2020-01-0173 Published 14 Apr 2020

Energy, Fuels, and Cost Analyses for the M1A2 Tank: A Weight Reduction Case Study

John L. Sullivan EcoSpherica LLC

Geoffrey M. Lewis and Gregory A. Keoleian University of Michigan

Rob Hart CCDC Ground Vehicle Systems Center

Citation: Sullivan, J.L., Lewis, G.M., Keoleian, G.A., and Hart, R., "Energy, Fuels, and Cost Analyses for the M1A2 Tank: A Weight Reduction Case Study," SAE Technical Paper 2020-01-0173, 2020, doi:10.4271/2020-01-0173.

Abstract

Reducing the weight of the M1A2 tank by lightweighting hull, suspension, and track results in 5.1%, 1.3%, and 0.6% tank mass reductions, respectively. The impact of retrofitting with lightweight components is evaluated through primary energy demand (PED), cost, and fuel consumption (FC). Life cycle stages included are preproduction (design, prototype, and testing), material production, part fabrication, and operation. Metrics for lightweight components are expressed as ratios comparing lightweighted and unmodified tanks. Army-defined drive cycles were employed and an FC vs. mass elasticity of 0.55 was used. Depending on the distance traveled, cost to retrofit and operate a tank with a lightweighted hull is 3.5 to 19 times the cost for just operating an unmodified tank over the same distance. PED values for the lightweight hull are 1.1 to 2 times the unmodified tank. Cost and PED ratios decrease with increasing distance. Fuel savings from lightweighting do not offset lightweight part production and retrofitting costs for realistic distances. A life cycle refurbishment/refitting analysis of these components was conducted to evaluate part production and operational impact differences between lightweight and heavier components. The cost ratio between lightweight and heavier hull varies (with distance) from 1.58 to 1.96 and the PED ratio ranges from 1.0 to 1.07. These ratios are more favorable than those above, primarily due to the inclusion of upstream life cycle stages for unmodified tanks. Lightweighting decisions usually consider cost and energy tradeoffs, but other logistical and mission-oriented objectives are also critical in deciding to lightweight vehicles, especially military ones.

Introduction

The United States Army is charged with the development and maintenance of an effective fighting force enabled with modern technology and capable of rapid deployment. The Abrams M1A2 main battle tank is an important component of this fighting force and keeping its performance up to date is critical. Over the past few decades the M1A2 has become progressively heavier, impacting its transportability, mobility, and the amount of fuel needed to operate and support it. A lighter tank would be easier to deploy and more operationally effective, e.g., more mobile and capable of safely traveling over bridges. A recent U.S. Army study utilized the combat modeling software One Semi-Automated Forces (OneSAF) to observe the influence of combat vehicle weight on the operational effectiveness in an urban ambush scenario [1]. In this study, the lighter weight vehicles (assuming equivalent survivability) were able to maneuver out of the kill box more quickly, which reduced the number of hits sustained and increased overall combat effectiveness. Given operational benefits of lightweighting, the Army is exploring ways to reduce the current mass of (i.e., lightweight, or LW) the M1A2 tank while maintaining its lethality, survivability, and mobility. A more detailed discussion of the impact of tank mass reduction on programmatic and operational considerations has been presented by Gerth and Howell [2].

The Combat Capabilities Development Center Ground Vehicle Systems Center (CCDC GVSC) of the U. S. Army has identified three candidate tank components for mass reduction: hull, suspension, and track. Since such changes generally have system-wide impacts, the Army wants to estimate the difference in cost, primary energy demand (PED), and fuel consumption (FC) for lightweighting these tanks but also for operating them over their lifetimes. Hence, these cost and energy metrics are best evaluated within life cycle assessment (LCA) and cost (LCC) frameworks.

LCAs for cars and light duty trucks have been conducted, mostly by the auto industry, in efforts to quantify the environmental performance benefits of advanced vehicle design and engine initiatives (including lightweighting). An early example is the "generic vehicle family sedan" life cycle inventory analysis [3], and since then numerous other LCA studies on cars and light duty trucks have been conducted [4, 5]. LCA studies have also been conducted for a wide range of vehicles, including trains, heavy and medium duty trucks, buses, jet aircraft, and ships [6, 7, 8]. All of these studies not only quantified the impact of mass reduction on vehicle fuel consumption

(FC) but also the energy and emission impacts associated with material choices and associated part production processes.

The Army's approach for lightweighting the M1A2 is to upgrade existing tanks with lighter weight components, such as the three cited above, and to evaluate the tradeoff between any increase in production burdens and any operational benefit for lighter weight components. Conducting cost, energy, and fuel analyses on a set of lightweighting scenarios can help the Army identify good lightweighting options that better meet important programmatic and operational objectives [2].

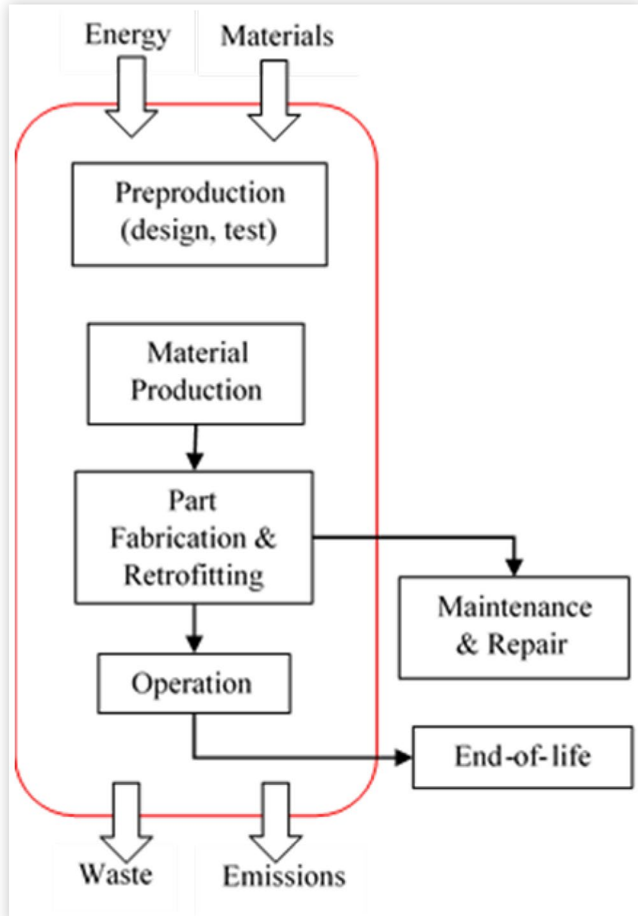
The purpose of this study is to estimate cost, PED, operational fuel use, and greenhouse gas emissions (GHG) metrics for lightweight tanks (LWT) and compare them to those for existing unmodified (base case) tanks (BCT). GHG emissions were tracked but are not reported here. The study focuses specifically on quantifying the impacts of tank mass reductions on these metrics through the use of lightweight materials on three separate tank components. The three components considered were the hull, suspension, and track, and these components were analyzed individually (not in combination). The analysis aims to determine whether the fuel savings from LW offsets any increased cost associated with manufacturing LW components and whether the increment in PED for LW components is recovered during tank operation. Compared to prior studies that focused on mission-specific impacts of combat vehicle lightweighting [1], this weight reduction case study uses a holistic approach to capture the engineering, manufacturing, and operational cost impacts of lightweight technologies over the entire lifecycle of the vehicle. The methods and results in this study provide a foundation to inform future vehicle weight-related studies, directly addressing a knowledge gap identified by the Army's Lightweight Combat Vehicle Science and Technology Campaign [9]. We pursue these aims through two separate analyses, the first comparing the impacts of designing, building, retrofitting lightweight components, and operating a lightweighted tank with the impacts of operating a base case tank, and the second evaluating the production of lightweight and conventional parts and the operation of lightweighted and base case tanks.

Methods

The LCA framework employed for this study is shown in Figure 1. The life cycle stages included in the analysis were preproduction, material production, part fabrication and vehicle assembly, and tank operation. The end-of-life stage and routine maintenance and repair activities such as oil changes, batteries, etc. were not included as they were assumed to be identical for the base-case and LW vehicles. Because our focus is on upgrades and refitting the fleet of existing tanks, burdens incurred during the original construction of the tank were not included.

Specific activities included in these life cycle stages are: 1) preproduction, which includes technical, engineering, and manufacturing development, and prototype testing, 2) tank component production comprising material production and

FIGURE 1 System boundary (in red) and life cycle stages used in the evaluation of lightweight M1A2 tank components.



component fabrication, and 3) tank operation. The operational stage was evaluated according to three Army-defined drive cycles (time, speed, and distance profiles), each set of three to be executed once a decade for up to three decades. For brigade analysis, the operation of 84 tanks and their shipment along with required fuels 100 miles to the training site by rail are included. All fuels used for shipping are assumed to be diesel; tanks are assumed to use Jet A fuel. Tank mass is assumed to be 74 short tons [10], with a unit cost of around $9 million [10], and an average fuel consumption of around 3.1 gallons/mi over the duty cycles used here. A spreadsheet model was built for this analysis, and results are presented for both a single tank and a brigade of 84 tanks.

Tank operational duty cycles are a set of speeds, distances, and road types (primary, secondary, or cross-country). These duty cycles included a range of speeds, distance, and terrain type and were intended to be representative of the movement, fuel use, and costs of operating M1A2 tanks during peacetime operations. Per-tank distances used in the three cases for this study are:

Case 1 - Low usage: 2,023 miles driven over 1 decade.
Case 2 - Moderate usage: 2,555 miles driven over 1 decade.
Case 3 - High usage: 4,578 miles driven over 1 decade.

Fuel costs incurred during these time periods are distributed evenly over each 10, 20, and 30 year period, respectively.

All costs developed here include inflation and were discounted back to $FY2019.

The two energy metrics reported here are PED and operational fuel use. PED denotes primary energy demand, which is the sum of all primary energy resources (coal, oil, natural gas, renewables) used to provide fuels for making materials and products or providing services, including for vehicle operation. PED also includes all the energies needed to produce the energy carriers (gas, oil, gasoline, diesel, Jet A, electricity). Two types of vehicle fuel consumption (FC) were also tracked: FC for the tanks and FC to transport tanks and fuel to training locations via rail and heavy duty truck, respectively. We include costs incurred over the vehicle life cycle, presented as $FY2019. These costs arise from part production and fuel use for operations and transportation.

PED values for the production of relevant raw materials were taken from Argonne National Laboratory's GREET2 model [11], and PED values for fuel production were taken from GREET1 [12]. Titanium data came from the literature [13]. Material costs for the LCC analysis came from Army sources (R. Hart, CCDC GVSC). Fuel prices were taken from [14]. Unlike LCI material production data, which are based in physical science, material costs tend to be quite variable over time and quite dependent on market forces. Lightweight material production and fabrication metrics are shown in Table 1, where they are expressed relative to a component made with the original material on the unmodified base case tank (BCT). For example, the LWT hull weighs 88% of the BCT hull but costs a little over 2 times as much, including both material and fabrication costs. The fractions listed in the mass column of Table 1 are substitution ratios (f), i.e., f units of substituting material mass replacing one unit of existing material mass. Production efficiencies for making parts (material out/material in), were assumed to be 0.85 for all fabrication processes. PED values for part fabrication operations tend to be relatively small.

To quantify the dependence of tank FC (gal/mi) on tank mass, fuel/mass elasticities (defined in Eq. 1) were employed.

$$\varepsilon_{fm} = \Delta FC \cdot M / \left(\Delta M \cdot FC\right) \tag{1}$$

Fuel/mass elasticities are dependent on both terrain and tank operating mode. The value used here is 0.55, which is an average value for movement over the various surfaces in the duty cycles. Gerth and Howell [2] reported a value of 0.447 for unspecified terrain. Not only do tanks consume fuel while driving, they also consume considerable fuel while idling. Since this study is focused on tank FC impacted by mass reductions, idling was not included in this study.

Estimated costs and fuel use were based on fuel intensity (F_{int}) values for rail and heavy truck, shipping distances, mass being shipped, and a rule of thumb developed for this study based on the literature [15, 16, 17]. The rule assumes that 17% of transportation costs were due to fuel costs.

Equation 2 represents life cycle environmental and cost stocks and flows for a tank (B_{tk}):

$$B_{tk} = B_{pp} + B_{mp} + B_{fb} + B_{op} \tag{2}$$

where B is a generic symbol used here to represent life cycle burdens (fuels, PED, GHG, and cost). Subscripts denote life cycle stages: "pp" for preproduction, "mp" for material production, "fb" for part fabrication, and "op" for vehicle operation.

The engineering and manufacturing development effort and prototype testing associated with B_{pp} was allocated across 1,600 tanks (R. Hart, CCDC GVSC). Of PED, fuels, and cost values, B_{pp} costs are the most significant. Otherwise, PED and fuels are small to negligible when compared to those from the other life cycle stages for each LW scenario. In the suspension and hull cases, preproduction costs are around 1% of total costs, whereas they are around 30% for the LW track scenario.

For the unmodified (BCT) tank, equation (2) becomes:

$$B_{BCT} = \alpha \cdot FC\left(M_{BCT}\right) \cdot DST \tag{3}$$

where FC is a linear function of tank mass (FC = A + dFC/dM · M_{BCT}), and the constant α denotes a set of three factors for converting FC to cost, GHGs, or PED. DST is distance driven. The "A" term in the FC equation is dependent on accessory load, aerodynamic drag, and other vehicle system loads. The term dFC/dM is computed from an appropriate elasticity, i.e., $\varepsilon_{fm} \cdot FC_{bc}/M_{bc}$.

For a LWT, the burden expression is written as:

$$B_{LWT} = B_{pp} + B_{mp2} + B_{fb2} + \alpha \cdot FC\left(M_{BCT} + \Delta M_{tk}\right) \cdot DST \tag{4}$$

where ΔM_{tk} is the change in tank mass, $(M_2 - M_1)$, from replacing an existing material 1 with a lower mass material 2. The burden terms B_{mp2} and B_{fb2} are computed from mass dependent usage rates for material 2 such as b'_{mp2} (e.g., 18.8 MMBTU/ton of hot rolled steel plate) where $B_{mp} = b'_{mp2} \cdot M_2$. Though Eq. (4) covers four life cycle stages and Eq. (3) only one (operation), we nevertheless report results in the form of B_{LWT}/B_{BCT} values as B_{BCT} is the basis of comparison employed here. These ratios reflect the additional burdens from retrofitting and operating LWTs relative to operating BCTs. Note that Eq. (3) comprises only a variable term (dependence on DST), whereas Eq. (4) has both fixed and variable terms.

Another way to treat tank lightweighting is to consider a refurbishment/refitting operation where two options are available to replace one of the three components considered here (hull, suspension, or track). Each of these components could be replaced by a component made either from conventional

TABLE 1 LWT material production plus fabrication mass, cost, and energy values over BCT counterpart values

	Mass Input	Cost	Energy	
Component	$f=M_{LWT}/M_{BCT}$	$\$_{LWT}/\$_{BCT}$	PED_{LWT}/PED_{BCT}	Comment
Hull	0.88	2.1	1.2	Steel Alloys
Suspension	0.75	1.02	1.4	Multi-material
Track	0.91	0.94	0.91	Steel Alloys

materials or lightweight materials. For that circumstance, we write a difference expression:

$$\Delta B_{tk} = \{[(b'_{mp1}/C_{fb1} + b'_{fb1}) - (b'_{mp2}/C_{fb2} + b'_{fb2}) \cdot f]/(1-f) + \alpha \cdot dFC/dM \cdot DST\} \cdot \Delta M_{tk} \quad (5)$$

where factors for both the original material 1 and lightweight material 2 are included and the component burdens are a function of the difference in the conventional and lightweight material burdens.

To quantify the additional costs, PED, and fuel values to retrofit and operate a brigade (BRG_{LWT}) of LWTs or to just operate a brigade of BCTs, we write:

$$BRG_{tk} = n_{tk} \cdot \{B_{tk} + \alpha \cdot DST_{trnp} \cdot [R_{int} \cdot M_{tk} + HDT_{int} \cdot Fuel_{tk}]\} \quad (6)$$

where n_{tk} is the number of tanks, R_{int} is the fuel intensity of rail to deliver a tank to the site of operations, HDT_{int} is the fuel intensity to deliver fuel to the site, DST_{trnp} is the transport distance from the tank's home base to the site of operations, and $Fuel_{tk}$ is the mass of fuel per tank needed for its operation. Note that $Fuel_{tk}$ is dependent on tank mass. For simplicity, we assume that DST_{trnp} is the same for both tank and fuel transport. Consistent with our individual tank analysis, Eq. (6) can be readily used for computing BRG_{LWT}/BRG_{BCT} values.

Note that material changes and refurbishments come with a cost. Lightweighted vehicles, including tanks, use less fuel and thus offer some cost offsets from fuel savings to the retrofitting cost. However, the motive for lightweighting tanks also includes improved operational (faster on station, use less fuel, weigh less), logistical (compatible with bridges, roads, and rail), and programmatic benefits. These benefits are not included this study, but are significant components of the decision to lightweight a vehicle, especially a military one. The two logistical considerations we have included are transport of tanks by rail and delivery of fuel via heavy truck to site of operations.

Results and Discussion

Mass reductions for the three components proposed for lightweighting are: 12% for the hull, 25% for the suspension, and 8% for the track. The percent changes in part mass, tank mass, fuel consumption (FC), and brigade fuel consumption between base and lightweight cases are given in Table 2, with fuel consumption being measured over three decades of operation. The largest percent decrease of tank mass is observed for the hull. The percent decreases in tank mass for the other components are quite small. Percent changes in fuel costs, not listed in the table, are identical to FC reductions, due to a direct relationship between fuel used and cost. Percent brigade FC reductions over three decades is only slightly less than tank FC reductions due to some brigade fuel being consumed in vehicles other than tanks. This is evident only for the hull case due to the magnitude of its mass reduction.

In the figures that follow, we denote duty cycle/decade period scenarios by total distance traveled, DST. These values are sufficiently unique to clearly define each duty cycle/decade scenario by its DST. More specifically, 2,023 miles denotes Case 1 (low usage) for 1 decade; 5,110 denotes Case 2 (moderate usage) for 2 decades (2 x 2,555); 6,069 represents Case1 for 3 decades (3 x 2,023); and finally 13,734 represents Case 3 (high usage) for 3 decades (3 x 4,578). To facilitate a comparison of LWTs to their BCT counterparts, we present a series of relative plots for costs, fuel used, and PED values, i.e., B_{LWT}/B_{BCT}.

TABLE 2 Listing of percent reductions in part and tank masses and percent reductions in tank FC and brigade fuel use over three decades.

Component	$\%\Delta M_{prt}$	$\%\Delta M_{tk}$	$\%\Delta FC_{tk}$	$\%\Delta FC_{brg}$
Hull	12	5.1	2.8	2.4
Suspension	25	1.3	0.8	0.8
Track	8.4	0.6	0.3	0.3

M1A2 Upgrades with LW Materials

Figure 2 shows the relative costs to retrofit and operate an Abrams M1A2 tank over the duty cycles described above for three separate lightweight components. Note that the costs to retrofit the hull and operate the LWT range from 3.5 to about 20 times the costs to operate the BCT. The cost ratio ranges for the suspension and track scenarios are 1.8 to 6.8 and 1.2 to 2.5, respectively. In all three scenarios, the cost ratios decrease with increasing DST. This is due to the progressively decreasing relative magnitude of component production costs (fixed costs term) relative to increasing operating costs (variable costs term) as DST increases. Also note that the magnitude of the cost ratio ranges decreases with decreasing magnitude of tank mass reduction, which is considerably less for the suspension and track scenarios than for the hull (Table 2). Overall, we find that the magnitude of the cost ratio ranges for all three scenarios is dependent on the amount of the mass reduction and life time distance traveled. Within practical lifetime distances traveled by the tanks, fuel saving

FIGURE 2 Relative costs (B_{LWT}/B_{BCT}) for retrofitting and operating a LWT over various DSTs

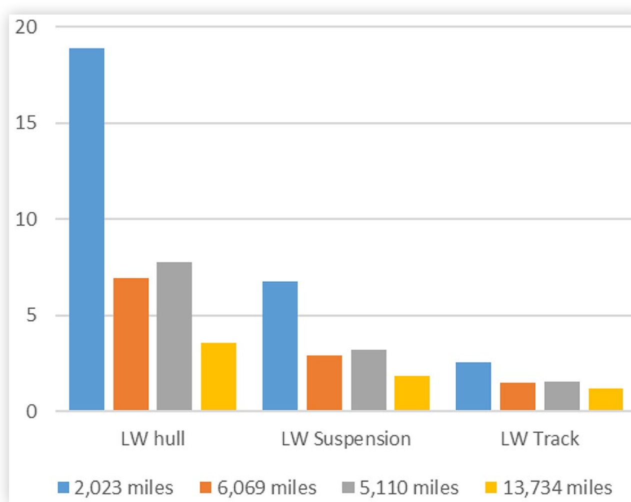
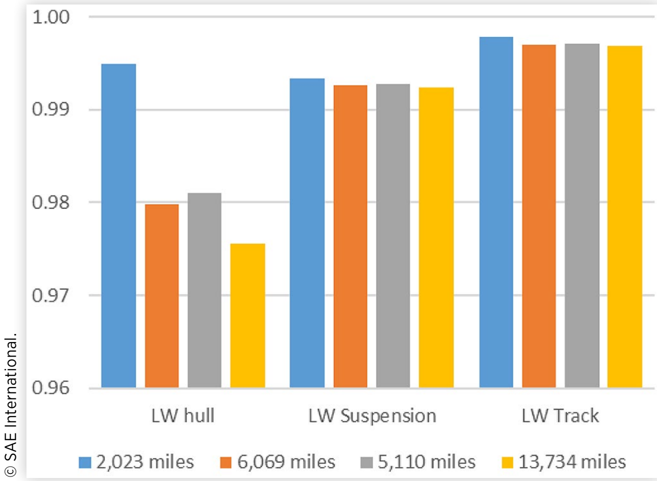


FIGURE 3 Relative fuel use (B_{LWT}/B_{BCT}) for the LWT over the BCT operated over various DSTs



costs due to retrofitting can only partially offset the costs incurred in making the lightweight components. Hence, the lightweighting costs for these components must be considered an investment towards improving their programmatic and operational performance.

Figure 3 illustrates the relative fuel use dependence of the LWT vs. the BCT. The fractional changes in fuel use for each of the lightweighting scenarios inferred from the figure (1 - B_{LWT}/B_{BCT}) are reasonably consistent at the largest DST with the % ΔFC values given in Table 2. Departures from the FC percentage reductions given in Table 2 (most conspicuous for the hull scenario) increase with decreasing DST. This is a result of a decreasing operational (variable) fuel term with decreasing DST for B_{LWT} and a constant fixed fuel term resulting from retrofitting and production activities.

PED results are shown in Figure 4. PED includes not only energy burdens associated with fuel use during tank operation but also the total energy associated with producing lightweight materials and fabrication of parts (not the incremental energy when compared with the conventional components). This is

FIGURE 4 Relative PED values (B_{LWT}/B_{BCT}) for retrofitting and operating a LWT over various DSTs

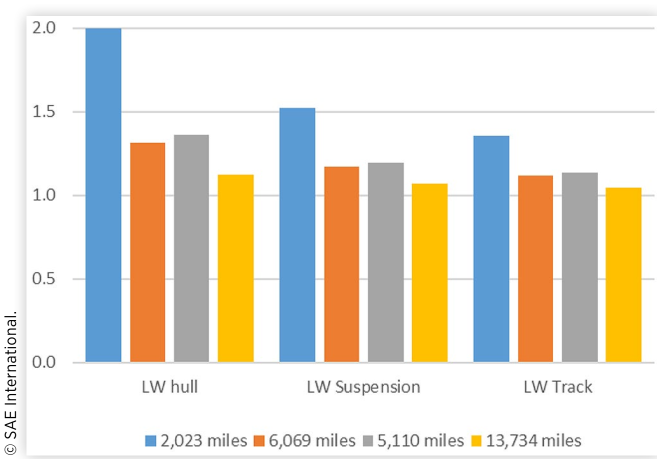
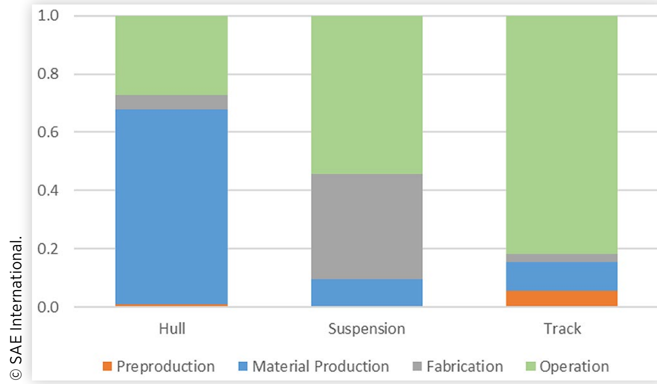


FIGURE 5 Fractional costs for upgrading the M1A2 with lightweight components over duty cycle 3 over 3 decades



why the relative PED values shown in the figure are greater than unity for all three scenarios. Further, like the trends shown above, the PED values for each lightweight scenario decrease with increasing DST. This behavior is due to increasing variable terms in B_{LWT}/B_{BCT} with increasing DST and a constant fixed term.

The relative costs associated with developing, retrofitting, and operating the M1A2 with a lightweight hull, suspension, or track are shown in Figure 5. The figure illustrates that as the magnitude of the mass reduction increases, the relative costs for developing and retrofitting (material production and part fabrication) also increase, the most for the hull and the least for the track. Because mass reductions range from 0.6 to 5.1 percent of total tank mass, only small improvements in FC can be expected given that the overall tank mass has changed little. However, the substantial magnitude of fuel used to operate the tank indicates that fuel saving costs (2.8%, 0.8%, and 0.3% for hull, suspension, and track, respectively) are a small fraction of the fuel fraction (green bars) shown in Figure 5, and hence, can only partially offset retrofitting costs.

Lightweighting M1A2 Impacts on Brigade Metrics

As per Eq. (6), brigade (BRG_{tk}) PED, fuels, and cost burdens are dependent on tank numbers, tank mass, distance transported, and assets needed to transport tanks and fuel to a site of operations. In the case of the LWT, burdens for retrofitting (material production, part production, and associated PED, fuels and cost) are included. However, an important subcomponent of Eq. (6) is brigade transportation fuels and costs for tank operation and for logistical purposes (transport tank and fuels to the operational site). The only transport (shipping) costs included in this study are those dependent on tank mass. We find for a brigade of either LWTs or BCTs that the cost to transport its tanks 100 miles is around 2% of brigade transportation expenditures, whereas it is around 10% for a 500 mile shipping distance. This dependence of brigade transportation costs with distance are represented by the DST_{trnp} term in Eq. (6). Our analysis also shows that the primary impact of lightweighting tanks on the brigade transportation expenditures is savings in fuel and costs. For example, our LWT hull scenario yields about a 3% transportation cost savings over that for a brigade of BCTs. This percentage is dependent on the tank mass ratio M_{LWT}/M_{BCT}, and is independent of transport distance or the number of decades of operation considered. The other lightweight scenarios (suspension and track) provide less benefit due to their lower tank mass reduction. Due to the dominance of the n_{tks} term in Eq. (6), the trends in the B_{LWT}/B_{BCT} ratios recorded above in Figures 2 - 4 for LWT vs. BCT individual tanks are sensibly the same for brigades of tanks.

M1A2 Upgrades with a Choice of Materials

We now explore a refurbishment/refitting case where there is a choice to replace the hull, suspension, or track with either a lightweight component or one made from the original heavier materials. This case considers the production burdens of both original and lightweighted components as well as the operational burdens associated with the different components. Whatever the choice, all other tank components and systems are assumed to be the same. Unlike the B_{LWT} vs. B_{BCT} analysis above where only operational burdens were included for the BCT, in this case both lightweighted and original components are compared across the same life cycle stages (material production, part fabrication, and operation). Preproduction for the original heavier components was not considered, but preproduction for lightweight components was included here.

To avoid confusion with the previous analysis, our ratios for this analysis are labeled B_{LWT}/B_{OMT} where OMT denotes a tank refitted with parts made of the original (heavier) materials. B_{OMT} is computed from Eq. (4), but using material production and fabrication data for the original materials. To compute ΔB_{tk} values, eq. (5) is used. Figure 6 presents the PED ratios for this B_{LWT}/B_{OMT} analysis. Notice in the figure that the ratios are generally greater than unity for the hull and suspension components whereas the ratios for the track are less than unity. The reason for this is that the lightweight materials employed for the hull and suspension have greater energy requirements than the materials used in parts for the original tanks. On the other hand, for the track, the same materials are used for both lightweighted and original parts except the lightweight track uses less of them. As DST increases, the relative PED for the track increases, converging to a value less than unity $(1 - \Delta M_{tk}/M_{tk})$.

Like Figure 4, Figure 6 shows a clear dependence of PED ratios on distance driven. Notice that the hull value at 13,734 miles is less than unity. The reason for this is that the fuel savings due to lightweight material of the LW hull have offset the extra energy needed to make the lightweight materials vs. those for making the heavy hull. In fact, the breakeven distance for the hull is about 13,000 miles. This breakeven is where the distance driven is sufficient for $\Delta PED_{mp/fb} = \Delta PED_{op}$. As DST increases, the lightweight components accumulate additional energy savings. Breakeven distance values will vary depending on the metric being used. For costs the breakeven distance for the hull is about 650,000 miles, a value well out of the lifetime distance range driven by tanks. Breakeven distances are dependent on the difference between the fixed and variable terms in Eq. (5), but in the case of cost the difference in fuel and material costs tends to be quite variable and dependent on market forces. On the other hand, breakeven distances from PED (or GHG or fuel) values are more meaningful on a life cycle basis as they are governed by the physics and chemistry of material and component production processes and the mass vs. FC dependence of the vehicle.

B_{LWT}/B_{OMT} cost values shown in Figure 7 range from around double for the hull to around unity for the suspension, with values for the track being slightly greater than unity. B_{LWT}/B_{OMT} values for the suspension are nearly constant with DST due to a fortuitous near equal magnitude of fixed and variable term coefficients in B_{LWT} and B_{OMT}. For the hull and track, the B_{LWT}/B_{OMT} values decrease with increasing DST as expected, due to the increasing dominance of the variable terms relative to their respective fixed terms.

We found that for preproduction cost values, only those for the lightweight track are significant, and they are negligible for hull and suspension. Preproduction PED and fuel values for all three components are negligible. The fixed component

FIGURE 6 Relative PED values (B_{LWT}/B_{OMT}) for refurbishing/refitting and operating an LWT over various DSTs

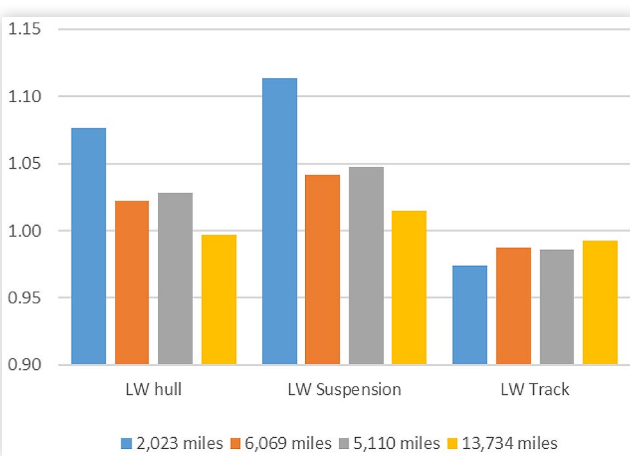
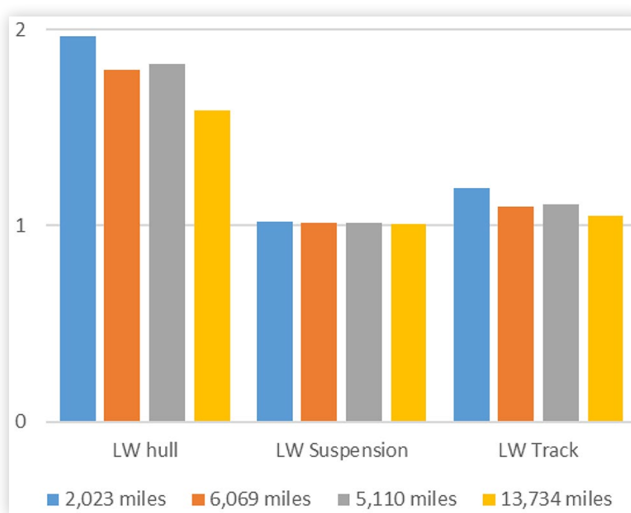


FIGURE 7 Relative cost values (B_{LWT}/B_{OMT}) for refurbishing/refitting and operating an LWT over various DSTs



of B_{LWT} contains preproduction contributions but B_{OMT} does not, so the track case B_{LRT}/B_{OMT} cost values are never less than unity despite less of the same material being used.

An important consideration for life cycle assessments of a vehicle is sensitivity to costs, especially fuel costs. For our tank system, a 50% increase in fuel costs increases the operating fuel costs of the unmodified tank by 50%. On the other hand, for the tank with a lightweighted hull, its operating fuel costs also increase by 50%. However, the cost ratio (B_{LWT}/B_{BCT}) now ranges from 13 to 2.7 instead of its original range of 19 to 3.6. This applies to the distance range used throughout this paper. i.e., from 2,023 to 13,734 miles. As expected, the reduced fuel cost ratios with increasing fuel costs reflects a decreased relative magnitude of the fixed term (retrofitting).

Keep in mind that any refurbishment or refitting of these tanks carries considerable cost, fuel, and PED burdens that are incurred whether or not LW or original material parts are used. Our B_{LWT}/B_{OMT} assessment compares the two options: lightweight or original (heavier) components.

Conclusions

This study assessed the costs, energy use, and fuel consumption impacts of replacing hulls, suspensions, and tracks made of lightweight materials on the M1A2 tank. All results are presented on a relative basis using the operational fuels, costs, and PED equivalences for the existing unmodified base case M1A2 tank. Life cycle stages included for the lightweighting scenarios are pre-production, material production, part fabrication, and operation. All lightweighting component scenarios were analyzed separately. Operational duty cycles were provided by the Army. Material life cycle data were taken from the literature.

The retrofitting weight reduction scenarios resulted in 12%, 25%, and 8.4% reductions in hull, suspension, and track mass, respectively, yielding corresponding 5.1%, 1.3%, and 0.6% reductions in tank mass. Based on fuel/mass elasticities provided by the Army for the M1A2, these tank mass reductions induced 2.8%, 0.8%, and 0.3% reductions in fuel consumption, respectively. The reductions in fuel consumption, energy use, and associated costs induced by tank lightweighting increase with increasing mass reduction, fuel cost, and tank distance driven over their lifetimes. Due to the amount of hull mass reduction and associated material cost, it was the most expensive part to lightweight. Though incremental costs for all three lightweighting scenarios are net positive, some payback is realized from fuel savings due to lightweighting. As expected, all lightweight scenarios realized at least some fuel consumption savings relative to the base case.

Tanks with lightweight hulls did reduce transportation costs and fuel needs for brigade exercises by about 3% over those for a brigade of base case tanks. Transportation costs and fuels can amount to about 2% of total brigade fuels and transport costs for a 100 mile shipment distance and 10% for a 500 mile distance.

The refurbishment scenario involved a more direct comparison of lightweighted and original hull, suspension, and track and the effect of component choice on operational burdens. When making a tank component from either original or lightweight materials, a lightweight component generally has greater production and fabrication costs and PED values, but results in a tank using less fuel than one built with original heavier components. In the hull scenario, PED for the lightweighted tank becomes less than that for the heavier tank at about 13,000 miles of tank travel due to its lower FC. Track lightweighting yielded immediate PED savings relative to a track replaced with original materials, since less of the same material is used for the lightweighted case.

Whenever a component is replaced, whether with lighter or original weight materials, there will always be costs and energy consumption associated with the replacement. Lighter weight materials offer fuel savings, which are dependent on the amount of mass reduced, and they can offset retrofitting and refurbishing costs and energy consumption. Despite these extra costs, the motive to lightweight is dependent on logistical and operational effectiveness of tanks for meeting their mission. As the Army looks toward modernizing the combat vehicle fleet, there is an urgent need to add performance at the lightest weight possible, as well as find weight reduction opportunities elsewhere in the vehicle [9]. As evidenced by this current study, the most cost effective time to implement lightweight solutions is in the design phase of a new program of record, because the engineering and manufacturing costs of a retrofit may never be recovered through lifecycle cost savings.

References

1. Hart, R.J. and Gerth, R.J., “The Influence of Ground Combat Vehicle Weight on Automotive Performance, Terrain Traversability, Combat Effectiveness, and Operational Energy,” in *Ground Vehicle Systems Engineering and Technology Symposium*, 2018.
2. Gerth, R. and Howell, R., “What is a Ton of Weight Worth? A Discussion of Military Ground System Weight Considerations,” *SAE Technical Paper 2017-01-0270*, 2017, 2017, https://doi.org/10.4271/2017-01-0270.
3. Sullivan, J.L., Williams, R., Yester, S., Cobas-Flores, E. et al., “Life Cycle Inventory of a Generic U. S. Family Sedan: Overview of Results of USCAR AMP Project,” SAE Technical Paper 982160, 1998, 1998.
4. Koffler, C. and Rohde-Brandenburger, K., “On the Calculation of Fuel Savings Through Lightweight Design in Automotive Life Cycle Assessments,” *Int. J. LCA* 15:128-135, 2010.
5. Kim, C., Wallington, T., Sullivan, J.L., and Keoleian, G.A., “Life Cycle Assessment of Vehicle Lightweighting: Novel Mathematical Methods to Estimate Use-Phase Fuel Consumption,” *Environ. Sci. & Technol.* 49:10209-10216, 2015.
6. Sullivan, J.L., Lewis, G.M., and Keoleian, G.A., “Effect of Mass on Multimodal Fuel Consumption in Moving People and Freight,” *Transportation Research Part D* 63:786-808, 2018.
7. Delmore, A., Karbowski, D., Vigayagopal, R., and Sharer, P., “Evaluation of Fuel Consumption Potential of Medium and

Heavy Duty Vehicles though Modeling and Simulation," Report to the National Academy of Science, October 23, 2009, Contract No: DEPS-BEES-001.

8. Helms, H., Lambrecht, U., and Hopfner, Energy Savings by Lightweighting - Final Report, Institute for Energy and Environmental Research, 2003.
9. Hart, R., Thyagarajan, R., O'Brien, D., Littlefield, A., and Robeson, M., "A Summary on the 2018 Update to Lightweight Combat Vehicle S and T Campaign," No. 2208, U.S. ARMY CCDC GVSC (FORMERLY TARDEC), Warren, MI, 2019.
10. Abrams, M., Wikipedia, https://en.wikipedia.org/wiki/M1_Abrams, accessed April 12, 2018.
11. GREET2, "Greenhouse Gas, Regulated Emissions and Energy in Transportation (GREET2) Model," Argonne National Laboratory, 2017, http://greet.es.anl.gov/greet_2_series.
12. GREET1, "Greenhouse Gas, Regulated Emissions and Energy in Transportation (GREET1) Model," Argonne National Laboratory, 2017, http://greet.es.anl.gov/greet_1_series.
13. Norgate, T.E., Rajakumar, V., and Trang, S., "Titanium and Other Light Metals - Technology Pathways to Sustainable Development," in *Green Processing Conference*, Freemantle, WA, 2004, 105-112.
14. Fuel Prices from http://www.dla.mil/Energy/Business/StandardPrices/, accessed October 26, 2018.
15. "How to Calculate Cost per Mile for Your Trucking Company," https://www.rtsfinancial.com/guides/trucking-calculations-formulas.
16. "Calculate Your Cost per Mile - Truckers & Owner-Operators, https://www.comcapfactoring.com/blog/cost-per-mile-calculator-trucking/.
17. "Want to Optimize Your Fleet? Know Your Average Trucking Cost per Mile," https://www.paragontruckrouting.com/paragon-blog/want-optimize-your-fleet-know-your-average-trucking-cost-mile.

Contact Information

jlsullivan@ecospherica.com

Acknowledgments

This work was conducted at the University of Michigan under Subaward agreement 4007-01 to cooperative agreement N00014-14-2-0002 between the Office of Naval Research (Prime Sponsor) and American Lightweight Materials Manufacturing Innovation Institute (Prime Recipient).

The authors would like to acknowledge Karen Kunkler of U.S. Army TACOM and Dr. Katherine Sebeck, Andrew Kruz, Kevin Kauth, and Dr. Richard Gerth of U.S. Army CCDC GVSC for their expertise and assistance in completing this work.

ISSN 0148-7191