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A PERFORMANCE COMPARISON OF TRACKED VEHICLE DYNAMOMETER SYSTEMS FOR MOBILITY LOAD EMULATION OF A COMBAT HYBRID ELECTRIC POWER SYSTEM

Jarrett Goodell
SAIC
Austin, TX

Tom Connolly, PhD
SAIC
San Jose, CA

Ed Leslie
Wilford Smith
SAIC
Manassas, VA
Marietta, GA

ABSTRACT

The United States Army Tank-Automotive Research, Development and Engineering Center (TARDEC) is actively researching methods to advance the state of hybrid-electric power system technology for use in military vehicles. Supporting this research, Science Applications International Corporation (SAIC) is the lead contractor for developing the Hybrid Electric Re-Configurable Movable Integration Test-bed (HERMIT), which is operated at TARDEC in Warren, Michigan. The HERMIT is a ground-vehicle-sized series hybrid-electric test-bed featuring a diesel engine, permanent magnet generator, high voltage bus, DC-DC converter, lithium ion battery pack, left and right traction motors, thermal management system, and left and right bi-directional dynamometers. The power system is sized for a 20-22 ton tracked vehicle. The dynamometers are responsible for emulating loads that the tracked vehicle would see while running over a military theater-type course.

This paper discusses the control system design for achieving mobility load emulation and compares experimental results obtained from two different sets of dynamometers running the same virtual course and duty cycle. Load emulation is defined as the ability of the measured left and right sprocket speeds to track the left and right sprocket speeds of the tracked vehicle model. The two types of dynamometers used to obtain the experimental results are an AC dynamometer and a DC dynamometer. The DC dynamometer has an inertia that is three times larger than the AC dynamometer inertia. The experimental results are analyzed with respect to the chosen duty cycle and the dynamometers used. Finally, the effect of the duty cycle on the dynamometer choice is discussed.

INTRODUCTION

The US Army Tank-Automotive Research, Development, and Engineering Center (TARDEC) and Science Applications International Corporation (SAIC) are examining methods to improve the state of combat hybrid-electric power system technology to benefit the future force. SAIC is the lead contractor for designing, developing, and maintaining the Power and Energy System Integration Laboratory (P&E SIL) for TARDEC. The P&E SIL contains a combat hybrid electric power system sized for a 20-22 ton tracked vehicle. The power system is a series hybrid power train, and it is packaged into a Future Combat Systems (FCS) Manned Ground Vehicle (MGV)-like hull such that thermal interactions and electro-magnetic noise become significant. This series hybrid power system is most commonly referred to as the HERMIT, or Hybrid Electric Reconfigurable Movable Integration Test-bed shown in Figure 1. The physical outputs of the HERMIT power system are the left and right sprockets, which connect directly to the left and right bi-directional dynamometers (blue items on far left and right of Figure 1). The dynamometers are the mechanisms used to achieve mobility load emulation. The dynamometers work hand-in-hand with the left and right torque sensors and the Tracked Vehicle

Virtual Proving Ground (TVVPG) vehicle model. More details on the preceding interactions are discussed in the Control System Layout section of the paper. In addition to discussion of the HERMIT power system and TVVPG vehicle model, this paper investigates the differences in performance between the AC dynamometer pair and the DC dynamometer pair.

Figure 1: HERMIT front view

HERMIT SERIES HYBRID POWER SYSTEM

The HERMIT series hybrid power system includes a 250 kW diesel engine, 410 kW generator, 600 V DC bus, 150 kW continuous DC-DC converter, an 18 kW-hr lithium ion battery pack, and left/right 410 kW induction motors. A schematic of the power system is shown in Figure 2. The HERMIT power system components are sized for a 20 to 22 ton skid-steered, tracked vehicle. The left and right traction motor output shafts are connected directly to the left and right dynamometers by means of a 16.6 to 1 gearing and a mechanical coupling.

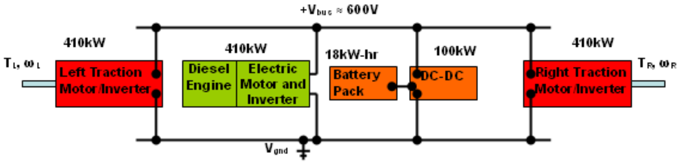

Figure 2: HERMIT power system layout

HERMIT DYNAMOMETERS

The purpose of the HERMIT dynamometers is to apply loads to the HERMIT power system that correspond to the interaction between the vehicle dynamics model and the simulated terrain. The dynamometer specifications were determined by the maximum torque, speed and power characteristics for a 20 to 22 ton skid-steered tracked vehicle. Existing data [1] was found (see Figure 3) for a 26 ton Jaguar tracked vehicle and was used as a reference point.

The performance specifications of the DC and AC dynamometers are listed in Table 1. For the purpose of comparing transient performance, the most significant parameters are inertia, torque control update rate, controller type. The parameters will be discussed in greater detail in the Results From Churchville B Runs section.

Table 1: Dyno Parameters

	DC Dyno	AC Dyno
Dyno Inertia (kg-m2)	800	276
Max Torque Rating (Nm)	35217	28000
Max Power Rating (kW)	922	1000
Torque Control Info	500 Hz PID	1000 Hz P only

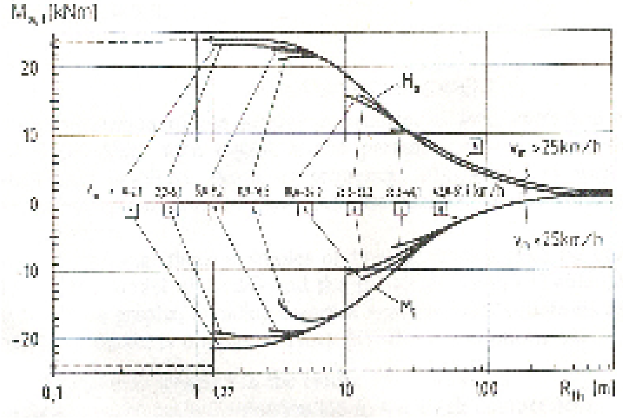

Figure 3: Experimental data for a 26-ton Jaguar tracked vehicle from [1]

HERMIT VEHICLE MODEL

The purpose of the HERMIT vehicle is to simulate the dynamics between a 20-22 ton skid-steered tracked vehicle and a virtual terrain. The HERMIT vehicle model was developed by SAIC and TARDEC in 2003. It is a soft-soil, skid steered, tracked vehicle model called Tracked Vehicle Virtual Proving Ground or TVVPG [2]. Given a power system's left and right sprocket torques as inputs, TVVPG simulates mobility over a 3D terrain surface using a single 6DOF rigid-body model for the vehicle hull and two rotational track and sprocket subsystems. The tracks' interaction with the terrain surface is represented using a combination of Bekker-Wong soft-soil models [3, 4], a longitudinal shear-slip displacement model for tracked vehicles [5], and a newly developed lateral shear slip displacement model [6]. The track-terrain interaction model is parameterized to account for differences in vehicle geometry, weight, and terrain type.

With respect to validation of the model, TVVPG was compared against the experimental data shown in Figure 3 for the Jaguar vehicle. This comparison was performed by substituting Jaguar weight and geometry as inputs for the TVVPG vehicle model. Figure 4 below shows an overlaid plot of sprocket torque versus turning radius for the Jaguar experimental data and the TVVPG modeled data. The modeled curves are generated by driving in a spiral on flat ground using the same terrain and Jaguar vehicle geometry as was used in the Jaguar experimental data.

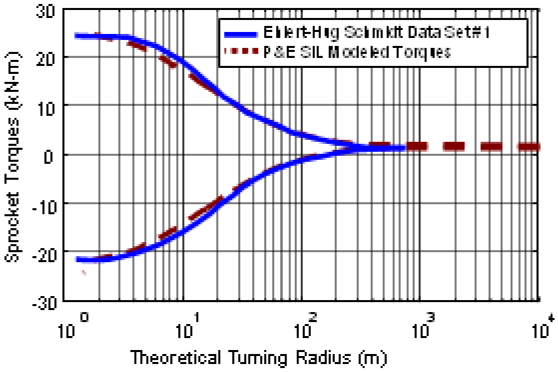

Figure 4: Representative Dataset comparing HERMIT's tracked vehicle model to Ehlert-Hug-Schmid Experimental Data

CONTROL SYSTEM LAYOUT

Mobility load emulation using a simulated vehicle model can be viewed as a dynamometer speed control problem with tracking and disturbance rejection objectives. In this framework, the dynamometer motors represent actuators receiving commands from speed controllers inside the TVVPG vehicle model. The tracking references for the speed controllers come from sprocket speeds computed by the TVVPG model. Thus, to the extent that the dynamometers can achieve their commanded speeds, the complete HERMIT control system achieves tracked vehicle mobility load emulation. Figure 5 illustrates the HERMIT control system layout used to achieve mobility load emulation with speed control of the dynamometers. It also outlines relevant communication rates, sensors, and actuators. Significant items in Figure 6 include the power system, torque and speed sensors, the dynamometer motors, inverters and controllers, the driver's station, and the 3D vehicle model.

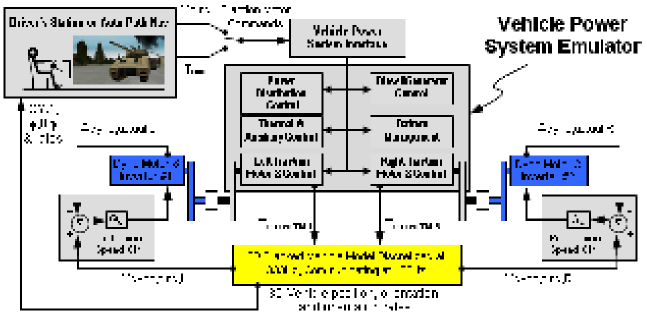

Figure 5: Mobility Load Emulation Layout

Shown on the top left portion of Figure 5, driver inputs are generated either by a live driver-in-the-loop or by an automated waypoint-based path navigator. The driver input signals include throttle, brake, steer, and power system operating mode, which is a flag indicating the type of hybrid electric power management scheme.

As the HERMIT power system traverses a virtual course, the traction motors apply torque to accelerate the vehicle. These torques are transmitted to the left and right sprocket shafts and measured by traction motor torque sensors. Left and right sensed traction motor torques are the inputs to the TVVPG model running in real-time. Depending on the track-terrain interaction and states of the vehicle model, the torque signals will begin to change the modeled left and right sprocket speeds. As the modeled sprocket shafts turn, the vehicle develops traction and traverses the digitized terrain in the virtual environment.

Next, the modeled sprocket speeds are sent to the Load Emulation Controller. Using the dynamometer final-drive gear ratio, the left and right modeled sprocket speeds are converted to real dynamometer speed commands. Figure 6 shows that the traction motor torque is both an input to the vehicle model and also an external disturbance to the dynamometer speed control loop. The torques imposed upon the traction motors by the dynamometers represents terrain and inertia reaction torques. The dynamometers are sized with a larger power rating than the traction motors to ensure the dynamometer motors can achieve their commanded speeds. A detailed control system synthesis is presented in [7]. Methods are presented for disturbance rejection and elimination of steady state dynamometer speed error.

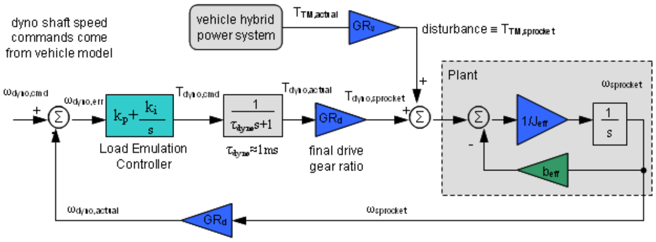

Figure 6: A Dynamometer Speed Control Loop with Traction Motor Torque Disturbance

SIGNIFICANCE OF DYNO COMPARISON

The main purpose for comparing the two types of dynamometers discussed in this paper is to determine if the DC dynamometer is appropriate for long term use with the HERMIT power system. Results obtained from loading the HERMIT power system with the AC dynamometer pair over a digitized virtual version of the Churchville B course at Aberdeen Proving Grounds are presented by Goodell [8]. As Table 1 illustrates, there are significant differences in rotational inertia, controller type, and control system update rate between the two dynamometer pairs. Goodell concludes that the AC dynamometer pair successfully achieves mobility load emulation, which allows the vehicle model to traverse the Churchville B course without diverging from the desired path.

After testing concluded with the AC dynamometer pair, it was desired to determine if the DC dynamometer pair was suitable for use with a real-time tracked vehicle model and combat hybrid electric power train hardware-in-the-loop experiment. The direct consequence of having a system with larger dynamometer inertia and a lower control system update rate is slower transient response time to a desired speed set-point. In this application of a tracked vehicle model attempting to traverse the tight hair-pin turns of the Churchville B course, a slow dynamometer transient response could potentially cause the vehicle model to diverge from the desired path. On the other hand, the DC dynamometer pair possesses greater controller flexibility since it is a PID controller compared to just a P controller for the AC dynamometer. The last factor to consider is the relationship between the rotational inertia of the dynamometer and the summation of the rotational inertia of the track, road wheels, and sprocket in the vehicle model. In this case, the DC dynamometer inertia is closer to the summation of the vehicle model's track, road wheels, and sprocket inertia than the AC dynamometer inertia. Consequently, the errors between desired and actual speeds during transients on the DC dynamometer should be smaller than the errors on the AC dynamometer. Therefore, the relative importance of all of the competing factors listed above is unknown. Thus, running a hardware-in-the-loop experiment with the HERMIT power system, DC dynamometer pair, and the Churchville B digitized course presents an appropriate means to compare and evaluate the performances of the AC and DC dynamometer pairs.

RESULTS FROM CHURCHVILLE B RUNS

The Churchville B course at the Aberdeen Proving Grounds was chosen due to its reputation as a rigorous course for power-train testing due to its significant slopes and tight turns. The vehicle model traverses the course by means of a waypoint-based path navigator. An automated path navigation scheme was employed in order to prevent biases in course runs due to human variability. A plot of desired and actual driver's side motor speed for the AC dynamometer pair is shown in Figure 7.

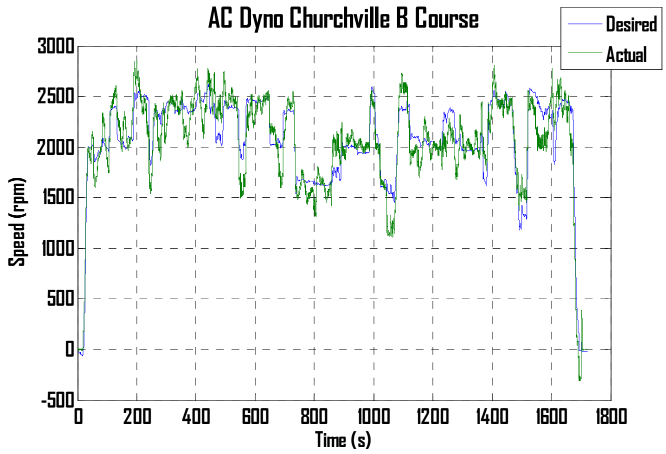

Figure 7: Driver's Desired versus Actual Traction Motor Speed for AC Dyno Churchville Run

The tracking in Figure 7 is acceptable because the vehicle never strays from the desired path on the Churchville B course. The best attribute of this run is that the actual speed trajectory never experiences any significant amount of oscillation. On the other hand, the draw-back of this run is that on some of the tightest turns, the desired and actual speeds diverge by as much as 100 to 200 rpm. This corresponds to no more than an 18% error. The divergence between desired and actual speeds on some turns can be attributed to the fact that the torque control is only a proportional controller. By definition, a proportional controller can reduce, but not eliminate, a steady state error.

A plot of desired and actual driver's side motor speed for the DC dynamometer pair is shown in Figure 8. Similar to the AC dynamometer pair, the DC dynamometer pair performs well enough to allow the HERMIT's vehicle model to traverse the Churchville B course without straying from the desired path. Therefore, the DC dynamometer pair has acceptable tracking. In fact, visual inspection of Figures 7 and 8 reveals that the DC dynamometer pair exhibits better tracking behavior than the AC dynamometer pair for the majority of the course. This behavior can be credited to the additional controller flexibility of the DC dynamometer pair. Specifically, the presence of the integral term in the DC dynamometer torque controller allows the steady state error term to be eliminated. However, the draw-back to the inclusion of the integral term in the controller is also evident in Figure 8. A significantly greater oscillation in motor speed (compared to the AC dynamometers) is apparent during any of the tight turns of the Churchville B course.

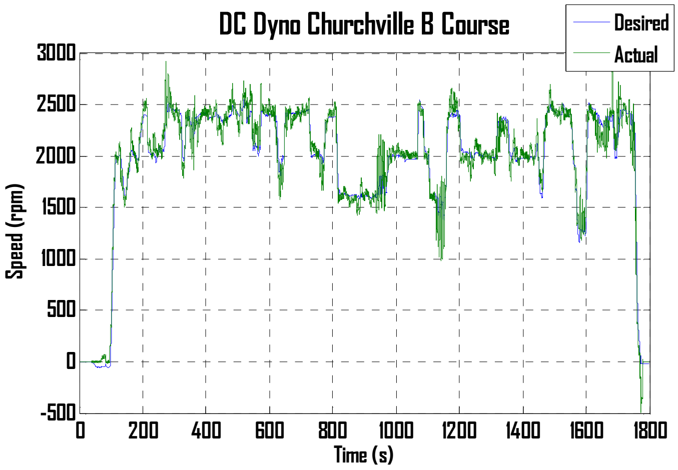

Figure 8: Driver's side desired versus actual traction motor speed for DC dyno Churchville run

Figures 9 and 10 show the overlaid plots of desired waypoints and actual path followed for the AC dynamometer pair and the DC dynamometer pair. No significant difference is noticed between the desired waypoints and actual path followed for either of the dynamometer pairs.

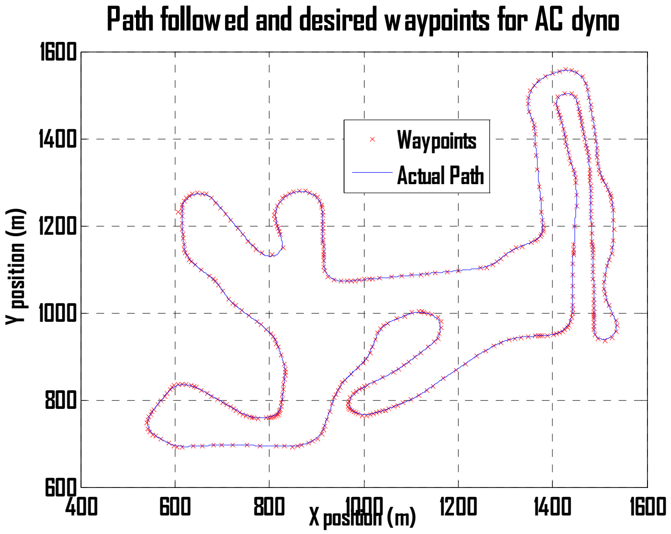

Figure 9: Plot of Path Tracking Performance for DC Dyno

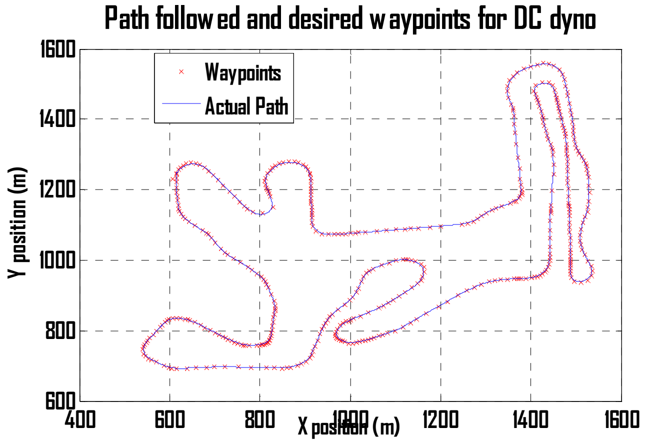

Figure 10: Plot of Path Tracking Performance for AC Dyno

LESSONS LEARNED

The results from these experiments prove the importance of both the controller and the plant in a hardware-in-the-loop vehicle model emulation experiment. The performance of the AC dynamometer system is limited by the simplicity of the controller on the system and the difference between its dynamometer inertia and vehicle model inertia. Conversely, the stability of the DC dynamometer system is limited by the relatively larger inertia of the dynamometer system compared to the AC dynamometer system and the dynamics imposed by the integral term of the PID controller. The results have also shown that the duty cycle is a critical portion of a vehicle model emulation experiment. Specifically, the tight turns present in the Churchville B course have highlighted weaknesses in each of the dynamometer systems examined in this paper. Another important component of the duty cycle is the speed at which the vehicle traverses the course. In this study, vehicle speeds were not at stressing levels for these dynamometer systems. As the speed over the course increases, the dynamometers must respond faster in order to traverse the same turns as the vehicle would traverse at lower speeds. Thus, an important lesson learned from these experiments is that the duty cycle is as critical to the performance and stability of a vehicle model emulation experiment as the dynamometer plant and dynamometer controller.

CONCLUSIONS

The US Army TARDEC and SAIC have developed a valuable capability in the area of hybrid electric power system modeling, simulation, and testing. The design of the HERMIT control system and the ability to run repeatable hardware-in-the-loop vehicle model experiments is and will be an asset for testing and development of hybrid electric technology for the future force. This study has shown that the HERMIT can function with a variety of different dynamometer systems. Furthermore, the HERMIT's utility goes beyond its original scope of testing power-train components, but also can be used to evaluate the dynamometer systems to which it is connected.

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