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The Pennsylvania State University's Advanced Vehicle Team: EcoCAR3 Year One Final Technical Report

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This paper details the powertrain modeling and control strategies the Penn State Advanced Vehicle Team (PSUAVT) developed for submission to the EcoCAR 3 competition, an advanced vehicle design competition in which university teams compete to hybridize a stock 2016 Chevrolet Camaro. The team utilized model-in-the-loop studies using both public-domain and custom-built vehicle simulation packages to undergo an iterative powertrain model development process. This analysis lead to the development of a pre-transmission plug-in parallel hybrid electric vehicle that uniquely meets PSUAVT's goals. The design process was guided by vehicle technical specifications (VTS) based on consumer market research as well as the team's emphasis on producing a technically-feasible but performance-weighted hybrid architecture.

Component models are presented that blend physics-based and map-based methods. A heuristic master vehicle controller (MVC) is described that splits the required driving torque between the motor and engine so engine brake-specific fuel consumption (BSFC) is minimized. Fault analysis of this controller is also presented based on design failure mode and effects analysis (DFMEA) performed in previous studies.

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1. INTRODUCTION

The EcoCAR 3 competition challenges sixteen collegiate student teams to redesign and build a hybrid Chevrolet Camaro following the four year EcoCAR Vehicle Development Process (VDP). The design goal is to reduce fuel energy consumption and environmental impact of the vehicle, while maintaining the expected sports car performance. The PSUAVT researched and designed four potential hybrid vehicle architectures for the Camaro, one of which was approved by Argonne National Laboratory (ANL) for implementing on the Camaro in the later competition years. This approved architecture is a pre-transmission parallel plug-in hybrid architecture, referred to as the P2 architecture in this paper for brevity. This paper summarizes the team's software model of this architecture, shown in Fig. 1.

This paper elaborates the process used to model the final vehicle architecture, the control strategies within the model, and the predicted vehicle performance results. The remainder of this paper is organized as follows: "Vehicle System Modeling" describes the process used to model the final vehicle architecture powertrain and entire vehicle; "Powertrain Control Strategies" discusses the control algorithms modeled to control the multiple tractive power subsystems within the vehicle; and "Vehicle Modeling Results" describes the performance, fuel economy, and emissions data obtained through the simulations.

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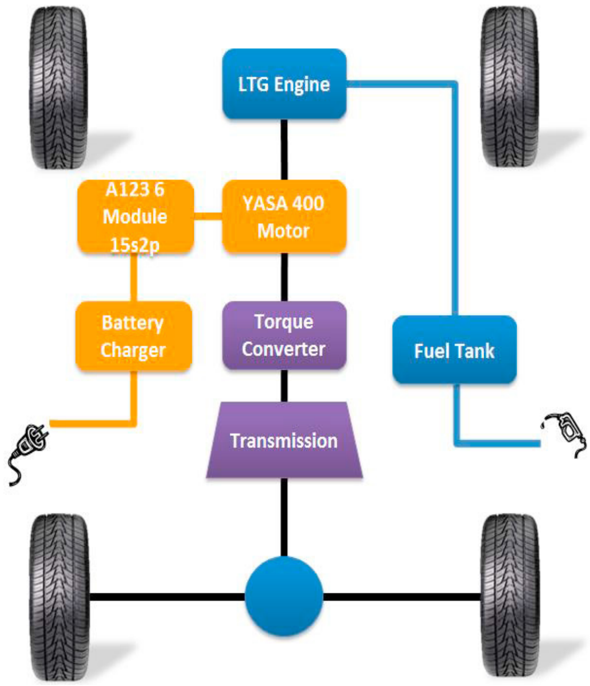

Fig. 1. Diagram of P2 Parallel Pre-Transmission Plug-in Hybrid Electric Vehicle

2. VEHICLE SYSTEM MODELING

2.1 Overview

The PSUAVT used team-built models constructed within Mathwork's MATLAB and Simulink software. At the highest level, the final vehicle model consists of models of the drive cycle, driver, MVC, and vehicle powertrain components. The driver receives current vehicle velocity and desired drive cycle velocity and outputs the required brake and accelerator pedal positions. These and the diagnostic signals from the powertrain components are received by the MVC, which outputs the command signals to the vehicle model and powertrain components. The vehicle powertrain component models then represent the dynamics and interactions of the components and vehicle body.

The powertrain components being modeled are the engine, motor, transmission, battery pack, and vehicle chassis road loads. Within each powertrain component model is a controller and a plant model. The controller interacts with the inputs and outputs of the component model whereas the plant model represents the dynamics of the component being modeled. This strategy aims to guarantee that the component model does not exhibit physically impossible behavior within the overall model. Additionally, this format allows the team to separate the component physics and controller, such that behavior and modifications of one does not affect the other. Furthermore, this format enables the aggregation of behaviors in a manner allowing the simulation or testing of actual ECUs used to control and manage the physical powertrain components.

2.2 Modeling the Driver

The driver was modeled as a proportional integral (PI) controller which receives desired and actual vehicle velocity from the drive cycle and vehicle models. The desired vehicle velocity was generated based on the drive cycle being simulated and current time within that drive cycle. Additionally, desired vehicle velocity was dependent on a look-ahead distance by the simulated driver. The look-ahead and error-driven approach has a long historical use in driver modeling (MacAdam, 1981). This look-ahead capability is meant to model a real world driver's ability to anticipate the immediate future desired velocity of the vehicle. The driver model determined the error between the actual velocity of the vehicle and the desired velocity of the vehicle. This error through the PI controller to determine a required effort command.

The model of the driver also included three separate states to represent the physical limitations of the driver. These states included the accelerator pedal depressed, no pedal depressed, and the brake pedal depressed. These states allow control logic to ensure that the driver did not depress the brake and accelerator pedals at the same time while the vehicle was in motion. Additionally, these separate states enable realistic modeling of the delay in the effort commanded by the driver as the driver physically changes between pedals.

2.3 Modeling the Engine

The engine was modeled as a soft electronic control unit and a physical plant model. The engine controller received a throttle command from the MVC and checked this throttle signal to ensure the signal did not exceed 100%. The controller also received and checked the speed of the engine to ensure that the engine did not exceed the peak engine speed of 628.3 rad/s, simulating a speed limit on the engine. It was assumed the engine and the impeller within the torque converter were rigidly connected and spun at the same speed. The controller then sent the throttle command and engine speed signals to the engine plant model.

The plant model simulated the output torque and fuel consumed by the engine. The available output torque of the engine was determined by the characteristic torque curve and current speed of the engine. This value was then multiplied by the desired throttle command from the controller to determine the output torque of the engine, which was then modeled as going through the flywheel.

The primary limitations in producing a high-fidelity engine model were the difficulty in modeling the throttle-torque curve and predicting fuel flow. The team was unable to obtain a publicly-available torque curve and fuel flow rate for the intended engine. In order to resolve this, the team used Autonomie to model a 4 cylinder engine with identical peak torque, power outputs, and fuel characteristics including carbon density, lower-heating value, and density. The team then used the closed-throttle torque curve and fuel flow rate map from the Autonomie engine model as an approximation to the performance expected from the 2.0L four cylinder General Motors LTG engine utilized in the team's architecture. This approximation introduces a potential source of uncertainty within the modeling results.

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