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THE INFLUENCE OF GROUND COMBAT VEHICLE WEIGHT ON AUTOMOTIVE PERFORMANCE, TERRAIN TRAVERSABILITY, COMBAT EFFECTIVENESS, AND OPERATIONAL ENERGY

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ABSTRACT

This study utilized computer simulations to analyze the influence of vehicle weight on automotive performance, terrain traversability, combat effectiveness, and operational energy for the M1A2 Abrams, M2A3 Bradley, and M1126 Stryker. The results indicate that a 15% reduction in combat vehicle weight correlates to 0-20% or greater improvements in: automotive mobility (top speed, speed on grade, dash time, fuel economy), terrain traversability (minimum required soil strength, % Go-NoGo, off road speed), combat effectiveness (% of combat effective outcomes, hits sustained, time, average and top speed in kill zone), and operational energy (gallons of fuel and fuel truck deliveries). While it has always been "understood" that vehicle weight impacts performance, this study has actually successfully quantified the impact. Through the use of multiple simulation tools, this study shows that reduced vehicle weight improves automotive performance, which directly improves the combat effectiveness in this current combat scenario. This study demonstrates that weight has a far more significant impact than previously known, and traditional methods of simply adding capability at the expense of weight could actually be self-defeating: reduced combat and operational capability of the combat platform. This paper also examines the relevance of mobility-based combat effectiveness within the framework of Brigade Combat Team fundamental operations, which provides direction and context for future studies.

INTRODUCTION

Weight reduction of ground vehicles is a high priority for the US Army to increase expeditionary capability. For decades, vehicles have been increasing in weight due to increased requirements, which has had detrimental impact on transportability and other factors [2]. A recent study by Gerth and Howell outlined some of the reasons lightweighting solutions have been so elusive [2]. Further complicating the issue is a lack of understanding into the impact of weight growth on: operational capability, cost, reliability, logistics, and more. As vehicle weight increases beyond design, support system, and operational limits, the need for lightweighting solutions is becoming increasingly urgent.

The Army's Lightweight Combat Vehicle S&T Campaign (LCVSTC) calls for operational metrics to evaluate the benefit of weight reduction and better prioritize weight reduction technology [3]. Understanding the operational value of weight reduction would help prioritize research investments in weight reduction and the impact that requirements can have on weight issues. Based on the hard point analysis presented in Gerth & Howell, a recent study on lightweighting the Abrams utilized cost, risk, and schedule to determine the combination of lightweighting technologies most likely to have an operational transportability impact [4].

However, prior work has not looked at the impact that vehicle weight has on mobility, combat effectiveness, reliability, spare parts logistics costs, lifecycle costs, etc. There exists a strong need for a comprehensive approach for analyzing the impact that heavy vehicles have on relevant operational metrics such as: readiness, combat effectiveness, and freedom of movement. This comprehensive approach and associated operational metrics is critical to shaping the future acquisition programs in the Analysis of Alternatives (AoA) phase. Without such an approach, we will continue to see weight growth in future vehicles and in future upgrades of the existing fleet.

This study expands upon prior work and is a set of studies that examine the impact vehicle weight has on automotive performance, terrain traversability, combat effectiveness, and operational energy. In every study, unless otherwise specified, three vehicles were studied: (i) M1A2 Abrams Main Battle Tank (MBT), (ii) M2A3 Bradley Fighting Vehicle, and (iii) M1126 Stryker Infantry Carrier Vehicle (ICV). Each simulation was conducted with the vehicles at 100% of their Gross Vehicle Weight (GVW) and at 85% of their GVW. No other vehicle performance characteristics, such as survivability or lethality were altered. In other words, it was assumed that the weight reduction occurred through implementation of technology that did not otherwise change vehicle capabilities.

The reader is cautioned not to compare the results between vehicles. The vehicles have different requirements and are used for different missions. Hence comparisons should only be within a vehicle type and between the different weights studied.

AUTOMOTIVE PERFORMANCE ANALYSIS

The automotive performance metrics analyzed in this study were: (i) top speed (mph), speed on 10% grade (mph), (iii) speed on 60% grade (mph), (iv) dash speed (time to cover 50 meters from a dead stop in seconds), (v) fuel economy at a constant 30 mph convoy speed (mpg), and (vi) vehicle range (miles). Clearly vehicle range is also a function of the vehicle's fuel tank size, which is different for every vehicle.

The tools used for the analysis were GT-Suite Software and MATLAB. GT-Suite enables fuel economy and performance modeling simulations of a vehicle. MATLAB is a matrix-based language optimized for solving engineering and scientific problems using computational mathematics. GT-Suite models of the M2A3 and M1126 Stryker were developed for the analysis. The engine library of GT-Suite did not include a turbine engine. Therefore, a MATLAB script was created and used to calculate the performance of the M1A2. The models were first validated by comparing model performance predictions to test data. After validating, each vehicle model analysis was conducted at the current GVW as well as at 85% of the current GVW, and the mobility metrics were calculated and recorded in Table 1.

Vehicle	Top Speed (mph)	Speed on 10% Grade (mph)	Speed on 60% Grade (mph)	Dash Speed (s)	Fuel Eco (mpg)	Range (mi)
M1A2						
M1A2 85% wt		+27.4%	+19.5%	-6.1%	+12.0%	+12.0%
M2A3		---	---	---	---	---
M2A3 85% wt		+15.2%	+100%	-6.0%	+14.3%	+14.3%
M1126		---	---	---	---	---
M1126 85% wt		+9.8%	+14.2%	-5.3%	+7.8%	+7.8%

Table 1: Automotive Performance Results

For many of these metrics in Table 1, the weight had a significant influence on the automotive performance. For the M1A2, the 15% weight reduction led to an improvement in top speed of 8%. Similarly, speed on grade increased by 20% or more, and fuel efficiency improved by 12%. The M2A3 did not demonstrated a significant improvement in speed on 60% grade. The fuel efficiency improved by an impressive 14% across a variety of terrains. Stryker also showed significant improvements in speed and fuel efficiency due to lightweighting. This is noteworthy, because these results demonstrate that lightweighting has a significant influence on automotive performance for both tracked (M1A2 and M2A3) and wheeled (Stryker) vehicles. All vehicles demonstrated an improvement in acceleration, as measured by their dash speed. The lighter weight vehicles were all 5-6% faster in the 50 meter dash.

TERRAIN TRAVERSABILITY ANALYSIS

Terrain Analysis consisted of running the three vehicle through the NATO Reference Mobility Model (NRMM) over different terrain conditions. The NRMM software tool is the current industry standard tool for predicting vehicle mobility. NRMM has detailed soil data for different regions of the world and predicts terrain traversability as a function of various vehicle parameters, including weight. While the NATO committee AVT-248 is currently working on the Next Generation NRMM (NGNRMM), it was not available for this study.

The vehicle studies included wet and dry conditions in the following three terrain types: (i) terrain 1: foliage and muddy terrain, (ii) terrain 2: sandy terrain, and (iii) terrain 3: mountainous terrain.

The terrain traversability metrics considered in this study were: (i) Vehicle Cone Index (VCI), (ii) % NoGo, (iii) V50 speed, and (iv) V80 speed. VCI quantifies the minimum soil strength required for a vehicle to consistently make a specified number of passes [5]. It is proportional to the vehicle's ground pressure, and a lower VCI typically means better soft soil mobility performance. In this case VCI1 relates to one vehicle pass on the soil. Lower VCI1 is better. % NoGo quantifies the percentage of the terrain in which the vehicle will not be able to travel. A smaller value is better. V50 and V80 speeds represent the average speed the vehicle is able to travel over 50% and 80%, respectively, of the most trafficable terrain. V80 Speed - The average speed the vehicle is able to travel over 80% of the most trafficable terrain.

All travel was over open, cross country terrain. Paved or secondary roads are not considered in this analysis. The % NoGo, V50 Speed, and V80 Speed were computed using a representative unit area for each country studied. The unit area was assumed to provide a reasonable representation of the terrain present in that country. The VCI1, on the other hand, was only computed for a single soil condition.

In the current context of vehicle weight analysis, the VCI1 was selected as a metric to provide insight into soft soil mobility performance. The VCI1 results in Table 2 and Figure 1 show that for

Terrain Type 1: Primarily Foliage and Mud					
	Vehicle	GVW	% NOGO (% chg)	V50 (% chg)	V80 (% chg)
Dry	M1A2	100%	---	---	---
		85%	+5.1%	+10.4%	+6.7%
	M2A3	100%	---	---	---
		85%	-32.1%	+10.7%	+11%
	M1126	100%	---	---	---
		85%	-2.2%	+5.5%	+4.5%
Wet	M1A2	100%	---	---	---
		85%	-9.6%	+21.0%	+16%
	M2A3	100%	---	---	---
		85%	-39.2%	+21.2%	+23%
	M1126	100%	---	---	---
		85%	-8.7%	+18.0%	+0.0%

Terrain Type 2: Primarily Sand					
	Vehicle	GVW	% NOGO (% chg)	V50 (% chg)	V80 (% chg)
Dry	M1A2	100%	---	---	---
		85%	-87.2%	+11.0%	+9.0%
	M2A3	100%	---	---	---
		85%	0.0%	+6.6%	+8.8%
	M1126	100%	---	---	---
		85%	+5.4%	+3.7%	+1.9%
Wet	M1A2	100%	---	---	---
		85%	-87.2%	+11.2%	+10%
	M2A3	100%	---	---	---
		85%	0.0%	+9.4%	+11%
	M1126	100%	---	---	---
		85%	+5.1%	+6.1%	+3.4%

Terrain Type 3: Primarily Mountainous					
	Vehicle	GVW	% NOGO (% chg)	V50 (% chg)	V80 (% chg)
Dry	M1A2	100%	---	---	---
		85%	-11.1%	+13.5%	+12%
	M2A3	100%	---	---	---
		85%	-43.8%	+14.4%	0.0%
	M1126	100%	---	---	---
		85%	+12.3%	+9.1%	-100%
Wet	M1A2	100%	---	---	---
		85%	-11.1%	+14.3%	+14%
	M2A3	100%	---	---	---
		85%	-43.5%	+16.5%	0.0%
	M1126	100%	---	---	---
		85%	+5.4%	+10.5%	0.0%

Table 2: Metric % Change Due to Weight

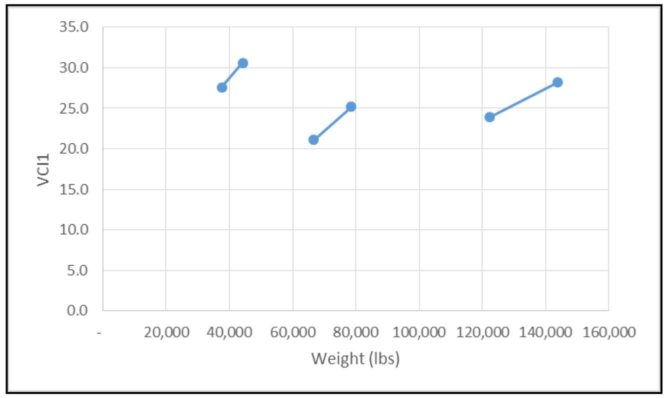

Figure 1: Vehicle Cone Index (VCI1) For A Single Vehicle Pass.

all three combat vehicles, as weight decreased, the VCI1 decreased as well. Since VCI1 correlates to the soil strength, this result indicated that decreasing vehicle weight could allow the vehicle to successfully traverse softer soil. The VCI1 is not purely proportional to vehicle weight, but relates to ground pressure through other factors such as: type of propulsion system (wheeled or tracked), wheel/track width and length, minimum ground clearance, etc. [6]. Since these factors were different for each of the vehicles studied, the VCI1 results cannot be directly compared between systems. One can see by examining the values in Table 6 that there is a significant difference between the tracked vehicles (M1A2 and M2A3) versus the wheeled vehicle (Stryker). These results are consistent with the Engineering Research and Development Center (ERDC) VCI1 procedure, where VCI1 is highly dependent on vehicle configuration [6].

As one can see in Figure 1, for a given vehicle configuration, the minimum required soil strength for a single pass was lower for the lighter vehicles. For the 15% weight reduction in this study, the VCI1 decreased by 15.2% (M1A2), 16.3% (M2A3), and 9.8% (Stryker). This data provided encouraging support for the influence of lightweighting on soft soil mobility.

While the VCI1 provides a performance metric for a given soil condition, the %NoGo provides a metric for analyzing the ability of a vehicle to traverse cross-country terrain under varying soil conditions.

Based on the results in Table 2, several observations are made. In general, the 15% reduction in weight did not improve the % NoGo for the Stryker system (wheeled). For the Bradley and Abrams systems (track), on the other hand, the 15% reduction in weight did generally improve the % NoGo depending on the terrain. When comparing wet versus dry soil conditions, the moisture content only had a significant impact in terrain type 1 (foliage and muddy terrain). When comparing across all three combat vehicles, the Stryker was most significantly affected by wet/dry soil conditions in terrain type 1. This result is consistent with the VCI1, where the wheeled Stryker vehicle required greater soil strength compared to the tracked Abrams and Bradley vehicles. The other terrain types had no significant difference on % NoGo due to soil moisture. The results indicate a substantial terrain type – weight interaction for each system.

Stryker (wheeled) demonstrated the ability to traverse terrain type 2 (primarily sandy) well. In general, if a vehicle has a low %NoGo, i.e., can traverse near 100% of the terrain, weight reduction will not improve the metric, since it is not possible to drop below 0% NoGo. Stryker, however, was not shown as capable in traversing terrain type 3 (primarily mountainous) or terrain type 1 (foliage and mud). Weight reduction did not significantly improve its ability to traverse those particular terrains. Similarly, Bradley demonstrated ability to traverse sandy terrain well, but mountainous and foliage/mud less well. However, reducing the weight appeared to greatly improve the % NoGo performance in those two particular terrains. The % NoGo metrics for Abrams differed from two other vehicles. At the current GVW, Abrams was least capable in traversing sandy terrain. At 15% weight reduction, however, the % NoGo improved to be the best of the three terrain types. One additional noteworthy finding was that for Stryker in mountainous terrain, the % NoGo improved for the heavier system by a small amount. At this time, it is unclear whether this change in % NoGo is statistically significant and whether this result would generate a trend if additional data points were acquired. Based on these results, several observations were considered notable.

First, when weight was reduced, all three vehicle systems were able to achieve higher maximum speed across all terrain types and soil moisture conditions. Consistent with the % NoGo, the foliage/muddy terrain was significantly more difficult to traverse under wet conditions, while the other terrain types were unaffected. When considering the V(80) results for Stryker in mountainous terrain, it was helpful to consider these results within the context of the previous % NoGo discussion. The % NoGo in mountainous terrain for the 85% GVW Stryker was 21%, which meant it can only traverse 79% of the terrain. Hence the corresponding V(80) was zero, since the vehicle could not achieve the 80% threshold required for V80. In wet terrain, it cannot traverse over 20% of the terrain, and hence, the V(80) was zero for both light and heavy Stryker vehicles. Likewise the heavy Bradley vehicle in mountainous terrain could not traverse over 20% of the wet and dry terrain, so it had a V(80) speed of zero. The 85% GVW Bradley vehicle, on the other hand, was capable of traversing significant portions of the terrain models. Comparatively, Abrams was capable of traversing all significant portions of terrain in the models at relatively high speed.

COMBAT EFFECTIVENESS ANALYSIS

Generally, combat effectiveness measures the ability of the military force to accomplish the objective. In the current study, combat effectiveness was evaluated at the platoon level using the software tool One Semi-Automated Forces (OneSAF). For all simulations in this study, unclassified data was utilized.

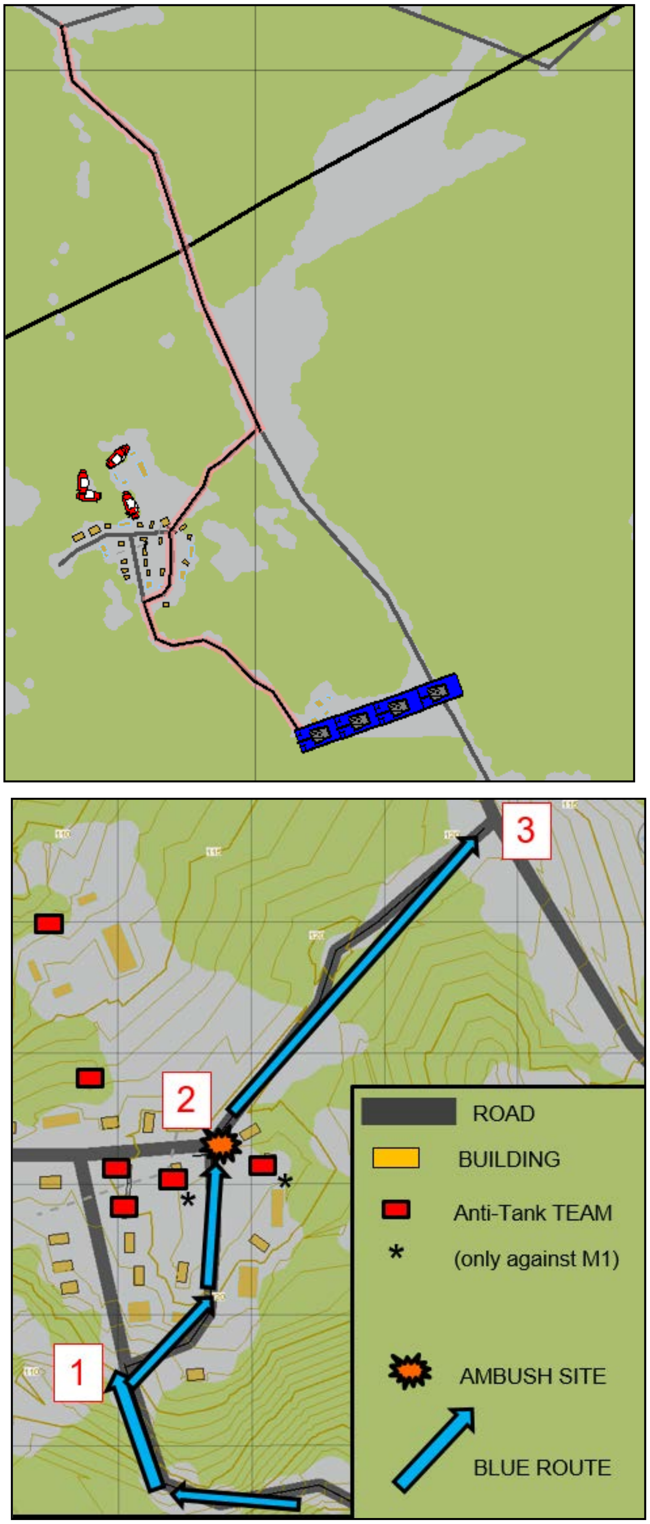

Figure 2: Map of urban ambush vignette from OneSAF with (top) the full route highlighted in red and (bottom) a close up view of the urban area and ambush.

The OneSAF simulation tool provides a framework for entity-level models and behaviors in either a semi-automated or fully-automated environment. The OneSAF package provides real world representations of vehicle platforms, aviation assets, soldiers, equipment, logistical supplies, communication systems, and emerging threats across a full range of military operations. In the current study, the combat vignette included a Blue Force (BLUFOR) consisting of single platoon (4 combat vehicles). The 4 combat vehicles operated in linear formation with a spacing of approximately 100 m between vehicles. The lead vehicle was labeled BLUE1, followed by BLUE2, BLUE3, and BLUE4.

BLUFOR's mission was to traverse through a village in hostile territory on route to reinforcing another unit, as shown in 2 (top). Within the village, a heavy Opposition Force (OPFOR) instigated an ambush scenario, which occurred primarily between points 2 and 3 in 2 (bottom). The OPFOR was heavy enough to cause significant damage in the majority of combat simulations. The BLUFOR was ordered to minimize engagement in the ambush and engage the threat only as necessary to traverse the route, since their primary mission was to reinforce another unit. The vignette assumed that a follow on Quick Reaction Force (QRF) would later secure the village and route. During the ambush, OneSAF utilized stochastic models for determining the outcome of each shot fired.

For each shot fired by the OPFOR, the OneSAF model would determine if a vehicle was hit, which depended on factors such as: weapon/munition, shot distance, angle, vehicle speed, trajectory of munition, etc. If the result indicated a hit, then the outcome would depend on additional factors such as munition and target pairing, aspect angle, range, elevation, and dispersion. For a given hit, the following outcomes were considered: (i) No Kill, (ii) Mobility Kill (loss of mobility), (iii) Fire Kill (loss of weapons), (iv) Mobility + Fire Kill, and (v) Catastrophic Kill (All systems lost – Fire, Mobility, Communications, Sensors, etc.). Under any outcomes (ii) – (v), the vehicle would be considered combat ineffective. For a given platoon of 4 vehicles, if 2 or more vehicles were rendered combat ineffective, the entire platoon was considered combat ineffective. For instance, if all 4 vehicles arrived at the assembly area, but two vehicles lost fire capability, then the simulation resulted in a status of combat ineffective. Conversely, if 3 vehicles arrived at the assembly area with no damage, but 1 vehicle was lost catastrophically, the simulation resulted in a status of combat effective. The OneSAF simulations were conducted using Monte Carlo methods, where the 6 vehicle alternatives were simulated with 301 repetitions each.

Metrics relevant to analyzing combat effectiveness were: (i) percentage of simulations where at least 3 vehicles remained combat effective (% CE), (ii) average number of hits sustained, (iii) time in the kill zone, (iv) average speed in the kill zone, and (v) maximum speed in the kill zone.

The only difference between the standard vehicle weight and the 85% weight platforms was the vehicle weight. The models assumed that survivability and other characteristics remained constant between the alternatives. This ensured that any measured differences in combat effectiveness could be attributed solely to vehicle weight. This strategy created a mobility-focused analysis: reduced weight improves mobility performance, which improves combat effectiveness. This strategy also aligns with the automotive analysis. The OneSAF models incorporated a medium-fidelity physics-based mobility model. In the OneSAF mobility model, vehicle weight contributes primarily to: (i) acceleration, (ii) ground frictional force, and (iii) weight force due to terrain slope [7]. Within this vignette, the vehicles remained on road with minimal terrain slope change. Therefore, acceleration was more directly influenced by vehicle weight compared to the terrain type and terrain slope.

In the automotive performance analysis in, the vehicle weight was shown to improve vehicle acceleration by 5% as measured by dash speed. It was not known, however, whether this change in dash speed would lead to noticeable improvements in combat effectiveness. In order to assess the influence of vehicle weight (acceleration) on combat effectiveness, several metrics were considered including: percentage of simulations where at least 3 vehicles remained combat effective (% CE), average number of hits sustained, time in the kill zone, average speed in the kill zone, and maximum speed in the kill zone. The % CE provides a simple yes/no answer to the question: is the platoon combat effective when arriving to the reinforcement area? The hits sustained, time, average speed, and maximum speed in the kill zone provide a statistical merit for weight-dependent trends.

When reviewing the data in Table 3, the first observation is that lighter weight vehicles demonstrate noticeable improvements in all metrics when compared to the standard weight vehicles. When comparing % CE, the 85% M1A2 was combat effective in 32.9% of simulations compared to 27.0% for the standard weight M1A2. This corresponds to a 21.9% improvement for only a 15% weight reduction. Similarly, for the M2A3, %CE increased from 9.6% to 15.6%, corresponding to a 62.5% improvement. For

Vehicle	% CE (% chg)	Avg. Hits (% chg)	Time in Kill Zone (% chg)	Avg. Speed in Kill Zone (% chg)	Max. Speed in Kill Zone (% chg)
M1A2	---	---	---	---	---
85% wt	+21.9%	-13.6%	-7.7%	+7.5%	+8.6%
M2A3	---	---	---	---	---
85% wt	+62.5%	-17.6%	-7.4%	+8.4%	+10.0%
M1126	---	---	---	---	---
85% wt	+30.9%	-13.5%	-1.0%	+0.7%	+5.3%

Table 3: Combat Effectiveness (CE) Results. Note: % CE denotes the percentage of simulations where at least 3 of 4 vehicles remained combat effective.

Stryker, %CE increased from 27.2% to 35.6%, corresponding to 30.9% improvement. Compared to the standard weight vehicles, the 85% M1A2, M2A3, and Stryker sustained 13.6%, 17.6%, and 13.5% fewer hits, respectively. When analyzing time in the kill zone, the influence of weight was slightly less evident. For example, compared to the standard weight vehicles, the 85% M1A2, M2A3, and Stryker were in the kill zone 7.7%, 7.4%, and 1.0% less, respectively. The average speed and maximum speed were also influenced similarly. These trends are represented graphically through speed versus distance plots (see Figure 3).

Examination of the slopes of the curves in Figure 3 (top) shows that the lighter weight vehicles (85% GVW) were able to both accelerate and brake more rapidly (steeper slopes) than the heavier vehicles (standard GVW). In addition, the greater acceleration enabled the lighter vehicles to reach higher peak speeds than the heavier vehicles. In general, the M1A2 and M2A3 were more greatly affected by weight compared to Stryker, shown by the larger difference in vehicle speeds at a given point. This observation was also supported by the time, average speed, and maximum speed in kill zone in Table 3.

When looking deeper into the active ambush in Figure 3 (bottom), these conclusions continue to hold (note: The dip in speed curves in 3 (bottom), corresponds to the kink in the road between points 2 and 3 in Figure 2 (top)). While difference in the speed vs. distance curves for Stryker were not as strikingly visible compared to Abrams and Bradley, the weight-related improvement in mobility resulted in a % difference in combat effectiveness. In addition, all vehicles demonstrated noticeable improvements in hits sustained, top speed achieved, average speed, and time in the kill zone.

It is noteworthy that in this vignette, the vehicles did not approach the automotive mobility top speed limits, which were generally not influenced by vehicle weight (M2A3 and Stryker). This represents the operational impact of path length and curves. The automotive top speed is presumably limited by vehicle system characteristics related to the powertrain and suspension. However, in the operational vignette, the vehicles never had a long enough straight path to reach their automotive top speed before they had to slow to take a curve. This fact indicates the importance of weight in real operational scenarios on top speed. Lighter vehicles can move faster over the same distance and reach a higher speed sooner than the heavier vehicles.

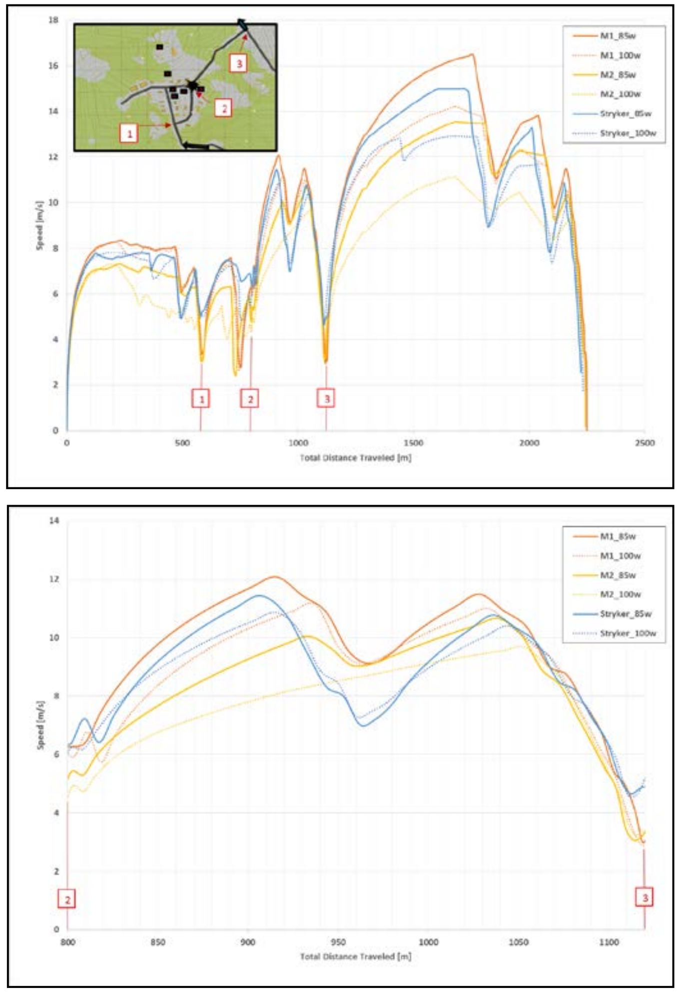

Figure 3: Map of urban ambush vignette from OneSAF with (top) the full route highlighted in red and (bottom) a close up view of the urban area and ambush.

OPERATIONAL ENERGY ANALYSIS

An operational energy study was completed to quantify the impacts of combat vehicle weight reduction in Major Combat Operations (MCO) utilizing the System of Systems Analysis Toolset (SoSAT). SoSAT is a discrete-event stochastic simulation toolset designed to model and simulate multi-echelon operations and logistics support activities at a System of Systems level. SoSAT provides the ability to define operational and support environments and ascertain measures of performance effectiveness. SoSAT can be used to characterize sensitivity changes to systems, support systems, processes, and decision rules and includes system reliability and maintainability characteristics. SoSAT is designed to be a robust decision support tool for evaluating reliability and logistics support attributes including fuel, water, ammunition, and other supply class consumption and maintenance and sustainment operations.

The key input metric for SoSAT analysis was fuel economy for each of the 6 combat systems/weight alternatives (M1A2, M2A3, and Stryker at 85% and 100% GVW). The fuel economy improvements determined from the automotive analysis were inserted into scenario models. The fuel economy improvements for M1A2, M2A3, and Stryker were 12%, 14%, and 8%, respectively. The fuel consumption rates within the SoSAT model further depended on factors such as: moving vs. idle and road type (primary, secondary, cross-country). In the operational energy study, the combat systems followed the same Operational Tempo (OPTEMPO) and route distances as the existing force structure.

The M1A2 Abrams and M2A3 Bradley were analyzed using a 10 day Major Combat Operations (MCO) model for Armored Brigade Combat Teams (ABCT). The Stryker weight reduction was analyzed using a similar MCO model for a Stryker Brigade Combat Teams (SBCT). 30 repetitions of each model run were conducted in order to obtain representative data. The scenarios included an ABCT with 87 M1A2s and 125 M2A3s and SBCT with 328 Stryker systems impacted. It is significant to note that only the M1A2, M2A3, and Stryker were analyzed for weight reduction impacts. These three combat vehicles only account for a fraction of the vehicles, gear, personnel, etc. associated with their respective BCTs.

When considering the influence of weight on operational energy, the primary impact was on overall fuel consumption. When considering the M1A2 Abrams and M2A3 Bradley within the ABCT, the 15% lighter weight vehicles resulted in a reduction in fuel consumption of 8,000 gallons of JP-8 diesel, which corresponded to a 1.2% reduction in operational energy for the entire ABCT. Within the SBCT, the 15% lighter Stryker corresponded to a reduction in fuel consumption of 1,870 gallons, or 1.4% of total SBCT fuel usage. While the average of 1.3% reduction in operational energy may not seem significant, it is important to note that the combat vehicles account for only a fraction of the total operational energy. Further, some of the combat vehicles spend a significant amount of time in idle position, where weight has no influence on operational energy. For the M2A3 Bradley, for example, the 15% lighter vehicle corresponded to a 14% reduction in fuel economy. The 14% value could be considered a ceiling for the maximum possible improvement in overall operational energy from this vehicle. The M2A3 Bradley only accounted for a fraction of the total energy consumed in the scenario, so the overall influence of the M2A3 Bradley was reduced. The impact of fuel economy was further reduced, since the M2A3 Bradley spent only a fraction of the time in motion versus idle. This compounding effect explains how a substantial improvement in fuel economy can become diluted within the context of being placed in a large, operational unit, such as a brigade.

The next step in the analysis was to consider any potential second order impacts of vehicle lightweighting. The influence of lightweighting on logistics was assessed by considering the number of convoy trucks required. When considering the ABCT, the reduction in fuel consumption enabled a reduction in the number of fuel trucks by 6 over 13 days of operation. For the SBCT, on the other hand, the number of fuel trucks remained the same over 10 days.

This is believed to be due to two major factors. First, in order for vehicle fuel economy to translate to a reduction in fuel truck deliveries, the fuel savings (in gallons) must be at least as much as the capacity of a fuel truck. In other words, if in the designated amount of time between convoy trips, the fuel consumption savings are only ½ a truck, then a full fuel truck is delivered and there is no secondary impact from the fuel savings. This correlates to the second factor. If a supply convoy is triggered by a water or cargo need, fuel is still delivered, regardless of immediate fuel need.

DISCUSSION

When considering the various studies within the larger picture, there are interactions and trends across the studies. The terrain traversability studies clearly show the complexity of terra-mechanics on mobility. While lightweighting did not significantly degrade terrain traversability as measured by %NoGo and V50 and speed metrics, it clearly indicated that the specific magnitude of the effect varied across terrain type, moisture content, and vehicle type. There were many interactions between these three factors that made interpretation difficult. However, the general conclusion is that lighter weight can improve performance and heavier vehicles only have the same or poorer performance.

The automotive and combat effectiveness studies definitively demonstrated that reduced weight affects vehicle mobility, and vehicle mobility affects combat effectiveness. The automotive performance analysis showed that reduced weight correlates to an improvement in acceleration, quantified through the dash speed metric. When considering this metric on its own, one could not determine if the 5-6% improvement in dash time would have any impact on combat effectiveness. The OneSAF combat effectiveness model results confirmed that, in fact, the increase in acceleration capability led to an increase in combat effectiveness, increase in top speed achieved, decrease of time in the kill zone, and decrease in the number of hits that the vehicle sustained. When considering these two studies as a part of the larger operational context, the results demonstrate the power of vehicle lightweighting.

Another insight is the interaction between the automotive metrics of top speed versus terrain constraints encountered in operational scenarios. While reduced weight had no effect on a system's ultimate top speed, it did have an impact on the operational top speed, which was below the automotive ultimate top speed, because the terrain path was such that the vehicle had to slow down to take a curve before it ever reached its ultimate top speed. However, lighter weight vehicles were able to achieve a higher operational top speed than their heavy counterparts.

When considering the operational energy results with the automotive performance fuel economy results, one can begin to understand the impacts of lightweighting a single vehicle on the larger, operational energy usage of an ABCT. These results suggest that lightweighting a single combat system may drastically improve fuel economy of that vehicle, but that this improvement gets diluted when considered in a larger unit context. In order to achieve more substantial improvements in overall operational energy, would require improvements to the entire fleet and not just a single combat system. This conclusion is analogous to lightweighting of a single combat system: i.e. lightweighting at the single component level may not result in a significant improvement in vehicle performance, but holistic lightweighting at the system level will.

The fuel economy impact of lightweighting will always be greatest at the vehicle unit level. Any higher unit analysis, which includes other vehicles and system that have no fuel economy improvement, will only dilute the fuel efficiency savings from the lightweight system. Hence, from a lightweighting perspective it is recommended to keep operational energy analyses at the unit vehicle level and to look at overall cost savings over a significant time period for that vehicle in isolation. This also makes sense within the context of the operational metrics as a guide to evaluating specific investments in lightweighting technologies. Given the holistic approach in this study, it is prudent to consider how these results might fit within establish BCT doctrine.

BRIGADE COMBAT TEAM RELEVANCE

The Brigade Combat Team (BCT) is a modular organization that is designed for operations encompassing the entire spectrum of conflict. The Heavy, Infantry, and Stryker Brigade Combat teams are the Army's combat power building blocks for maneuver, and are the smallest combined arms units that can be committed independently [8]. Field Manual 3-90.6 provides the commander and staff of the BCT and subordinate units with doctrine relevant to Army and joint operations. This section will review portions of the doctrine outlined in FM 3-90.6 that may be influenced by vehicle weight. The statements in italics are excerpts directly from FM3-90.6.

Brigade Combat Team Organization

FM 3-90.6 1-31: *"HBCTs are balanced combined arms units that execute operations with shock and speed. […] HBCTs require significant strategic airlift and sealift to deploy and sustain. Their fuel consumption may limit operational reach."[8]*

The current study has demonstrated that lighter weight vehicles support "*operations with shock and speed*" through: higher top speed, speed on grade, and acceleration both on road (automotive performance study) and off-road (terrain traversability study). Gerth and Howell [1] discussed the impact of combat vehicle weight on air transportability: lighter weight vehicles could potentially reduce the closure time of transporting a BCT via air. The automotive performance and operational energy studies in this paper demonstrated that the 15% lighter weight vehicles had 8-14% better fuel economy, which can translate into significant fuel savings and/or an improvement in vehicle range.

FM 3-90.6 1-32: *"The combined arms battalion (CAB) is the HBCTs primary maneuver force. The CAB's mission is to close with, and destroy or defeat enemy forces within the full spectrum of modern combat operations. A CAB maintains tactical flexibility within restricted terrain."[8]*

Based on the results of the terrain traversability study one can reasonable conclude that lighter weight vehicles have more operational flexibility on off-road terrain. This conclusion is based on improvements in minimum required soil strength (lower vehicle cone index), % of trafficable terrain (reduction in %NoGo), and off road speed (increased V50 and V80). Generally speaking, lighter weight vehicles can cross more terrain at higher speeds compared to heavier vehicles.

Offensive Operations

FM 3-90.6 2.3: "*[…] the movement speed of BCT units either mounted or by air, provides the BCT commander with the option to position combat power rapidly, this limits the enemy's ability to react."[8]*

As discussed previously, lighter weight vehicles have been shown to improve speed and acceleration both on- and off-road, which support rapid execution of offensive operations.

FM 3-90.6 2-8: *"The commander considers the mission, enemy, terrain and weather, troops and* *support available, time available, and civil considerations (METT-TC) when choosing the combat formation that best balances firepower, tempo, security, and control."*

FM 3-90.6 2-68: *"The BCT uses six basic formations […] The type of formation the BCT commander selects is based on: Planned actions on the objective, the likelihood of enemy contact, the type of enemy contact expected, the terrain the BCT must cross, and the balance of speed, security, and flexibility required during movement."*

FM 3-90.6 2-69: *"The commander and staff must also determine when, where, and how the BCT transitions into different movement formations based on the terrain and anticipated situation. The commander and all subordinate units also maintain the flexibility to adapt to new formations based on changes in the terrain and enemy situation."[8]*

Based on the terrain traversability study, having lighter weight vehicles gives more operational flexibility by increasing the percentage of terrain that can be crossed (reduction in %NoGo). In addition to greater flexibility, lighter weight vehicles are able to cross off-road terrain at higher speeds than heavier vehicles (V50 and V80).

Defensive Operations

FM 3-90.6 3-1: *"Successful defenses are aggressive. Defending commanders use all available means to disrupt enemy forces. […] Defenders seek to increase their freedom of maneuver while denying it to attackers. Defending commanders use every opportunity to transition to the offense, even if only temporarily. As attackers' losses increase, they falter and the initiative shifts to the defenders. These situations are favorable for counterattacks. Counterattack opportunities rarely last long. Defenders strike swiftly when the attackers reach their decisive point. Surprise and speed enable counterattacking forces to seize the initiative and overwhelm the attackers."*

FM 3-90.6 3-9: *"Common planning considerations apply to all types of defensive operations (i.e., area, mobile, and retrograde) and focus on several key questions: Where is the key and decisive terrain? How can the BCT use key and decisive terrain to defeat/destroy the enemy?"[8]*

Similar to offensive operations, in defensive operations, speed is an important aspect of conducting swift counterattacks. Lighter weight vehicles would support swift counterattacks through improvements in speed and acceleration compared to heavier vehicles. While the *"key and decisive terrain"* may be unique for each operation, generally speaking, lighter weight vehicles could potentially "open up the playbook" and allow greater flexibility when determining how to maneuver the BCT around the key and decisive terrain. Again, the terrain traversability study demonstrated that lighter weight vehicles can cross a higher percentage of terrain (reduction in %NoGo) at higher speeds (V50 and V80) compared to heavier vehicles.

CONCLUSIONS

This study illuminated the significant impact of vehicle weight on combat effectiveness. While it has always been "understood" that weight impacts mobility, which in turn impacts survivability and combat effectiveness, this is the first published study that has successfully quantified the impact. While further study is warranted, this body of work already demonstrates that weight has a significant and quantifiable impact, and traditional methods of simply adding capability at the expense of weight could actually result in the opposite effect: reduced combat and operational capability of the combat platform.

Based on the automotive mobility analysis, the 15% weight reduction resulted in a significant improvement in mobility metrics, particularly speed on grade and fuel economy. The automotive mobility results demonstrated that lightweighting had a significant influence on automotive performance for both tracked (M1A2 and M2A3) and wheeled (Stryker) vehicles.

In the terrain traversability analysis, the lighter vehicles exhibited superior soft soil capability, as measure by VCI1, which improved by as much as 16% (M2A3). In general, the 15% reduction in weight did not improve the % NoGo for the Stryker system (wheeled), however the Bradley and Abrams systems (track) did show an improvement in the % NoGo. When analyzing cross-country speed capabilities (V(50) and V(80)), the lighter weight vehicles for all three systems were able to achieve higher maximum speed across all terrain types and soil moisture conditions.

The combat effectiveness (CE) models showed that a 15% weight reduction led to marked improvements in combat effectiveness. %CE improved by up to 63% (M2A3), time in kill zone was reduced by as much as 10% (Stryker), maximum speed in kill zone increased by up to 10% (M2A3), average speed in kill zone increased by up to 8% (M2A3), and hits sustained were reduced by as much as 18% (M2A3).

In the operational energy study, within the ABCT, the 15% lighter Abrams and Bradley saved 8,000 gallons of fuel over 13 days of operation. This fuel savings compounded into a reduction in the logistics burden by eliminating the delivery of 6 fuel trucks. For the SBCT, the 15% lighter Stryker saved 1,870 gallons of fuel over the 10 day duration of the combat operation with no secondary savings.

When considering these results within BCT doctrine, the relevance of vehicle lightweighting becomes apparent. Both speed and terrain traversability are clearly key components for in theater maneuver. Lighter weight vehicles are able to accelerate faster, sustain higher speeds across various terrains, and have the ability to cross more difficult terrains compared to heavy vehicles. This highlights an extremely important takeaway from this study: if the vehicle weight is increased to improve survivability or other performance requirements with substantial weight gains, then there is an associated mobility performance cost downstream that can now be quantified. For example, a higher performance powertrain may increase the acceleration of a vehicle, but if the overall vehicle weight increases, soft soil performance may be degraded. Holistically reducing the overall vehicle weight is the only way to improve all of these performance metrics without sacrificing performance elsewhere.

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