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**Fuel Consumption Modeling And Simulation (M&S) to Support Military Systems Acquisition and Planning**  
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**2008 NDIA Power and Energy Workshop (18-19 November)**

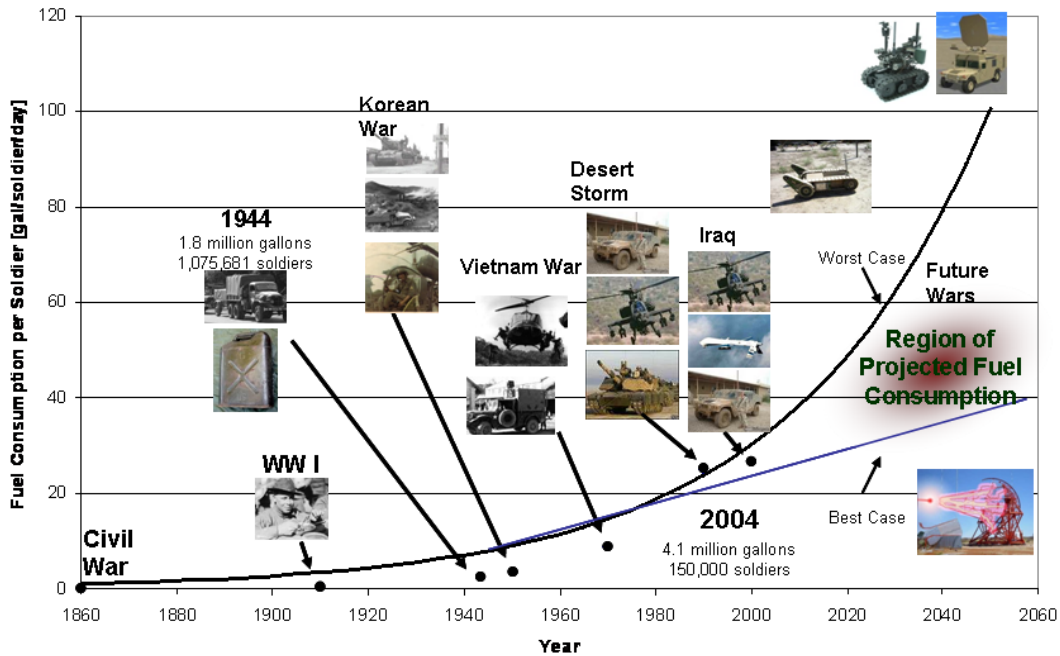
**Introduction:** With the continued development and fielding of a digitized, network-centric battlefield, Power and Energy (P&E) resources have become critical to enhancing Future War Fighter capability. P&E issues are increasingly a significant driver for future Army acquisitions: the programmatic, science and technology development, the potentially higher fuel consumption and the ever-increasing energy prices. For the near future, fossil fuels will remain the primary energy source to supply the power needed. However, with current fuel constraints, the Army must look to reduce and/or minimize the impact to its fuel consumption footprint due to enhanced capability (e.g., armor protection, electrical power equipment, etc). The Army must continue to develop new and/or enhance current technologies to minimize the impact of fuel consumption to reduce the vulnerability of Soldiers supplying fuel on the battlefield, while still enhancing capability. This reduced consumption will likewise reduce the strategic dependence on foreign energy supplies & ease the taxpayer's financial burden. The vision above and/or derivatives have been outlined in several high level reports (e.g., 2001 and 2008 Defense Science Board Reports) with several recommendations made, but a gap exists on how to execute a path forward.

To support the power and energy analysis needed, AMSAA has developed a modeling capability to estimate vehicle fuel consumption characteristics/metrics for various terrains, power-loading conditions, and mission usage. AMSAA developed the Fuel Consumption Prediction Model (FCPM), which enables the Army to study parametric and/or discrete fuel performance of various new technologies over a mission profile/power demand profile. Fuel consumption is a function of the duty cycle / power demand (moving and non-moving) and the efficiency of the system to fulfill that demand. AMSAA has applied an engineering approach to studying fuel performance per this theory. AMSAA developed the modeling capability over the last several years and applied it to several major Army acquisition programs as well as assisted the Army planning community in revising burn rate performance databases used to generate operational planning factors.

The purpose of this paper is to provide an overview of AMSAA's FCPM mentioned above and its application to support military systems acquisition and planning. The following sections highlight various aspects of the model and the catalysts leading to its development to include: historical trends, metrics, and data sources.

**Background:** This section examines the background of why Army/AMSAA needed to develop tools capable of examining the energy footprint within a military environment to include historical trends and fuel data availability. Primary drivers are increasing future power demands and the need to examine new P&E technologies that will be used to support and manage this demand while giving the Soldier the needed capability.

*Historical Trends:* Figure 1 provides a historical perspective and forecast of US military fuel consumption trends. This figure was generated by the Research, Development, and Engineering Command (RDECOM) P&E technology Integrated Product Team (IPT) now Technology Focus Team, and presented by the Commanding General, Army Materiel Command at last year's P&E symposium (Aug 07). It provides Soldier daily fuel consumption estimates for various major US military operations from the Civil War to Operation Iraqi Freedom (OIF). It should be noted this was based on various sources and usages, but the bottom-line is that Army fuel consumption usage has increased significantly over time primarily due to power demand increases for both moving and non-moving operation to provide the necessary capability for those operations. With the increased power demands of the network-centric future battle field, P&E issues will take on greater importance in future system acquisition. The Army will need these methods to address the analytical challenges of future power growth while satisfying Soldier requirements.



**FIGURE 1. Historical US Military Fuel Consumption Trends.**

*Fuel Consumption Metrics (Ground Vehicles):* There are several related metrics used to measure fuel consumption performance, which are shown in Table 1. All these metrics will influence cost. Many times, these metrics are misused due to the lack of a common definition or a misinterpretation of the definition and/or question being addressed. A common mistake is directly relating an increase in fuel economy to a proportionate reduction in fuel consumption. This is not completely accurate because fuel economy is based on distance traveled or moving operation while fuel consumption is based on the overall mission including fuel consumed during idle operation. This misinterpretation is made because fuel economy is the predominant fuel metric used in the commercial sector, but it may not completely apply in a military scenario, depending on the analytical question at hand. Another common misuse is using percent differences without referencing the baseline. A percent change represents an implied improvement/degradation in capability versus a common baseline. Percent change implies a comparison, and does not give a metric's magnitude difference. For instance, a 10 percent decrease in fuel consumed by a light-wheeled tactical vehicle is significantly different from a 10 percent decrease in fuel consumed by a main battle tank even though both are stated as a 10 percent reduction in fuel consumed.

Another common metric used is "Transport Efficiency" (ton-mile per gallon), which is a distance based fuel usage metric similar to mpg, but normalized to weight. It is important to point out that this metric was developed in the commercial sector as transport efficiency for payload and comparing similar vehicles. The intention was not to use gross vehicle weight as the normalization factor, but payload weight. This could in fact show a heavier platform with greater efficiency yet consume more fuel, if only shown by itself.

The correct metrics are needed for the particular analysis or issue being addressed. Fuel economy may not be the correct metric for every program. The Army's focus should be on sustainment impact (i.e., demand...fuel consumed and rate of consumption, logistics footprint...number of trucks, personnel needed to supply and distribution...where to distribute, how much, and how often). The Army also cannot ignore the life cycle costs of associated with batteries in both conventional and hybrid electric vehicles.

It should be noted that AMSAA provided a more detailed discussion in an RDECOM P&E IPT White Paper delivered to Training and Doctrine Command (TRADOC) recommending a potential P&E Key Performance Parameter development process.

**TABLE 1. Fuel Consumption Metrics.**

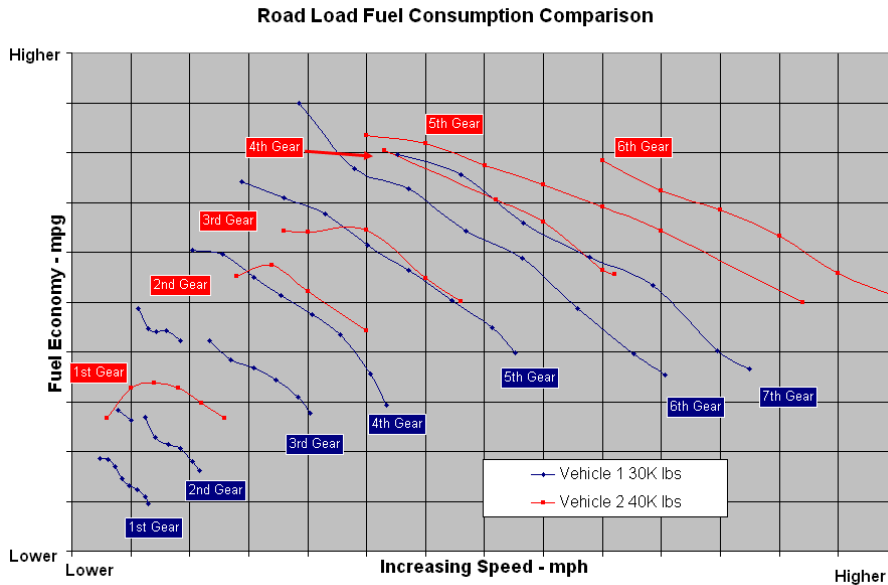
Metric (Typical units)	Description / Notes
<b>Fuel Economy</b> (miles per gallon)	Distance based metric. Typically focused on <u>moving</u> operations, but can include non-moving for mission calculations. <b>System Efficiency/Resupply Quantity - impact on Range / Fuel Capacity</b>
<b>Transport Efficiency</b> (ton-miles per gallon)	Distance based metric similar fuel economy, but normalized to weight. Metric developed in the commercial sector for <u>payload (not gross)</u> on similar vehicles / trains. <b>System Efficiency/Resupply</b>
<b>Burn Rate</b> (gal/hr or liters/hr)	Time based fuel usage metric for overall mission or single operating condition. Represents time based demand for a single system for moving and non-moving operation. <b>Resupply frequency</b>
<b>Fuel Consumed</b> (gallons or liters)	Amount (volume) of fuel consumed for a mission or single operating condition (distance and time are often implied). <b>Item or Unit Level Demand / Life Cycle Cost (\$) Driver</b>
<b>Fuel Capacity</b> (gallons or liters)	System on-board fuel capacity. Can be combined with fuel economy or burn rate to compute range or operating time, respectively. <b>Resupply quantity and frequency</b>
<b>Range</b> (miles or km)	Distance a system can move given fuel economy and useable fuel capacity. Often ONLY focused on moving operations. <b>Distribution Concept / Force Structure</b>
<b># Supply Trk Loads</b>	Dependent on volumetric capacity of the support truck (e.g., 2.5K gallon HEMTT Fueler). <b>Unit level calculation &amp; effects force structure depending on fuel distribution unit size (4 trucks/unit)</b>
<b>Percentage Change</b> (% difference)	Can be applied to any metric to represent implied improvement / degradation in capability. Requires baseline / context for comparison to determine potential logistics impact. <b>Metric Dependent</b>

**Available Fuel Data Sources:** The following paragraphs discuss available fuel data sources and the advantages and disadvantages that occur when using them for fuel modeling to support acquisition and planning. Table 2 provides the spectrum of available fuel data from developmental testing (performance and endurance) to operational testing and field data. Several categories are compared amongst the various data types to included terrain, transient operation, operational usage, speeds availability, repeatability of the data, focus the data element (i.e., purpose was fuel test), data availability, and quantifiable. It is left to reader to examine the table in detail. For purpose of simplicity, a simple summary of the advantages, disadvantages, and differences of the data types are discussed here.

- Performance data has the detail needed, is well defined, highly available for most systems, and great for model development / verification, but is not operational and mostly ideal (steady-state, little/no non-mobility power loading).
- Endurance data is similar to performance data and has more operational terrain, but is only moderately available depending on system. It is great for model validation to compare to models developed from performance data.
- Operational test data gives the appropriate mission/operational test context, but lacks the mission detail needed for analysis. Often an analyst has total gallons consumed and number of miles for the mission, but lacks the mission context (i.e., definition of terrain driven and non-moving operation).
- Field Sample Data Collection and Exercises is actual performance data, but gives even less mission detail than operational testing, but great for validation, if appropriate detail can be approximated.



Figure 3 shows another example of “road-load” performance data (level paved surface at steady-state) for two systems. This example is shown to illustrate key fuel performance drivers and that performance is not always what is expected. Weight is a key driver to fuel consumed (function of slope), but engine, transmission, aerodynamic parameters are also significant. An analyst must consider all factors (configuration and condition) when analyzing fuel consumption performance. For example, Vehicle 2 (40K lbs) is 10K lbs heavier than Vehicle 1 (30K lbs). Vehicle 2 has greater fuel economy on level paved road at higher speeds than Vehicle 1 even with higher weight, which maybe caused by gearing. It should be noted that more severe slope condition might make weight difference more significant.



**FIGURE 3. Example Army Fuel Consumption Data Sets (Key Drivers).**

**Item Level Prediction Methodology:** Fuel consumption is primarily a function of the power demanded on a system due to an operational condition and the efficiency of the system to fulfill this demand by converting fuel to usable power and supplying that power to the source through the power train. The AMSAA item level fuel consumption methodology is a variation of J.Y Wong’s “Theory of Ground Vehicles” fuel economy of cross-country operations. Equation 1 (Wong, p. 197) depicts Wong’s theory to calculate a vehicles fuel consumption. Fuel consumption per hour of operation ( $\mu_h$ : fuel flow, lbs/hr) is primarily a function of the power output of the engine ( $P_{output}$ : Power, horsepower, hp) and efficiency of the system to convert fuel to usable power ( $\mu_s$ : specific fuel consumption, lb/hp-hr).

$$\mu_h = P_{Output} \times \mu_s \quad \text{(Equation 1)}$$

AMSAA has modified this equation to make it easier to analyze a system and the relation to the surrounding environment. Equation 2 shows the modified version. The summation of the power demands divided by the efficiency from the engine to the power demand point replaces  $P_{output}$ . The equation now reads fuel consumption per hour of operation ( $\mu_h$ ) is primarily a function of the sum of each power demand ( $P_{demand}$ ) and the efficiency to provide that power to each of demand points ( $\eta_{engine\ to\ demand}$ ) multiplied by the efficiency to convert fuel to power ( $\mu_s$ - specific fuel consumption).

$$\mu_h = \sum \left( \frac{P_{demand}}{\eta_{engine \rightarrow demand}} \right) \times \mu_s \quad \text{(Equation 2)}$$

To implement this theory, AMSAA generated two engineering sub-models, a duty cycle, and power train model.

**Duty Cycle Model:** The duty cycle model predicts the mobility and non-mobility power demands on a system, given a set of input conditions (terrain, weather, speed, slope, etc.). Mobility power demands (propulsion) are determined using the surface motion resistance relationships from the NATO Reference Mobility Model (NRMM). Non-mobility power demands are accounted for as accessory loads.

**Power train Model:** The power train model predicts the ability of the system to fulfill the duty cycle demands. The model determines the overall system efficiency for converting the fuel into useable power. It can be used for both conventional (mechanical) and hybrid-electric drivelines.

Combining these two models provides the capability to predict system fuel consumption. Inputs to the models include vehicle characteristics and power loads while outputs include various fuel consumption metrics. The model input assumptions and output data can be tailored to support a wide range of data and analysis needs. Figure 4 shows an overview of inputs and example out. A key point to notice from the figure is fuel burn rate is highly dependent on operating conditions in particular the magnitude of moving and non-moving power demand:

- Non-moving consumption is driven by the non-mobility power demand.
- Moving consumption is driven by the both the mobility (propulsion) and non-mobility power demand.

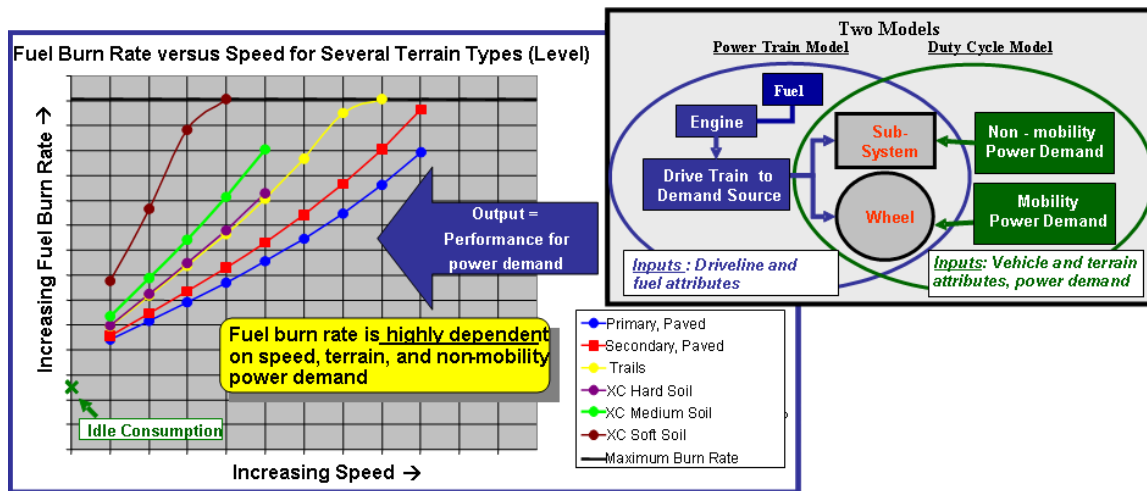


FIGURE 4. AMSAA Item Level Fuel Consumption Methodology.

**Mission Level Methodology.** The purpose of the mission methodology is to estimate the amount of fuel available and required by a force for a particular given mission usage/profile. Figure 5 shows a flow diagram of the FCPM at the mission level. The fuel needed for one system over a given mission profile is calculated by summing the fuel consumed by all parts of the mission using the Operational Mode Summary / Mission Profile (OMS/MP) and the burn rates for a given condition from the item level methodology. The fuel needed by the force is calculated by summing the product of fuel consumed by an individual system over its mission and its system density in the force for each class of system. The fuel available to the force is calculated by summing the product of an individual system's usable fuel capacity and its system density in the force for each class of system.

AMSAA studies have shown that although the non-moving fuel consumption rate is typically less than the moving fuel consumption rate, the contributions for both need to be accounted for in mission fuel estimation and logistics planning factors. More specifically, if a system spends a large portion of its mission stationary (non-moving with

the engine operating), the stationary fuel consumed (idle consumption) can account for a significant portion of the total fuel consumed for the overall mission.

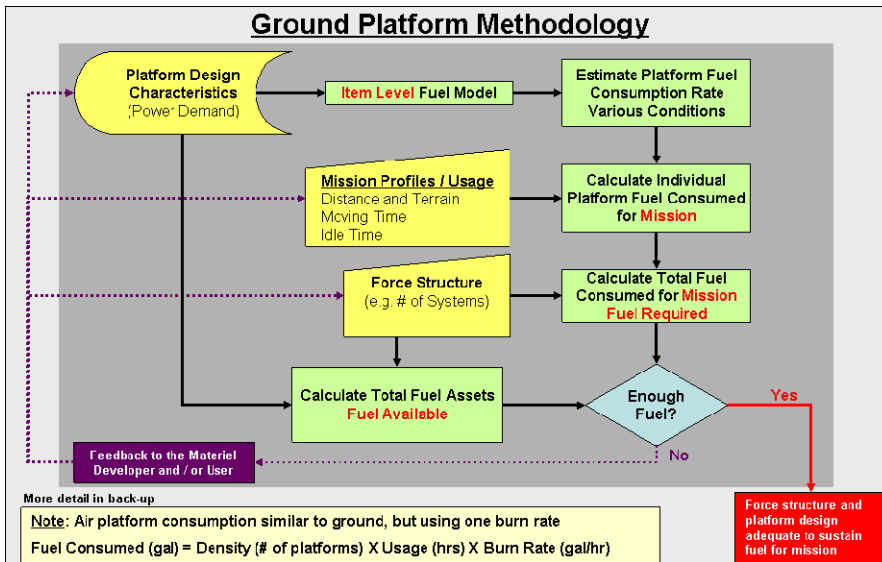


FIGURE 5. AMSAA Mission Level Fuel Consumption Methodology.

*Mission Level Methodology Examples:* Figure 6 presents a generic example fuel analysis using the FCPM for an example force and mission. There are several key findings from this example analysis:

1. The bar chart shows that the fuel sustainment structure is adequate to support the force over this mission because the available fuel exceeds the fuel consumed/demanded. If the results were reversed (i.e., demand exceeds available fuel), the difference would quantify the fuel shortfall. AMSAA can use the FCPM to assess how proposed changes to vehicle designs and/or force structure would impact force level fuel sustainment
2. The pie chart in the upper right corner of Figure 6 indicates that Systems 1 and 7 (38% and 28% respectively) are primary fuel consumers. The FCPM helped to identify which system(s) is/are the key consumers in the force; therefore, providing information that can be used to identify where the greatest impact can be made to potentially reduce force level fuel consumption.
3. The pie chart in the lower right corner of Figure 6 shows that a significant portion (40%) of the fuel consumed by System 1 is the result of non-moving operations.

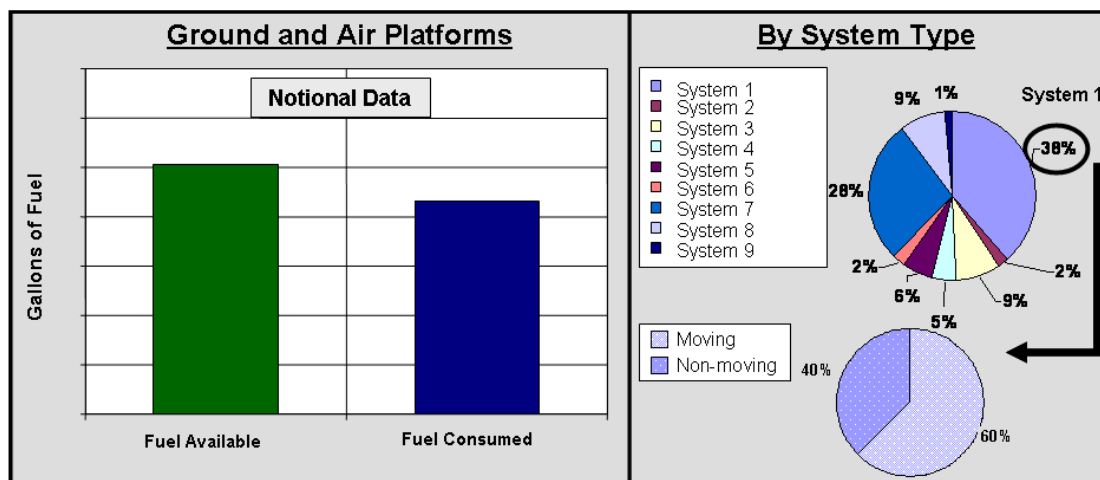
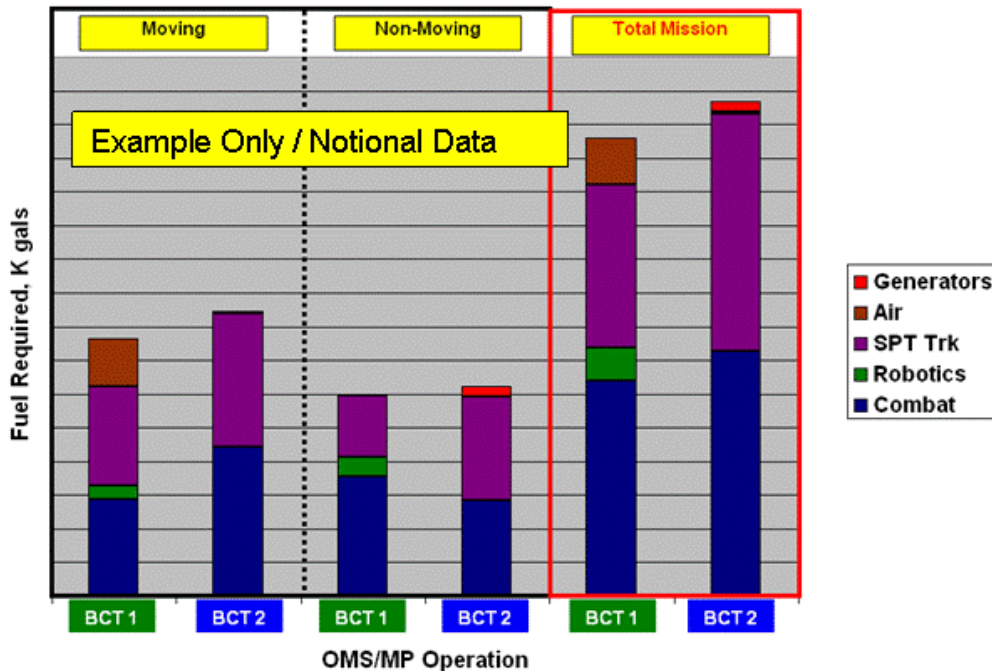


FIGURE 6. AMSAA Mission Level Fuel Consumption Methodology Example.



**FIGURE 7. BCT Comparison.**

The AMSAA FCPM can also be used to compare Brigade Combat Teams (BCTs). Figure 7 provides a comparison of two BCTs over a normalized Operational Mode Summary / Mission Profile (OMS/MP). It should be mentioned that significant assumptions may be required at times to compare forces of different structure, design, and capability (i.e., they will use different tactics). BCT 1 is a lighter, network centric future force, which relies on information for capability, while BCT 2 is more like a current force that is heavily armored for survivability. Possible conclusions that can be made include:

- BCT 1 consumes less fuel than BCT 2 for moving operation mostly due to weight reduction, but also due to fuel efficiency increase and differences in vehicle force density;
- BCT 1 and BCT 2 consume approximately the same fuel for non-movement, but the BCT 1 combat platforms consume more fuel due to energy demands of accessories providing information and protection (e.g. network);
- BCT 1 consumes less fuel for the total mission due to the reasons listed above.
- Numerous variables contributing to fuel consumption not just fuel efficiency;
- Non-movement time is significant portion of the mission and contributes to total fuel consumed.

**Summary:** In summary, the future force will have need increasing power demands / fuel consumption due to increased capability with ever-increasing costs. The Army needs to develop tools capable of examining the energy footprint within a military environment and comparing new P&E technologies that will be used to support and manage this demand while giving the Soldier the needed capability. Fuel consumption prediction is complex with many variables (demand, terrain, configuration) and how much detail can operational planners and modelers use / take into account. There are several Army data sources available, which all with advantages / limitations. To meet these challenges, AMSAA developed a fuel consumption prediction model to support both the Army Acquisition and planning community by leveraging fuel related data sources and modeling capabilities (Item / Mission Level).

**References:**

*Theory of Ground Vehicles, J.Y. Wong, Ph.D, P. 197-200, John Wiley & Sons Publishing 1978.*