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FUEL CONSUMPTION TEST PROCEDURES FOR MILITARY WHEELED HYBRID VEHICLES

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ABSTRACT

The Hybrid Electric Vehicle Fuel Economy Methodology Study was conducted by the Automotive Instrumentation Division, US Army Aberdeen Test Center (ATC), Aberdeen Proving Ground (APG), Maryland, from June 2006 through August 2009. The program objectives were to develop a test protocol that can be used to evaluate the fuel consumption characteristics of a hybrid electric vehicle regardless of weight class, battery chemistry, and/or driveline configuration, and to characterize the performance of currently developed hybrid vehicles and tactical wheeled vehicle prototypes with regard to fuel consumption and energy usage. Eleven hybrids and eight conventional vehicles were provided for the methodology study. Fuel consumption tests were conducted on a wide spectrum of terrains ranging from level paved road surfaces to hilly cross country secondary road surfaces. Test vehicles were operated over the full range of speed capabilities on each of the terrain scenarios. Results for ground-up or conversion hybrid vehicle designs were compared to conventional vehicles of similar test weight or of the original chassis design in the case of conventional vehicles converted to hybrid propulsion. In accordance with a Design of Experiment (DOE) established by US Army Tank Automotive Research Development and Engineering Center (TARDEC), individual test trials were conducted with conventional and hybrid comparison vehicles in a leader-follower arrangement. Electrical energy storage system State of Charge (SOC) correction methods were evaluated and established to present hybrid vehicle fuel economy and consumption by correcting fuel measurements to a ΔSOC=ZERO fuel economy. Candidate vehicles were also characterized for power loss, weight distribution, center of gravity, and selected automotive performance capabilities.

INTRODUCTION

The use of fuel is an absolute necessity for modern military operations. In the foreseeable future, the effectiveness and participation of U.S. military marine, air, and ground operations on the modern-day battlefield will not exist in a tactical sense without petroleum based fuels. Logistical and supply, and combat and tactical operations in theater require the consumption of fuel for aircraft, the vast majority of surface ships, electrical power generation, and almost all tactical and combat ground vehicles. Reduction of fuel consumption from any one of these usage sources offers obvious advantages in the tactical, combat, and logistics of military operations. In the area of ground vehicle operations, a way to reduce the total fuel consumed is to increase efficiency of individual vehicles. Potentially, one approach to realizing reduced fuel consumption is through the hybridization of a vehicle's powertrain.

Through the development and testing of hybrid demonstration vehicles, the U.S. Army has sought to evaluate, in part, the potential for increased fuel economy of individual platforms. As in the commercial automotive industry, one of the advantages of hybrid vehicles is the highly publicized claim of increased fuel economy. Traditional existing test procedures for the U.S. Army to evaluate and quantify fuel consumption did not adequately address the complexity of hybrid vehicles. Typically with two on-board energy sources used for propulsion of hybrids, traditional test procedures expressing energy consumption, or fuel usage, were lacking when addressing hybrid designs. A viable, practical procedure was needed to address energy consumption of hybrid vehicle designs that accounted for both energy sources (typically petroleum based fuel and electrical or hydraulic potential energy) and yet yielded results that were comparable to existing conventional vehicles expressed in common units of fuel economy.

BACKGROUND

Fuel consumption measurements in the automotive industry as expressed in fuel economy values are resultant from well defined chassis dynamometer duty schedules. By comparison, the military combat and tactical fuel usage duty cycle is ever changing, unknown, and is certainly not defined by an agreed upon duty schedule available for all platforms and weight classes of wheeled and tracked vehicles. The US Army test community has expressed fuel consumption as discrete load conditions and terrain scenarios that are building blocks indicative of a vehicles performance for likely operating conditions and terrains for military vehicles.

With the emergence of military hybrid vehicle demonstrators, ATC and TARDEC have worked together since 1995 using available assets to define fuel economy for hybrid military vehicles in a meaningful way with respect to the unique and broad operating requirements.

Several approaches have been used historically to define the relationship between the stored electrical energy in the traction batteries and measured fuel economy. The goal was to express the overall vehicle fuel economy as distance traveled per fuel consumed in units of miles per gallon. The relationship between the change in the stored electrical energy and fuel energy was accounted for using two different approaches for field testing.

The first field test procedure for estimating the delta zero SOC fuel economy was as follows. The fuel consumption for each trial was recalculated compensating the vehicle for traction battery capacity and battery energy used or stored. An equivalent volume of fuel was determined from separately conducted recharging tests. Recharging tests were conducted by discharging the traction battery pack using an AeroVironment, ABC-150 to its minimum suggested SOC, 100-percent DOD, at the rate provided by the vehicle or battery manufacturer. The batteries were then recharged using the vehicle's engine generator. Vehicle performance was measured during the recharge. A relationship between the fuel volume consumed and the battery capacity, ampere-hours (Ah) and battery energy (kWh) was developed. These relationships were then used to calculate an equivalent fuel volume as a function of consumed battery energy and/or battery capacity. The recharging test was conducted initially and repeated again whenever a significant change in battery capacity was detected. A reduction in battery capacity would indicate degradation in the ability of the traction batteries to accept energy at the same initial rate. Battery capacity was tracked throughout testing by conducting discharge-charge cycles at regular usage intervals.

For scenarios in which the traction batteries were depleted as a result of operation, the calculated fuel volume was added to the fuel volume used by the engine, and the fuel consumption rates for each test run were recalculated. During testing when surplus battery capacity and energy were logged, the equivalent fuel volume was subtracted from the engine fuel use. Fuel consumption rates were recalculated using the new volume.

A second method was also used for field corrected fuel consumption testing. Engine fuel consumption was measured as is done for conventional tests. The SOC of the traction batteries was stabilized at a predetermined level, high or low, prior to the start of each specific test run. Electrical energy used was measured in and out of the battery as a function of terrain type and course speed. At the end of each trial, the vehicle was stopped and the engine generator was allowed to recharge the traction battery back to its' initial SOC under the ambient conditions. Data were collected during the recharging portion of the cycle to include the electrical energy returned to the traction batteries and the fuel consumed by the engine. That fuel volume was included with the operational fuel volume to calculate a compensated fuel consumption value for those specific conditions.

Both methods, while proven field expedient, had issues that directly impacted the quality of the metrics they produce. The primary concern with both methods was the engine operating state during the recharging process. In order to accurately represent the electrical energy consumed by the traction battery, charging should be consistent with the operating load and speed conditions of the engine while operating on the specific duty cycle. This was impractical using either method. Based on these findings an alternative method was deemed necessary.

Testing was sponsored by US Army TARDEC and conducted for the Hybrid Electric Vehicle Evaluation and Assessment (HEVEA) Program. Concurrent with HEVEA fuel consumption testing and methodology development conducted for the Hybrid Fuel Economy Methodology Study under U.S. Army Test and Evaluation Command (ATEC) Project 2010-DT-ATC-ARSPT-D2644, ATEC Project 2008-DT-ATC-TOPRO-D8101 was established for the purposes of review and update to Developmental Test Command Test Operations Procedure (TOP) 2-2-603, Vehicle Fuel Consumption [1].

METHODOLOGY FIELD TEST APPROACH

The objectives of testing were:

1 To develop a test protocol that can be used to evaluate the fuel consumption characteristics of a hybrid electric vehicle regardless of weight class, battery chemistry, and/or driveline configuration.

2 To characterize the performance of currently developed hybrid vehicles and tactical wheeled vehicle prototypes with regard to fuel consumption and energy usage.

To define testing, a Design of Experiment (DOE) was developed by TARDEC (See Table 1).

Table 1. DOE Experimental Structure

1. EXPERIMENTAL VARIABLES	
Response Variables (outputs, what is being measured)	
Vehicle miles driven	
Fuel consumed	
Elapsed time	
Signal Factors (inputs we can control)	
Signal Factor 1. Test Course	4 different tracks (estimated)
Signal Factor 2. Road Speed	4 different speeds (estimated)
Signal Factor 3. Driver	4 different drivers (estimated)
Signal Factor 4. Vehicle	10 different vehicles (planned, 19 actual)
Noise Factors (inputs we cannot directly control)	
Ambient temperature	
Ambient pressure	
Ambient humidy	
Traction battery internal resistance	
Traction battery State of Charge (SOC)	
Traction battery age	
Traction battery temperature	
Driver variability	
Test Course surface variation from day to day	
2. METHOD OF RANDOMIZATION	Fractional factorial run in a randomized block design, blocking on drivers.
3. DATA COLLECTION FORMS	ATC data collection forms
4. PLANNED METHODS OF STATISTICAL ANALYSIS	Analysis of Variance (ANOVA)

To characterize the vehicle, the weight distribution, center of gravity location, and static rollover threshold were recorded. Automotive performance characterization tests included: acceleration, maximum speed, and coastdown (power loss).

Fuel Consumption Tests conducted include:

- Stationary No-Load
- 24-Volt Electrical Load
- Steady State Paved Road-Load
- Full-Load
- Terrain-based Test Course Scenarios listed in Table-2.

TABLE-2. Test Course Scenario and Terrain.

TEST COURSE	**TERRAIN TYPE**
Harford Loop	Rolling paved
Munson Test Area (MTA) Standard Fuel Course	Composite paved & improved secondary, longitudinal slopes
Perryman Test Area (PTA) 2 and 3 Courses	Level cross country
Churchville Test Area (CTA) B-Course	Hilly cross country

Candidate test vehicles are listed in Table 3. The light weight class contained one commercial passenger vehicle, one ground-up series hybrid, four conventional High Mobility Multi-Purpose Wheeled Vehicles (HMMWVs), and one hybrid conversion HMMWV. The medium weight class group contained three technology demonstrator Utility Vehicles (UV) from the Future Tactical Truck System (FTTS) program, two conventional Family of Medium Tactical Vehicles (FMTV), one conventional FMTV with continuously variable transmission (CVT) drive train, and one series conversion FMTV. The heavy weight class group contained one FTTS demonstration vehicle, one ground-up series hybrid Heavy Expanded Mobility Tactical Truck (HEMTT), one conventional HEMTT tested at two weight configurations, one conventional dump truck, and one commercial parallel hybrid dump truck.

TABLE 3. HEVEA Test Vehicles

	VEHICLE	TYPE	COMPANY	TEST WEIGHT (LB)
1	Ford Escape Hybrid SUV	Power split hybrid	Ford	4,780
2	RST-V	Series hybrid	GDLS	9,990
3	HMMWV High-Powered CMPS M1038	Conventional	BAE	7,730
4	HMMWV M998	Conventional	AM General	7,880
5	HMMWV M1113	Conventional	AM General	11,480
6	HMMWV XM1124	Series hybrid	AM General & DRS	11,580
7	HMMWV M1152	Conventional uparmored	AM General	15,200
8	FTTS UV	Parallel hybrid	International MG	22,080
9	FTTS UV	Parallel hybrid	Lockheed Martin	25,060
10	FTTS UV	Conventional "mode"	AM General	24,820
11	LMTV M1078	Conventional	BAE	23,520
12	FMTV CVT	Hydraulic hybrid	BAE & SuperDrive	23,520
13	FMTV M1086	Series hybrid	BAE	32,100
14	FMTV M1084	Conventional	BAE	32,230
15	M917 Dump Truck	Conventional	AM General	66,000
16	Mack Granite Axle Back Dump Truck	Parallel hybrid	Mack	66,040
17	HEMTT A2	Conventional	Oshkosh	62,500
18	HEMTT A3	Series hybrid uparmored	Oshkosh	67,360
19	HEMTT A2	Conventional uparmored	Oshkosh	69,160
20	FTTS MSV	Parallel hybrid	BAE	74,300

SUMMARIZED TEST RESULTS

Complete and comprehensive fuel consumption test results are presented in the Final Report, ATC-10453 Hybrid Electric Vehicle Fuel Economy Methodology Study [2].

RESISTANCE TO MOTION POWER LOSSES

Because there was such a wide variation in vehicle test weights, payload capability and driveline configurations, the power loss was normalized as a function of weight and presented as Hp/ton. The hybrid vehicles in the light class showed the biggest reductions in power loss compared with their conventional drive counterparts. The hybrid vehicles had an average power loss at 80 km/hr (50 mph) of 8.69 Hp/ton compared to 11.48 Hp/ton for the conventional drive.

The medium and heavy class vehicles' power losses were similar within their respective weight classes and showed little difference between the conventional and hybrid drivelines. The medium class vehicles had average power losses of 7.36 Hp/ton for the conventional drivelines and 7.35 Hp/ton for the hybrid vehicles.

The heavy vehicles exhibited similar characteristics, consuming an average of 4.61 Hp/ton for the conventional drives and 4.60 Hp/ton for the hybrid vehicles.

Across all of the weight classes there were no significant distinctions between the parallel and series hybrid drivelines with regard to power losses indicating that the biggest contributions to the power loss budgets of the tactical vehicles were the inertial and frictional losses of the tires, wheels and axles.

The resistance to tow power is shown in Figure 1. Values have been normalized for comparison by calculating Hp/ton at 50 mph.

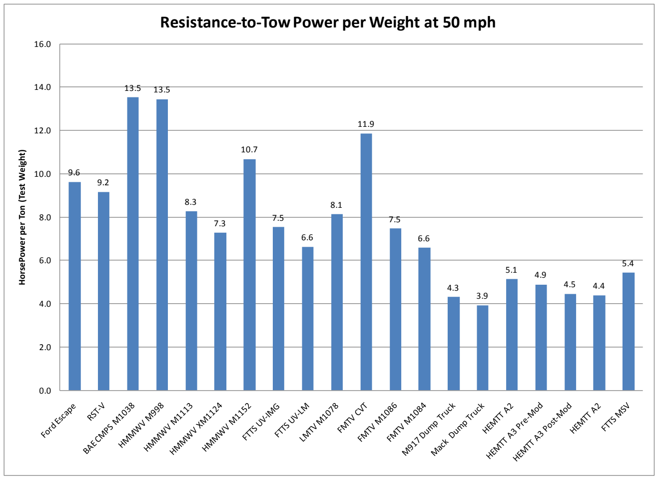

Figure 1. Normalized resistance to tow (power loss).

STEADY STATE ROAD LOAD FUEL CONSUMPTION

The best observed fuel economy results of each vehicle for road load fuel consumption are presented in Table 4. Summary results for road load are presented at the vehicle speed and transmission gear for which the highest fuel economy occurred.

TABLE 4. Best Observed Value of Steady State

Road Load Fuel Consumption.

	Vehicle	Type	Test Wt (lbs)	Road Load			
				Gear	Speed	Fuel	
					mph	mpg	pph
1	Ford Escape Hybrid SUV	Power split hybrid	4,780	Drive	34.2	39.5	5.92
2	RST-V	Series hybrid	9,990	Drive	15.4	20.4	7.16
3	HMMWV High-Powered CMPS	Conventional	7,730	Drive	35.1	11.4	N/A
4	HMMWV M998	Conventional	7,880	Drive	35.3	10.5	N/A
5	HMMWV M1113	Conventional	11,480	Over Drive	25.5	14.6	11.60
6	HMMWV XM1124	Series hybrid	11,580	Drive	25.5	15.1	11.10
7	HMMWV M1152	Conventional uparmored	15,200	4th	40.0	11.0	24.17
8	FTTS UV-IMG	Parallel hybrid	22,080	3rd	25.2	11.4	14.66
9	FTTS UV-LM	Parallel hybrid 'Pre-EV' mode	25,060	4th	16.4	13.2	10.05
10	FTTS UV-AMG	Conventional "mode"	24,820	N/A	N/A	N/A	N/A
11	LMTV M1078	Conventional	23,520	6th	21.0	12.1[b]	11.50[b]
12	FMTV CVT	Hydraulic hybrid	23,520	Drive	36.2	7.2	19.23
13	FMTV M1086	Series hybrid[b]	32,100	Drive	20.5	8.0	17.13
14	FMTV M1084	Conventional	32,230	7th	30.2	9.9	20.30
15	M917 Dump Truck	Conventional	66,000	3rd	20.0	8.5	16.62
16	Mack Granite Axle Back Dump Truck	Parallel hybrid	66,040	Drive	35.9	8.5[c]	30.10[c]
17	HEMTT A2	Conventional	62,500	4th	36.8	5.3	46.40
18	HEMTT A3	Series hybrid uparmored	67,360	Drive High	40.7	5.0	55.60
19	HEMTT A2	Conventional uparmored	69,160	4th	31.5	5.0	42.30
20	FTTS MSV	Parallel hybrid	74,300	Drive	25.3	5.4	31.24

[a] *Power on-the-Move (24-volts) equals 183 ampere at NATO slave receptacle*
[b] *Fan operating normal*
[c] *Results following repairs and control strategy changes*

TERRAIN-BASED SCENARIO FUEL CONSUMPTION

The best observed fuel economy results of the light vehicle group of vehicles for the test course terrains are shown in graphical form in Figure 2. Summary results are presented at the vehicle road speed for which the highest fuel economy occurred and represent only a single point of the fuel economy characteristic curve across the entire operating speed range of each vehicle on each terrain. The terrains represented are listed in Table 2.

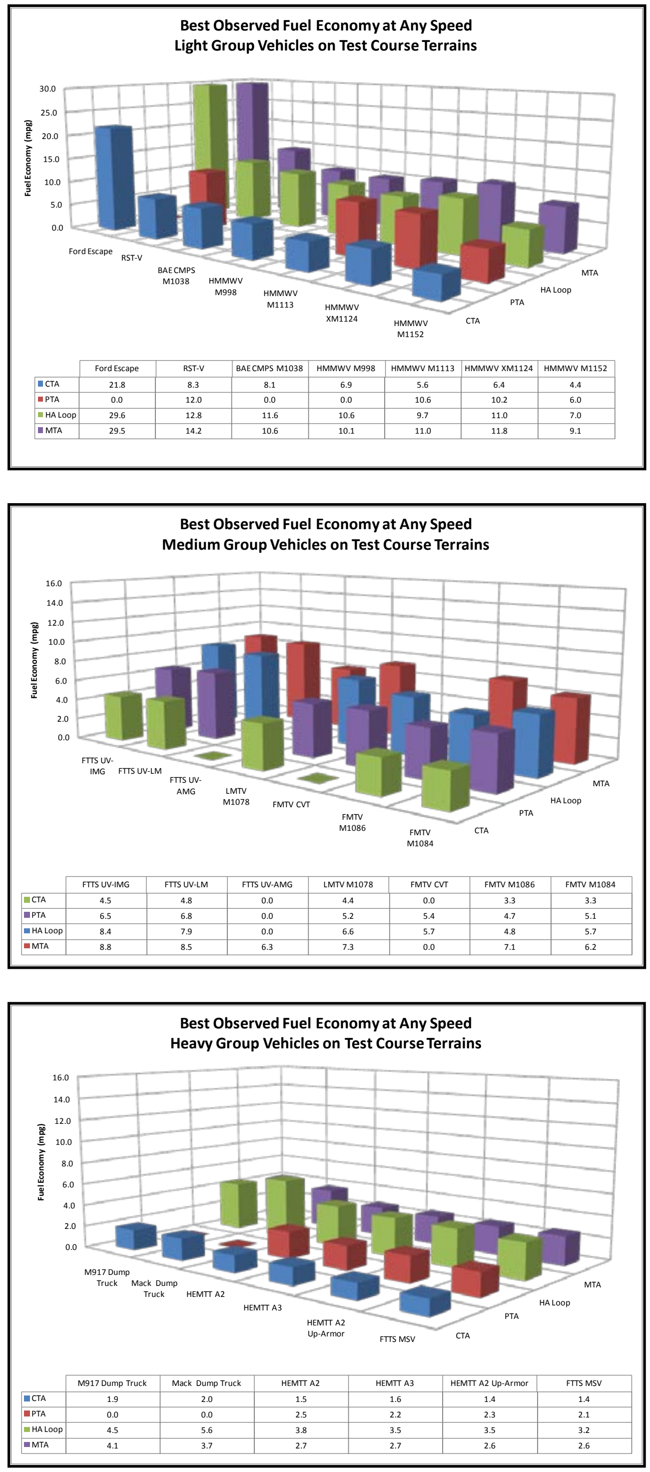

Figure 2. Fuel economy and terrain for light, medium, and heavy weight classes of vehicles.

FULL LOAD FUEL CONSUMPTION

The maximum drawbar reserve power is presented in Table 5 for all vehicles. The associated tractive effort to weight (TE/Wt) ratio was calculated for comparison. The maximum drawbar reserve power represents the full load fuel consumption.

TABLE 5. Best Observed Value of Steady State Full Load Fuel Consumption.

	Vehicle	Type	Test Wt (lbs)	Full Load				
				Speed	Drawba	TE/Wt.	Fuel	
				mph	hp	ratio	gph	pph
1	Ford Escape Hybrid SUV	Power split hybrid	4,780	55.0	10	0.053	2.5	15.28
2	RST-V	Series hybrid	9,990	14.1	103	0.290	5.2	34.60
3	HMMWV High-Powered CMPS	Conventional	7,730	10.0	123	0.618	9.9[a]	65.60[a]
4	HMMWV M998	Conventional	7,880	N/A	N/A	N/A	N/A	N/A
5	HMMWV M1113	Conventional	11,480	20.0	104	0.184	11.3	77.20
6	HMMWV XM1124	Series hybrid	11,580	10.0	100	0.340	6.4	42.14
7	HMMWV M1152	Conventional uparmored	15,200	13.1	105	0.215	11.9	79.50
8	FTTS UV-IMG	Parallel hybrid	22,080	5.2	163	0.540	11.0	73.20
9	FTTS UV-LM	Parallel hybrid 'Pre-EV' mode	25,060	26.2	164	0.106	14.1	94.65
10	FTTS UV-AMG	Conventional "mode"	24,820	N/A	N/A	N/A	N/A	N/A
11	LMTV M1078	Conventional	23,520	8.1	188[b]	0.387	14.3[b]	95.01[b]
12	FMTV CVT	Hydraulic hybrid	23,520	N/A	N/A	N/A	N/A	N/A
13	FMTV M1086	Series hybrid[b]	32,100	9.8	235	0.293	16.6	110.10
14	FMTV M1084	Conventional	32,230	9.7	221	0.278	17.0	113.50
15	M917 Dump Truck	Conventional	66,000	6.4	290	0.271	16.1	113.27
16	Mack Granite Axle Back Dump Truck	Parallel hybrid	66,040	N/A	N/A	N/A	N/A	N/A
17	HEMTT A2	Conventional	62,500	N/A	N/A	N/A	N/A	N/A
18	HEMTT A3	Series hybrid uparmored	67,360	5.7	301	0.298	21.0	141.70
19	HEMTT A2	Conventional uparmored	69,160	9.1	338	0.215	22.3	148.91
20	FTTS MSV	Parallel hybrid	74,300	10.9	343	0.166	25.0	167.80

[a] *Power on-the-Move (24-volts) equals 183 ampere at NATO slave receptacle*
[b] *Fan operating normal*
[c] *Results following repairs and control strategy changes*

The maximum drawbar force are to be compared with TE/Wt design requirements associated with cooling system designs of tactical and combat vehicles. Performance capabilities of the vehicle for gradeability and towing are indicated by the maximum drawbar force. None of these values represent sustained operation, and no cooling system performance capabilities should be inferred.

The maximum tractive effort to weight ratio for each vehicle are shown in Figure 3 for all vehicles. Not all vehicles were capable of conducting drawbar pull tests.

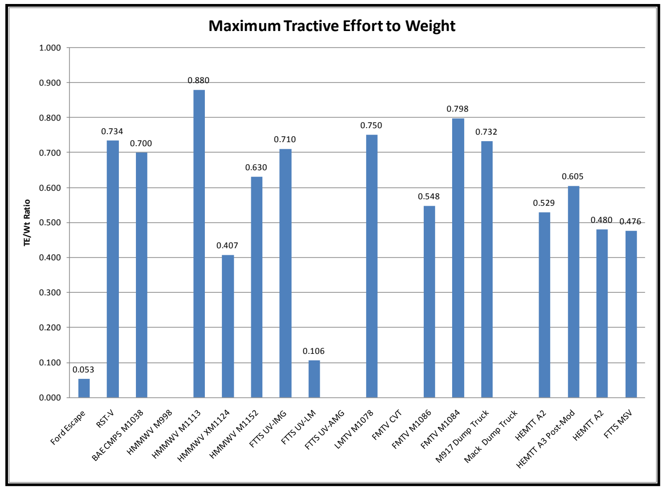

Figure 3. Tractive effort to weight comparison.

There were significant variations in the observed performance of all vehicles tested across each weight class and driveline configuration. Typical tactical vehicle performance requires sustained operations at a 60-percent TE/Wt ratio. Meeting this requirement requires special attention to overall driveline gearing, structural integrity, cooling system design and engine selection. Vehicles meeting this requirement generally meet gradeability, towing/recovery and operations in environmental extremes criteria.

The full-load fuel consumption was normalized using the calculated reserve power at its' measured maximum and the condition where the maximum drawbar force was observed along with the measured fuel consumption for each condition yielding units of lb/Hp-hr. There were no distinct trends between hybrid configurations or hybrid versus conventional vehicles.

RESULTING HYBRID TEST PROCEDURE

The Hybrid Electric Vehicle Test, paragraph 4.4 excerpted, from the draft TOP 2-2-603 addresses the procedure for measurement of fuel consumption of hybrid electric vehicles, and is presented below:

"Hybrid Electric Vehicle Test. *Determination of fuel consumption characteristics of hybrid electric vehicles is accomplished by subjecting the test vehicle to a series of individual tests and operational duty cycles designed to address the full range of vehicle performance. During each test the vehicle performance data are measured by the use of installed transducers and/or the vehicle data bus.*

a. For a propulsion system utilizing traction batteries, battery pack performance will be determined using current *and voltage measurements, and state-of-charge (SOC). The traction batteries provide variable proportions of power necessary for propulsion depending on the test course being traversed, driver demands and the initial state-of-charge (SOC) of the batteries.*

b. Vehicle performance to include fuel consumption characteristics, electric energy use and/or storage and traction motor output (battery voltage, current, and SOC) will be determined during vehicle operations at predetermined road speeds over various designated test courses. Testing is typically initiated at 8 km/hr (5 mph) and increased incrementally to maximum safe speed. For each trial the road speed will be held as constant as possible while data are obtained. Multiple trials will be conducted at each speed to characterize control strategy behavior and Electrical Energy Storage System (EESS) characteristics. Testing at each speed will be conducted at predetermined initial high and low SOC. Additional trials will be performed within the manufacturer SOC limits to achieve statistical confidence interval goals. A sufficient number of test course laps at each speed will be conducted to adequately characterize the status (increasing, decreasing or steady state) of traction battery SOC.

c. A variety of testing scenarios are available and should be used to fully characterize the fuel consumption performance of hybrid electric vehicles. These include road load testing (para 4.1.1), full load testing (para 4.1.2), Munson standard course testing (para 4.1.4), level cross-country operations (i.e., PTA courses no. 2 and 3), and hilly cross-country operations (i.e., CTA course B).

d. To determine the relationship between the change in battery SOC and fuel economy the procedure is summarized as follows:

(1) For each designated test course test trials are performed at discrete road speeds incrementally from 8 km/hr (5 mph) to maximum safe speed.

(2) For each road speed perform multiple test runs at various initial SOC's including, if they exist, those at or near SOC equilibrium points.

(3) For all test runs at each target road speed, calculate a delta SOC by subtracting the initial SOC from the final SOC.

(4) Calculate net battery energy expended (kW-hr) and net battery capacity (Ah) for each individual test run by integrating the total.

(5) Determine the relationship between fuel economy (mpg) and the various battery parameters (delta SOC, net kW-hr, and net amp-hr) using Analysis of Variance techniques.

(6) For each discrete speed, determine the estimated value of fuel economy that is statistically equivalent to the point at which there is no change in net battery energy from the start to the end of the run (delta zero SOC).

(7) Conduct individual test runs such that at least one test run has a net positive energy change (+ΔSOC) and at least one test run has a net negative energy change (-ΔSOC) to ensure SOC corrections are interpolated values rather than extrapolated.

(8) Per Recommended Practice SAE J2711 [3]*: "Because using the SOC correction procedure effectively turns multiple test values into a single value, the coefficient of determination, R2, of the linear best fit is used to determine whether the collected data are valid. For the purposes of this recommended practice the data are considered acceptable if the R2, which compares the predicted and actual values of the linear regression, is equal to or greater than 0.80."*

METHODOLOGY RESULTS/LIMITATIONS FOR THE HYBRID VEHICLE FUEL CONSUMPTION TEST PROCEDURE.

This proposed test method for determination of fuel economy through state of charge correction using linear interpolation will be limited to regions of operation that include charge sustaining conditions.

To quantify the fuel economy at operating regions where the ΔSOC = zero is achievable, the following steps are to be taken:

1 State the volumetric fuel economy (mpg) of the internal combustion engine for each test run.

2 State ΔSOC of traction batteries for each test run as a percentage.

3 For multiple test runs of the same target speed on a given terrain scenario, plot the engine fuel economy versus battery ΔSOC.

4 Determine the relationship between fuel economy & ΔSOC using linear regression. If the test data includes the point at which ΔSOC=zero, interpolate to determine the fuel economy (mpg) slope intercept where traction battery ΔSOC=zero, as displayed in Figure 4.

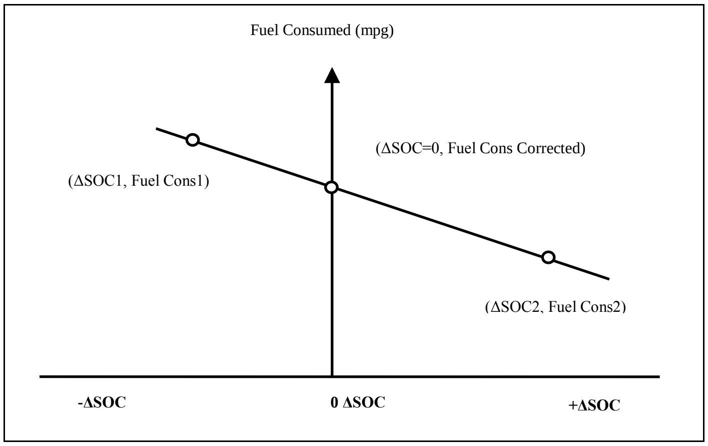

Figure 4. SOC correction procedure, charge sustaining.

To quantify the fuel economy at operating regions where ΔSOC = zero is NOT achievable as illustrated in Figure 5, and only charge depleting results emerge, the following steps are to be taken:

1 State the volumetric fuel economy (mpg) of engine for each test run.

2 State the ΔSOC of traction batteries for each test run as a percent.

3 State the stored/depleted battery energy (kWh) as percent total of energy with respect to the total fuel consumed (MJ)

4 For charge depleting operations the following conditions should be defined based on the terrain:

- Automotive performance limitation of speed as defined by the specific terrain based duty cycle.
- Range limitations based upon available stored energy and/or control strategy limitations and safeguards expressed as either time or distance resulting from operation on a specific terrain based duty cycle.

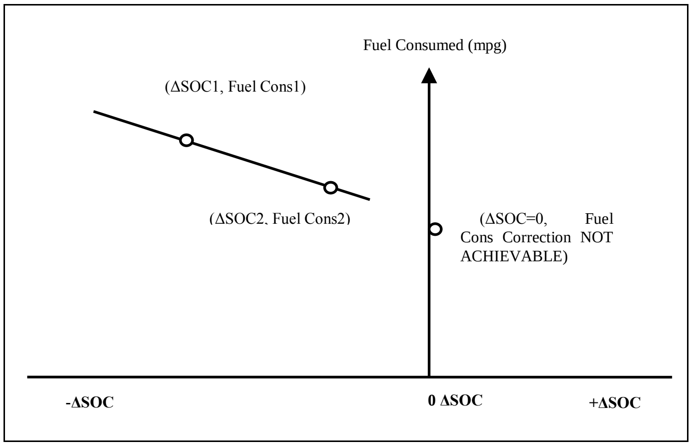

Figure 5. SOC correction procedure, charge depleting.

Fuel economy is calculated over the speed range for which the terrain can safely be traversed within the performance capabilities of the vehicle. Average vehicle speed is used for fuel economy calculations rather than using distance traveled per volume of fuel (miles per gallon) due to the differences between terrain based duty scenarios versus time/speed based duty cycles.

- Close adherence to a defined second by second vehicle speed trace is not the method or control parameter used to define these terrain-based duty scenarios as compared with chassis dynamometer duty cycles.
- Closed circuit test courses are used that replicate real world terrain where dynamic stability and surface conditions are considerations.
- Use of incremental target vehicle speeds provides the best test control method for repeatability and control on terrain based scenarios.
- Calculate average vehicle speed from real time speed measurements.

Automotive (system) performance limitations for conducting fuel consumption runs should be established when the resulting average vehicle speed is less than 10 percent below the target vehicle speed. Criteria for conducting the target speed fuel consumption runs are as follows:

Allowable upper tolerance for target vehicle speed acceptance shall be +5 mph, where less than 1-percent of values are greater than the target vehicle speed plus the allowable upper tolerance.

Allowable lower tolerance for target vehicle speed:

- No lower value for the target vehicle speed.
- Some terrain profiles include multiple stops to zero vehicle speed.
- There exist points of the test course (duty cycle) that the vehicle may/will not be capable of meeting the power requirements for the given target vehicle speed, and will decrease speed.
- There exist points of the test course that course surface severity may dictate a vehicle speed considerably less than the target vehicle speed.
- There exist points of the test course that vehicle dynamic stability would be compromised at the target vehicle speed, and the driver must decrease speed to prevent loss of vehicle control.

For hybrid vehicles, performance limitations will exist so that not all candidates will be charge sustaining on every terrain at all speeds. Load requirements attributable to grade ascension and/or maintaining sustained speeds on certain terrain will require the traction batteries to supplement the power shortfall if the engine is undersized with respect to the power requirements. When the traction batteries begin to charge deplete and a lower operating SOC limit is reached, depending upon the control strategy one of several outcomes is possible.

The control strategy could limit power output resulting in vehicle speed limitations. The vehicle system could remain on, yet have no power for propulsion. The entire system could fault and shut down. These scenarios assume no other cause of power limitation. Other facets of vehicle design could manifest limiting capabilities before the traction batteries would limit speed or range. Undersized or deficient cooling systems could potentially cause power limitations before a lower SOC operating limit is achieved.

To illustrate, one candidate test vehicle of a series hybrid design was charge depleting at specific speeds operating on CTA-B, hilly cross country course. The vehicle was charge sustaining for sustained speeds less than or equal to 24 km/hr (15 mph). At speeds greater than 24 km/hr (15 mph), the vehicle was charge depleting. The result will eventually be either reduction of performance and drop-off of speed, or termination of operations. In either case, the range at sustained speeds greater than 24 km/hr (15 mph) on hilly cross country terrain represented by CTA-B was determined by traction battery usable capacity, and/or the battery management or control strategy implemented to protect the system.

METHODOLOGY LESSONS LEARNED.

(1) For hybrid designs utilizing energy storage systems of significant capacity such that considerable distance/range is achievable without use of the engine (all-electric):

(a) Regions of operation where $\Delta SOC \neq ZERO$ are more likely.

(b) Additional test runs should be conducted if possible to characterize these regions of operation.

(c) Correlation of power and torque required to operate on specific test course profiles would be of great benefit to more accurately quantify vehicle requirements and validate the electric to fuel conversion efficiencies.

(2) Of the vehicles tested, more hybrids tend to operate as diesel electric hybrid architecture as opposed to range-extending hybrid design

(3) Traction battery reliability and performance is highly variable and was observed to have significant impact upon the overall reliability of some vehicle designs

RECOMMENDATIONS

Further refinement of the fuel economy for regions of charge depleting operation can be defined as the fuel consumed by the engine, and the net energy expended by the traction batteries. Through greater iterations of testing and more detailed characterization of the vehicle, the fuel economy could be estimated for charge depleting scenarios.

The conversion efficiency of the engine generator combination and the charge efficiency of the batteries operating on a charge depleting terrain cycle must be established. A map of vehicle speed, accelerator pedal position, tractive force, and engine fuel consumption must be constructed prior to operation on terrain that induces the charge depleting conditions. This map must be made for power production and absorption, since the vehicle will encounter areas of terrain that cause power to be absorbed into the drivetrain. The vehicle must then be operated on the terrain at the charge depleting speeds in order to calculate the power requirements.

The SAE J2711, Recommended Practice for Measuring Fuel Economy and Emissions of Hybrid Electric and Conventional Heavy Duty Vehicles [2] used a similar state of charge interpolation process for the emissions based analysis for charge increasing vehicles.

CONCLUSION

The delta SOC method has been adopted as the preferred method for determining the fuel consumption of hybrid electric tactical vehicles. This method allows direct comparison to other hybrid vehicles independent of driveline architecture, energy storage type/chemistry, or engine type or displacement.

REFERENCES

[1] Developmental Test Command TOP 2-2-603, Vehicle Fuel Consumption, 04 February 1986.

[2] Report ATC-10453, Final Report Hybrid Electric Vehicle Fuel Economy Methodology Study, March 2011

[3] Society of Automotive Engineers J2711, Recommended Practice for Measuring Fuel Economy and Emissions of Hybrid-Electric and Conventional Heavy-Duty Vehicles, September 2002.

[4] SAE Paper 2000-01-2955, Nigel Clark