

# Motion Base Simulation of a Hybrid-Electric HMMWV for Fuel Economy Measurement

**Mark Brudnak, Mike Pozolo and Matthew McGough**

U.S. Army RDECOM-TARDEC

**Todd Mortsfield and Andrey Shvartsman**

DCS Corporation

**Richard Romano**

Realtime Technologies, Inc.

## ABSTRACT

This paper describes a human-in-the-loop motion-based simulator which was built to perform controlled fuel economy measurements for both a conventional and hybrid electric HMMWV. The simulator was constructed with a driver's console, visualization system, and audio system all of which were mounted on the motion base simulator. These interface devices were then integrated with a real-time dynamics model of the HMMWV. The HMMWV dynamics model was built using the real-time vehicle modeling tool SimCreator®, which, in turn was integrated with two powertrain models implemented with Gamma Technologies GT-Drive product. These two powertrains consisted of a conventional configuration and a series hybrid-electric configuration. They were then run on four different standard Army fuel consumption courses to replicate tests which had previously been conducted at the proving ground. Experiments were performed for varying speeds with two experienced proving ground drivers. This paper describes the design and implementation of the simulation environment, the execution of the experiment and presents some experimental results.

## INTRODUCTION

### HEVEA PROGRAM

The US Army Tank Automotive Research Development and Engineering Center (TARDEC), along with the Office of Naval Research (US Marine Corps) are collaborating on the Hybrid Electric Vehicle Experimentation and Assessment (HEVEA) program. One end product of the HEVEA program will be an updated standard test operating procedure (TOP) for measuring fuel economy

of military vehicles (the current TOP may be found at [3]).

Hybrid vehicle fuel consumption characterization is an area of vehicle performance that requires a systematic approach for evaluation. Procedures available for conventional vehicles, when applied to hybrid systems, often do not yield consistent results. This is due to multiple energy sources for propulsion and system control strategies that employ energy recovery during braking and downhill descents. The updated test operating procedure will be independent of propulsion system type and therefore applicable to current and future military vehicles with advanced propulsion systems.

Aberdeen Test Center (ATC) is participating in the TOP development providing instrumentation, field test support, data collection and analysis. TARDEC has supplied an XM1124 hybrid-electric HMMWV equipped with Li-ion traction batteries, along with a conventional M1113 HMMWV as the initial test vehicles for the methodology study. These two vehicles were modeled for the DCE-TOP experiment.

### MOTIVATION AND PURPOSE

As part of the Power & Energy (P&E) program, TARDEC has been building, developing and using human-in-the-loop simulation technology for the purposes of measuring military vehicle duty cycles. We have called these duty cycle experiments (DCEs). This paper describes an experiment which was executed to evaluate TARDEC's ability to use motion simulators to measure the fuel economy of hybrid-electric vehicles according to the procedures developed under the HEVEA program. This experiment, called duty cycle experiment – test operating procedure (DCE-TOP), has attempted to replicate the APG test in every pertinent detail.

UNCLAS: Dist A. Approved for public release.

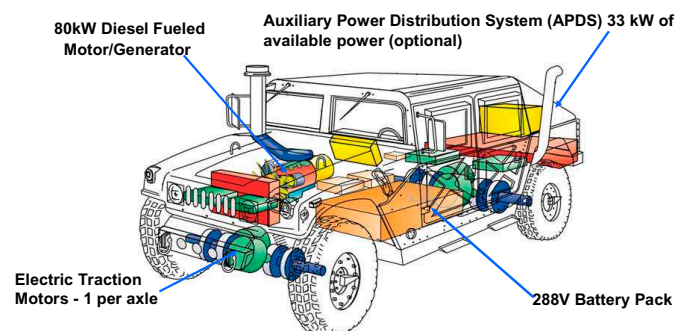


Figure 1. Diagram of the XM1124 Hybrid Electric HMMWV.



Figure 2. M1113. [source: AM General. Permission granted for non commercial uses.]

The remainder of the paper first lays out the experimental design. It then describes the technical design and implementation of the simulator to include the integration of a real-time vehicle dynamics model with a real-time version of a power-train model. It next describes some of the major components in the simulator. Finally it presents some experimental results and offers some conclusions.

## EXPERIMENT DESIGN

As stated earlier, the intention of DCE-TOP was to evaluate the utility of human-in-the-loop simulation in the measurement of hybrid-electric vehicle fuel economy. To demonstrate this utility, TARDEC designed and executed this experiment to replicate measurements done at Aberdeen Proving Ground (Aberdeen, MD). In the Aberdeen-designed experiment there were five experimental variables. The first variable was the

Table 1. Experimental variables.

| Variable    | Scope                       | Values                                                                   |
|-------------|-----------------------------|--------------------------------------------------------------------------|
| Vehicle     | -                           | M1113, XM1124                                                            |
| Terrain     | -                           | Harford Loop<br>Perryman Paved<br>Munson SFC<br>Churchville B            |
| Speed       | Not varied for Harford Loop | Perryman: 10 – 60 mph<br>Munson: 10 – 30 mph<br>Churchville: 10 – 25 mph |
| Driver      | -                           | A, B                                                                     |
| Initial SOC | XM1124                      | High: ~80%<br>Low: ~50%                                                  |

vehicle under study. They ran a conventional HMMWV (M1113) and a series hybrid-electric HMMWV (XM1124) (See Figures 1 & 2). The vehicles were run in a convoy so that they experienced the same circumstances with regard to speed, terrain, temperature, etc. The M1113 served as the control in the experiment. The second variable was terrain. APG chose to evaluate the fuel economy on four different courses which represented a reasonable range of grades and surface types. These terrains were referred to as Harford Loop, Perryman Paved, Munson Standard Fuel Course (SFC), and Churchville B; they will be described later in this paper. The third experimental variable was the vehicle speed which was varied in 5 mph (8 kph) increments on all courses except for Harford Loop. The fourth experimental variable was the initial battery state of charge (SOC) of the XM1124 which was set either high (approximately 80%) or low (approximately 50%). The fifth variable was the vehicle operator; each vehicle, speed, terrain and SOC combination was run with at least two different operators. In this way the experiment results were not dependent on the particulars of one driver's driving method. These variables are summarized in Table 1.

In the TARDEC implementation of DCE-TOP we attempted to replicate the design of the APG experiments. First we implemented a real-time vehicle dynamics model of the HMMWV chassis to include its chassis, suspension, tires, and steering system. Coupled with this dynamics model we developed two power train models, one for the conventional M1113 and one for the hybrid XM1124. Second, we built models of the four terrains which were run at APG. Third our experimental design sought to match the speed ranges and increments which were run at APG. Fourth, because we had a modeled power train, which modeled the SOC as an independent state, we were able to precisely set the initial SOC at either a high or low value. For high we used 80% and for low we used 50%. Finally for driver variation, we recruited as participants two experienced APG drivers.

As mentioned earlier one of the vehicles evaluated was a conventional M1113 HMMWV. This vehicle was modeled with a GVW of 5,216 kg (11,500 lbs). The weight was distributed front to rear in a 40/60 proportion. The tires were modeled at 276 kPa (40 psi) in the front and 344 kPa (50 psi) in the rear. The XM1124 is a hybridized version of the M1113. So the chassis parameters and dynamics as modeled were the same for this vehicle.

The DCE-TOP experiment was conducted during the week of February 12-16, 2007. In all there were 166 runs completed and all planned runs were completed.

## TERRAIN DESCRIPTIONS

We next describe the four terrains on which the experiment was executed. We begin with the simplest. The Perryman Paved terrain is a level, straight, paved

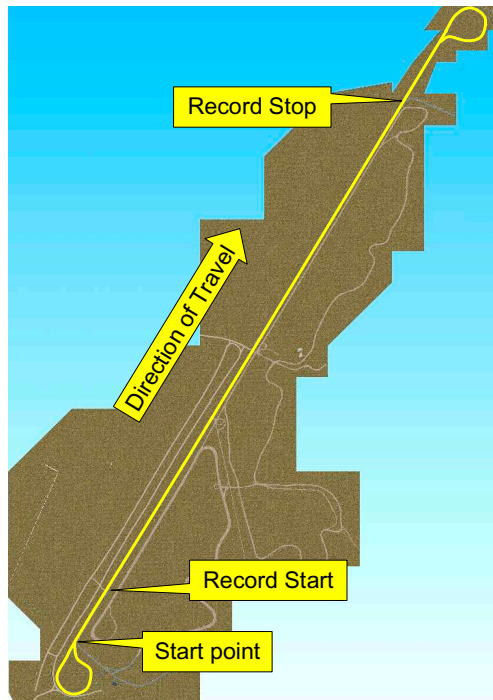


Figure 3. Perryman Paved course shown in yellow.

course which is approximately 2 miles (3.2 km) long with flat turn-a-ounds at the ends. A picture of the Perryman Paved course is shown in Figure 3. (The course is fully described in an APG TOP [2]). At the start of a run the operator would be stationary. He would then accelerate up to the desired speed by the time he reached the "Record Start" point. After that point he would hold the vehicle at a constant speed until he reached the "Record Stop" point at which time the simulation was stopped. Unlike the APG runs, all of the simulation runs were done in a South-to-North direction. The actual length of the record was over 2.4 km (1.5 miles) of the course. Speeds on this course varied from 10 mph (16 kph) to 60 mph (96.6 kph) in 5 mph (8 kph) increments.

The other paved course was the Harford Loop. This course, unlike the other three, is not APG-owned. Rather it is a closed circuit of public roads in Harford County, MD. The roads are all paved, have posted speed limits and are open to normal traffic. The country side in which the roads reside is rural. There are four turns in the course, one at each an intersection. Three of these intersections are regulated with stop signs and one is regulated with a stop light. An illustration of the course is shown in Figure 4. For this experiment the course was driven in a clockwise sense. Each run began at the "tail" in the south-east corner on SR-136 driving North. The operator then proceeded to SR-440 turning left and proceeding West. The operator then successively proceeds through SR-543, SR-165, and SR-136 successively making right turns and the course ends at the intersection of SR-136 and SR-440. The total length of the course is approximately 17.6 mi (28.3 km). The course varies in elevation as much as 463 ft. (141 m), it contains grades from -15% to +18% and has a mean absolute grade of 3.3%. Because the course

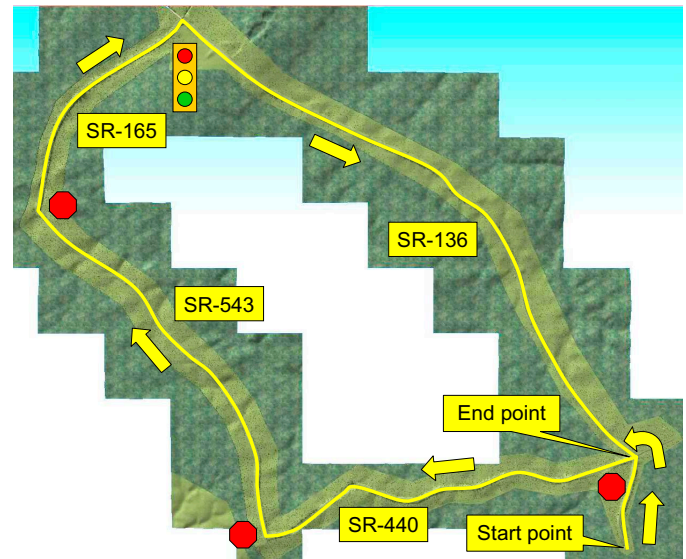


Figure 4. Harford Loop course shown in yellow.

consists of public highways, the speeds were regulated by the posted speed limits which varied from 30 mph (48 kph) to 50 mph (80 kph).

The third course used for this experiment is the Munson Standard Fuel Course (SFC) at APG (see Figure 5). The Munson SFC course consists of a loop of approximately 1.67 miles (2.7 km) situated at the Munson Test Area (MTA). The course is composed of both paved and gravel surfaces. The gravel portion is driven on the Munson Gravel course. The course also traverses the gradeability portion of the MTA. For each loop the vehicle makes two passes by the gradeability area. On the first pass it ascends an approximate 6% slope and descends a 5% slope. On the second pass the vehicle

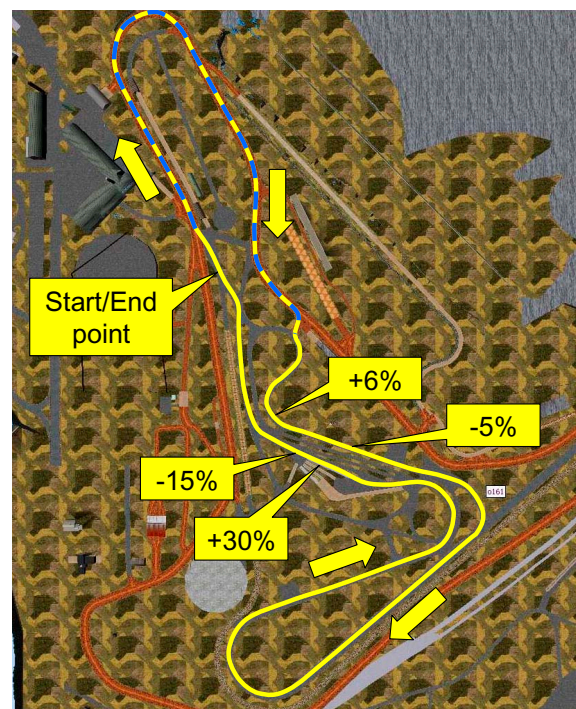


Figure 5. Munson SFC shown in yellow. The gravel segment is dashed.

ascends 40 ft. (12 m) up a 30% slope and descends a 15% slope. The speeds on the course varied from 10 mph (16 kph) to 30 mph (48 kph) in 5 mph (8 kph) increments. It is difficult to maintain the target speed on the 30% grade, so drivers tended to make up time in other portions of the course to make the average loop speed correct. The total elevation change over the course is 42 ft. (12.7 m), its grades range from +30% to -15% and it has a mean absolute grade of 2.5%.

The fourth course used in the experiment was a hilly cross-country course called Churchville B, which is situated at the Churchville Test Area in close proximity to APG. The course is described in the Government publication [2]. The course is shown in Figure 6. Churchville B is a 3.7 mile (6 km) closed loop course. Its grades vary from -23% to + 29% and it has a mean absolute grade of 8.9%. The course has four stop signs positioned at the bottom of its (29%, 14%, 19% and 14% grades). These are positioned so that all vehicular momentum will be dissipated in braking at the bottom of these hills. Furthermore, the North-East section of the course contains four passes of moguls. There are 39 moguls in all and they range in height from 15 to 20 inches (38 to 51 cm). These moguls dramatically increase the ride severity in these sections and therefore cause the drivers to reduce their speed when going down hill. It is difficult to maintain a constant speed on the course due to the steep grades. Like the Munson SFC course, the drivers “made up” lost time on other sections of the course. The course was run at speeds ranging from 10 mph (16 kph) to 25 mph (40 kph) in 5 mph (8 kph) increments.

## SIMULATION ARCHITECTURE AND DESIGN

In this section we discuss the design and construction of the simulator which was used to conduct the experiment. We begin with a description of the top-level design. We

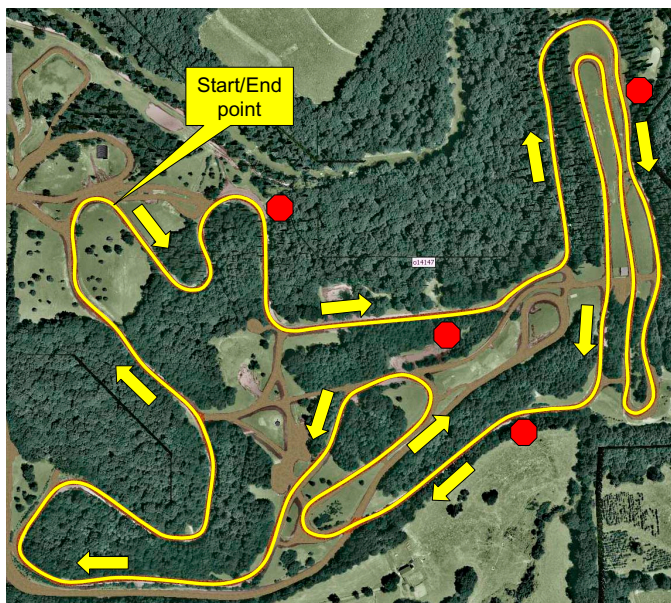


Figure 6. Churchville B course shown in yellow.

then discuss in detail several of the key components used to implement the experiment.

## TOP-LEVEL DESIGN

The simulator designed for this experiment consists of a HMMWV driving station, display system, and sound system mounted on a motion base simulator. A picture of this setup taken during the experiment is shown in Figure 7. The motion base simulator is the Ride Motion Simulator (RMS). The driver interface is implemented as a HMMWV built-up cab (BUC) and is shown in Figure 8. The displays were implemented with three Samsung® SyncMaster™ 226BW displays which are 22" 1680x1050 LCD flatpanels. They are shown in Figure 9. The displays were driven by NVIDIA® GeForce® 8800 GTX video cards. The software which drove the simulator was implemented using a simulation integration framework called SimCreator. Using SimCreator, the software was developed and distributed for execution over six computers, five of which were PCs running Windows XP Pro® and one of which was a dual-processor iHawk™ running RedHawk™ Linux. One other computer was used to record video of the experiment using a tool called SimObserver®. Finally one PC was used to monitor and control the motion base simulator.

Functionally, the software executed in real-time and data flow among the components was managed by SimCreator using either shared memory and UDP/IP transfer data among components. The principal software components were the dynamics, BUC interface, motion base interface, sound generation, visual channel drivers, stealth viewer (for recording), and SimObserver.



Figure 7. Simulator used for the DOE-10P experiment.