A study on Emulating On-Road Operating Conditions for Electric-Drive Propulsion Systems

EE 580 Electrical Machines & Drive Systems

Submitted by

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Abstract:

A new approach for emulating road load conditions for an electric-drive vehicle (EDV) system (a drive motor (DM) connected to a dynamometer). The effect of total vehicle inertia is considered and a control scheme is developed based on vehicle equivalent rotational inertia. This method of EDV emulation not only takes into account all of the stress imposed on the DM due to vehicle inertia effect, but also allows electric vehicle emulation for any standard drive cycle. Simulations are conducted using MATLAB/Simulink.

Introduction:

Emulating an electric-drive vehicle (EDV) by means of an electric motor/dynamometer test bench is a timely research topic that has received increased attention in recent years.

- Low-cost approach
- Possible in academic environments

How can we do?

- System simulation
- HIL
- Real vehicle testing

The advantages of system software simulation include flexibility, low cost, and time effectiveness; however, software simulation provides no guarantee that the real-time performance constraints can be met. Therefore, in most cases, the simulation results should be verified and validated using other methods. The main advantage of real vehicle testing is good fidelity; however, this method often leads to a dedicated system that is very expensive, rigid, and difficult to test and adjust. As a combination of the advantages of these two approaches, HIL simulation using a test bench is drawing increasingly more attention.

Vehicle and Testbench specifications:

▪ Vehicle mass	400 kg
▪ Air density (ρ_α)	1.22 kg/m^3
▪ Aerodynamic drag coefficient (C_d)	0.3
▪ Frontal area (A_f)	1.6 m^2
▪ Rolling resistance coefficient (f_r)	0.01
▪ Wheel radius (r_d)	0.28 m
▪ Ground slope angle (α)	0
▪ Overall gear ratio (G)	2.3
▪ DM inertia (J_{DM})	0.016 kg.m^2
▪ Dynamometer motor inertia (J_{Dyno})	0.019 kg.m^2
▪ Coupling inertia ($J_{coupling}$)	0.003 kg.m^2
▪ Equivalent vehicle rotational inertia (J_{ew})	33.029 kg.m^2

- Vehicle drive train overall efficiency (η) 90%
- DM viscous coefficient (B_{DM}) 0.086 N.m/(rad/s)
- Dynamometer viscous coefficient (B_{Dyno}) 0.0133 Nm. /(rad/s)

Acting forces on a vehicle:

In order to better understand a vehicle's moment of inertia, all forces applied to a moving vehicle should be known. The dynamic equation of a vehicle with regards to the second law of motion and under consideration of the resistive forces can be expressed as,

Force = Mass * Acceleration

$\mathrm{F} = \mathrm{m} * \mathrm{a}$

Including resistive forces, $\mathrm{F_D} = \mathrm{F_R} + \mathrm{ma}$

$$\mathrm{F_R} = \mathrm{F_r} + \mathrm{F_w} + \mathrm{F_g}$$

Force due to,

Rolling resistance, $\mathrm{F_r} = \mathrm{mgf_r}\cos(\alpha) = 400 * 9.8 * 0.01 * \cos(0) = 39.2$ N

Aerodynamic drag, $\mathrm{F_w} = \frac{1}{2}\rho_\alpha \mathrm{C_d A_f}(\mathrm{v} + \mathrm{v_W})^2 = \frac{1}{2} * 1.22 * 0.3 * 1.6 * v^2$

$$= 0.2928\, v^2 \quad \mathrm{N}$$

Grading resistance, $\mathrm{F_g} = \mathrm{mg}\sin(\alpha) = 400 * 9.8 * \sin(0) = 0$

$$\therefore F_R = 39.2 + 0.2928\, v^2 + 0$$

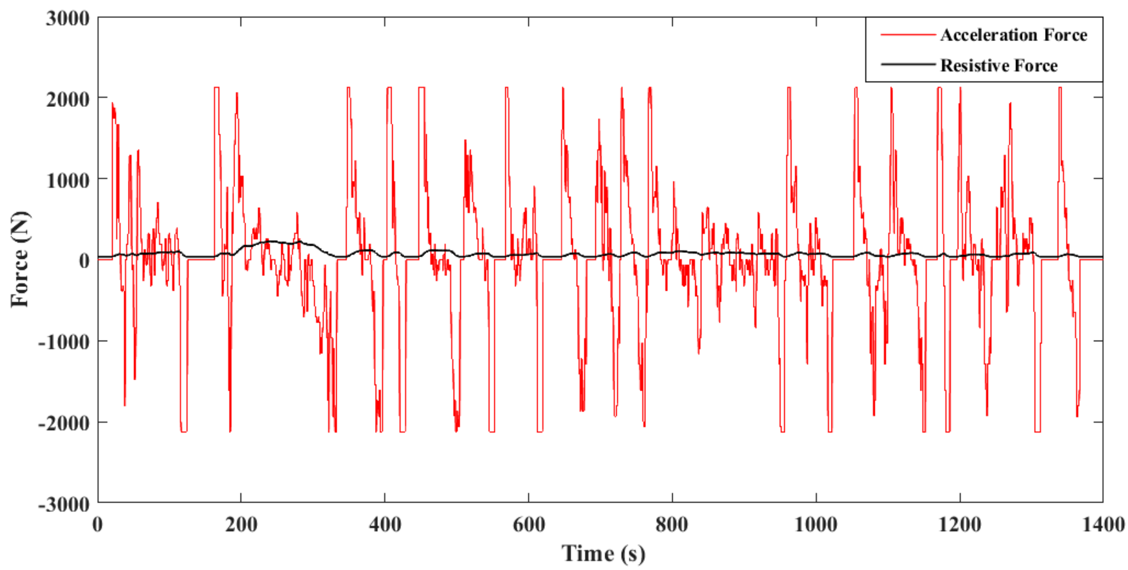

Figure 1:Resistive and acceleration forces of a typical vehicle for the UDDS

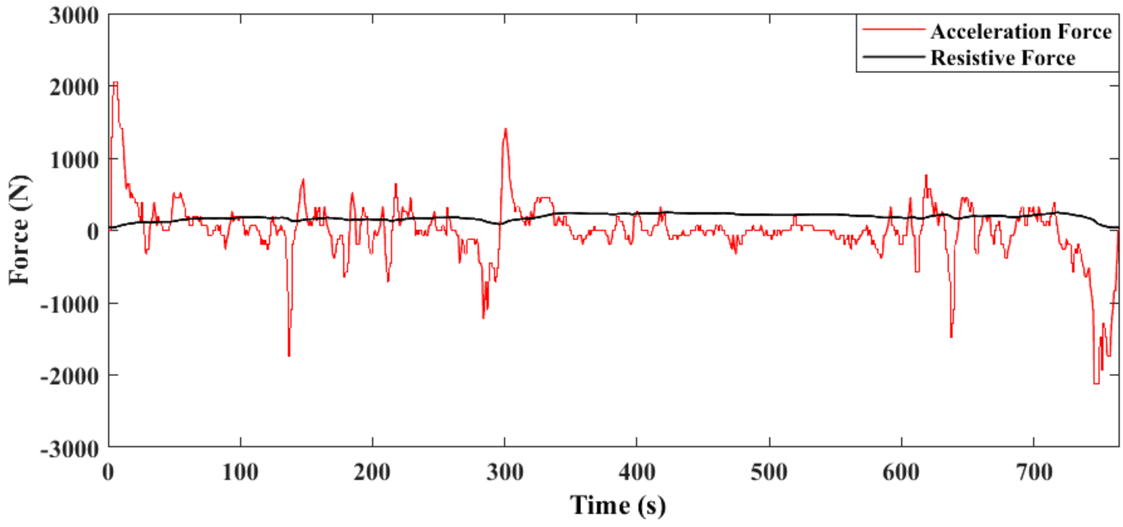

Figure 2:Resistive and acceleration forces of a typical vehicle for the HWFET

Vehicle Equivalent Rotational Inertia:

Equivalent inertia relates to the amount of flywheel rotational inertia that would be sufficient for emulating the vehicle inertia effect while rotating at the same speed as the vehicle's electric motor

Total kinetic energy stored, $E = \frac{1}{2}mv^2 + \frac{1}{2}Jw_w^2$

This energy can be expressed as a non-rotating energy of some equivalent mass such that the kinetic energy of this equivalent mass equals the total energy at the same speed.

$$\frac{1}{2}m_e v^2 = \frac{1}{2}mv^2 + \frac{1}{2}Jw_w^2 \text{ , } v = wr$$

$$m_e = m + J\left(\frac{1}{r_d^2}\right)$$

In order to calculate m_e one must first calculate J which requires knowledge of the weight, form, and dimensions of each rotating component within the vehicle. Another approach to calculating m_e is given below. In this approach, the equivalent mass increase caused by the angular moments of all rotating components in a vehicle is calculated using a rotational inertia factor, which is

Alternate approach

$$m_e = \delta * m$$

$$\text{Mass factor, } \delta = 1 + \frac{I_w}{mr_d^2} + \frac{i_o^2 i_g^2 I_p}{mr_d^2}$$

$$\delta = 1 + \delta_1 + \delta_2 i_o^2 i_g^2 = 1 + 0.04 + 0.0025\ \mathrm{G}^2$$

$$= 1 + 0.04 + 0.0025 \cdot 2.3^2 = 1.053225$$

$$\therefore m_e = 1.053225 \times 400 = 421.29\ Kg$$

$$\frac{1}{2}m_e v^2 = \frac{1}{2}J_{ew} w_w^2$$

$$\boldsymbol{J_{ew}} = m_e r_d^2 = 421.29 * 0.28 * 0.28 = 33.029\ \mathrm{Kg.m^2}$$

Vehicle Dynamics:

The dynamic equation of a vehicle in the rotational context can be expressed as

$$T_w - T_R = J_{ew}\frac{dw_w}{dt}$$

$$T_w = T_R + J_{ew}\frac{dw_w}{dt}$$

$$T_{DM} = \frac{T_w}{nG}, w_m = w_w.G$$

$$T_{DM} - T_{Dyno} - (B_{DM} + B_{Dyno})w_m = J_{total} * \frac{dw_w}{dt}$$

$$= (J_{DM} + J_{Coupling} + J_{Dyno}) * \frac{dw_w}{dt}$$

$$\frac{J_{ew}\frac{dw_w}{dt} + T_R}{nG} - T_{Dyno} - (B_{DM} + B_{Dyno})w_m = (J_{DM} + J_{Coupling} + J_{Dyno})\frac{dw_w}{dt}$$

Controller block:

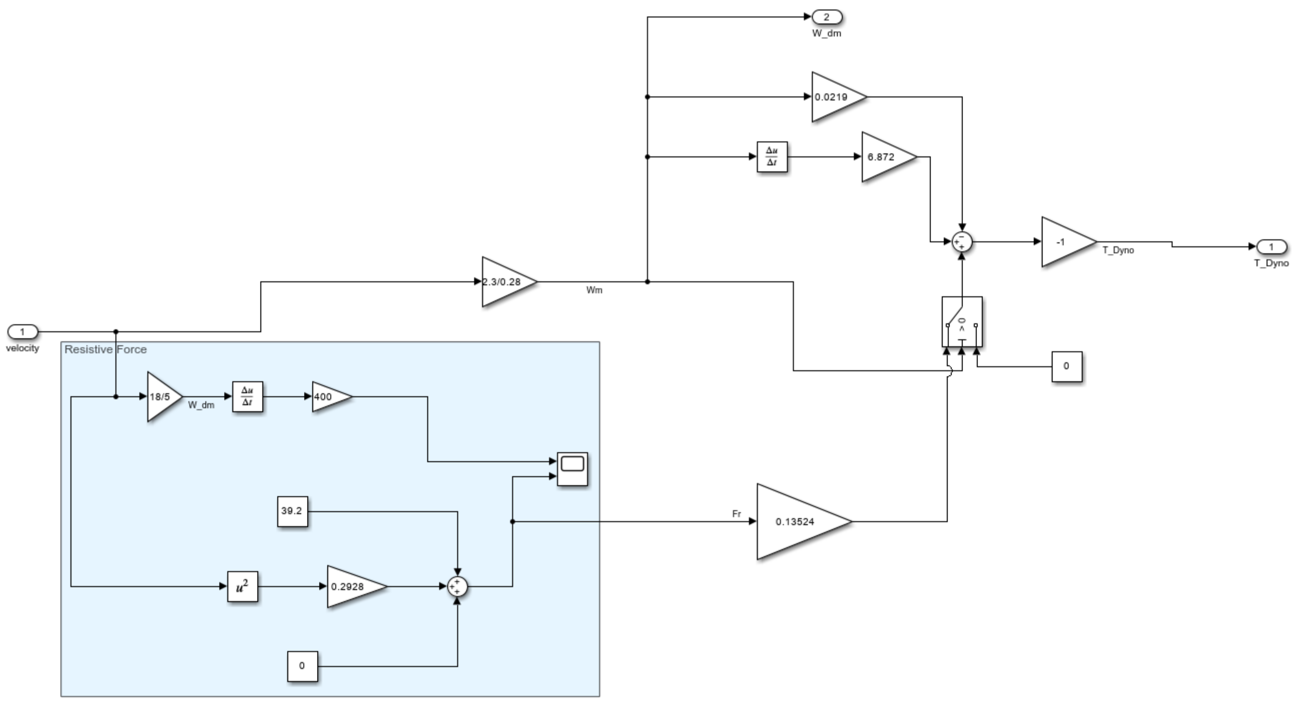

Figure 3:Controller block for the system

In this configuration, the reference for the vehicle's translational speed is obtained from a predetermined drive cycle and translated into a required rotational speed, which is then given to the DM through a PI controller that ensures accurate speed tracking. The required dynamometer resistive torque is calculated directly from the speed trace using the test bench and vehicle dynamic equations at each instance. In this approach, it is assumed that the trace is always met and, hence, that the derivative of speed at each operating point can be mathematically computed from the drive cycle instead of the actual motor speed

Simulation:

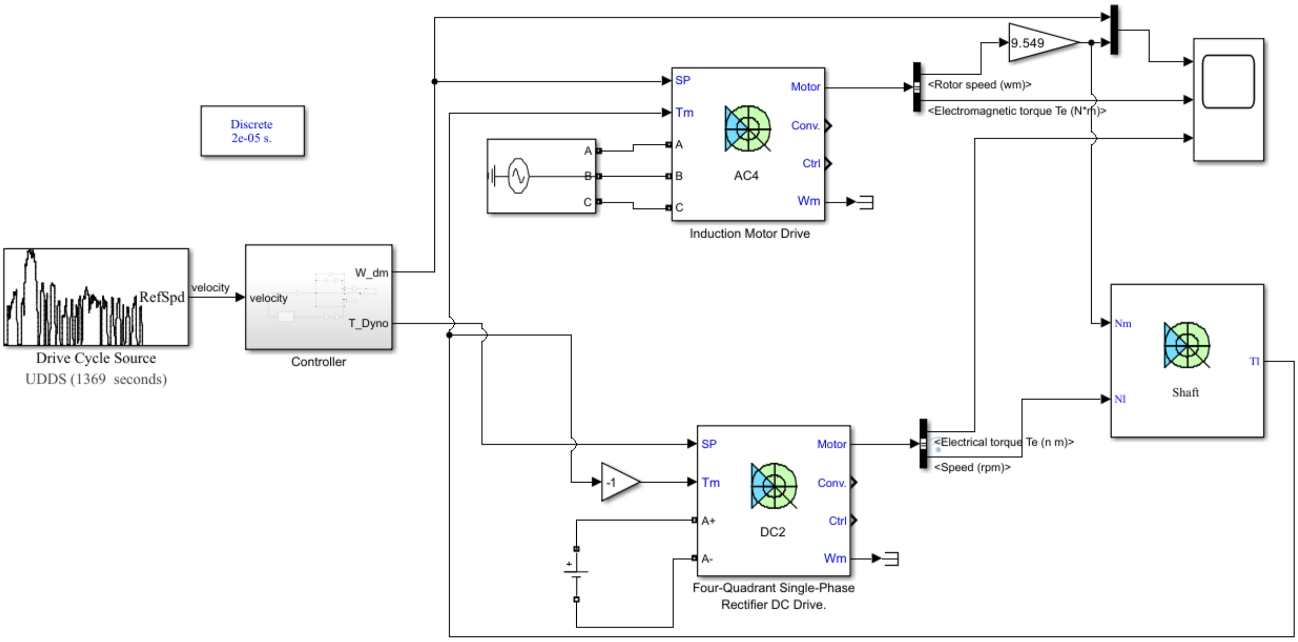

Figure 4:Simulation Diagram of the system

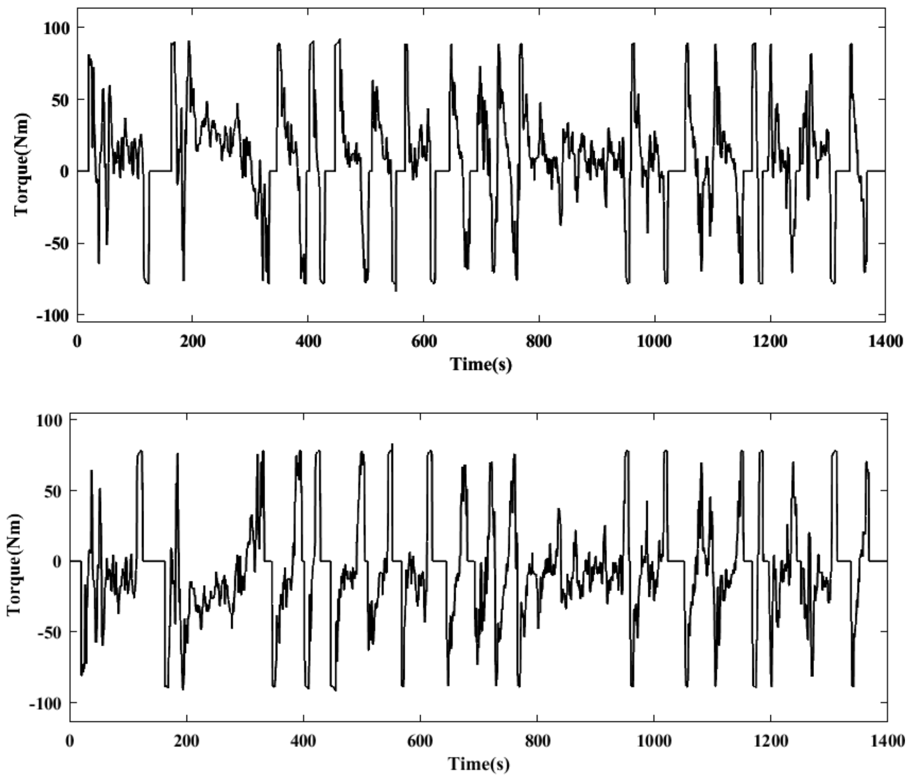

Figure 5: Induction Motor Torque(top) and DC motor torque(bottom)

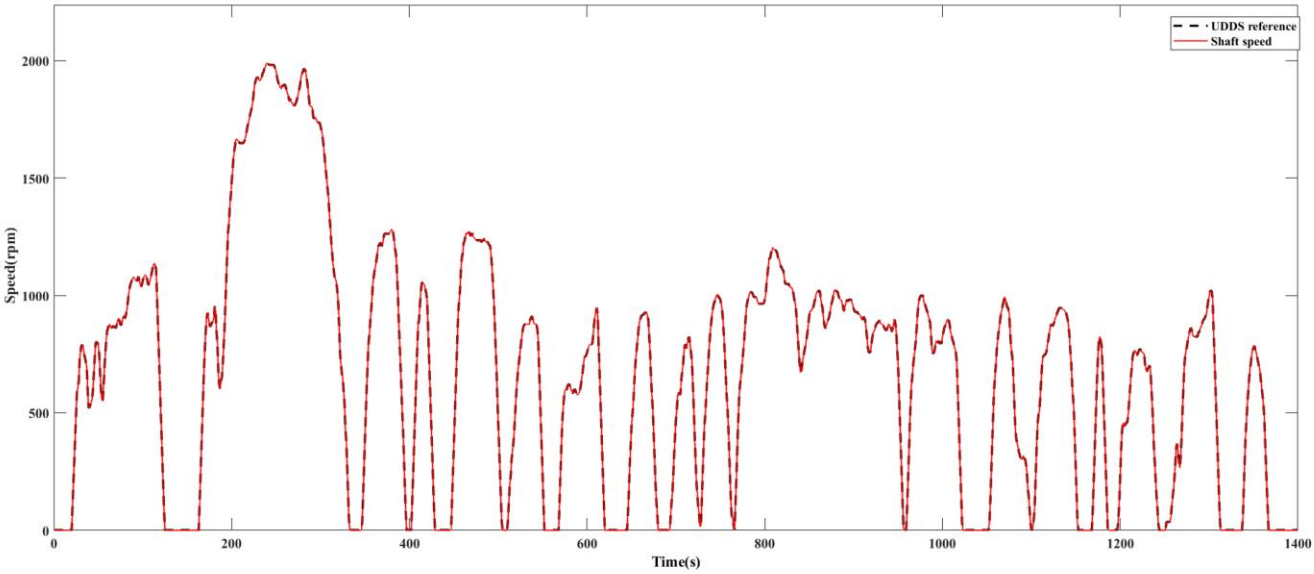

Figure 6:Plot showing motor following the reference

Conclusion:

A new approach for emulating the behavior of EDVs was proposed based on vehicle equivalent rotational inertia. The method used to properly map the linear inertia of a vehicle to an equivalent rotational inertia was described in detail, and an expression for the equivalent rotational inertia of a vehicle was derived analytically. Using this expression, control approach was developed and simulated. The maximum torque required to complete this cycle was found to be approximately 92 Nm for this vehicle.

References:

1. Emulating On-Road Operating Conditions for Electric-Drive Propulsion Systems, IEEE TRANSACTIONS ON ENERGY CONVERSION, VOL. 31, NO. 1, MARCH 2016