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Abstract

This paper describes a human-in-the-loop motion-based simulator interfaced to hybrid-electric power system hardware, both of which were used to measure the duty cycle of a combat vehicle in a virtual simulation environment. The project discussed is a greatly expanded follow-on to the experiment published in [1,7]. This paper is written in the context of [1,7] and therefore highlights the enhancements. The most prominent of these enhancements is the integration (in real-time) of the Power & Energy System Integration Lab (P&E SIL) with a motion base simulator by means of a "long haul" connection over the Internet (a geographical distance of 2,450 miles). The P&E SIL is, therefore, able to respond to commands issued by the vehicle's driver and gunner and, in real-time, affect the simulated vehicle's performance. By thus incorporating hardware into a human-in-the-loop experiment, TARDEC engineers were able to evaluate the actual power system as it responds to actual human behavior. After introducing the project, the paper describes the simulation environment which was assembled to run the experiment. It emphasizes the design of the experiment as well as the approach, challenges and issues involved in creating a real-time link between the motion-base simulator and the P&E SIL. It presents the test results and briefly discusses on-going and future work.

INTRODUCTION

The Army has been developing hybrid electric propulsion technology to assess and use its many advantages. Among these advantages are better fuel economy and the ability to maintain "silent" operations. As such, many alternatives exist in the implementation of such systems in terms of architecture, component sizing, energy management and control. Anticipating all of these choices, the Army initiated the Power and Energy Combat Hybrid Power Systems (P&E CHPS) program as a TARDEC effort to advance and develop hybrid electric power and propulsion technology for application to combat vehicles. The product of the P&E CHPS program will be a compact, integrated hybrid electric power system that will provide efficient power and energy generation and

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management suitable for spiral integration into the Future Combat System (FCS) Manned Ground Vehicle (MGV) program. A major goal of the program includes designing, developing and using a full-scale hardware/software-in-the-loop Power & Energy System Integration Laboratory (P&E SIL for short). The P&E SIL is a full-scale laboratory-based combat vehicle power system with programmable dynamometers for applying road loads to the propulsion and power system. When combined with high-fidelity vehicle and terrain models, the P&E SIL can be used to predict the reaction of the power system to mobility loads as well as non-mobility loads caused by the interaction of the vehicle with its environment. The P&E SIL is more-fully described in [3,5,10].

In order to effectively use the P&E SIL to design, develop, and test a hybrid electric power system for advanced combat vehicles, accurate estimates of a duty cycle are required. The TARDEC P&E program is addressing this need by measuring advanced combat vehicle duty cycles in simulation. These duty cycles are derived from the virtual representations of advanced combat vehicles and combat scenarios using both warfighter-in-the-loop and power system hardware-in-the-loop simulation described in detail in the remainder of this paper. These duty cycle measurements combine engineering level power supply systems with performance-level models of power consumption devices within a warfighter simulation that represents several tactical scenarios.

For our purposes 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 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.

In order to measure such a duty cycle, TARDEC Simulation Laboratory (TSL) has been building a motion base/ warfighter-in-the-loop simulation capability in which soldiers can virtually operate their vehicles in relevant combat scenarios. This simulation is then used to perform experiments in which duty cycle information is captured. This series of experiments has been called the Duty Cycle Experiments (DCEs). The first such experiment (DCE1) was conducted in November – December 2005 and is described in [1,7]. After the completion of DCE1, another experiment was designed and executed in June – July 2006 which was called DCE2. This experiment went beyond the capabilities of DCE1 in several respects, one of which was the long-haul integration of the P&E SIL into the simulation design. The fundamental challenge in this regard is that the motion base, the Ride Motion Simulator (RMS), and the P&E SIL are geographically separated by 2,450 miles. Add to this the fact that the vehicle dynamics (running at the TSL) and the power system (running at the P&E SIL) are tightly coupled components of the vehicle and function best if they are run in close proximity. This problem and its solution will be referred to as the *long haul* interface or the *RemoteLink* in the remainder of this paper.

This paper describes the simulation which was designed and constructed to execute the DCE2 experiment. It then goes into depth regarding the rationale, design and implementation of the long haul long haul interface. It then discusses the scenario which was used in the experiment. Finally, it presents some results and finishes with conclusions and future work.

SIMULATOR ARCHITECTURE AND DESIGN

Top-level Design

The DCE2 experiment was composed of several independent systems that were integrated to provide the functionally necessary to support two vehicle operators, each controlling a crew station cockpit in an immersive synthetic battlefield environment. For this experiment the driver’s crewstation was mounted on a motion base simulator, while the gunner’s crewstation was stationary. In this experiment, the motion is provided by the ride motion simulator (RMS) on which the driver’s station is mounted. The crew interface for the driver and gunner are provided by the Crew-integration and Automation Test-bed (CAT) crewstations. The simulation backbone is the Embedded Simulation System (ESS) which provides the sole interface to the CATs, the interface to OTB, the weapons model, and generates the visuals for the CAT displays. OneSAF Test Bed (OTB) was used to generate both the red and other blue forces. The dynamics are responsible for generating own-ship vehicle motions as generated by the response to driver commands, gunner commands, traversal of the terrain, and internal or externally generated events. Such motion is then used to drive the RMS and visual channels via the ESS. The power component is a modeled representation of the P&E SIL running locally in the TSL. The power system model, vehicle dynamics and P&E SIL will be described in the next sections and then the Long Haul component will be described.

Power System Model Description

The power system model is responsible for modeling the MGV's hybrid-electric power system at the TSL. It models power generation, storage, conversion and management systems. It receives commands from the driver and gunner and provides torques to the vehicle dynamics model. The power system is implemented in Simulink® as a library of standardized interconnected power system components. This toolset is called *CHPSPerf*. The power system is in a series hybrid-electric configuration and uses a diesel engine coupled to an induction motor/generator unit (Prime Power in Figure 1) to provide continuous electrical power through an inverter to an unregulated high-voltage DC bus. A battery pack (Energy Storage in Figure 1) sized to provide P&E silent watch and P&E silent mobility functions is attached directly to the bus and maintains bus voltage at approximately 600 Volts. Attached to the high voltage bus are two independent induction motors for the left and right sprocket drives (Traction Drive Motors in Figure 1) capable of providing 410 kW of continuous power and over 900 kW of burst power for braking and acceleration functions. A brake or dump resistor is also attached to the bus to protect it from over-voltage conditions that might arise due to heavy braking or long duration regeneration events.

Vehicle Dynamics Description

The vehicle mobility model is responsible for the computation of the vehicle's position, velocity, and acceleration as influenced by the power system and the terrain. It generates the commands for the motion base simulator and updates vehicle global position for the ESS. Because the vehicle dynamics model feeds motion commands to the RMS, it must model the tracks, suspension, and terrain to a high degree of fidelity. As such it was implemented in a real-time dynamics code called SimCreator's® multi-body dynamics component library [8,9] which implements the algorithms developed by Walker and Orin [11].

McCullough and Haug [6] developed a tracked vehicle model that calculates forces from both track and ground using the kinematic state of the vehicle and applies these forces through the wheel, sprocket, and idler centers. The SimCreator® track model used for the experiment also transfers the track/ground interface forces to the chassis in a similar manner. The track-terrain interface includes a soil model based on the work of Bekker as reported in Wong [12]. The model accepts sprocket torques from the power system, as well as other inputs from the ESS. It outputs vehicle state (position, orientation, and acceleration) information.

P&E SIL Description

The P&E SIL houses a full scale combat hybrid electric power system in a highly instrumented laboratory environment [5]. The objective power system was a series hybrid with a 250kW diesel engine/generator, two 410kW traction motors, and a 50 kW-hr battery pack connected via a 600V bus. Over 120 sensors were recorded to capture the power system's duty cycle performance. Mobility loads were imposed in the lab using bi-directional dynamometers coupled to a local real-time tracked vehicle model [3]. Non-mobility loads were imposed on the power system using a 250kW AeroVironment AV-900 bi-directional power supply. For DCE2, the power system under test was similar to the FCS objective power system except a single traction motor was operational rather than two. To achieve realistic power system results the second traction motor was simulated in software and the associated mobility load or supply was imposed on the hardware using the AV-900.

LONG HAUL INTERFACE

Problem Statement

The goal of the long haul interface is to provide coordination and coupling between the soldier-in-the-loop simulation at the TSL and P&E SIL, while operating both in real time at a distance of 2,450 miles. This long haul integration must provide realistic driving and gunning experiences in the TSL without any abrupt, jerky motion caused by the long haul connection (i.e. it should be seamless to the driver and gunner). Second, it should provide a realistic power system response as a function of the P&E SIL's current state, meaning that the presence of the hardware affects the vehicle performance at the TSL. Likewise the long haul integration should provide meaningful power system results in the P&E SIL. Finally, both mobility and non-mobility loads generated by the driver and gunner at the TSL need to be reflected on real power system hardware.

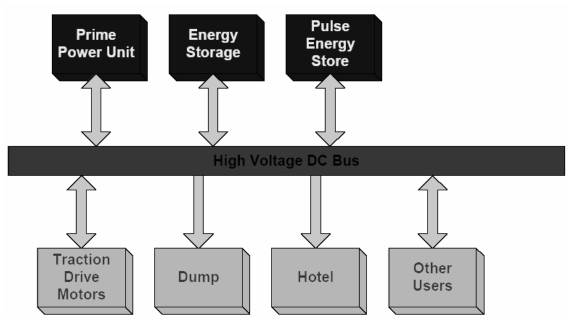

Figure 1: Layout and components of the series hybrid power system

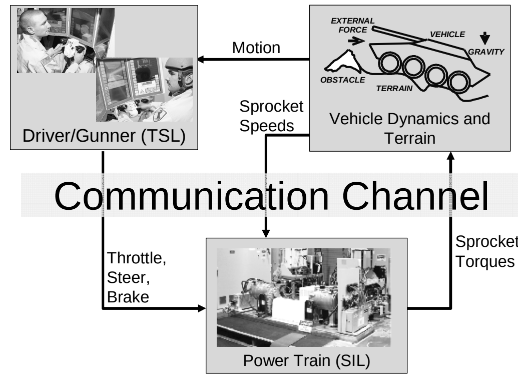

Figure 2: Long-haul topology showing logical information flow between the TSL and the P&E SIL over the chosen communication channel.

In addition to these goals of the long haul integration, the design is subject to several constraints. The first constraint is that both the TSL and the P&E SIL are at fixed locations separated by 2,450 miles. Second, the RMS at the TSL is manned and therefore the long haul must not compromise its safety. Third, the long haul integration must not compromise the closed-loop stability of either the TSL's or the P&E SIL's local control loops. Fourth, there are components at both the TSL and the P&E SIL which are not readily changeable (i.e. TSL's and P&E SIL's system latency, communication delays and reliability, P&E SIL's speed controller, P&E SIL hardware). Finally, the simulation design was limited by the maximum performance of the P&E SIL hardware, which is exceeded by current FCS MGV propulsion designs.

Given these goals and constraints, a top-level diagram of the minimal information flow for the long haul interface is shown in Figure 2. The information flow begins with the human participants who develop vehicle commands to include throttle, brake, steer, and gear from the driver and commands from the gunner. These vehicle commands flow to the power system which uses them to develop torque at the sprockets of the vehicle. These torques are then transferred to the vehicle dynamics which uses them along with information regarding the local terrain to solve the forward dynamics of the vehicle. As part of this solution the vehicle sprocket speeds are updated, which are then sent back to the P&E SIL. Likewise the solution of the forward dynamics is also used to develop the motion commands for the RMS and provide updated position information for the ESS visuals and weapon systems. The motion and visuals subsequently provide feedback to the driver and gunner who develop new commands to respond to what the see and feel, thus closing the loop.

The fundamental technical challenge of the long haul integration is the closed-loop coupling between the P&E SIL and the vehicle dynamics over the chosen communications channel. This is challenging in several respects. First, both the vehicle dynamics and the P&E SIL are dynamical systems in their own right. Given that they are separated by approximately 2,450 miles, there is significant delay in the communication channel. It is known that coupling two dynamical systems with delay introduces instabilities in the coupled system. The solution must therefore address the delay to assure stability. Second, the communication channel may not be reliable and may be subject to outages of varying duration. The solution, therefore, must account for the expected reliability of the channel. Third, the delay of the communication channel will not be constant but will likely be subject to jitter.

Choice of Communication Channel

The first task in the design and implementation of the long haul was to evaluate different communication channels. In this regard our desire was to find a channel which experiences minimum delay and maximum reliability. In our evaluation we considered two alternatives (1) a dedicated connection over 56K bps modems and (2) a non-dedicated connection over the Internet. Benchmark testing revealed that an Internet-based communication channel was preferable to a modem channel. Once the Internet was chosen as the communication channel, we next had to choose the transport protocol, UDP or TCP. Further testing revealed that UDP and TCP experienced the same average delays, but TCP experienced longer delays and jitter in delay times. Thus, UDP was chosen as our transport protocol. A UDP benchmark test was performed over 4.3 hours and involved the round trip measurement of 215,777 packets of which 209 were dropped for a drop rate of 0.1%. The delay times varied from 31 ms to 188 ms with the typical round trip time being 94 ms. (Note that round trip time limit is 26 ms.)

Long Haul Design

Given the network performance numbers described above, we chose to design the long haul interface to be tolerant of packet loss and jitter. In addition, because the coupled system would affect the motion of the RMS and the behavior of the P&E SIL, the system had to safe in the event of complete loss of the communication channel. We therefore designed it so that if the communication channel were lost, the P&E SIL would gracefully shutdown and the TSL would be able to continue the experiment without the P&E SIL

In order to obtain this robustness, the logical system shown in Figure 2 was implemented as shown in Figure 3. Observe that two components (highlighted by bold-outline boxes) have been added, namely the Power Train Observer and the Vehicle Dynamics and Terrain Observer. In this design, the Power Train Observer serves as a proxy of the P&E SIL so that the vehicle dynamics coupling to the power train is tight. Conversely, the Vehicle Observer serves as a proxy of the TSL vehicle dynamics so that the P&E SIL has tight coupling between the hardware and the vehicle dynamics. At both the P&E SIL and TSL, the power trains receive driver and gunner commands, which in turn develop sprocket torques which propel the vehicle dynamics over the terrain and likewise the vehicle dynamics provides sprocket speeds back to the power train. In effect this design implements two parallel simulations, one running at the TSL and one running at the P&E SIL. It may now be clearly seen that in the event of a loss of the communication channel, the TSL has all that it needs to continue the simulation safely on its own. The P&E SIL on the other hand would not have driver/gunner commands available in the event of communication loss and would therefore shut down gracefully in such an event.

Because the design incorporates two parallel simulations and because the Power Train Observer does not exactly represent the P&E SIL hardware, the two simulated vehicles will drift apart in their states over time if not otherwise kept together. It is particularly important that the vehicle observer position be consistent with that in the TSL (e.g. when traversing a bridge). In order to maintain consistency between states which are deemed important, both the Power Train Observer and Vehicle Observer were designed to track the states of the P&E SIL and TSL vehicle respectively (indicated by the state flows in Figure 3). The techniques used to implement this tracking are referred to as *State Convergence* (SC) in the remainder of the paper.

State Convergence

The state convergence approach is summarized here and discussed in much greater detail in [2,4,13]. The objective of state convergence is to have the outputs of the controlled system track the outputs of the observed system. The observer does this using a *feed-forward* term to give a near-term estimate of the system behavior and a *feedback* term to give long-term tracking. The balance between near-team and long-term tracking is controlled by the choice of the correction function. Ultimately this balance is chosen based on the nature of the noise in the system and the accuracy of the estimated dynamics. Additionally, if time horizon of the correction term is much larger than the communication channel delay, then the correction tem will not destabilize the system.

State convergence inputs can be applied via system inputs (augmented inputs) or by artificial inputs (skyhooks) to the rates of change of the system states. Both approaches have their pros and cons. The artificial inputs approach, or *skyhook* approach allows complete control over the states of the observer, however, the

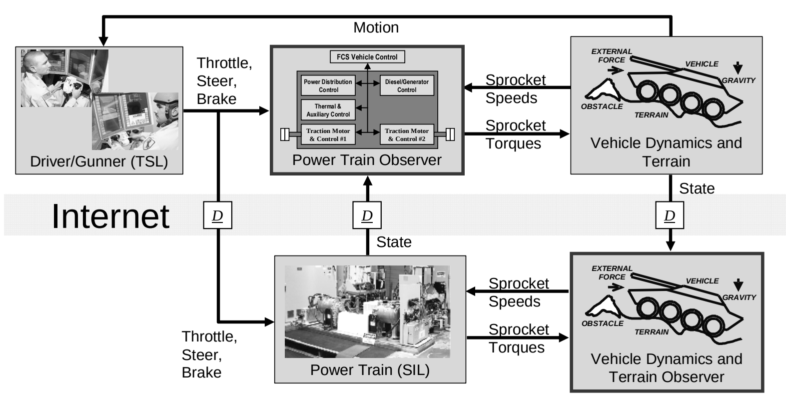

Figure 3: Long-haul topology showing driver inputs, real and modeled hybrid power systems, and two identical mobility models.

skyhooks do work on the system and therefore add or remove energy to/from the system. Ideally the work done by the skyhooks should be small as compared to the work done by the actual inputs. On the other hand, the augmented inputs approach is more physical in nature because it modifies the states through the system inputs (e.g. throttle, brake, steer command), however the ability to influence the states is limited by the controllability of the system. As it turns out, both approaches were used to implement the state convergence in the final system.

Mobility State Convergence. Mobility state convergence provides inputs to the P&E SIL's vehicle dynamics model to ensure the position and velocity track the TSL's mobility model in real time. The P&E SIL model represents the observer and the TSL's model represents the truth, or reference. In the case of the mobility model, the dynamics of the observed system are exactly known and are given by the SimCreator® dynamics model discussed earlier. Therefore, we should expect that the near-term tracking will be very accurate.

Power System State Convergence. Power system state convergence is also implemented as an observer-based, non-linear control system problem. However, in this case, the P&E SIL Power Model was only a rough approximation of the actual P&E SIL. CHPSPerf is the observer to the P&E SIL's hardware reference. The observed state for the experiment was the P&E SIL's bus voltage. Bus voltage tracking provides realism to the experiment by including the influence of real power system hardware. As a result, variations and limitations in the P&E SIL's power system can influence how the driver and gunner operate the simulated vehicle. This real-time coupling between vehicle operation and real hardware power system response is a distinguishing feature which separates the DCE2 experiment from DCE1 and other record-and-playback approaches.

EXPERIMENT DESIGN

The experiment was designed to measure the duty cycle of the MCS vehicle given the scenario. Each experimental run incorporated three soldiers (2 subjects and one experimenter). The experiment was designed to evaluate the duty cycle over twelve teams each consisting of a driver and a gunner. A total of twelve soldiers were used to compose these teams and these soldiers participated in the experiment in groups of four per week. At the beginning of their respective week, each soldier was assigned a subject number and also assigned a partner (partially determined based on their working together in their normal duties). Each soldier would then execute the experiment twice as a member his team, once as the gunner and once as the driver. Each different configuration was additionally assigned a team number, which corresponded with the subject number of the soldier who was driving.

Scenario Description

To measure a proper duty cycle, the choice of scenario was very important. In the design of the experiment, the TSL engineers wanted a scenario which stressed the system and yet was militarily relevant. The Unit of Action Maneuver Battle Laboratory (UAMBL) at Ft. Knox, KY agreed to develop such a scenario. The TSL wrote a document describing its desirable aspects, i.e. that it contain particular events such as hill climbing, main gun use, defensive system use, etc. UAMBL recommended the Ft. Knox terrain for the DCE2 experiment because it is within the continental U.S. and it contains the grade features necessary to stress the power system. The scenario consists of two phases, the first being a road march and the second being a tactical maneuver. The length of whole route traveled was approximately 13 km and typically took approximately 35 to 40 min to complete. Red dismount forces were placed in ambush positions throughout the scenario and were equipped with RPGs. In total there were nine areas in which these RPG teams could be placed within range of the passing convoy.

OTB Implementation

The scenario as described above was implemented in OneSAF Test Bed (OTB) v2.5. The balance of the MCS platoon was implemented in OTB and all of the red forces were implemented in OTB. The terrain on which the OTB was run was a CTDB version of the Ft. Knox database.

EXPERIMENT RESULTS

Measured Duty Cycles

Of the twelve teams which performed the experiments, ten of them ran to completion, the other two had to be aborted mid-way through and had to be resumed at the point where the simulation stopped. Of the twelve runs, the P&E SIL began running with the TSL on six of them. For four of these runs the P&E SIL and/or TSL had to abort the run due to a technical difficulty, two of the runs saw the TSL and P&E SIL run to completion. In these two runs, the long haul solution was shown to be robust in the presence of variable propagation delays. In practice the actual round trip delay was measured to be approximately 800 ms and during one run the Internet communications experienced an outage of 7 seconds and gracefully recovered. A plot showing the round trip delay characteristic is shown in Figure 4.

All pertinent vehicle and power system duty cycle data were recorded for each run and archived for further use and analysis. All crew behaviors were recorded to include instantaneous driver and gunner commands. For those runs with which the P&E SIL ran, time-correlated P&E SIL data were recorded. Figure 5 shows an example of some of this time-recorded data with some relevant current plots. For non-mobility loads, all of the fire and detonation events for both the red and blue forces were logged. Figures 6 and 7 show some more traditional duty cycle data. Figure 6 shows grade as a function of the distance traveled. Figure 7 shows driver commands and speeds as a function of distance traveled. More detailed duty cycle results are presented in [13].

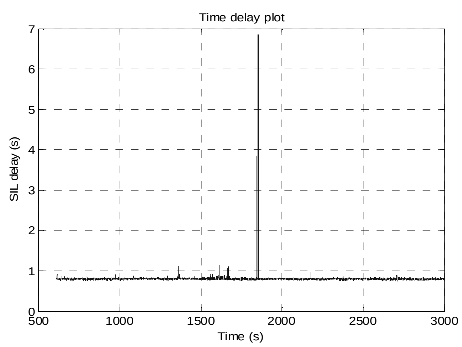

Figure 4. Plot of round trip delay between TSL and the SIL..

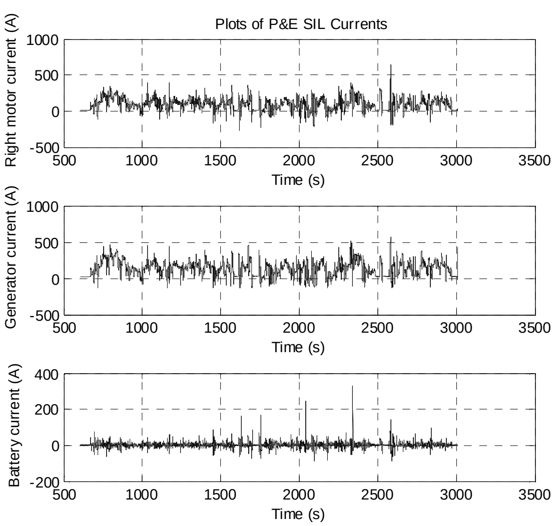

Figure 5. Over laid plot of SIL's main component currents as recorded for one run

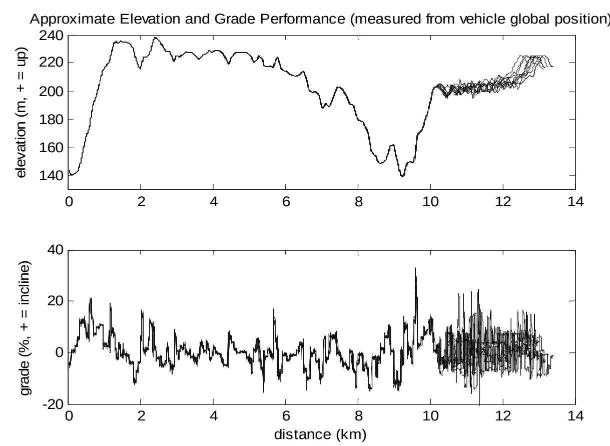

Figure 6. Grade and elevation for all 12 runs as a function of distance..

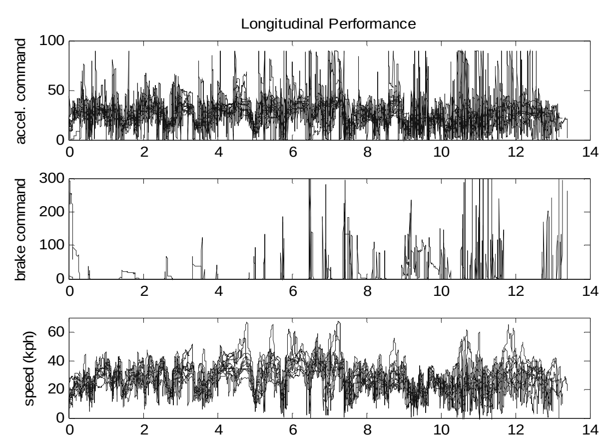

Figure 7. Longitudinal performance for all twelve runs as a function of distance.

CONCLUSIONS

In this paper we have presented an approach to integrating two Army laboratories in a real-time hardware/man-in-the-loop experiment. We discussed the unique challenges in developing such a simulation and presented our approach to solving them using the observer-based state convergence approach. We discussed the design and execution of the experiment and have presented results with respect to the performance of the long-haul solution. Finally, we have presented some data which are representative of the types of results measured in the DCE2.

After having successfully completed the DCE1 and DCE2 experiments TARDEC's Mobility Business Group and the TSL have planned an additional three follow-on experiments in FY07. The first, called DCE-TOP, is intended to measure the fuel economy of hybrid tactical vehicles, the second, called DCE3 is intended as a follow-on to DCE2, and the third, called DCE4 will evaluate the combat duty cycle of a future hybrid tactical vehicle.

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