

# Evaluation of Logistic and Economic Impacts of Hybrid Vehicle Propulsion/Microgrid Concepts: Demonstration of LOCSS Applied to HE HMMV in Future Unit of Action

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## ABSTRACT

Computer models have been developed and used to predict the performance of vehicles equipped with advanced fuel and power train technologies such as hybrid electric or fuel cells. However, simulations that describe the interaction of the vehicle with the rest of the vehicle fleet and infrastructure are just emerging. This paper documents the results of an experiment to demonstrate the utility of using these types of simulations. The experiment examined the business case of fielding hybrid electric, High-Mobility Multipurpose Wheeled Vehicles (HE HMMWVs) in a future Army organization. The hypothesis was that fielding HE vehicles would significantly reduce fuel consumption due to the economy offered by the HE technology and reducing the number of generators as a result of using the vehicles to generate electrical power. The Logistical and Combat Systems Simulation (LOCSS) was used to estimate differences in fuel consumption and associated equipment during a 72-hour operation with and without HE HMMWVs. There was a 25 percent reduction in fuel consumption over the systems examined. However, due to the relatively low density of the HE vehicles in the organization, the total difference in fuel consumption was not operationally significant; and the savings in fuel costs did not overcome the additional procurement costs over a twenty-year life cycle.

**Keywords:** Logistics, Hybrid, LOCSS, Economic, Models

## 1. INTRODUCTION

Several goals such as reducing the United States' dependency on imported oil, reducing the amount of greenhouse gas emissions, and avoiding increasing costs of transporting ourselves and heating our homes are motivating a great deal of research on advanced technologies, such as fuel cells, to produce energy. Some technologies, such as hybrid electric, are in production and are being used to power automobiles and other equipment today. Many consumers are paying more for hybrid electric vehicles in order to reduce the amount of fuel they consume and the amount of emissions they produce.

The military forces of the United States, particularly the Army, are pursuing ways to reduce the amount of fuel and other commodities they consume. Current forces are being reorganized, and future forces and systems are being designed so that they can be deployed rapidly over great distances and sustained using much less logistics support than is required today. Smaller forces with more efficient vehicles that consume less means that a smaller "logistics footprint" with fewer personnel and less equipment that must be deployed to supply the necessary food, water, fuel, ammunition, and other material needed to support the force. The core of the US Army's transformation is the Future Combat Systems (FCS), a family of systems consisting of 18 manned and unmanned ground and air platforms. The manned ground vehicles are currently envisioned to be equipped with hybrid electric drives.

Computer models have been developed that predict the performance of vehicles equipped with advanced fuel and power train technologies such as hybrid electric or fuel cells. However, it is also important to understand what infrastructure and supplies are needed to support vehicles and equipment equipped with these new technologies. Hybrid electric vehicles use gasoline so the infrastructure that supports conventional vehicles can also support them. However, as fuel cell technology matures and fuel cell equipped vehicles are produced, a different infrastructure and a different fuel distribution process will be needed to provide the hydrogen needed for the fuel cells. The military also faces this challenge. What kind of logistics infrastructure will be required to support the force of the future?

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To address these types of questions, Altarum Institute developed the Logistical and Combat Systems Simulation (LOCSS). LOCSS simulates the logistics processes to supply Army organizations. LOCSS currently simulates the supply of food, petroleum products, and ammunition. It also simulates the supply of repair parts at an aggregated level. These four classes of supply constitute the majority of the tonnage delivered. LOCSS is currently being used to determine the degree to which logistics organizations and systems have the capacity to move the ammunition, fuel, and other supplies to enable future organization achieve the operational tempo (i.e., moving, shooting, etc.) envisioned.

The National Automotive Center (NAC) in Warren, MI, was interested in understanding how LOCSS could be used to determine the degree to which the logistics' infrastructure would be affected by fielding advanced fuel technologies. The experiment commissioned by the NAC was an initial business case analysis of fielding hybrid electric, High-Mobility Multipurpose Wheeled Vehicles (HE HMMWVs). This manuscript describes the logistics portion of the analysis.

About the time this project began, the Army canceled its HE HMMWV program and reassigned the personnel to other programs. The impact of this cancellation was that good future cost and performance estimates were not available. Altarum analysts researched existing publications,<sup>1,2,3</sup> reviewed the HE HMMWV test report,<sup>4</sup> and interviewed some of the former HE HMMWV program personnel to obtain their best estimates.

The remainder of this manuscript contains an overview of LOCSS (section 2) and a description of the analysis and the results of the logistics analysis (section 3). The experiment demonstrated that LOCSS can be used to determine the difference in infrastructure and other logistics requirements associated with fielding advanced-fuel technologies. LOCSS is flexible enough to represent either military or non-military infrastructure and supply distribution processes. These initial results should not be considered definitive and do not necessarily represent the opinion of the Army.

## 2. LOGISTICAL & COMBAT SYSTEMS SIMULATION

LOCSS is a stochastic, high-resolution model consisting of function-specific modules in a discrete-event simulation. Systems are represented in "classes" that are described by their processes and attributes. They interact with other systems and processes within the model, which tracks the status of each system throughout the course of the simulation. Figure 1 illustrates some of the classes of systems and their attributes and processes that are represented in LOCSS.

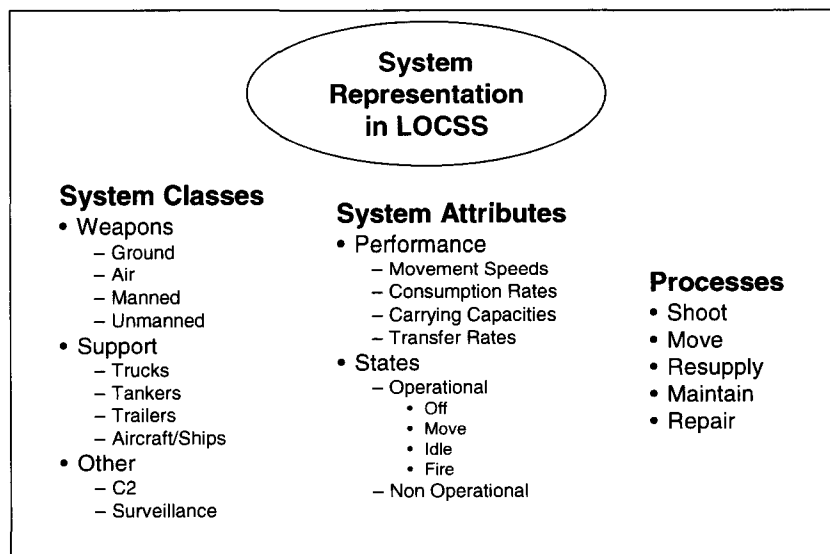


Figure 1. System Representation in LOCSS.

This approach to represent systems makes LOCSS flexible and adaptable. New systems can be introduced with characteristics that are defined by their performance data. Systems are assigned to organizations, and rules directing

their behavior such as movement frequencies and distances moved are developed. Support relationships such as where to obtain fuel or other supplies are also developed.

As noted previously, LOCSS currently simulates the supply of food, petroleum products, and ammunition, and repair parts. Reliability is modeled as a mean time between failures, and two types of failures can be represented (a system is inoperative or it can operate in a degraded mode). Repair is modeled as a mean time to repair and administrative and logistics delay time (ALDT). The representation of ALDT is flexible enough to reflect alternative repair parts stockage policies.

The environment represented within LOCSS encompasses a myriad of operations and processes acting across a user-defined infrastructure. The infrastructure can be notional or it can be an actual infrastructure developed using geographic information system (e.g., ArcGIS) files. Air and seaports can be represented to introduce supplies into the region. Routes and supply nodes physically and logically link the ports to the operating systems. Activities of the principal systems and logistical resources (e.g. trucks and material handling equipment) are represented and monitored. Systems create demands for commodities that are supplied through a combination of “push” and “pull” processes. LOCSS represents commodities that flow according to the user-defined relationships between the demand and support systems. Demands such as pounds of food per person per day, fuel consumption, ammunition expenditures, etc. are modeled in a detailed manner. Maneuver and support systems experience failures and consume commodities that trigger re-supply activities. Figure 2 depicts a possible operational environment in which a future organization is operating. All, some or none of the air and seaports and intermediate logistics nodes can be represented depending on the size of the operation and the logistics concepts being examined.

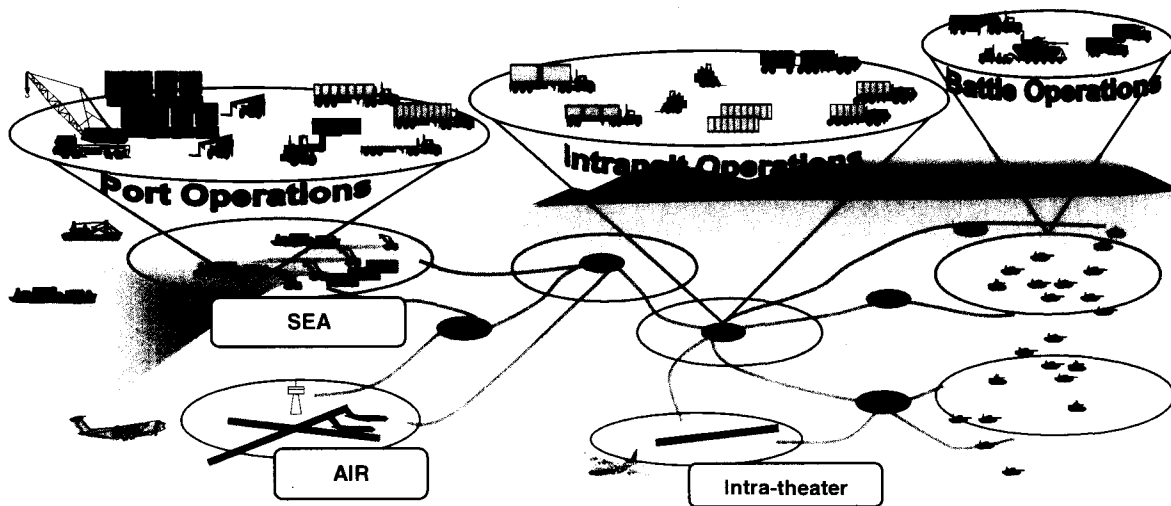


Figure 2. Operational Environment Represented in LOCSS.

LOCSS enables second and third order effects to be captured. For example, reductions in fuel consumption due to introducing the HE HMMWV would reduce the amount of fuel that needs to be delivered. The petroleum re-supply vehicles would make fewer trips and would consume less fuel. This, in turn, would affect the vehicles that supply them reducing their fuel consumption.

Output is written to a database and to text files and processed after the simulation. Output is usually extracted using a data extraction utility and loaded into spreadsheets where it can be analyzed and graphs created. Sometimes the output is used as input other simulations. Conversely, outputs from other simulations such as system activity requirements can be input to LOCSS to assess the degree to which the future logistics' capability can sustain that intensity.

Since LOCSS is stochastic, several replications are executed to be confident of the results. Figure 3 illustrates hypothetical results that might be observed. The measure being investigated (e.g., gallons or pounds delivered) is

depicted on the ordinate. The black dots are the throughput for each replication; the white dot is the mean of all the throughputs observed. The average “Baseline” throughput is higher than either of the alternatives. A standard significance test will demonstrate whether or not the differences are statistically significant. While the “Baseline” is higher, “Alt #2” provides a more predictable outcome. The analyst would analyze LOCSS output to understand why the throughput was about 25% higher in the Baseline but less predictable than in Alt #2. Insights might be used to take the best parts of the Baseline and Alt #2 processes to develop another alternative that provided higher throughput with greater predictability.

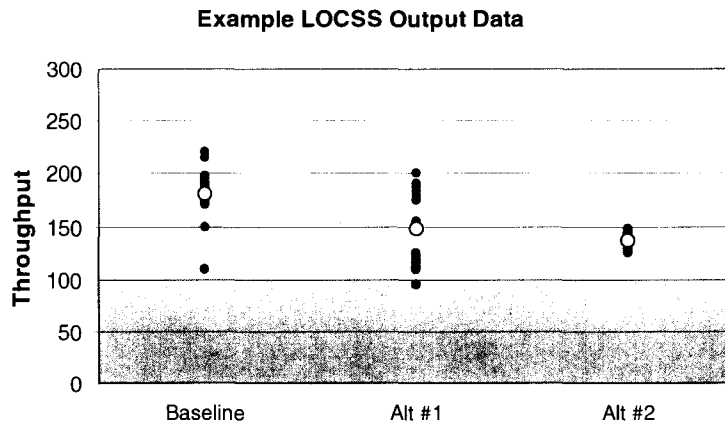


Figure 3. Example LOCSS Output – Mean and Variability.

A more extensive description of LOCSS including the pre-processor and post processor is contained in the main report.<sup>5</sup>

### 3. ANALYSIS OF LOGISTICS IMPLICATIONS

As noted previously, the purpose of the project was to demonstrate the utility of using models, simulations, and other analytic techniques to provide information useful to decision-makers concerning the impact of future power train and microgeneration capabilities. The topic selected by the NAC for the demonstration was the implications of inserting HE HMMWVs into an Army organization.

The timeframe that a HE HMMWV could be fielded (about 2010 or later) was after the six new Stryker Brigade Combat Teams would be fielded and a little before the timeframe for fielding a unit equipped with FCS. The analysis examined the implications of inserting a HE HMMWV into a future brigade combat team equipped with FCS, called FBCT. “The Future Combat System [FBCT] is organized in combat configurations to be 100 percent mobile and completely self-sufficient for up to 72 hours of high-intensity contact upon delivery into the area of operations.”<sup>6</sup> This is an ambitious undertaking. If introducing HE vehicles would reduce the fuel consumption significantly, achieving the 72-hour self-sustainment requirement could be easier to achieve.

#### 3.1. Estimating the Number of HE HMMWVs

The first task was to estimate the number of HE HMMWVs that might be fielded in a FBCT. A high-level organizational diagram describing the BCT organization is shown in Figure 4, below. The next two paragraphs provide a short explanation of the brigade composition for readers unfamiliar with Army organizations.

A brigade combat team contains combat and support organizations it requires to be a self-sufficient organization capable of operating independently. The FBCT will have about 3,000 soldiers. An Army Colonel normally commands a brigade.

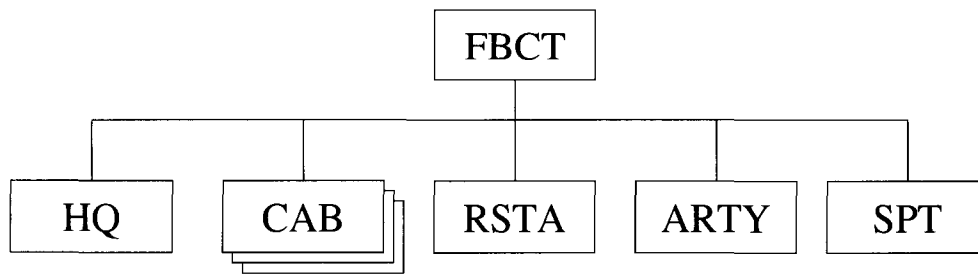


Figure 4. FBCT Organization.

The brigade headquarters (HQ) contains the brigade commander, the brigade staff, and the soldiers and equipment needed to enable the headquarters to function. This includes administration, the intelligence cell, communications and electronics experts, security, and the personnel needed to prepare and distribute food and supplies within the headquarters. There are three combined arms battalions (CAB) in the BCT. Each of these battalions contains infantry soldiers, soldiers on mobile combat systems, reconnaissance elements, mortars and the battalion headquarters. Each of the battalions also contains unmanned aerial vehicles to search areas not visible to soldiers on the ground. The reconnaissance, surveillance, and target acquisition squadron (RSTA) contains ground and air surveillance platforms including helicopters, unmanned aerial vehicles, and mounted ground sensors designed to generate information about the enemy and the environment and to acquire targets to be attacked by other systems. The FBCT also has a battalion equipped with cannons and rocket launchers. For simplicity, that battalion is called an artillery (ARTY) battalion; however its official name is non-line of sight (NLOS). In addition to the cannons and rockets, the battalion has unmanned aerial vehicles to conduct target acquisition and radars to acquire enemy artillery, rocket, and mortar launchers and to acquire and track enemy and friendly aircraft. The final organization, the support battalion (SPT), supports the brigade by providing the supplies it requires, repairing the vehicles that fail, and providing the medical support needed to maintain healthy soldiers and to heal them when they become sick or are wounded. The initial design included almost 200 HMMWVs.

HE vehicles were believed to provide two benefits. First, they should be more economical than a standard vehicle. Second, the on-board generator could be used to generate power eliminating the need for some generators. Eliminating the generators reduces the amount of equipment that must be bought and deployed, and connecting the HE vehicles and the supported equipment in a power grid should enable the generator on the HE vehicles to substitute for several small generators further reducing fuel consumption.

The difference in the HMMWV fuel economy was not as large as anticipated. A standard HMMWV of the type that would have been converted to HE operates at less than 10 miles per gallon.<sup>7</sup> The improvement in economy realized in the test was only about ten percent, less than the goal of 30 percent. The relatively small increase was due to the demands placed on the HMMWV when operating in austere environments. If every HMMWV in the FBCT realized a 30 percent increase in fuel economy, the BCT would consume less than 1,000 fewer gallons of fuel at the movement rates realized in this experiment. Examining the differences in peacetime operating costs was not any better with HMMWVs being driven 1,000 or 4,000 miles per year depending on the type of vehicle.

Instead of replacing every HMMWV in the FBCT, the approach was to determine where generators could be eliminated. A design of the FBCT in sufficient detail that specified the number of generators, by type in each organization did not exist. The objective design of the Stryker BCT was used as a surrogate, because its organization was very similar to the FBCT. There were two considerations in determining whether a vehicle should be a candidate for HE power. The first consideration was whether a unit within the FBCT needed generators. Since the FCS manned systems were envisioned to be fielded with hybrid electric drives, they can provide the power required for their unit. The second consideration was which HMMWVs would be expected to remain in the vicinity of the unit to provide electrical power. There were two general classes of HMMWVs. One, termed C2 (command and control), would be used to move people (e.g., leaders and staff officers) around the battlefield. Some of these would be moving a lot; others would move only when the personnel in the unit moved. The other, termed SPT (support), would be used to move equipment. Some of the HMMV(SPT) move supplies or tow trailers containing other equipment such as radars; others have shelters mounted on

them. These shelters can contain, for example, mobile offices, communications equipment, maintenance facilities, or medical supplies.

After reviewing the FBCT subordinate organizations, assuming that the manned FCS vehicles would be hybrid electric, we concluded that the brigade headquarters, the Combined Arms Battalions, RSTA squadron, and most of the NLOS battalion would not benefit from HE HMMWVs. Either the FCS manned vehicles would provide sufficient power, or the HMMWVs in the organizations would probably be away from their respective organizations enough that they could not be depended upon to provide power. Overall, within the FBCT, it was determined that 21 HE HMMWVs could be fielded instead of standard HMMWVs replacing 33 generators and 15 trailers. A summary of the organizations affected and the equipment replaced is depicted in Table 1.

Table 1. Equipment Differences Due to Fielding HE HMMWVs.

FBCT Organization	Number of HE HMMWVs	Equipment Replaced in addition to standard HMMWVs
Radar Section, ARTY Battalion	6 HE HMMWV(SPT)	6 10KW generators 6 trailers (potentially)
Headquarters, SPT Battalion	2 HE HMMWV(SPT)	3 generators (5KW, 10KW, 15KW) – all skid mounted
Medical Company, SPT Battalion	3 HE HMMWV(SPT)	5 3KW generators – skid mounted 1 10KW generator – trailer mounted
Maintenance Company, SPT Battalion	2 HE HMMWV(C2) 8 HE HMMWV(SPT)	1 3KW generator – skid mounted 9 5KW generators – skid mounted 7 15 KW generators – trailer mounted 1 30 KW generator – trailer mounted

The number of generators by type and line item number (LIN) in the sections affected is depicted in Table 2. The LINs refer to the current family of generators in the Stryker BCT organization.

Table 2. Number of Generators With and Without HE HMMWVs.

LIN	Description (From SBCT TO&E)	Qty w/ Std HMMWV	Qty w/ HE HMMWV
G11966	GEN SET: DED SKID MTD 5KW 60HZ	10	0
G12170	GEN SET: DED SKID MTD 15KW 50/60HZ	1	0
G18358	GEN SET: DED SKID MTD 3KW 60HZ	6	0
G35851	GENERATOR SET DIESEL ENGINE TM: PU-803	1	0
G42170	GEN SET DED TM: 10KW 60HZ MTD ONM116A2 PU-798	2	1
G53778	GENERATOR SET DIESEL ENGINE TM: PU-802	12	5
G74711	GEN SET: DED SKID MTD 10KW 60HZ	1	0
G74779	GEN SET: DED SKID MTD 10KW 400HZ	6	0
		39	6

The number of HMMWVs, by type, in the sections is depicted in Table 3. The results are reported for these vehicles and generators.

Table 3. Number of Standard and HE HMMWVs.

Standard HMMWV Alternative		Hybrid Electric HMMWV Alternatives			
HMMWV(C2)	HMMWV(SPT)	Standard HMMWV		HE HMMWV	
		HMMWV(C2)	HMMWV(SPT)	HMMWV(C2)	HMMWV(SPT)
12	29	10	10	2	19

### 3.2. Performance Data

The Army intends to begin fielding the next family of generators around the end of the decade. The next family of generators will be more efficient and reliable than the current generators. The Project Manager, Mobile Electric Power (PM MEP) provided the performance characteristics of the next family of generators.

The HMMWV and assumed HE HMMWV fuel consumption are depicted in Table 4. The Office of the Project Manager, Light Tactical Vehicles, provided the standard HMMWV characteristics using the M1113 variant. Two levels of improved fuel economy for the HE were used. As noted previously, the 10% improvement was realized in the HE HMMWV test, and a 30% improvement was the goal.

Table 4. HMMWV Performance Characteristics.<sup>7</sup>

	Fuel Economy (miles/gallon)		
	Std HMMWV	HE HMMWV @ 10% Better	HE HMMWV @ 30% Better
HMMWV C2	9.3	10.23	12.09
HMMWV SPT	7.2	7.92	9.36

The degree to which one HE HMMWV can replace more than one generator is important. A 30-kw generator consumes less fuel per hour than three 10-kw generators, for example. This ability to establish an electric grid with HE vehicles and replace generators was the principal reason for the difference in the amount of fuel consumed when a FBCT was equipped with standard HMMWVs or equipped with HE HMMWVs.

The number of HE HMMWVs generating power and the amount of power each generates are shown in Table 5. There were two assumptions regarding fuel consumption when generating power. The first was that generators on HE HMMWVs would be as efficient as the next family of generators when generating peak power of 30KW. During the test the generator on the HE HMMWV used less fuel than standard generators when generating power at less than 30KW. The second assumption was that the generator on the HE HMMWV would have a similar characteristic, and the percent reduction in fuel consumption (gallons per hour) when generating at power levels less than 30KW was applied to the future generator consumption rates provided by PM MEP.



Table 5. HMMWV Power Generation Characteristics.

HE HMMWVs Generating Power and Fuel Consumption			
KW	Number of HMMWV(C2)	Number of HMMWV(SPT)	Gal/Hr
3	1		0.25
6		1	0.39
9		1	0.54
10		12	0.59
20		2	1.07
30	1	3	1.56

### 3.3. Operational Logistics Implications

This section presents some of the operational implications of fielding 21 HE HMMWVs in place of the 21 standard HMMWVs and eliminating 33 generators. The information presented here, along with other measures, illustrates the type of information that can be provided by LOCSS. This type of information enables the user to understand the cause and effect and to present useful information to a decision maker. It turns out that the differences in this experiment were not operationally significant. Knowing that differences are not significant is useful to decision makers as they decide how to allocate scarce resources.

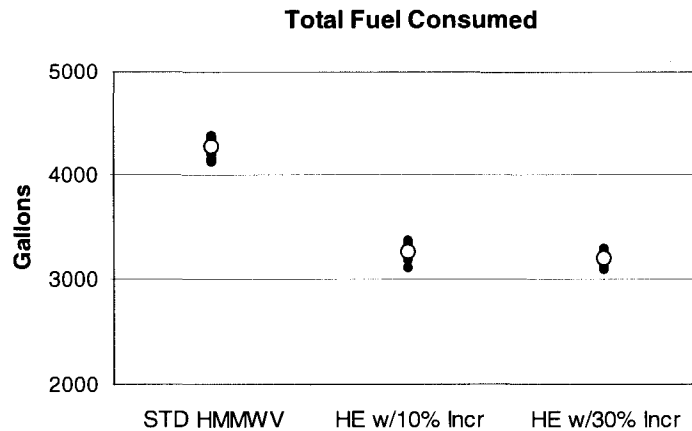


Figure 5. Fuel Consumption.

Figure 5 displays the total fuel consumed by the HMMWVs and the generators (those listed in Tables 2 and 3) and the support vehicles needed to supply them over a 72-hour operation. The mean (average) is the clear dot; the other dots depict the results of each of the 15 replications. The dispersion of the dots provides an indication of the variability of the fuel consumption.

With HE HMMWVs in the FBCT, fuel consumption was reduced about 1,000 gallons. This is about a 25% reduction in the fuel consumption for the vehicles and generators included in the experiment; however, it is not significant operationally from the point of view of the total FBCT fuel consumption. 1000 gallons is only 40% of one 2,500-gallon fuel tanker.

Most of the reduction in fuel consumption was due to the difference in the fuel required to generate electricity (replacing generators by HE HMMWVs discussed previously). Improving HE HMMWV fuel economy from 10% to 30% more than the standard HMMWV reduced fuel consumption by less than 100 gallons. This was because only one-half the

vehicles were hybrid-electric, and all but two of the HE vehicles were HMMWV SPT, which had the lowest fuel economy and, therefore, the lowest marginal improvement for a 10% and 30% increase in miles per gallon.

Figure 6 depicts the total distance the 41 HMMWVs moved during 72-hour operation. This demonstrates that differences in fuel consumption were not caused by a difference in distance traveled. HMMWVs moved an average of about 110 km per day. This is not inconsistent with the distances expected to be traveled by FCS manned ground vehicles in the same amount of time. The distances moved by manned ground vehicles varied depending on the vehicle with most being about 125 km/day.

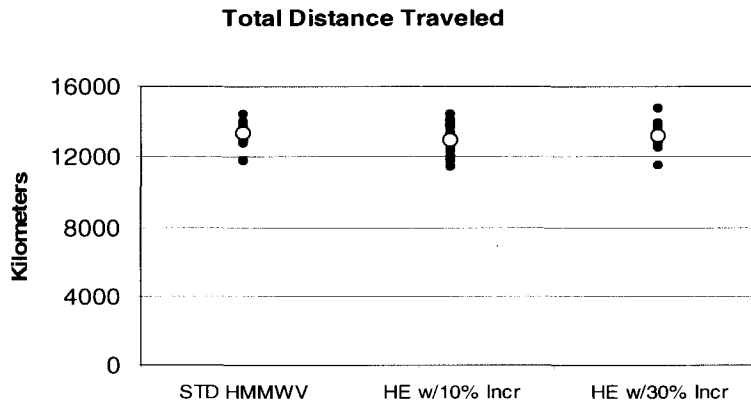


Figure 6. Distances Traveled by the HMMWVs.

LOCSS captures the second order effects. Figure 7 depicts a 13 percent reduction in the fuel consumed by the re-supply vehicles delivering fuel to the force.

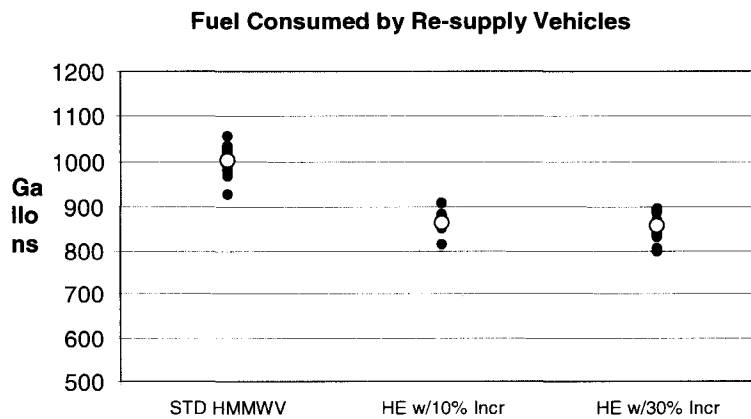


Figure 7. Fuel Consumption by Re-supply Vehicles.

The HE HMMWV exhibited significantly lower reliability and availability than the standard HMMWV during the test<sup>4</sup> due to a number of reasons including the HE technological maturity and the condition of the test vehicles provided for the test. The experiment assumed that the reliability and reparability of the standard and the HE HMMWVs would be the same.

The standard and HE HMMWVs were not operational about three to four percent of the time as depicted in Figure 8. The results demonstrate that the differences in fuel consumption were not due to HMMWV availability and usage. They also demonstrate the capability of LOCSS to capture information that will enable an analyst understand cause and effect. The apparently high degree of variability was expected. It was due to the high reliability of the systems (more than 1,800 hours between failures) and the relatively short, 72-hour operation.

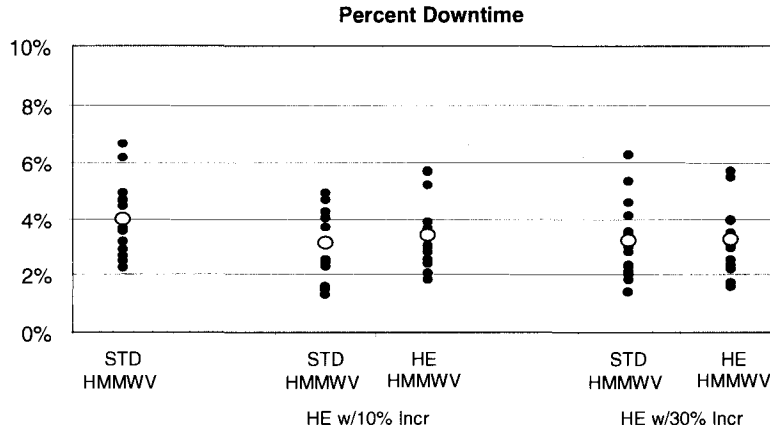


Figure 8. Percent of Time Unavailable.

The life cycle cost analysis is not included in this manuscript. As the reader has probably determined, fielding the FBCT with HE HMMWVs did not appear to be cost effective based on the available cost and performance information. It only became cost effective if the purchase price was significantly less than the cost that was provided, vehicle usage rates were much higher than currently experienced in peacetime, or the “actual” cost of fuel was on the order of \$10 or more per gallon.

#### 4. OBSERVATIONS

This analysis demonstrated that models like LOCSS can provide useful insights concerning the infrastructure and support requirements needed for alternative-fuel vehicles. The results demonstrated a reduction in the support requirements (measured in the gallons of fuel) needed to support a future Army brigade combat team. The differences were not large enough to warrant changes in infrastructure (e.g., fewer vehicles in logistics units). In retrospect, one would not expect them to have been large given the number of vehicles, the small increase in fuel economy of the HE HMMWV over the standard HMMWV, and the improved efficiency projected for the future family of generators. However, the factors that led to the small number of vehicles were not known at the time the HE HMMWV was selected. Models like LOCSS provide the structure to determine what types of data are needed and to begin collecting the data. As issues are identified and resolved, more is learned; and the model can be used to confirm the impact on infrastructure. The approach used in this analysis is also applicable to non-military applications where infrastructure and supply distribution requirements to support vehicles equipped with alternative-fuel propulsion, such as fuel cells, need to be estimated so that they can be provided when those new vehicles are ready for production and sale.

One of the benefits of using tools like LOCSS is that second- and third-order effects are captured. Not only was the amount of fuel used by the HMMWVs and generators reduced, so was the fuel consumed by vehicles delivering fuel to them and by vehicles external to the FBCT that deliver fuel to the support battalion. As vehicle fuel economies improve, the amount of fuel required would decrease and with it reductions in the number of delivery vehicles and fuel storage sites might be realized. In a military setting, the amount of personnel and equipment that have to be deployed and supported would decrease. In a non-military setting, the amount of people and equipment consuming fuel to distribute supplies would decrease further reducing the fuel distribution requirements.

## ACKNOWLEDGEMENTS

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