DEVELOPMENT OF AN ELECTRIC VEHICLE HARDWARE-IN-THE-LOOP EMULATION PLATFORM

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ABSTRACT

Hardware-in-the-loop emulation allows for rapid testing of new control algorithms and hardware components without the need for a full vehicle prototype. This paper outlines an electric vehicle emulation platform consisting of hardware and simulation components carefully integrated together in order to emulate the operation of the vehicle's powertrain. The main hardware components of the platform are two AC synchronous induction motors and their inverters/controllers, a rotary torque sensor, a battery pack, a programmable DC power supply, and a programmable DC load. The simulation components consist of a real-time data acquisition system with a control design and modeling interface. The control structure consists of speed and torque control mode selections for the two motors, vehicle and driver simulation models, as well as a feedforward component that improved the operation of the emulation platform during a typical EV drive cycle.

INTRODUCTION

Ever increasing transportation energy consumption, pollutant emissions, and the impact on climate change continue to stimulate broad research and development efforts into more sustainable vehicle propulsion systems. Electric propulsion systems are one such major solution being pursued by large and small vehicle manufacturers alike. While the electric vehicle (EV) itself is not a new concept, the components (energy storage, drive motors and associated power electronics) and the associated systems integration issues continue to evolve rapidly. To help with the assessment of design options, a variety of EV modeling and simulation tools have been developed [1-2]. However, the validity of pure simulation-based tools depends to a large extent on prior test data that support component and system modeling assumptions. One approach that reduces the need for prior test data is using available hardware within the simulation framework. This later approach has come to be known as Hardware-in-the-Loop (HIL) simulation.

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An EV HIL platform generally consists of some hardware components from the EV class under consideration, a real-time control and data acquisition unit, and a computer with simulation software that executes some system or subsystem models. The issue under investigation determines which hardware components will be included. The simulations will then retain the relevant model of the rest of the system dynamics. The interface between the simulation and the hardware components is handled with suitable real-time control and data acquisition units.

In this paper, we focus on describing a HIL platform intended for emulating the drivetrain of a neighborhood electric vehicle (NEV), but the setup can be scaled-up for larger EVs. The platform has been assembled using mainly off-the-shelf EV drivetrain components, namely, an AC machine and its inverter/controller, and the battery pack. The propulsion power is absorbed by another AC machine with its own inverter/controller and is connected to a programmable DC load and power supply. This configuration is analogous to a typical dynamometer set up. Using a carefully structured control strategy, commands are sent to the two inverter/controllers via the real-time control unit while the vehicle's forward dynamics are simultaneously simulated.

In the literature, one can find similar EV emulation platforms built and analyzed for specific purposes. An EV HIL platform built at University of Brest in France [3] used an AC motor as the emulated EV in torque control mode and a DC motor as a chassis dynamometer in PWM and hysteresis control modes. The authors showed that the DC motor in hysteresis control mode yielded better current tracking over PWM control mode because no specific PID gains were necessary for the AC motor control.

Another EV HIL platform was built at University of Maribor in Slovenia [4] that used an AC motor as the EV in torque control mode and a DC motor as a chassis dynamometer in torque control mode. The objective was to implement a control strategy that used no speed sensors because they were considered impractical sensors for a vehicle environment.

Instead, a speed observer was designed and sliding mode control was used to effectively transition into the field-weakening region of the AC motor controller.

A more complex hybrid EV HIL platform was built at Korea University of Technology and Education in South Korea [5]. The platform used one DC axial flux motor (AFM) with variable air gap in torque control mode as the vehicle. Another DC AFM was used in speed control mode as a dynamometer to load the vehicle. This platform was used with two different simulation programs to emulate a series hybrid EV with four AFMs in the vehicle wheels and a parallel hybrid EV with battery and fuel cell energy sources with two AFMs in the two front wheels.

A mechanical load emulation platform similar to the one we describe in this paper was built at University of Nottingham in England [6] in 1999. The platform consisted of two very small (0.55kW) AC induction motors coupled by a torque sensor. One motor acted as a dynamometer and the other as the electric drive but both were controlled with vector control. The authors presented a feedforward speed-tracking control strategy for the dynamometer that can be used for a wide range of nonlinear mechanical loads. This work was improved upon in [7] by using nonlinear control methods.

In this paper, we describe a HIL EV emulation platform design, which has similarities in intent and purpose to the above reviewed works. The focus will be less on the low-level control of the individual machines and more on the system integration of readily available components that can be used for educational and research purposes. In building the platform, we used off-the-shelf AC machines and their inverters/controllers, with limited knowledge of the low-level control techniques other than Controller Area Network (CAN) and other interfacing definitions. Typical uses of the platform include: 1) efficiency mapping of motors, controllers, and battery packs, 2) analyzing how vehicle design parameters (including mass, drag coefficients, etc.) affect performance such as regenerative braking capabilities, and 3) evaluating various driver models for analyzing the effects of

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driver behavior on the overall energy efficiency of the EV drive.

The remainder of the paper is organized as follows. First the hardware layout is described. Then the HIL platform control structure and the simulation models are discussed. This is followed by some experimental results and discussions on the platform control strategies considering a typical urban driving cycle. Then an experimental analysis that demonstrates one typical application of the HIL platform is presented. Finally, some conclusions are provided.

PLATFORM HARDWARE/SOFTWARE

The EV emulation platform presented in this paper consists of readily available hardware and simulation tools. **Figure 1** shows a photo of the platform. It consist of two 13kW 3-phase AC synchronous induction machines from HPEVS [8], two 1236 AC motor controllers/inverters from Curtis Instruments [9], a 100Nm torque sensor from Interface [10], a 48 volt battery pack from Rayovac, a 10kW programmable DC power supply from Amrel [11], and a 6 kW programmable DC load from NHR [12] (not shown in **Figure 1**). The real-time control and data acquisition system is dSPACE MicroAutobox (dS 1401) [13]. The simulation model is built in Matlab/Simulink and interfaced to dSPACE ControlDesk software for visualization of experiments.
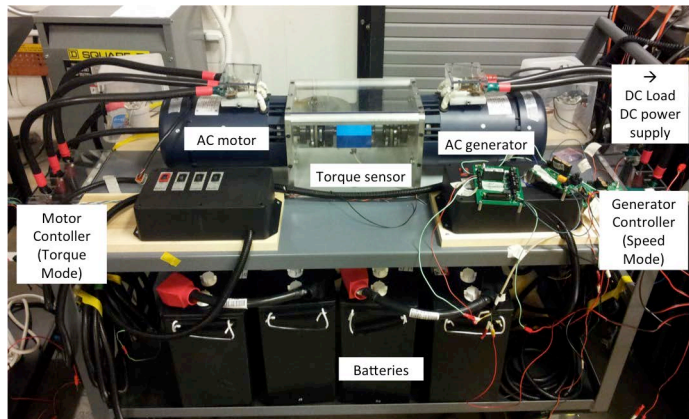

Figure 1: Hardware for the HIL platform

The EV is emulated by the AC motor on the left (**Figure 1**) powered by the battery pack. The output

of the drive motors is absorbed by the AC generator (similar machine operating in generator mode) and connected to the combination of a DC load in constant current (CC) mode and DC power supply in constant voltage (CV) mode connected in parallel. This configuration was chosen instead of another (absorber) battery pack to avoid dealing with overcharging issues and to add some testing flexibility to the setup. Both electric machines are capable of 4-quadrant operation. A rotary torque sensor is placed between the two machines and measures the shaft torque, which forms one input to the vehicle simulation model to be discussed below.

The 1236 AC motor controller came with a proprietary programming software made available by the supplier, Curtis Instruments. The software allows for selecting torque or speed control modes and settings, motor encoder settings, motor temperature settings, and even battery specification settings. For data acquisition and recording of motor speed (RPM), current, voltage signals during experiments, the controller can be configured to output CAN messages for monitoring desired variables. The CAN language utilized was CANopen and Curtis Instruments provided the CANopen identifiers for all the variables inside the controller (such as motor RPM, bus voltage, current, etc.). Special CANopen code was written in Simulink so that the dSPACE data acquisition system could read the RPM, current and other data during experiments.

CONTROL AND SIMULATION STRUCTURE

Figure 2 shows the schematic of the control and simulation structure for the whole HIL platform. The solid red lines denote power lines. The dashed red line denotes the interface between the hardware and simulation components and functions. In order to emulate the operation of the EV, the first machine (drive motor) was set to operate in torque control mode. This mode was selected from the available control mode options of the 1236 motor inverter/controller. The mode selection is justified by the fact that a driver would normally command a torque output from the EV's motor via the accelerator and brake pedals. The driver is modeled separately as a PID-type controller that requests torque commands to follow a desired drive cycle

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over time. The driver torque command is sent to the first motor controller, which accelerates or brakes accordingly. The motor controller uses DC power input from the battery pack but produces controlled AC output to the motor and therefore also includes an inverter.

The second AC machine (generator) was operated in speed control mode and acts as a dynamometer (absorber) for the power output of the first motor. The speed control mode is selected here as the only remaining option for stable operation of the whole setup, as the torque control mode has already been selected for the first machine on the same shaft of negligible inertia. It remains to determine what the command speed for the generator should be and this is assigned to the vehicle dynamics simulation part of the HIL platform. Note

that the AC generator controller also has an inverter as it connected to a DC bus.

The simulation part is largely comprised of a driver model, vehicle dynamics model, and throttle/brake control.

Driver Model

The drive cycle data provides the reference velocity that the driver tries to follow. The driver is modeled as a PID controller that compares this reference drive cycle velocity with the simulated velocity of the hardware (generator). The PID controller output is the driver torque command. The parameters of the PID controller can be changed to represent different kinds of drivers. The PID parameters used for this paper are given in the Appendix.
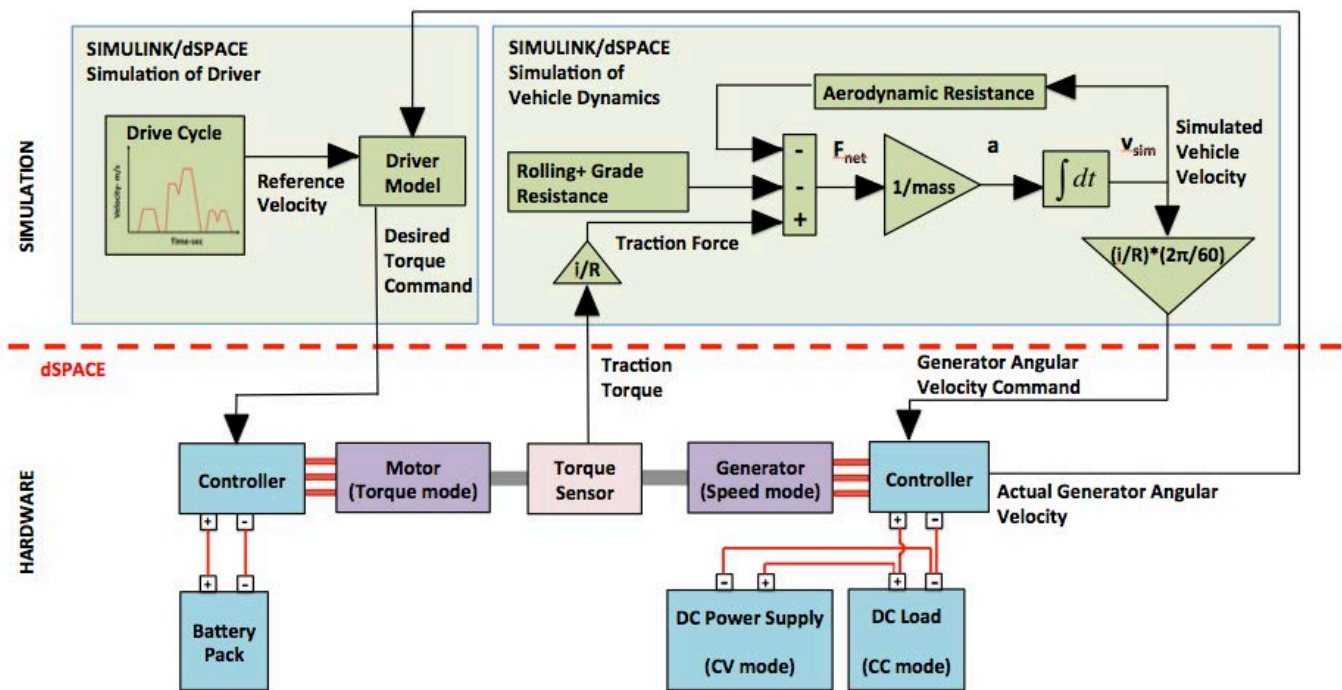

Figure 2: HIL platform with hardware and simulation components

Vehicle Dynamics Simulation

In this paper, the vehicle dynamics simulation essentially integrates the following forward dynamics equation:

$$m\frac{dv}{dt} = F_{traction} - f_r mg\cos\theta - \frac{1}{2}\rho AC_d v^2 - mg\sin\theta \quad (1)$$

The torque sensor emulates the traction torque at the wheel of the EV when ignoring the small mass of the torque sensor and couplings. Given the real-time measurement, and known vehicle parameters such as tire radius (R), operating gear ratio (i), and other road load parameters, the forward dynamics of the vehicle can be simulated. The road loads to be

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subtracted from the traction torque include the rolling, aerodynamic and grade resistances.

Given this simulated forward speed of the vehicle, the commanded rotational speed can be computed and sent to the generator's controller, which has been set in speed control mode.

Throttle and Brake Control

The motor and generator controllers receive analog wired throttle and brake inputs as command signals. The motor can receive throttle or brake commands in torque control mode. The controller configuration of the generator is such that it can throttle but not brake in speed control mode (i.e., for the generator, the speed commands are received as throttle only). The common shaft can slow down by the generator throttling less than the motor, the motor throttling less than the generator, or by the motor braking.

Figure 3 shows the scheme for the throttle and brake logic as implemented on the simulation side of the platform. If the reference velocity minus simulated velocity is greater than zero, then the motor accelerates at the torque value given by the driver PID block. Otherwise, the motor decelerates for two seconds. If the error is still positive after two seconds, then the motor brake is applied. The motor brake is applied gradually using an increasing ramp. When the error is negative then the motor begins to throttle at the new desired torque. These adjustments helped ensure smooth operation of the platform.
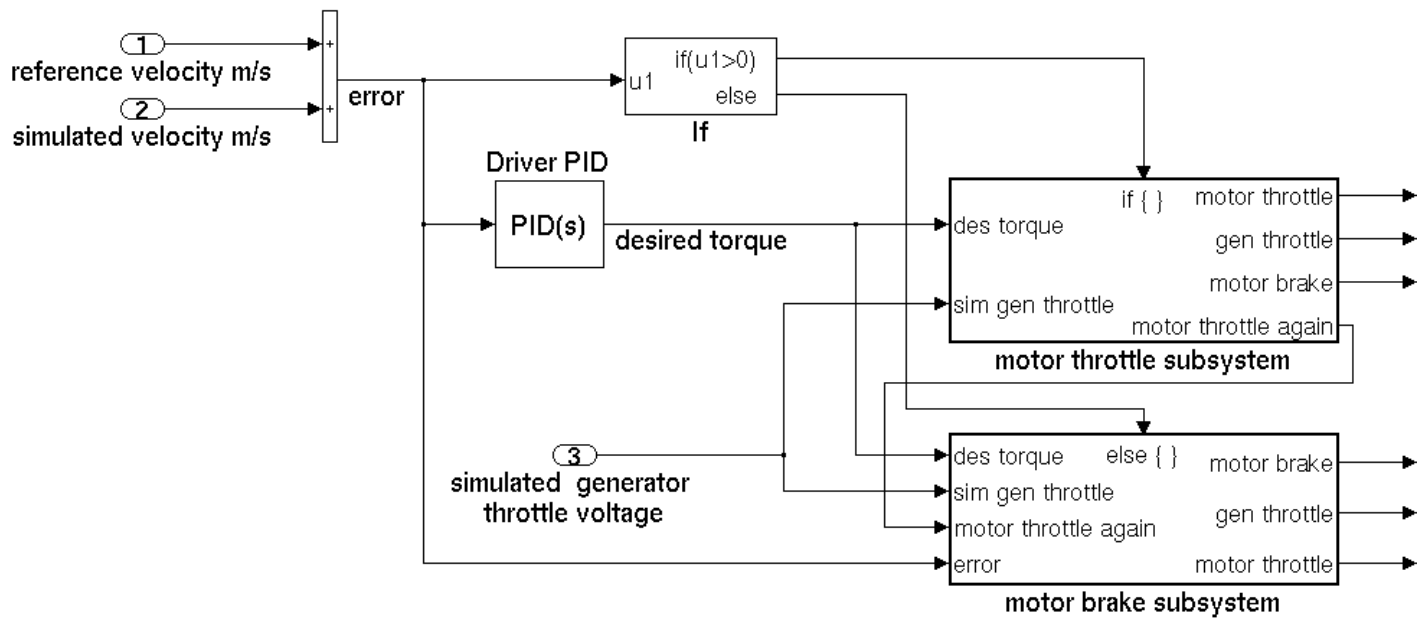

Figure 3: General throttle and brake logic

RESULTS AND DISCUSSIONS

The hardware components used in the HIL platform are sized for NEVs, golf carts, etc. In order to test the emulation platform, a drive cycle that our specific platform could achieve was needed. A scaled-down version of the Japanese 10-15 mode drive cycle was selected to represent a typical stop-and-go cycle with significant acceleration and braking events. The rest of the vehicle and driver parameters used in the HIL EV emulations are provided in the Appendix.

Velocity Tracking

Figure 4 shows the tracking performance for the emulated EV with a nominal mass of 150 kg. It can be seen that the generator speed (actual RPM converted to kph) tracks the simulated speed rather well, apart from measurement noise. The driver model also tracks the reference profile well with a tracking performance that improves with time according to the integral action of the PID model for the driver. The corresponding motor and generator current profiles are shown in Figure 5. When the

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motor current becomes negative, current is being put back into the motor's battery pack. This regenerative braking current occurs when the vehicle decelerates during the drive cycle.
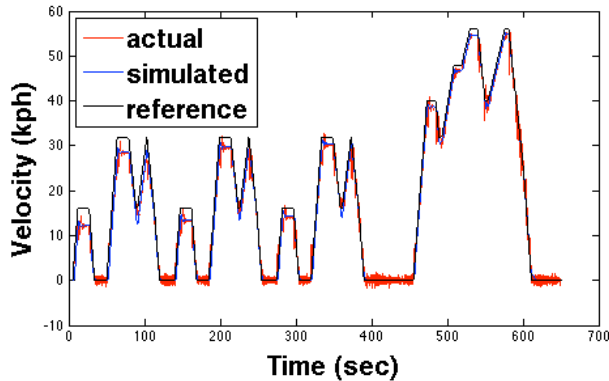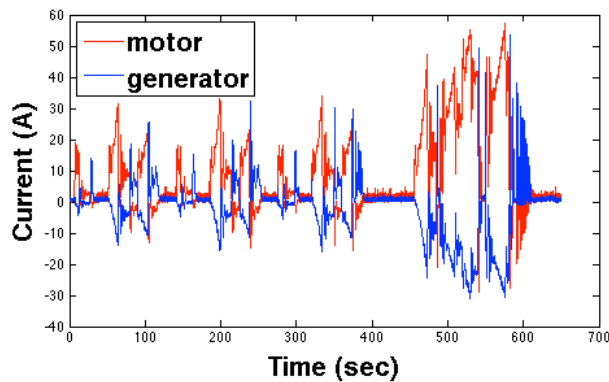

Figure 4: HIL velocity profiles

Figure 5: HIL current profiles

Closer inspection of the drive cycle reveals that the simulated velocity lags the actual and reference velocities as shown in Figure 6. The dynamics of vehicle simulation block causes this lag. The generator control loop also may contribute to this lag, but we assume it to be insignificant. To compensate for this lag, a feedforward torque can be calculated based an inversion of the forward vehicle dynamics.
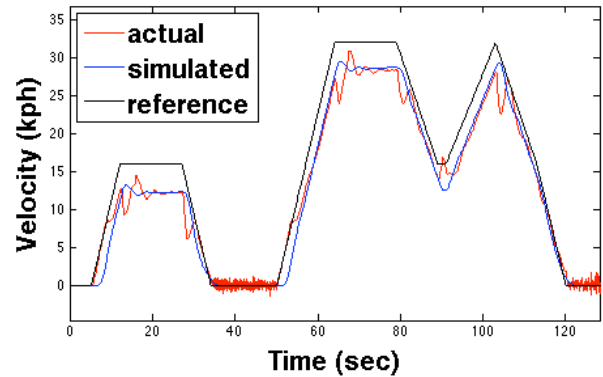

Figure 6: Zoomed-in view of first peaks with no feedforward torque

The feedforward is achieved by using the known reference velocity and the known parameters of the vehicle. We simply use the discretized form given in Eq (2), where V(t) stands for the reference velocity at the current time t and Δt is a time step selected to approximate the derivative. The feedforward scheme is added to the simulation side of the HIL platform as shown in Figure 7.

$$T(t) = \frac{R}{i}\left[\frac{m(V(t+\Delta t)-V(t))}{\Delta t} + \frac{1}{2}\rho A C_d V^2(t) + f_r mg\right] \quad (2)$$
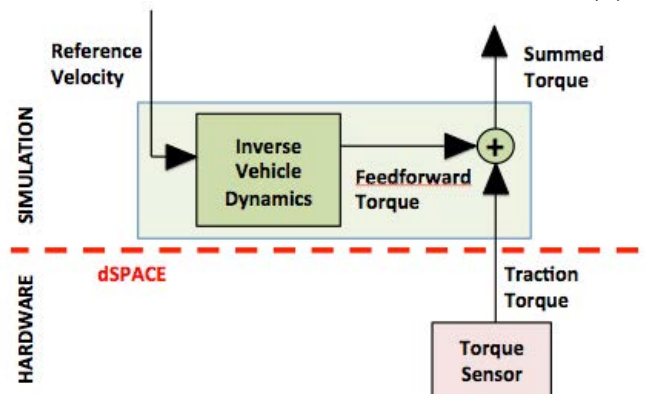

Figure 7: Construction of feedforward torque

Best results were achieved with feedforward for Δt=1 second. Figure 8 shows improved velocity tracking performance with feedforward implemented. The lag of the simulated (actual) velocity from the reference has been significantly reduced. The steady state errors could not be improved much further without destabilizing the platform with the current controller selections.
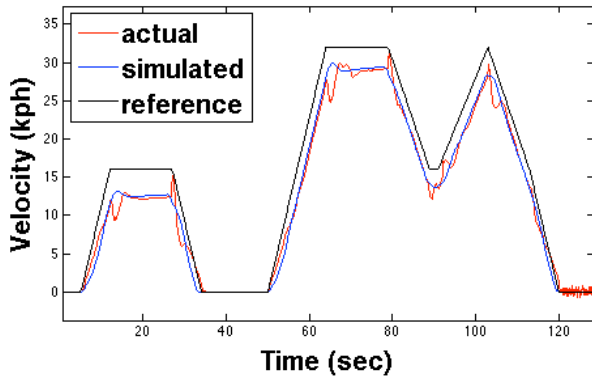
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Figure 8: Zoomed-in view of first peaks with feedforward torque

Velocity tracking performance of the no feedforward case and the feedforward case were compared using mean error and peak error between reference velocity and simulated velocity for the drive cycle. The feedforward case showed improvement in tracking performance. The results are given in Table 1.

	Mean Error (kph)	Peak Error (kph)
No Feedforward	1.17	5.41
With Feedforward	1.12	4.55

Table 1: Velocity tracking performance

APPLICATION EXAMPLE

Effect of Vehicle Mass on Energy Considerations

As already stated, one application of the EV emulation platform is to study the sensitivity of performance metrics to vehicle design choices. As an example, the HIL platform was used to investigate energy output and energy recovery ability of the EV for different vehicle mass values. The EV's motor ability was evaluated using the following metrics for the whole drive cycle: total regen energy, total energy consumed from battery pack, and the regen ratio for vehicle masses ranging between 150 kg to 400 kg. The regen ratio will be defined as the ratio of total regen energy over total energy consumed from battery pack. Table 2 shows the performance results for feedforward case.

The total regen energy, total consumed energy, and regen ratio increases as vehicle mass increases

under the feedforward. These results are as expected. The motor draws more battery current to accelerate a heavier vehicle resulting in increased consumed energy. The motor must also brake more often to achieve desired deceleration of the heavier vehicle resulting in increased regen energy.

	150 kg	250 kg	325 kg	400 kg
Total Regen Energy (kJ)	5.53	10.46	19.56	32.03
Total Consumed Energy (kJ)	125.20	216.53	295.17	380.75
Regen Ratio (%)	4.42	4.83	6.62	8.41

Table 2: Select EV performance metrics with changing vehicle mass for feedforward case

CONCLUSION

The HIL EV emulation platform presented here is built from off-the-shelf components for educational and research purposes. This paper provided the details on the system level integration and the control structure for the platform. Some uses of the platform have been outlined and at least one application study has been demonstrated.

Some aspects of the platform can yet be refined further. For example, more advanced control and compensation methods could be sought to improve the overall speed tracking performance, especially at steady state. The vehicle simulation models and the driver models could also be refined further per the requirements of the specific evaluation to be conducted on the elective vehicle.

NOMENCLATURE

R	tire radius (meters)
i	gear ratio
m	mass
g	gravitational acceleration constant
a	acceleration
A	frontal area
C_d	coefficient of drag
ρ	density of air

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θ	road grade
f_r	friction coefficient
F_{net}	net force of vehicle
$F_{traction}$	traction force from vehicle
$F_{Road\ Load}$	road load force on vehicle
F_{RR}	rolling resistance force
F_{aero}	aerodynamic force
F_{grade}	grade force

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APPENDIX

P	1.5
I	0.007
D	0

Table 3: Driver model PID parameters

Gravitational Acceleration, g	9.18 m/s^2
Vehicle Mass, m	150, 250, 325, 400 kg
Frontal Area, A	1.8 m^2
Air Density, ρ	1.224 kg/m^3
Coefficient of Drag, C_d	0.3
Grade Angle, θ	0 degrees
Overall gear ratio, i	3
Tire radius, R	0.2286 m
Friction coefficient, f_r	0.01

Table 4: Vehicle parameters