Soldier/Hardware-in-the-loop Simulation-based Combat Vehicle Duty Cycle Measurement: 
*Duty Cycle Experiment 2*

Mark Brudnak, Ph.D.
*U.S. Army RDECOM-TARDEC*
*TARDEC Simulation Lab (TSL)*
**Soldier/Hardware-in-the-loop Simulation-based Combat Vehicle Duty Cycle Measurement: Duty Cycle Experiment2**

**Authors:** Mark Brudnak

**Performing Organization:**
US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000

**Sponsor/Monitor:**
TACOM/TARDEC

**Availability:**
Approved for public release, distribution unlimited

**Notes:**

**Security Classification:**
a. Report - unclassified
b. Abstract - unclassified
c. This Page - unclassified

**Limitation of Abstract:** SAR

**Number of Pages:** 39
Prior Work

Prior experiment
DCE1, Nov 2005
06S-SIW-080

Human-in-the-loop Simulation-based Combat Vehicle Duty Cycle Measurement: Duty Cycle Experiment 1

Mark Budnick, Ph.D.
Patrick Nolte
Vicki Mathews
Mike Padula
U.S. Army RDECOM TARDEC
6511, E. 31 Mile Road
Warren, MI 48397-5000
989-574-7255, 7816, 7156, 5266, 6123
(budnickm@tarevcl.army.mil)
padula@tarevcl.army.mil

N. Sara Pearson, Ph.D.
Redstone Technologies, Inc.
151730, Main Street
Royal Oak, MI 48067
248-324-4814
bpearson@rsntech.com

Todd Mirschfield
DCE Cooperation
6901, E. 31 Mile Road
Warren, MI 48397-5000
248-840-9340, 248-369-9930
(tmmirschfield@tarevcl.army.mil)

Wilfred Smith
Science Applications International Corporation
4981, Old Towne Parkway, Suite 200
Manassas, VA 20110
703-779-4637
wilfred.smith@saci.com

Keywords:
Hybrid electric power train, duty cycle, motion base, human-in-the-loop

ABSTRACT: This paper describes the use of human-in-the-loop simulation-based simulation to measure the duty cycle of a hybrid-electric combat vehicle. The project is part of TARDEC’s Power & Energy program and is motivated by the need to accurately understand the duty cycle of a hybrid-electric combat vehicle in order to properly design and size its individual components. The project seeks to extract the duty cycle both in terms of mobility-type loads as well as combustion-type loads to include power-generating systems. After introducing the project, the paper describes the simulation environment which was assembled to measure such a duty cycle. It describes the features which drive the choice of particular components and how those components contribute to the simulation as a whole. It describes the design and includes the choice of scenario, terrain, and operator tasks. The design of the test results and briefly discusses ongoing future work.

1. Introduction

The Army has been developing hybrid-electric propulsion technology because of its many advantages, some of which are better fuel efficiency and the ability to maintain silent operations. Since, many alternative implementations are available for such a system, the Army has developed a Power and Energy Systems Integration Laboratory (P-SEL) to combine components into a series hybrid-electric power system. It is currently being used to investigate hybrid-electric propulsion for a tracked 24-ton Future Combat Systems (FCS) manned ground vehicle.

Since the hybrid-electric power system is the sole source of energy for mobility, survivability and lethality on an FCS vehicle, both the supply and demand of energy must be managed. In order to effectively design a power management system and properly integrate the components, accurate estimates of power loads throughout the complete range of operations are required. Little data exists on power flows for vehicles involved in future military operations. What is known of FCS operations to date has been determined from experience thinking, combining concepts of operations and extrapolation of the current state of technology. Simulations intended to measure the power demand of a vehicle system in typical operations are called duty cycle experiments (DCEs). These duty cycle experiments combine engineering-level power supply models with performance-level models of power-consuming devices in a worst-case simulation. The intent of these DCEs is to establish standard vehic
CHPS SIL

- Series Hybrid-electric power system
- Laboratory based evaluation of design alternatives
- Driven by automated controller
- Requires a-priori duty cycle

![Diagram of Series Hybrid-Electric Power System with labels: Engine/Generator, Traction Motors, Power Distribution, Battery]
Duty Cycle: Definition

- A military vehicle's *duty cycle* is specific to the mission and platform type but is a design- and configuration-independent representation of events and circumstances which affect power consumption.
- Such events and circumstances encompass (1) vehicle operation along the course such as speed, grade, turning, turret/gun activity, and gun firing plus (2) external scenario components that affect power consumption like incoming rounds, ambient temperature, and soil conditions.
- The event inputs can be distance based when the vehicle is moving or time based when the vehicle is stationary, or even triggered with some other state condition.
Ride Motion Simulator

- Man-rated motion base simulator
- Integrated immersive simulation environment
- Real-time vehicle model
- Integrated CAT Crewstation
- Ideal facility for capturing soldier behavior (i.e. duty cycles)
Duty Cycle Experiment 2 (DCE2)

- Measure the “duty cycle” of FCS-MCS-like vehicle
- Use a relevant combat scenario.
- Implement the driver and gunner stations of the vehicle
- Seamlessly operate the CHPS SIL in the loop
- Experienced soldiers as participants
- Measure mobility loads.
- Measure non-mobility loads.
  - Gun/Turret motion
  - Defensive system activity
  - Weapon activity
SIL/RMS Integration Concept

- Power Train (SIL)
- Combat Vehicle
- Driver/Gunner (TSL)
- Vehicle Dynamics and Terrain (TSL)
DCE2 Top Level Design

- OTB
- Long Haul
- SIL
- CAT
- ESS
- RMS

Power
- Dynamics
- Stealth View
- Audio
- SimObserver

UNCLASSIFIED
Geography of Assets: 2,450* miles apart

* As reported by MapQuest®
Interconnections

Communication Channel

Driver/Gunner (TSL) -> Motion -> Sprocket Speeds -> Power Train (SIL)

Vehicle Dynamics and Terrain

Vehicle

External Force

Obstacle

Terrain

Gravity

Communication Channel

Throttle, Steer, Brake

Sprocket Torques
Vehicle Dynamics and Terrain

- Implemented in SimCreator®
- Receives Torque
- Outputs
  - Speed
  - Motion
- Integrates its own states

Motion

Sprocket Speeds

Sprocket Torques
Power Train

- Implemented in Hardware
- Receives
  - Driver Commands
  - Speed
- Outputs Torques
- Dynamometers serve as vehicle proxy
- Hardware contains implicit dynamics

![Power Train (SIL)](image_url)
Communication Channel

Modem (56k bps)
- Analog/Digital
- Dedicated channel
- Connection-based
- Reliable??
- No firewall
- Noise-based corruption
- ~350 ms round trip
- 1.4% loss rate

Internet
- Digital
- No dedicated channel
- Packet-based
- Moderately Reliable
- Firewall configuration required
- Dropped packets
- ~94 ms round trip
- 0.1% loss rate
Protocol Choice

TCP: \( \Delta t \gg D \)
- (Virtual) Connection
- Layered on IP
- Stream
- Reliable

UDP: \( \Delta t \ll D \)
- Connectionless
- Layered on IP
- Packet
- Unreliable
UDP Performance

- Round trip times
  - 33 ms to 188 ms
  - Most at 94 ms
  - Limit 26 ms
- 209 packets dropped
- Vehicle dynamics ~2 ms
- SIL ~10 ms

- Problems
  - Substantial delay
  - Delay jitter
  - Data loss

System Instability

\( D \) is a random variable

Histogram of round trip times for 214,000 trials over 4.3 hours.

\( 2D \)
Simple Approach

- Delay > Dynamics response
- Delay > SIL response
- Simulator response
  - Driver → Motion
  - Increased by $2D$
- Safety risk to driver
- Damage risk to SIL
- Experimental quality degraded
- Potential instabilities
Parallel Simulation Approach

**Note:** The SIL always lags the TSL by $D$. 

**UDP**
Parallel – Evaluation

Pros
- SIL will receive proper commands delayed by $D$
- Immediate response
- The GVSL and SIL are not coupled

Cons
- The power train model does not exactly match the SIL
- The GVSL and the SIL will tend to drift apart over time.
Observer-Based Approach

Note: The SIL always lags the TSL by $D$. 
Power train dynamics

\[ \mathbf{u}_k^s = \begin{bmatrix} t \\ s \\ b \end{bmatrix} \]

\[ \mathbf{x}_{k+1}^s = \mathbf{x}_k^s + \mathbf{f}^s \left( \mathbf{x}_k^s, \mathbf{\omega}_k^s, \mathbf{u}_k^s \right) \]

\[ \mathbf{y}_k^s = \mathbf{h}^s(\mathbf{x}_k^s), \quad \mathbf{\tau}_k^s = \mathbf{g}^s(\mathbf{x}_k^s) \]

\[ \mathbf{\omega}_k^s = \begin{bmatrix} \omega_L \\ \omega_R \end{bmatrix} \]

\[ \mathbf{y}_k^s = \begin{bmatrix} \text{SOC}_b \\ V_{\text{bus}} \\ \omega_e \\ \ell_f \\ T_b \\ \vdots \end{bmatrix} \]

\[ \mathbf{\tau}_k^s = \begin{bmatrix} \tau_L \\ \tau_R \end{bmatrix} \]
Power Train Observer (skewed)

\[
\hat{\mathbf{x}}_{j+1}^s = \hat{\mathbf{x}}_j^s + \mathbf{f}^s \left( \hat{\mathbf{x}}_j^s, \hat{\omega}_j^s, \mathbf{u}_j^s \right) + \mathbf{p}^s \left( \mathbf{e}_j^s \right)
\]

\[
\hat{\mathbf{y}}_j^s = \mathbf{h}^s \left( \hat{\mathbf{x}}_j^s \right), \quad \hat{\tau}_j^s = \mathbf{g}^s \left( \hat{\mathbf{x}}_j^s \right)
\]

Biased Skew Comparison

\[
E \left( D + \tilde{D} \right)
\]

\[
\mathbf{x}_{k+1}^s = \mathbf{x}_k^s + \mathbf{f}^s \left( \mathbf{x}_k^s, \hat{\omega}_k^s, \mathbf{u}_k^s \right)
\]

\[
\mathbf{y}_k^s = \mathbf{h}^s \left( \mathbf{x}_k^s \right), \quad \tau_k^s = \mathbf{g}^s \left( \mathbf{x}_k^s \right)
\]
Power Train Observer (un-skewed)

\[ \hat{x}_{j+1}^s = \hat{x}_j^s + f^s(\hat{x}_j^s, \omega_j^s, u_j^s) + p^s(e_j^s) \]

\[ \hat{y}_j^s = h^s(\hat{x}_j^s), \quad \hat{\tau}_j^s = g^s(\hat{x}_j^s) \]

Unbiased Skew Comparison

\[ E(D - D) \]
Vehicle dynamics

\[ \begin{bmatrix} \tau^v_L \\ \tau^v_R \end{bmatrix} = \begin{bmatrix} \tau^v_k \end{bmatrix} \]

\[ \mathbf{x}^v_{k+1} = \mathbf{x}^v_k + \mathbf{f}^v \left( \mathbf{x}^v_k, \tau^v_k \right) \]

\[ \mathbf{y}^v_k = h^v \left( \mathbf{x}^v_k \right) \]

\[ \begin{bmatrix} x \\ y \\ h \\ v \\ \omega_L \\ \omega_R \end{bmatrix} \]
Vehicle Observer – Direct

- Imposes an artificial force on the vehicle
- Used to track
  - Lateral position
  - Heading
  - Sprocket speed

\[
\begin{align*}
\hat{\tau}_j^v &= \tau_j^v \\
x_{j+1}^v &= x_j^v + f^v\left(x_j^v, \hat{\tau}_j^v\right) \\
y_j^v &= h_j^v(x_j^v) \\
\end{align*}
\]

UDP

\[
\begin{align*}
E\left(D - \hat{D}\right) &= e_k^v \\
x_{k+1}^v &= x_k^v + f^v\left(x_k^v, \tau_k^v\right) + p^v(e_k^v) \\
y_k^v &= h^v(x_k^v) \\
\end{align*}
\]
Vehicle Observer – Indirect

\[ \hat{x}_{j+1}^s = \hat{x}_j^s + f^s\left(\hat{x}_j^s, \omega_j^s, u_j^s\right) + p^s\left(e_j^s\right) \]

\[ \hat{y}_j^s = h^s\left(\hat{x}_j^s\right), \quad \tau_j^s = g^s\left(\hat{x}_j^s\right) \]

\[ x_{j+1}^v = x_j^v + f^v\left(x_j^v, \tau_j^v\right) \]

\[ y_j^v = h_j^v\left(x_j^v\right) \]

\[ u_j^s \]

\[ D \]

\[ \sum \]

\[ p\left(e_k^v\right) \]

\[ e_k^v \]

\[ \sum \]

\[ u_k^s \]

\[ x_{k+1}^s = x_k^s + f^s\left(x_k^s, \omega_k^s, u_k^s\right) \]

\[ y_k^s = h^s\left(x_k^s\right), \quad \tau_k^s = g^s\left(x_k^s\right) \]

\[ x_{k+1}^v = x_k^v + f^v\left(x_k^v, \tau_k^v\right) \]

\[ y_k^v = h^v\left(x_k^v\right) \]

\[ \omega_k^v \]

\[ \omega_k^v \]

\[ \hat{\omega}_k^v \]

\[ D \]

\[ \sum \]

\[ \hat{y}_k^v \]

\[ y_k^v \]

Used to track longitudinal position
Scenario

- 4 km x 10 km area
- 13 km route
- Grades greater than 30%
- 5 RPG teams encountered on route black
- BMPs encountered after RP
- T80s encountered after BMP engagement.
MCS Platoon as implemented

- Played lead vehicle in the platoon
- Vehicles 1, 3, 4 modeled in OTB in “follow simulator” mode.
- Blue vehicles had little to no impact on behavior of vehicle 2.
- Other blue elements were notional
## Engagements

<table>
<thead>
<tr>
<th>Engagement</th>
<th>Scenario A</th>
<th>Scenario B</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>A-1</td>
<td>B-1</td>
</tr>
<tr>
<td>#2</td>
<td>A-2</td>
<td>B-2</td>
</tr>
<tr>
<td>#3</td>
<td>A-3</td>
<td>B-3</td>
</tr>
<tr>
<td>#4</td>
<td>A-4</td>
<td>B-4</td>
</tr>
<tr>
<td>#5</td>
<td>A-5</td>
<td>B-5</td>
</tr>
<tr>
<td>#6</td>
<td>A-6</td>
<td>B-6</td>
</tr>
<tr>
<td>#7</td>
<td>A-7</td>
<td>B-7</td>
</tr>
</tbody>
</table>
○ Each soldier was assigned a subject number S01 – S12
○ Soldiers were paired up and allowed to both drive and gun.
○ Each configuration was assigned a team number T01 – T12
○ Two scenarios used to maintain element of surprise

<table>
<thead>
<tr>
<th></th>
<th>Team</th>
<th>Driver</th>
<th>Gunner</th>
<th>Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Week 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jun 19-22</td>
<td>T01</td>
<td>S01</td>
<td>S02</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>T02</td>
<td>S02</td>
<td>S01</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>T03</td>
<td>S03</td>
<td>S04</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>T04</td>
<td>S04</td>
<td>S03</td>
<td>B</td>
</tr>
<tr>
<td><strong>Week 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jun 26-29</td>
<td>T05</td>
<td>S05</td>
<td>S06</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>T06</td>
<td>S06</td>
<td>S05</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>T07</td>
<td>S07</td>
<td>S08</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>T08</td>
<td>S08</td>
<td>S07</td>
<td>B</td>
</tr>
<tr>
<td><strong>Week 3</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jul 10-13</td>
<td>T09</td>
<td>S09</td>
<td>S10</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>T10</td>
<td>S10</td>
<td>S09</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>T11</td>
<td>S11</td>
<td>S12</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>T12</td>
<td>S12</td>
<td>S11</td>
<td>B</td>
</tr>
</tbody>
</table>
11th ACR
MOS19K
E7 Proxy Commander
12 Participants
- 1-E4, 6-E5, 5-E6
- Age [20-34], mean 26.8
- Avg. time in MOS 6.3 y
Path and grade

- Shown are the overlaid traces for all 12 runs.
- Variation at the end is due to tactical maneuver.
Results: Long & Lat

Longitudinal Performance

- Acceleration command
- Brake command
- Speed (kph)
- Distance (km)

Lateral Performance

- Steering command (normalized, + == right)
- Yaw rate (deg/sec, + == CW)
- Time (seconds)
Long Haul Performance

- Typical delay ~ 800 ms
- Experienced outage of ~7 sec.
- Recovered from outage.
- Vehicles tracked well.
SIL Performance

Plots of P&E SIL Currents

- Right motor current (A)
- Generator current (A)
- Battery current (A)

Time (s)

UNCLASSIFIED
Conclusions & Future Work

- Successfully integrated RMS, vehicle dynamics and CHPS SIL over distance of 2,450 miles
- Implementation based on observers.
- Shown to be robust in the presence of outages.
- A follow-on experiment is planned.
Backup Slides
Unclassified

2007 Spring SIW

RMS
CTR
CAT

Rack

Not to scale

DCE2 Test Configuration

Driver

Spotter
c

CAT Rack

Gunner

Sim
observer

Telex

Spotter

Driver

Test Operator

Sim
observer

OTB
Operator

Overhead
view of
gunner’s
sight

RMS
Operator

Proxy
Commander

Test Operator

Not to scale

Gunner
DCE 2.1: TMBS
Data Acquisition

- 293 channels at 50 Hz
  - 21 Power on/off
  - 21 Events
  - 157 Long Haul Channels
  - 28 power system states
  - 42 vehicle states
- External Events
  - Fire events
  - Detonation
- Entity State PDUs
- Video of experiment
- P&E HWIL SIL logged information
- Demographics