Designing and Simulating a Novel Blended Power Distribution System In a Parallel Hybrid Electric Vehicle

LAFAYETTE COLLEGE

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Question:

Is it feasible to design a power distribution system for parallel hybrid vehicles that blends power from an internal combustion engine and electric motor simultaneously in order to linearize power response?

Introduction

Climate change is one of the most urgent and severe problems facing humanity. Its effects are already being seen to a disastrous extent and are only projected to grow worse [1]. The consumption of fossil fuels—petroleum in particular—for energy generation is one of the most significant factors accelerating climate change. In the United States, transportation is the largest consumer of petroleum products, such as gasoline and diesel [2]. More efficient vehicles can decrease petroleum consumption, slowing the onset of severe climate change [3]. This can be done by optimizing hybrid electric vehicle (HEV) technology [4]. One possible route to optimize HEV technology that has been shown to require further investigation is the blending of power from an internal combustion engine (ICE) and electric motor (EM) in order to make efficient ICEs that could lack responsive torque drivable. This method was investigated.

Methodology

General Methodology

1. Develop a generic, data-based first order power model for ICE from multiple sources
2. Develop an ideal model for EM using proportional feedback response
3. Develop simple Python simulation to attain WeBots parameters
4. Develop WeBots simulation environment, including custom vehicle PROTO, world, and fluid interactions
5. Conduct WeBots simulations using speculative throttle inputs and gather data.

ICE Model Development

- Find steady state power and torque data (Fig. 1)
- Convert to usable numerical data using WebPlotDigitizer
- Scale numerical data to create steady state power data according to throttle input (Fig. 3)
- Determine time constant for the first-order torque response of a typical ICE [6] (Fig. 2, Eq. 1)
- Calculate the immediate power output of a generic ICE by interpolating the steady state data and given throttle position, RPM, and the previous output (Eq. 2)

EM Model Development

- Find steady-state ICE torque using ICE model and RPM
- Determine the difference between steady-state ICE torque and current ICE torque
- Output ICE torque difference
- Multiply output by constant (constant is one for all simulations, can be tuned for varying response) (Eq. 3)

WeBots Simulation Development

- Simplify WeBots highway sample world
- Develop basic car model as PROTO based on a 2012 Fiat 500 (same car as Fig. 1 engine data) mass, geometry, and drag
- Add fluid interactions to world to simulate drag
- Construct controller for car using WeBots Supervisor library for absolute position and speed, and setting motor torques to sum of EM and ICE torques (Fig. 4, Eq. 4)

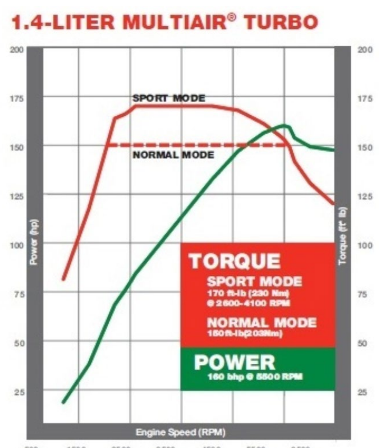

Fig. 1 – Power and torque vs. RPM curve for 2012 Fiat 500 [5]

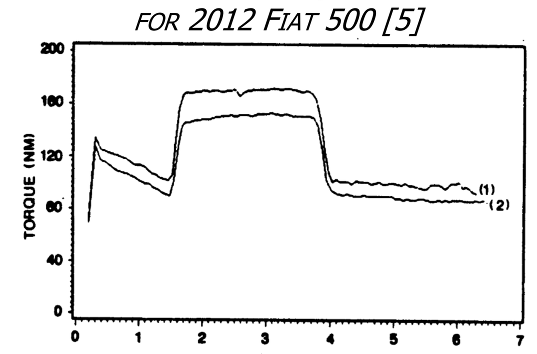

Fig. 2 – Torque vs. time from throttle step input, used to calculation time constant [6]

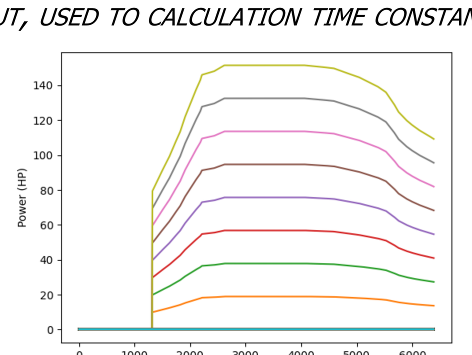

Fig. 3 – Power vs. RPM curves, scaled for throttle position

Eq. 1 $$\dot{T}_{\text{ICE}} = \frac{1}{\tau}(T_{\text{steady state}} - T_{\text{current}})$$

Eq. 2 $$T_{\text{ICE}} = T_{\text{current}} - \dot{T}\Delta_{\text{time}}$$

Eq. 3 $$T_{\text{EM}} = \frac{1}{\omega}K(P_{\text{steady state ICE}} - P_{\text{current}})$$

Eq. 4 $$T_{\text{output}} = T_{\text{ICE}} + T_{\text{EM}}$$

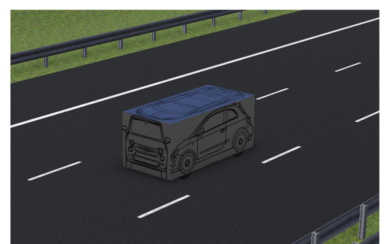

Fig. 4 – Car model PROTO in modified highway world

Results

Drag Run Scenario

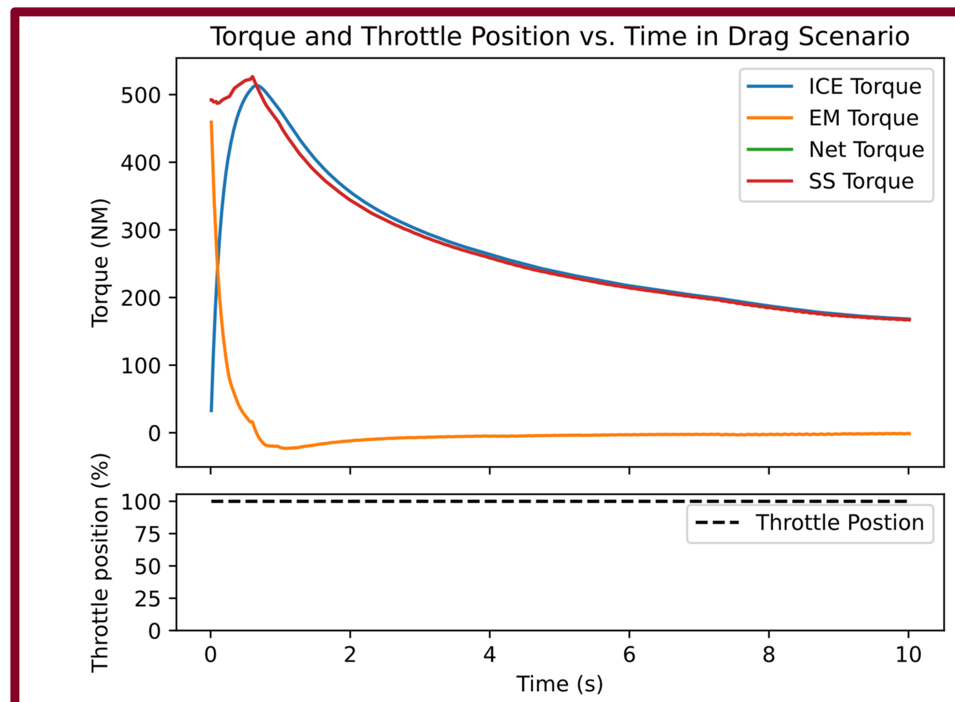

Fig. 5 – Showing torque response in scenario of max immediate acceleration from a slow speed in first gear, approximating a drag run

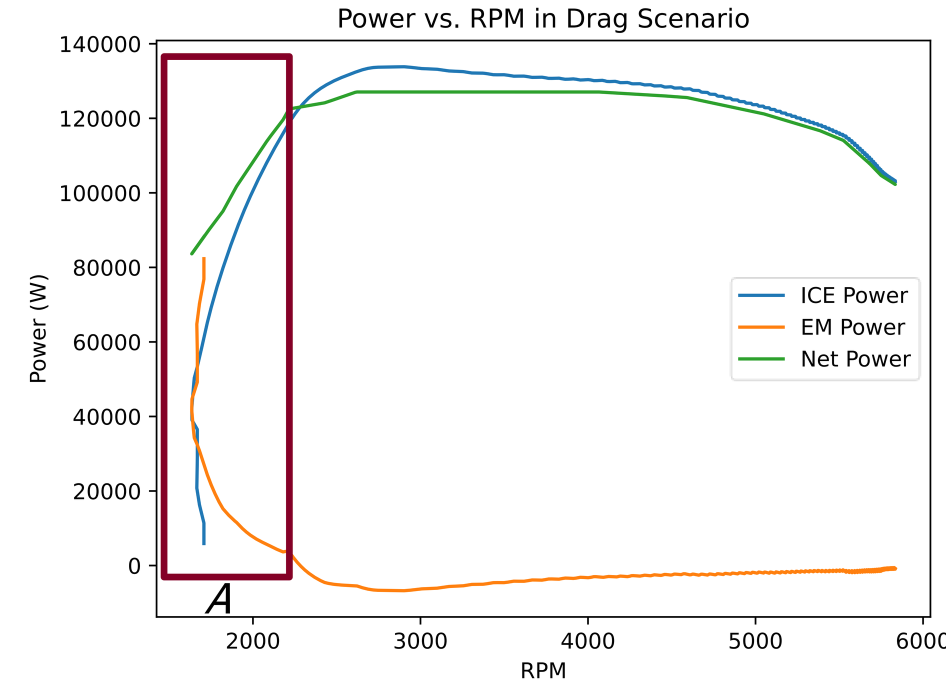

Fig. 6 – Showing power curve over engine speed in same scenario, annotated with meaningful regions

City Driving Scenario

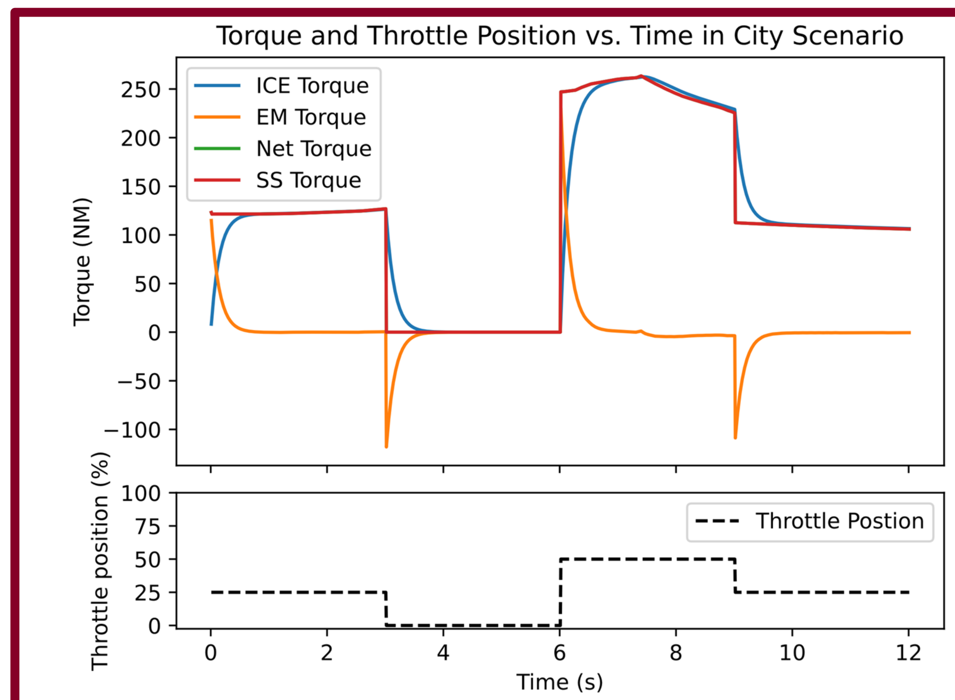

Fig. 7 – Showing torque response in scenario of large throttle changes in short periods of time in second gear, approximating city driving

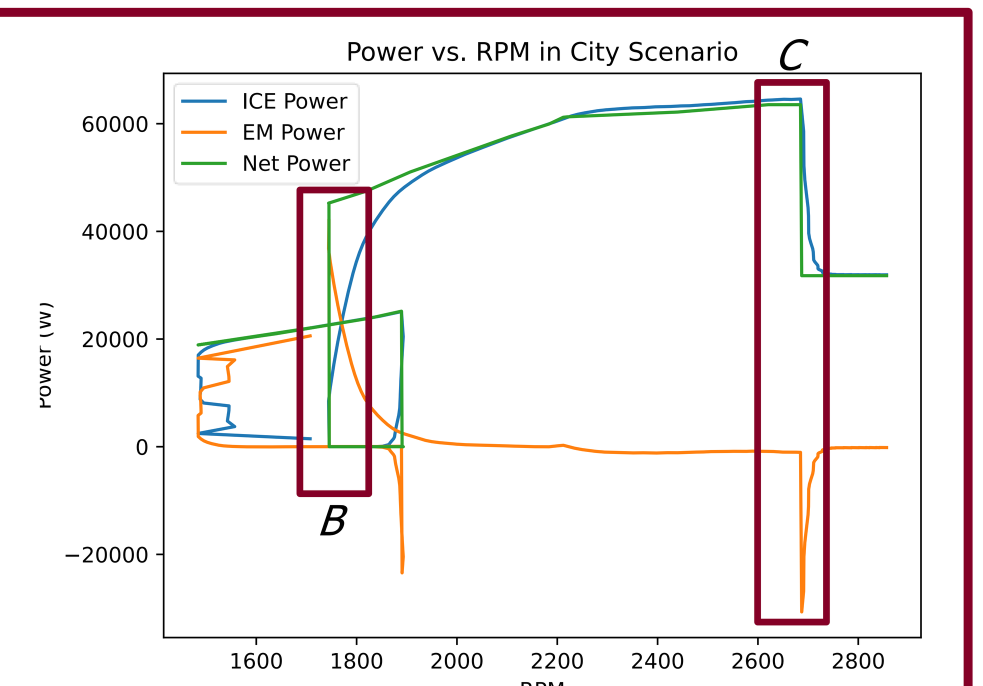

Fig. 8 – Showing power curve over engine speed in same scenario, annotated with meaningful regions

Drag Driving Scenario

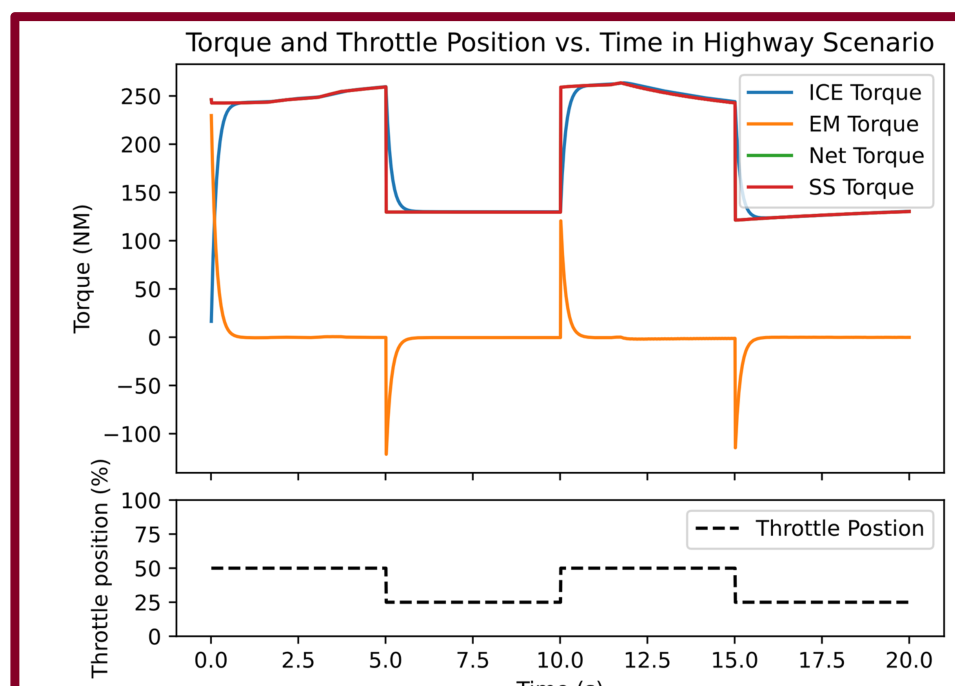

Fig. 9 – Showing torque response in scenario of small throttle changes in longer periods of time in forth gear, approximating highway driving

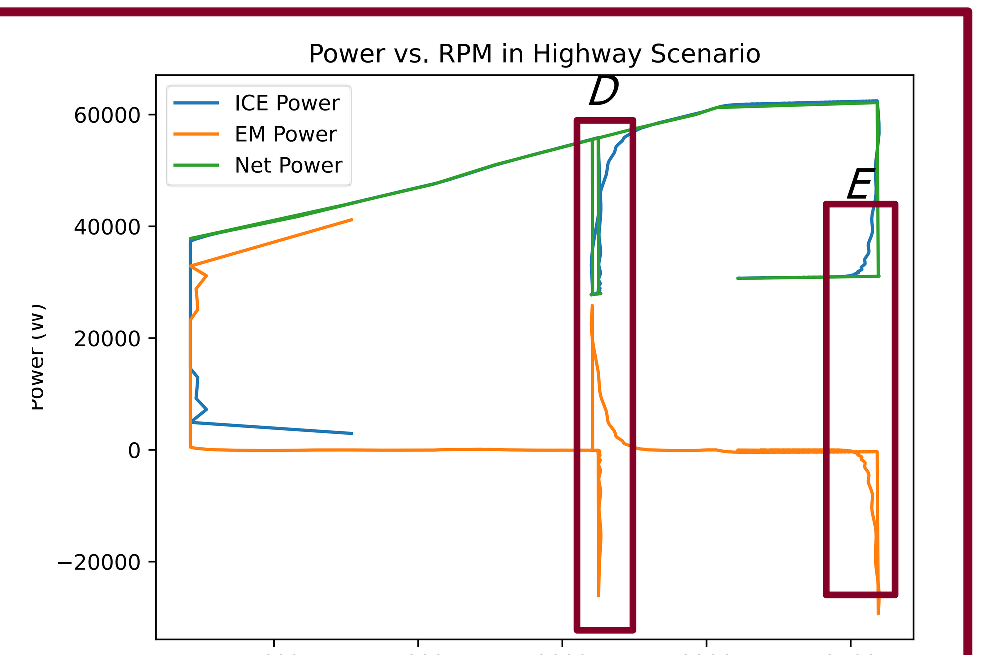

Fig. 10 – Showing power curve over engine speed in same scenario, annotated with meaningful regions

Conclusions

It is feasible to make an effective, linearizing hybrid power distribution system using blended power and parallel architecture

This conclusion is based on the plots shown in the results section. Ideal results would show the EM and ICE as perfect inverses in torque and power plots, summing to the steady state torque or power of the ICE. In all torque plots (Fig. 5, 7, 9), solid state torque and net torque overlap, indicating that the addition of the EM is effective in compensating for the transient torque lag of the ICE. This effect can be seen in all three scenarios, meaning that the system is effective across a wide range of conditions. One area of interest is the negative EM torque spikes seen in the city and highway scenarios where throttle input changes. This effect was not intended and would negatively effect drivability. It correspond to the car outputting its minimum power immediately when the throttle is released. The power plots (Fig. 6, 8, 10) demonstrate that the system effectively linearizes power-delivery. In the annotated regions A-E, this effect is particularly pronounced. When the ICE lacks immediate power, the EM compensates, keeping the net power roughly linear. This is a desirable driving characteristic. The negative spikes of EM behavior are also observed in the power plots.

Discussion & Future Work

When this project was proposed, the intent was to use an EM to linearize the power response from an efficient ICE with a non-linear, peaky solid-state power vs. RPM curve. In order to build a simulation, real data for an ICE was required. Data of the described characteristics was not able to be found, and thus the power vs. RPM curve from a 2012 Fiat 500 was used because there was additional data found in [] on the engine that was thought to be potentially useful. This engine's solid-state power vs. RPM curve was already impressively linear. Thus, it was decided to pivot to compensating for the transient power response of most engines, using [6] as justification for doing so. This approach did result in the intended effect of a linear power vs. RPM curve.

Additionally, this project was intended to use the built-in automotive simulation capabilities of WeBots to make a more realistic simulation. This was not successful because WeBots lacks a way to use a more accurate, custom engine model. The results of this simulation project are still useful and accurate, but there is room for future work. This could include a more sophisticated car model that can navigate more realistic traffic scenarios and includes internal losses, rolling resistance, and suspension response.

References

[1] J. Tollefson, "Climate change is hitting the planet faster than scientists originally thought," Nature, Feb. 2022, doi: 10.1038/d41586-022-00585-7.
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[3] "How electric vehicles and other transportation innovations could slow global warming, according to IPCC | PBS NewsHour." https://www.pbs.org/newshour/science/how-electric-vehicles-and-other-transportation-innovations-could-slow-global-warming-according-to-ipcc (accessed Nov. 14, 2022).
[4] S. Peach, "Ask Sara: 'What's the best kind of car for the climate?,'" Yale Climate Connections, Aug. 12, 2019. http://yaleclimateconnections.org/2019/08/whats-the-best-kind-of-car-for-the-climate/ (accessed Nov. 14, 2022).
[5] http://www.fiat500usa.com/2012/03/us-fiat-500-abarth-engine-output-dyno.html
[6] P. C. Baruah, "A Simulation Model for Transient Operation of Spark-Ignition Engines," SAE Transactions, vol. 99, pp. 1505–1516, 1990.