a value model takes the users' needs, wants, and desires and organizes them into a value hierarchy, as shown in Figure 1. In this case, the U.S. Army Ground Vehicle System Center (GVSC), who oversees the engineering of the BFV, indicated in interviews that they want to improve the vehicle performance, powertrain reliability, and overall vehicle sustainability. Each of these goals are then put in terms of a value measure. Note that these measures are all put in terms of percent changes from the current system, such that the current system will have values of 0 for each metric. These three value measures map well with the measures of effectiveness for the Optionally Manned Fighting Vehicle, which is slated to be the replacement for the BFV.

The first metric is the percent change in engine margin. Engine margin is the difference in power between what the powertrain can produce and what the vehicle needs to move at a certain speed and grade. The second metric is the percent change in the Mean Miles Between Combat Mission Failure (MMBCMF), which is the average number of miles the vehicle can operate without having a powertrain failure. The third metric is the percent change in fuel consumption. Each design alternative can be evaluated as it pertains to each of these three value measures through models discussed in Section 4. The output models provide raw data that can be converted to a score for that value measure, using the value functions shown in Figure 1. The scores for the individual value measures are then averaged to provide a total value score between 0 and 100 for each design alternative. Note that for this analysis all three value measures were equally weighted.

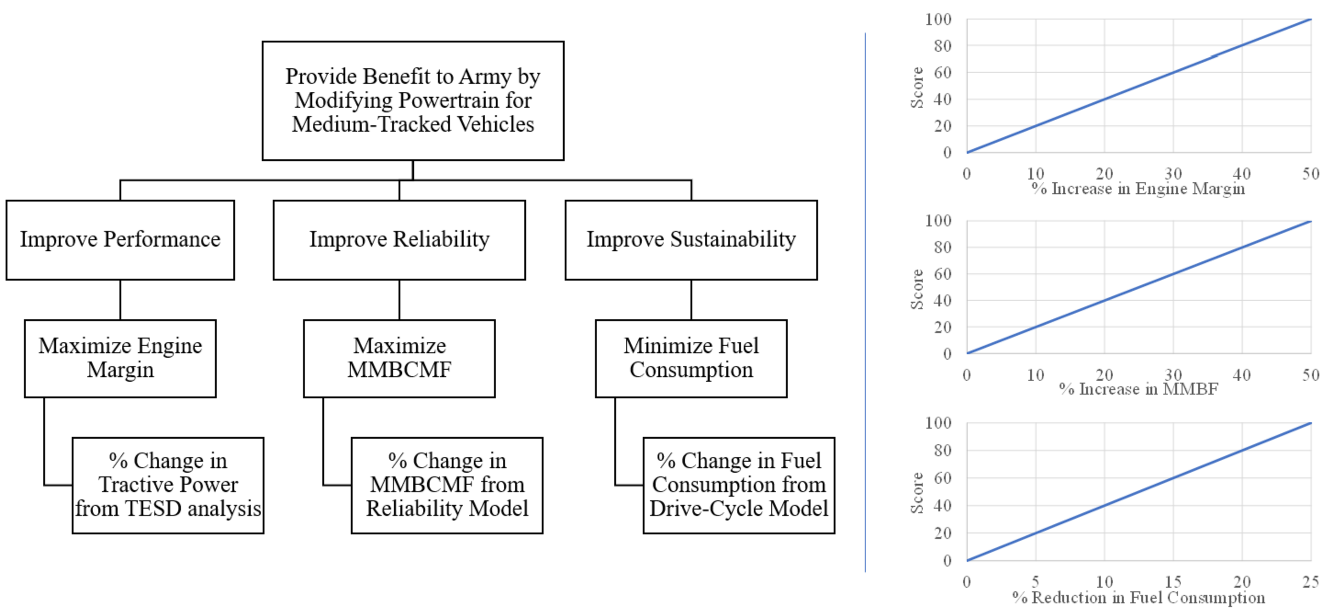


Figure 1. Value hierarchy (left) and value functions (right) for this analysis

3.2 Powertrain Alternatives

An engine powertrain consists of a number of components. The first is the engine itself, and all U.S. Army vehicles use diesel engines that can run on JP-8 jet fuel. The engine generates torque at a given speed typically in the range of 1500-4000 rpm. The output shaft of the engine is connected to a transmission which reduces the engine speed and increases the torque. The transmission shaft then goes to the final drive, which further reduces the engine speed and increases the torque. The final component of the powertrain is the sprocket, which turns the tracks and provide vehicle locomotion.

Table 1 displays the four different powertrain configurations considered in this analysis. The study assumes that there will be no change to the final drive or sprocket. The first configuration is what is currently used in the M2A3 BFV. The engine is a modified commercial diesel engine that provides approximately 650 hp (Grummitt, 2021). The transmission is a specialized continuously variable transmission (CVT) which covers the full range of speeds and torques required by the engine. The second alternative changes the engine to a new, advanced engine that uses a novel geometry to achieve a higher power output and efficiency. The third alternative retains the current engine but changes the transmission to a 32-speed automatic transmission, which is more efficient than the current transmission. The fourth alternative upgrades both the engine and transmission. Note that the actual names for the engines and transmissions are omitted from this paper due to operational security.

Table 1. Different powertrains considered in analysis

Designation	Engine	Transmission	Description
Powertrain A	Current	Current	Baseline – 650 hp, continuously variable transmission
Powertrain B	Upgraded	Current	Upgraded engine with novel geometry and higher power
Powertrain C	Current	Upgraded	Replace CVT with automatic transmission
Powertrain D	Upgraded	Upgraded	Upgrade engine and transmission

4. Powertrain Models

Although powertrain performance is important, the U.S. Army cares more about how the powertrain changes result in changes for the overall vehicle, as evident by the value measures used in this study. As such, modeling was required to translate changes in the powertrain to changes in the vehicle. This analysis required three separate models, each linked to one of the aforementioned value measures.

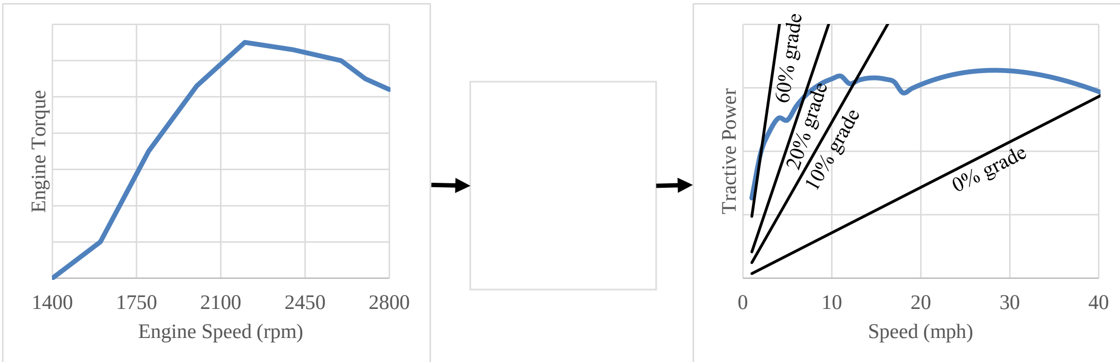
4.1 Engine Performance Modeling

The standard metric for comparing powertrain specifications to vehicle needs is through a tractive analysis (Gillespie, 1992). A tractive analysis, as shown in Figure 2, follows the below steps:

1) Determine the output speed from the transmission as a function of vehicle speed
2) Determine engine speed and torque as a function of vehicle speed based on empirical test data
3) Calculate speed ratio of the transmission (transmission output speed / engine speed)
4) Determine transmission efficiency based on empirical test data
5) Determine the total power output from the engine. Reduce the power output for transmission losses
6) Estimate the power required to drive cooling fan and alternator, and reduce the power output accordingly
7) Calculate the amount of power required to overcome rolling resistance at a given speed and grades
8) Plot the power requirements and the power provided by the powertrain on the same plot

The tractive power diagram, seen in the right figure of Figure 2, provides insight into the vehicle's maximum speed on a given road grade. At a given speed, if the blue line is above the black line, the powertrain can provide more power than what is required to move the vehicle. This term is commonly referred to as engine margin; this excess power can then be used to power additional electronics, accelerate the vehicle, or carry additional payload. The engine margin for this analysis is determined by looking at 3 vehicle conditions The three vehicle conditions selected are: 2 mph at a 60% grade, 6 mph at a 20% grade, and 12 mph at a 10% grade. These conditions were selected based on being the speed-grade combinations where the current powertrain has no margin.

The tractive effort models were validated by experts in military powertrains that have performed similar analyses in the past. Many of the inputs, including the required empirical data was provided by the same subject matter experts.



Power Available for Locomotion (blue)
Power Required for Locomotion (black)

Figure 2. Process for generating tractive power diagram. Torque data from the engine map (left) is used to derive the power available for locomotion (right). Values were removed from the vertical axes for operational security.

4.2 Reliability Modeling

Reliability for military vehicles is typically quantified as the MMBCMF. The overall requirements for a M2A3 BFV is for the vehicle to be able to achieve approximately 500 miles before failure. The allocated MMBCMF for the powertrain is approximately 6,500 miles. The data for the current engine and transmission, which have been fielded, is readily available from Army Depots. However, the Army has not fielded the upgraded engine and transmission used in Powertrains B, C, and D; as such, there is no failure data for these components.

A model was developed to estimate the MMBCMF for the powertrains with an updated engine and transmission. The model broke up the engine into a series of components including turbochargers, injectors, water pumps, and oil pumps. Studies on failure modes of large diesel engines indicate that the injectors and turbochargers are the common culprits for engine failure (Banks, 2001). Additionally, discussions with combat powertrain test engineers indicated that the oil and water pumps are also common components to break for the current systems. The model also accounted for the different components in the transmission and final drive including mechanical clutches, hydrodynamic clutches, planetary gear sets, and standard gear sets.

Since the failure of any single component in the powertrain would result in a system failure, all of the components can be treated as being in series. Furthermore, all components are assumed to be independent and have a reliability that decreases exponentially with time. As such, the model can estimate the MMBCMF for the powertrain based on the MMBCMF for each component using Equation 1.

$$\frac{1}{MMBCMF_{System}} = \sum_n \frac{1}{MMBCMF_{Component}} \tag{1}$$

Of note, for the baseline powertrain, the MMBCMF is driven primarily by the low reliability of the transmission (Gebicke, 1988), especially the hydrodynamic clutches. The upgraded engine does not use hydrodynamic clutches, allowing for a significant increase in reliability.

4.3 Drive-Cycle Analysis

One of the larger benefits of upgrading the engine and transmission is that the powertrain can leverage advances in technology to be more efficient. In turn, this can reduce the amount of fuel consumption. Given the large number of M2A3 BFVs in the fleet, even small changes in efficiency can have very large consequences. However, engine performance and efficiency maps do not readily capture the fuel consumption during a standard movement. As such, this study used a drive cycle analysis as shown in Figure 3. A drive cycle analysis is performed as follows:

1) Find a representative drive cycle consisting of a speed profile and elevation chart.
2) Determine the speed and change in elevation as a function of time in discrete time steps.
3) Determine the power required by the engine based on the change in speed, rolling resistance, air drag, powering electronics, and cooling. Account for losses in the transmission.
4) Determine the efficiency of the engine based on the power draw

5) Calculate the amount of fuel consumed for a given time step
6) Sum up the fuel for each time step to determine the total fuel consumed
7) Divide the distance travel by the total fuel consumed to get the fuel consumption in miles per gallon

A sample drive cycle for a M2A3 was attained from the National Training Center, which tracked vehicle movement during training exercises. The data analyzed includes time increments, speed, total power, incline, and other variables to identify the total speed and engine power. The drive cycle model indicated that the M2A3 BFV consumes approximately 0.69 miles/gallon, in line with what would be expected.

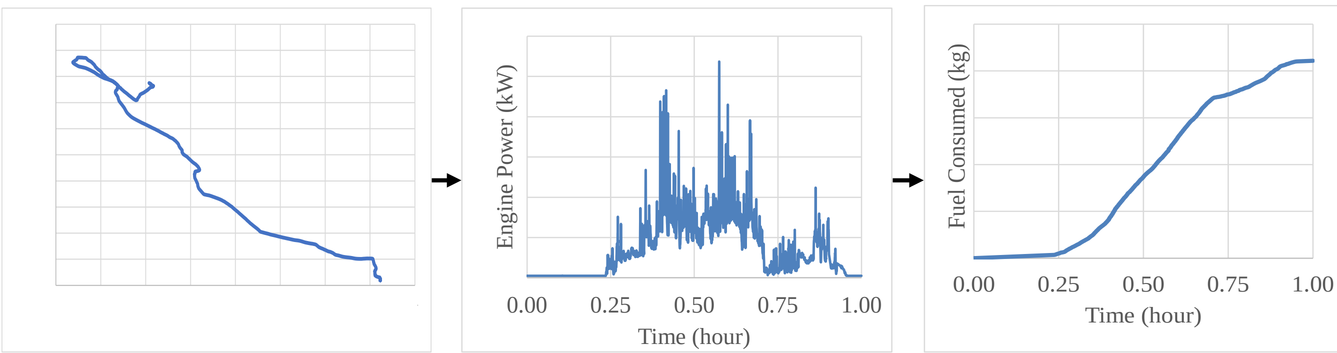


Figure 3. Process for drive-cycle analysis. Position data for a 1-hour BFV movement (left) was used to determine the engine power draw as a function of time (middle), which was then used to calculate the fuel consumption profile (right). Values were removed from the vertical axes for operational security.

5. Analysis and Results

The three models in the previous section yielded the results shown in Table 2 for the four different powertrains. Since Powertrain A is the baseline configuration, these values were compared to real world data to validate the models. As expected, when the powertrain system replaced the transmission and engine with newer, more efficient versions, the available tractive power increased along with the MMBCMF; meanwhile the miles per gallon increased showing an increase in efficiency.

Table 2. Outputs from the tractive effort analysis, reliability model, and drive cycle model

Powertrain Configuration	Tractive Power (kW)			Reliability (MMBCMF)	Fuel Consumption for Drive Cycle (miles/gal)
	12mph, 10%	6mph, 20%	2mph, 60%		
Powertrain A	289.9	249.1	170.8	6,683	0.69
Powertrain B	375.7	334.5	253.7	6,746	0.73
Powertrain C	315.4	317.8	315.5	8,358	0.71
Powertrain D	468.9	484.3	392.2	8,457	0.75

The data from Table 2 was entered into the value model discussed in Section 3 to determine the overall value score for each design alternative shown in Figure 4. As expected, the total value score increases with the engine and transmission upgrades. Note that since the alternatives were evaluated relative to the baseline powertrain, Powertrain A achieves a total value score of 0. All three upgrades showed a large increase in performance. However, the upgraded transmission resulted in a substantial increase in MMBCMF, hence increasing the value in the reliability value measure.

The results indicate that significant value can be achieved from upgrading both the engine and transmission in the powertrain for the M2A3 BFV. However, if this is cost prohibitive and the U.S. Army must choose to upgrade either the transmission or engine, there is more value in upgrading the transmission.

ISBN: 97819384962-2-6

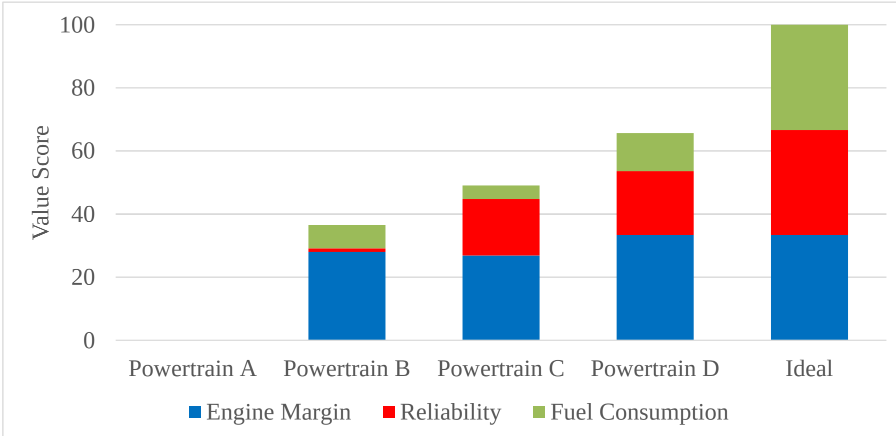


Figure 4. Value Score for the different powertrain alternatives

6. Conclusions and Future Work

Medium-tracked vehicles, especially the M2A3 BFV, will remain in the U.S. Army fleet for the foreseeable future. Upgrades to the powertrain can result in the vehicle having higher performance, increased reliability, and less fuel consumption. This study set out to use value modeling to evaluate the benefits of upgrading the powertrain for the family of medium-tracked vehicles. These benefits are quantified by changes in performance, reliability, and sustainability. Vehicle performance was captured through a tractive-effort analysis which converts engine and transmission performance data to vehicle performance measures. Reliability was modeled through a bottom-up component analysis. The study presented a drive-cycle analysis for the M2A3 to estimate the amount of fuel consumption to provide a sustainability metric. The study concluded that significant benefit can be realized from upgrading the powertrain for the M2A3 BFV. However, if only one powertrain component can be upgraded, the larger benefit comes from upgrading the transmission due to the current transmission's low reliability.

Future work will look at other engines and transmission configurations. This study focused on the current engine and a novel engine; however, there are several fielded engines that could be viable alternatives as well. The study will also factor in life-cycle costing to evaluate the trade-off between cost and value for the different powertrains. Finally, the study will also evaluate hybrid powertrains to identify the benefits associated with electrification.

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