33nd Electric Vehicle Symposium (EVS33)
Portland, Oregon, June 14 - 17, 2020

Simulation Twin Motors 4WD Plug-in Hybrid Electric Vehicle

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Summary

The paper presents the simulation results of twin motors 4WD Plug-in Hybrid Electric Vehicle (PHEV). Each of the twin traction motors can provide power of up to 50 kW; one drives the front wheels while the other drives the rear wheels. A 4-cylinders gasoline engine and a 60 kW generator coupled to the front axle through a hydraulic separation clutch. This configuration offers optimum PHEV performance in three different driving modes (EV, Series & Parallel). The simulation results of two different drive cycles cover the vehicle performance, energy consumption, efficiencies and performances of the powertrain components.

Keywords: Passenger Car, Simulation, Modelling, PHEV (plug in hybrid electric vehicle), Control System.

1 Introduction

The rising gas prices in the United States and the concern about air quality and pollution caused by the conventional Internal Combustion Engine (ICE) vehicles, has fuelled the interest in the development of the Hybrids Electric Vehicles (HEV's) [1-2]. HEV's combine at least two energy sources; from ICE and Electric Motors (E-Motor's) to meet the driver power demand, mileages range and safety as a conventional ICE vehicle while reducing fuel consumption and harmful emissions. The ICE used in HEV's allows a wider driving range and provides additional torque when higher torque required during fast vehicle acceleration or steep hill climbing. Plug-In Hybrid Vehicles (PHEV's), mostly operate in all-electric drive mode which results in less harmful tailpipe pollutants from the onboard source of power.

The PHEV configuration considered in this paper offers optimum performance in three different driving modes (EV, Series & Parallel). In EV mode, one or both twin motors can run to provide the power required to the front wheels or all wheels depending on the driver power demand. In Series hybrid mode, when the battery capacity power-State Of Charge (SOC) level is low, the ICE drives a generator to provide the requested "electric" energy to the twin motors and/or charge the battery pack. At higher vehicle speeds when the power demand is higher than the power provided from the twin motors and/or the battery capacity power (SOC) is low, the separation clutch is locked, and the Parallel hybrid mode is entered. In Parallel mode "Assist" operation, when the driver power demand is higher than the power provided from the twin motors, the ICE runs at optimal torque to add the extra power required to the front axle. In Parallel mode "Boost" operation, when the driver needs high torque especially during fast acceleration, the ICE operates under full load (maximum available torque) providing power to the front axle. In Parallel mode "Charge_byEngine" operation, when the battery power capacity (SOC) is low, the ICE runs at variable speeds to power the front axle and drive the generator to charge the battery pack. In addition, when the vehicle speed drops while braking, the regenerative braking power provided from the mechanical friction brakes is recovered from the twin motors acting in regenerating mode to charge the high voltage battery pack. For this study, Vehicle Longitudinal Dynamics "Velodyn" simulation tool [3] was used, which interfaces with MATLAB/Simulink/Stateflow software to create a full plant model for PHEV simulation. Velodyn provided a model of a complete vehicle architecture platform including the control strategy designed inside the Supervisor Hybrid Controller Unit (HCU), powertrain components/controllers, and plant model templates. The simulation results cover the vehicle performance, energy consumption, efficiencies and the performances of powertrain components obtained during two Environmental Protection Agency (EPA) defined drive cycles; the Supplemental Federal Test Procedure SFTP-(US06) and Urban Dynamometer Drive Schedule UDDS-(FTP-72).

The paper starts with a brief highlight of the main powertrain components of the simulated PHEV model, and then illustrates the top-level structure of the hybrid control strategies design used for driving the PHEV. Followed by a brief description of the Vehicle Longitudinal Dynamics "Velodyn" tool then the simulation results and finally, we present our conclusions.

2 Plug-in Hybrid Electric Vehicle Components

Figure 1 shows the main powertrain components of the PHEV model considered in this paper, which have a mechanical connection to the front and rear axles from both twin motors. The ICE/generator (Belt Starter Generator-BSG) coupled directly to the front axle through a hydraulic separation clutch. This 4WD configuration of PHEV offers optimal vehicle performance operation in three different driving modes (EV, Series & Parallel).

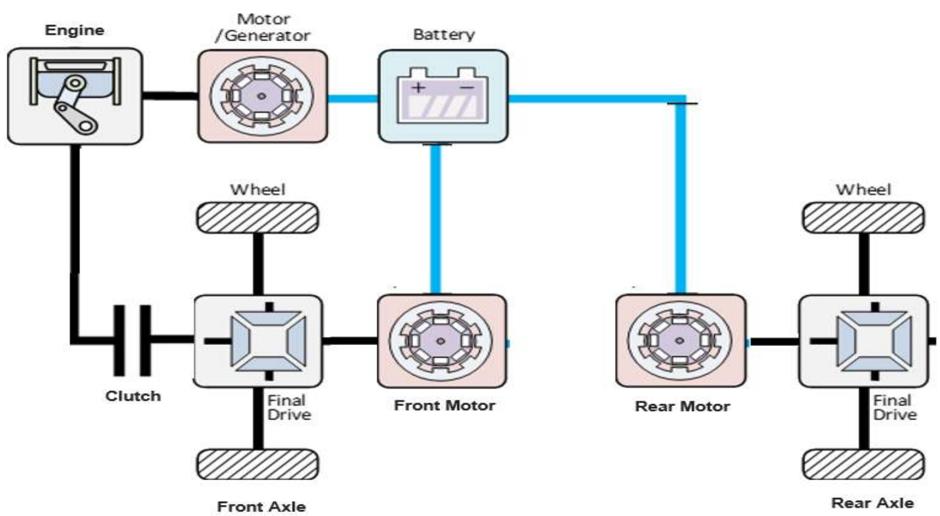

Figure1: Powertrain components of PHEV

2.1 Plug-in Hybrid Electric Controller

All control strategies points designed inside the supervisor Hybrid Controller Unit (HCU) are summarized in the "States" chart shown in Figure 2 [3]. This chart shows how to evaluate each state called "Hybrid States", the transition from one state to another and how the current driving state of the vehicle provide the correct torque distributions based on the driver torque demand. It switches between the 16 different operating "Hybrid States" depending on many conditions. When a selected hybrid state is activated, it provides the control signals to all vehicle powertrain subsystems including the generator, commanding ignition and requesting torques to the ICE and twin motors, in addition to the clutch status (Open/Closed). Furthermore, the HCU calculates the requested brake torque, which depends on the brake pedal position of the driver subsystem. When the selected "Hybrid State" is activated, it separates the requested brake torque of the recuperating motors torque and a requested torque of the mechanic brake with wheel vehicle brakes.

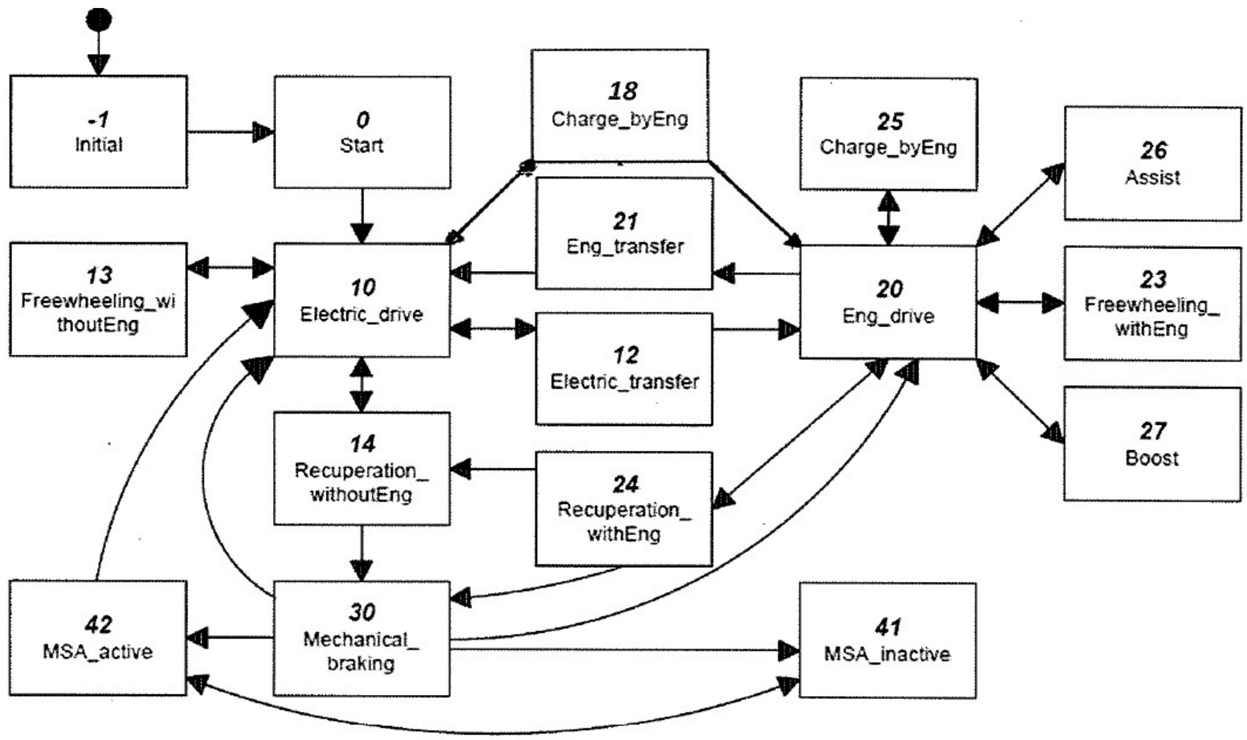

Figure2: PHEV control strategies "Hybrid States" chart

2.1.1 EV mode

The EV mode provides the driver torque demand to the twin motors for pure electric drive. In this mode, the state "Electric_drive", (State-10) is activated when the battery SOC capacity is higher than the lower limit and the twin motors are capable to provide the requested driver torque. The torque demand depends on the acceleration pedal, which is used as the requested torque to run one or twin motors to provide the torque to either front wheels or all wheels.

2.1.2 Series mode

When battery SOC capacity is close to the lower limit and the available power provided from the twin motors is enough to drive the vehicle, the Series mode is entered. In Series mode, the state "Charge_byEng", (State-18) is activated, commanding ignition and requesting torque to the ICE. The ICE drives a generator within its maximum efficiency at constant speed and constant torque load to provide the requested "electric" energy to run the twin motors and/or to charge the storage system when needed. In this mode, only the twin motors are connected to all wheels to drive the vehicle while both the ICE/generator decoupled from the vehicle speeds.

2.1.3 Parallel mode

At higher vehicle speeds, when the driver power demand is higher than the power provided from the twin motors and/or battery SOC capacity is low to power the twin motors, the Parallel Hybrid mode is entered and the transition state ’Electric_transfer”, (State-12) is activated. In Parallel mode, the separation clutch is locked and the state “Eng_drive”, (State-20) is activated in order to connect both the twin motors and the ICE to drive the vehicle. Several hybrid states may be activated in Parallel mode during a drive cycle.

The state “Assist”, (State-26) is activated, when the battery SOC capacity is high and the power from the twin motors is not enough to drive the vehicle. In this state, the ICE runs in optimal region of operation, greatly reducing fuel consumption and supplying power to the front axle. The requested torque to the twin motors is determined by the difference between the demanded torque and the optimal ICE torque. This state is used especially for better efficiency drive of the Parallel hybrid mode operation.

When the driver needs high torque especially during fast acceleration and the battery capacity is high, the state “Boost”, (State-27) is activated. In this state, the ICE operates under full load (maximum available torque) supplying power to the front axle. The requested torque to the twin motors is determined by the difference between the demanded torque and the available torque provided by ICE.

When the battery SOC capacity is low, the state “Charge_byEng”, (State-25) is activated. In this state, the ICE runs at variable speeds to power the front axle and drive the generator to charge the battery pack. The ICE request torque varies, and it is determined by the sum of the maximum twin motors requested torque and the requested torque from the driver command.

2.1.4 Recuperation Brake Energy

The states for “Recuperation Brake Energy”, (States-14 and 24) are used to simulate a recuperation of the brake energy. When the vehicle speed drops while braking, the regenerative braking power provided from the mechanical friction brakes is recovered from the twin motors functioning in regenerating mode to charge the battery pack. When braking occurs during EV mode, the state “Recuperation_withoutEng”, (State-14) is activated, the twin motors functioning as generators, charge the battery pack. When braking occurs during Parallel mode, the state “Recuperation_withEng”, (State-24) is activated, the separation clutch opens, the requested torque of the ICE is set to 0NM and the twin motors functioning as generators, charge the battery pack.

2.1.5 Freewheeling

The “Freewheeling_withEng/withoutEng”, (States-23 and 13) are used to simulate a freewheeling driving mode without any torque requesting from the mechanic vehicle wheel brake. When the state “Freewheeling_withEng”, (State-23) is activated, both ICE and twin motors connected to the axles. The ignition signal is turned on, the ICE torque requesting is set to 0 Nm and the requested torque to the twin motors is set to 0 Nm. When the state “Freewheeling_withoutEng”, (State-13), the ignition signal turned off, the ICE is not in use and the requested torque of the twin motors is set to 0 Nm.

2.1.6 Mechanical braking

The “Mechanical_braking”, (State-30) provides the brake torque for pure mechanic brake with vehicle wheel brakes. In this mode, the twin motors are not in use and the request torque set to 0 Nm. When activated, the ICE is connected to the front axles, with the requested torque set to 0 Nm. The requested brake torque from the driver command is used as the requested torque for the mechanic vehicle wheel brake.

2.1.7 Motor Start/Stop Automatic (MSA)

The “MSA_active/inactive”, (States-42 and 41) are used to simulate the automatic Start/Stop function and only used at vehicle standstill. In “MSA_active” (State-42), both the ICE and the twin motors are not in use. In this state, the ignition signal is set to 0 and the ICE shuts down in order to reduce the fuel consumption and disconnects from the front axle. In “MSA_inactive” (State-41), the ICE starting torque is requested from the generator to functioning as starter (E-Motor) in order to start the engine.

3 Vehicle Longitudinal Dynamics (Velodyn)

In this section, we briefly describe the Vehicle Longitudinal Dynamics “Velodyn” tool developed by IAV used for the simulation of conventional vehicle and any configurations for hybrid electric vehicle platforms with their powertrain components and analysing the vehicle performance. The Velodyn is a model-based design and does not require any building or compilation steps. It is flexible enough to operate on most computers in commercially available MATLAB/Simulink/Stateflow and graphical/object-oriented software environments. The advantages of using Velodyn simulation tool is to simplify the usage and the development of the complete vehicle powertrain models. Users can easily create and update the overall vehicle model by selecting the powertrain components types, sizes and parameters with different drive cycles. Figure 3, shows some of the library blocks available in Velodyn [3], and can cover all standard powertrain components with their controller units required for creating a complete vehicle plant model.

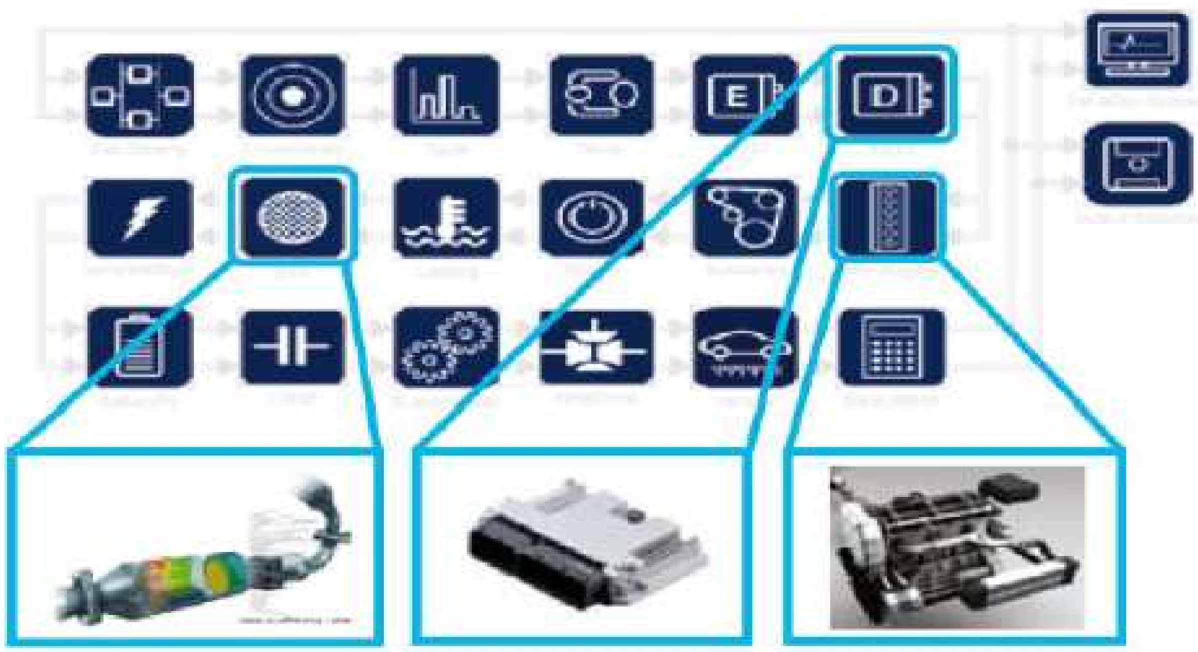

Figure3: Velodyn powertrain block library

4 PHEV Simulation

The simulation of a typical 4WD PHEV plant model considered in this paper using the Velodyn tool is shown in Figure 4. This PHEV model represents the complete subsystems of all powertrain components with their controller units, all accessories and cooling systems.

The sets of all vehicle dynamic specification and powertrain components parameters used to simulate this 4WD PHEV model are summarized in Table 1.

The supervisor Hybrid Controller Unit (HCU) controls all powertrain operation using the strategies illustrated in the “Hybrid States” chart shown in Figure 2. It acts as a master controller for all powertrain slave controllers such as ICE, generator, twin motors, battery and clutch open/closed status during drive cycle.

5 Simulation Results

The simulation of the PHEV with three modes of operation (EV, Series, and Parallel) and with most of the transition “Hybrid States” that can be captured by setting the battery starting capacity (SOC= 58%) with the allowed lower limit of (30%) during running the two EPA drive cycles; SFTP-(US06) and UDDS-(FTP-72).

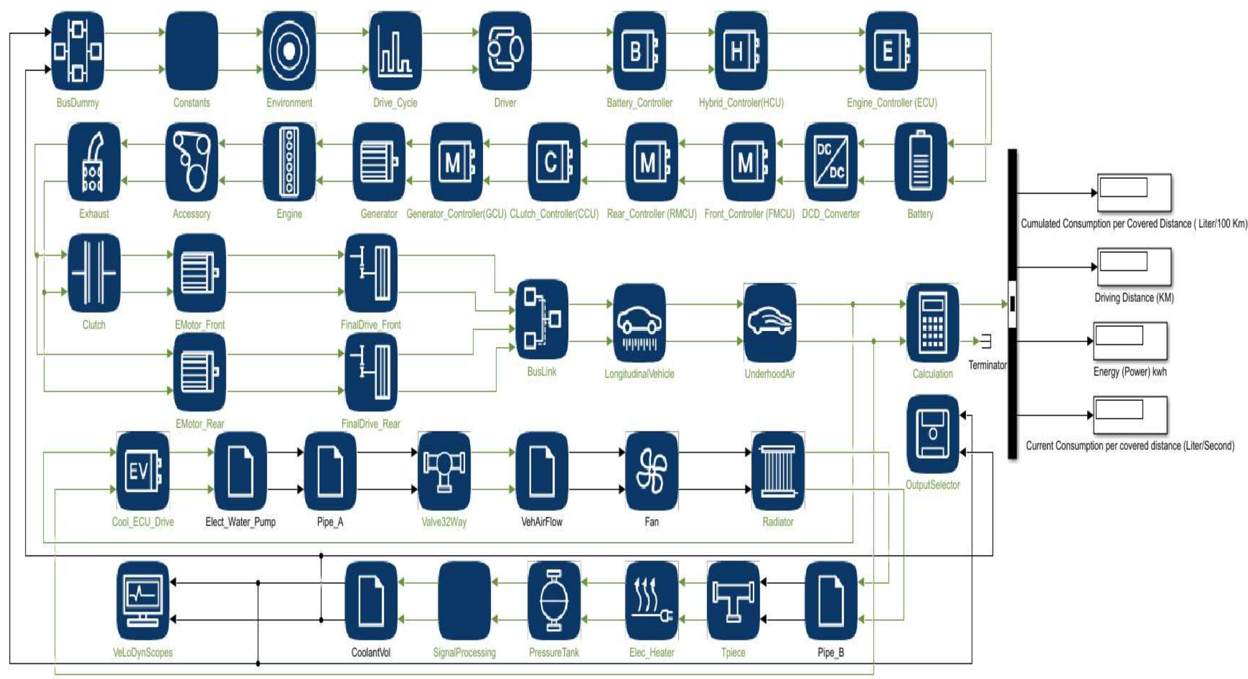

Figure4: Velodyn PHEV plant model

5.1 SFTP-(US06) Simulation Results

Figures 5-12, show the transition “Hybrid States” during the US06 drive cycle with the three modes of operation (EV, Series & Parallel), performances of the vehicle dynamics, all powertrain components and the regenerative braking torque.

It was noticed from Figure 5, the EV mode “Electric_drive”, (State-10) and Series Hybrid mode, state “Charge_byEng” (State-18) were the dominant modes of operation to achieve the drive torque demand during the US06 drive cycle. The transition from EV mode to Series Hybrid mode occurred, when the battery (SOC) level was close to (33%).

In Series Hybrid mode, the state “Charge_byEng”, (State-18) is activated and the ICE started to drive the generator within its optimal operation range, maximum efficiency at constant speed and constant torque load to provide “electrical” power to the twin motors and/or to charge the battery pack. However, during fast acceleration, when propulsion power demand is higher than the power provided from the twin motors and/or battery SOC was low to power the twin motors, the transition from Series Hybrid mode to Parallel Hybrid mode occurred and the state 'Electric_transfer", (State-12) is activated

In Parallel mode, the separation clutch locked and the "Eng_drive", (State-20) was activated; the twin motors and the ICE connected to both axles. In Parallel mode, when battery capacity (SOC) was higher than the limit and the power from the twin motors is not enough to drive the vehicle. The state "Assist", (State-26) was activated and the ICE ran and supplying power to the front axle. In Parallel mode, with low battery capacity (SOC), the state "Charge_byEng", (State-25) was activated; the ICE supplying power to the front axle as well as charged the battery pack. In Parallel mode, with a high torque demand especially during fast acceleration, the state "Boost", (Stat-27) was activated and the ICE operated under full load and supplying power to the front axle.

It was also noticed from these figures, how the "Recuperation Brake Energy" states used to recuperate the brake energy when the vehicle speed dropped while braking. The regenerative braking power provided from the mechanical friction brakes recovered from the twin motors functioning in regenerating mode, charged the battery pack.

Table1: Vehicle specification parameters.

Vehicle Dynamic Specification	
Vehicle Platform	Passenger Car
Vehicle Mass (kg)	1234
Dynamic Wheel Radius(m)	0.25
Aero Drag Coefficient	0.32
Air Mass Density (kg/m^3)	1.202
Vehicle Drag Coefficients(Nh^2/km^2)	0.33/0.0033
Wheel Drag Coefficient constant	0.014
Front Area (m^2)	1.83
Distance from COG to Front Axle(m)	1.6851
Height COG over Ground (m)	0.5
Engine Specification	
Gasoline Engine	4 Cylinders
Max Speed (rpm)	5500
Max Torque (Nm)	260
Inertia (kg*m^2)	0.12

Rear / Front Traction E-Motor Specification	
Motor Power (kW)	50
Max. Speed (rpm)	5500
Continuous Torque (Nm)	225
Peak Torque (Nm)	450
Mass (kg)	50
HV-Battery Specification	
HV-Type	NiMH
# Series/Parallel Cells	240/1
Capacity Each Cell (Ah)	5.5
Max. Capacity Power (kW)	60
(Min/Max) Cell (Volt)	0.8/1.68
Mass Each Cell (Kg)	0.2
Front / Rear Axles (AWD) Specification	
Final Drive Ratio(Front/Rear)	3.683
Inertia of Output Shaft (kg*m^2)	0.01

5.2 UDDS-(FTP-72) Simulation Results

Figures 13-20, show the transition "Hybrid States" during the UDDS drive cycle with the three modes of operation (EV, Series & Parallel), performances of the vehicle dynamics, powertrain components and the regenerative braking torque.

6 Conclusions

This paper presented the simulation results of a model for typical passenger 4WD Plug-in Hybrid Electric Vehicle (PHEV). The control strategies designed inside the supervisor Hybrid Controller Unit (HCU) manage the distributing of the driver torque demand to the powertrain drive components (ICE/generator and twin motors). The three different modes operation (EV, Series and Parallel) offer optimum vehicle performance during SFTP-(US06) and UDDC-(FTP-72) drive cycles. In addition, when the vehicle speed drops while braking; the regenerative braking power provided from the mechanical friction brakes recovered from the twin motors' functioning in regenerating mode is used to charge the battery pack.

References

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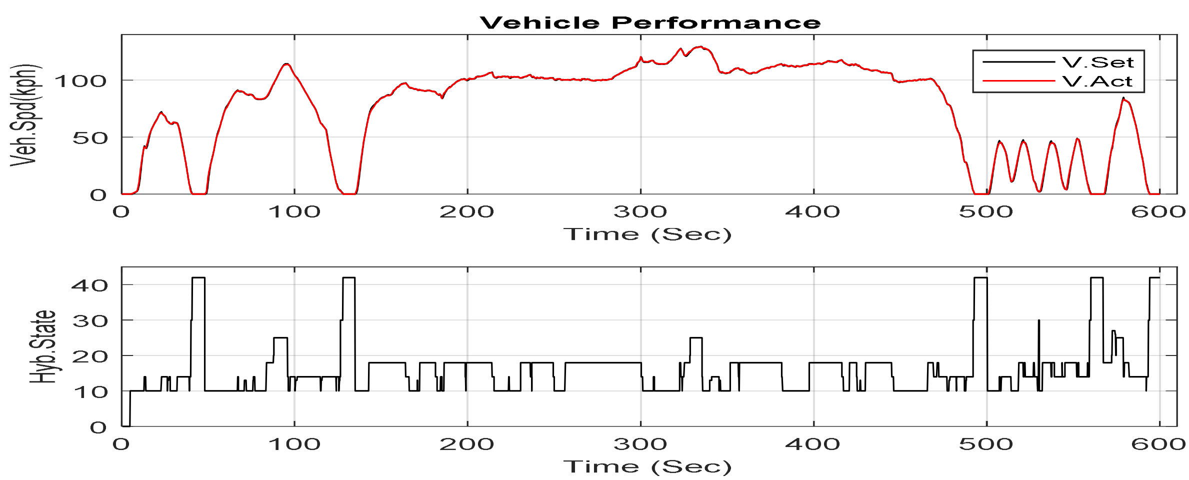

Figure5: Hybrid control states

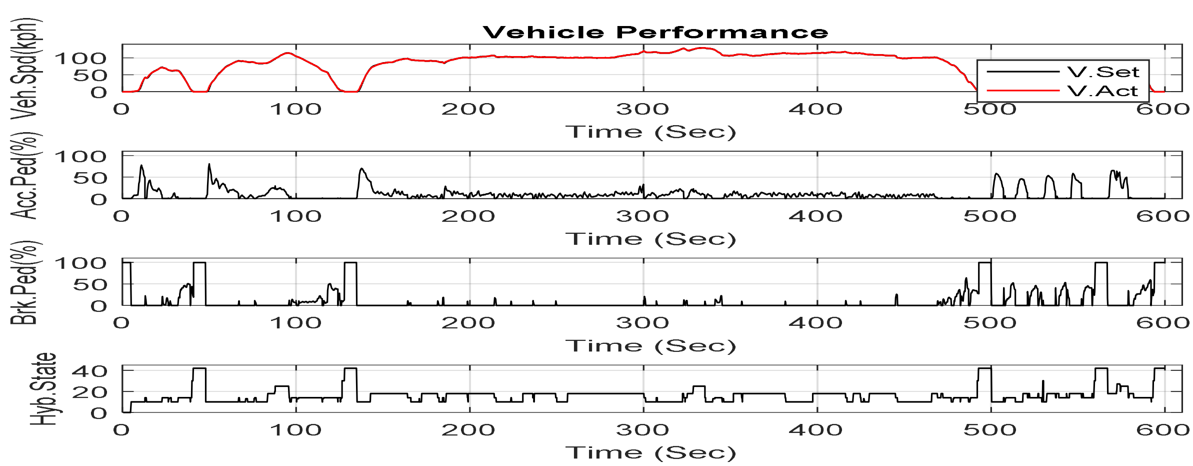

Figure6: Vehicle performance.

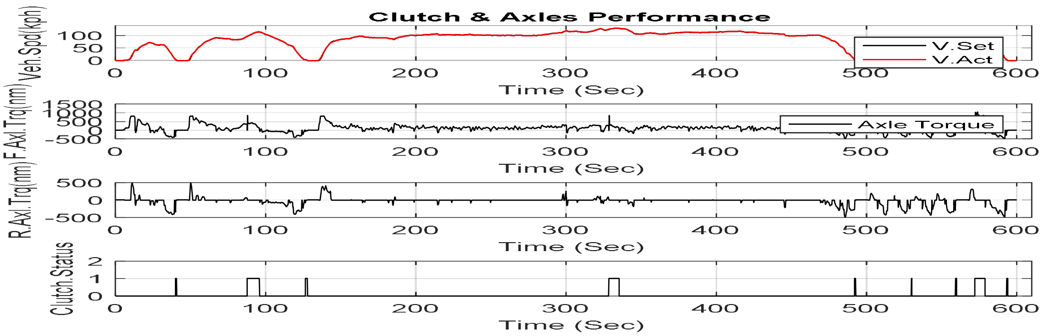

Figure7: Clutch & axles performances

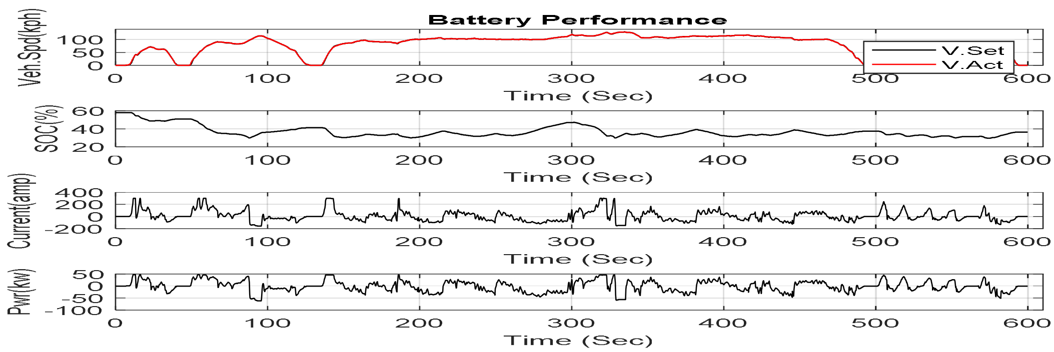

Figure8: Battery pack performance

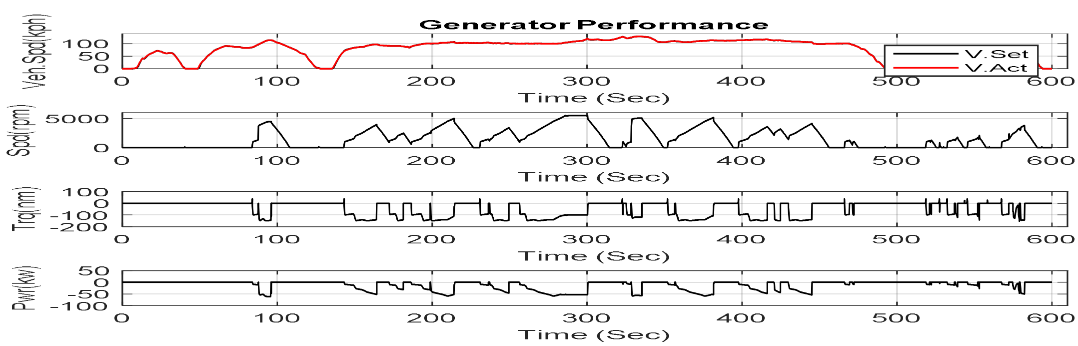

Figure9: Generator performance

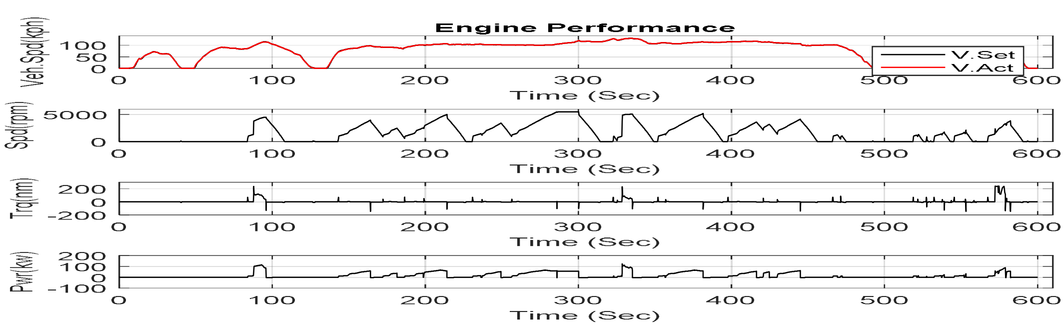

Figure10: Engine performance

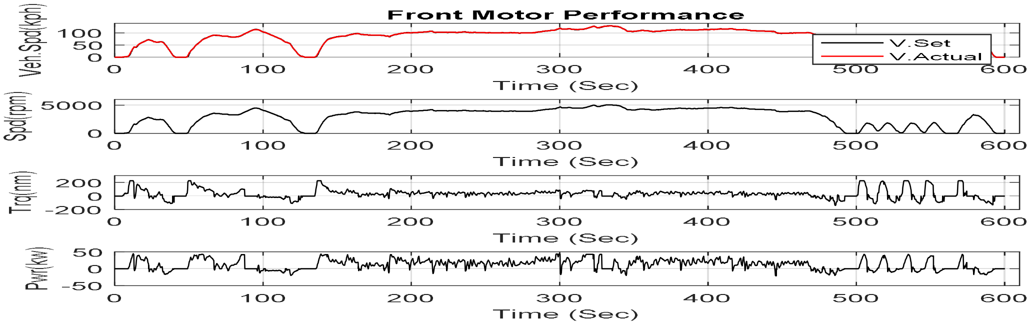

Figure11: Front E-Motor performance

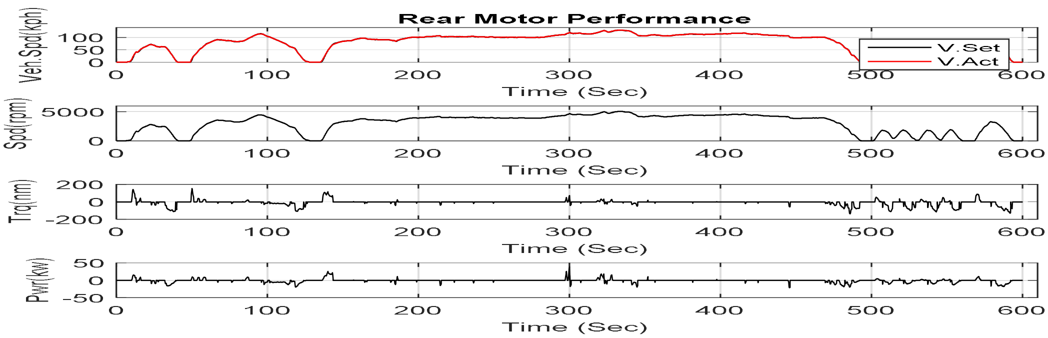

Figure12: Rear E-Motor performance

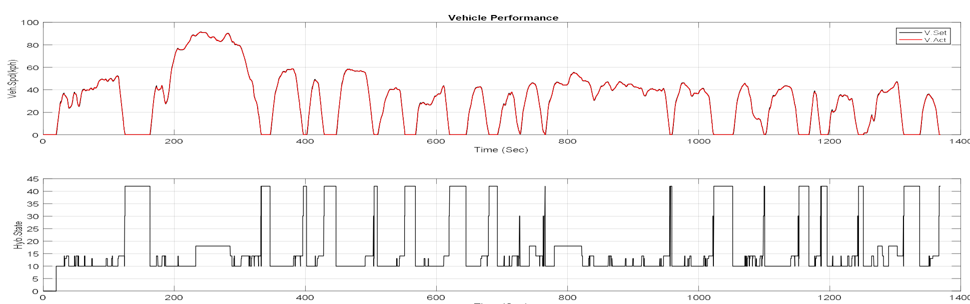

Figure 13: Hybrid control states

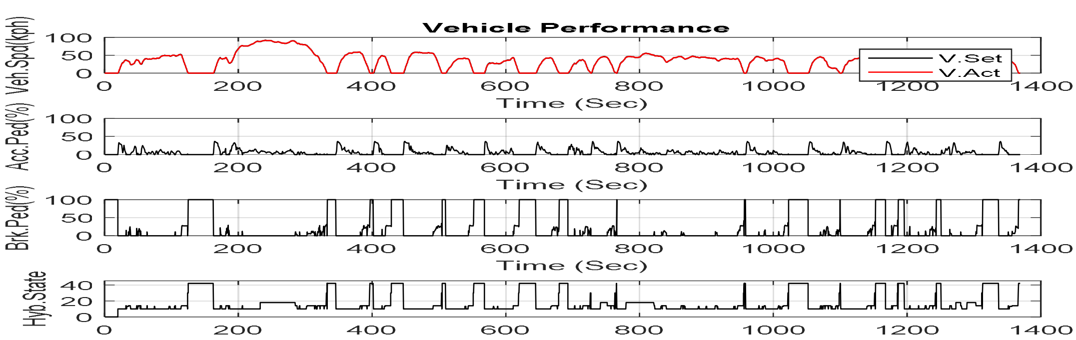

Figure14: Vehicle performance

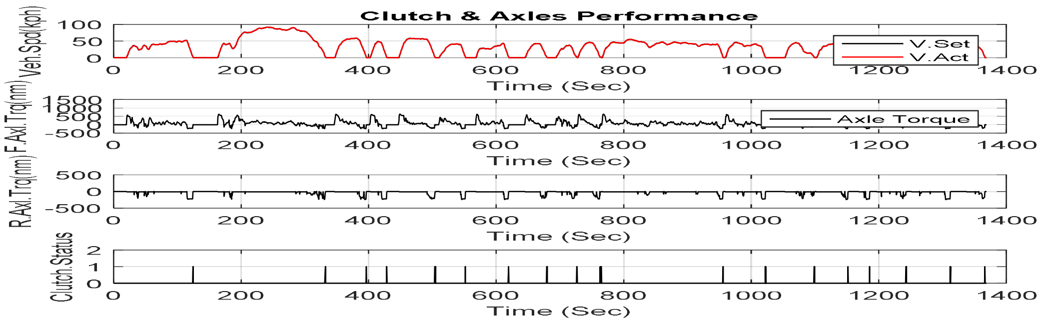

Figure 15: Clutch & axles performances

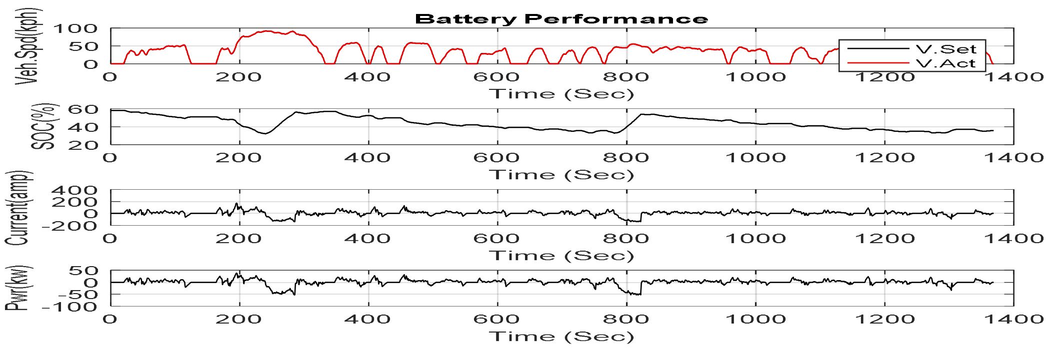

Figure 16: Battery pack performance

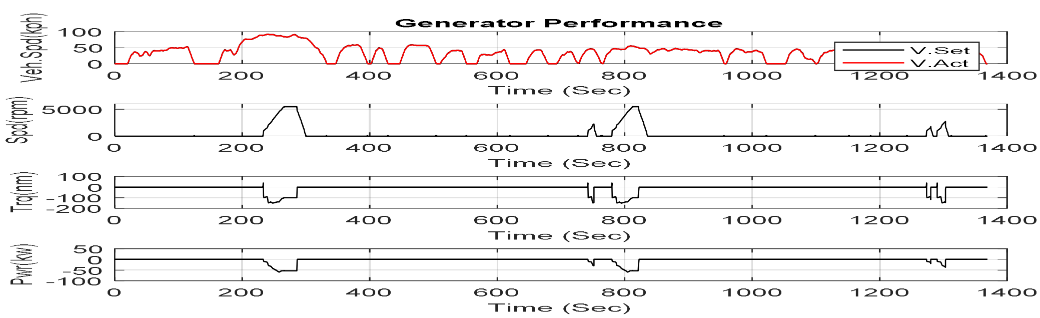

Figure17: Generator performance

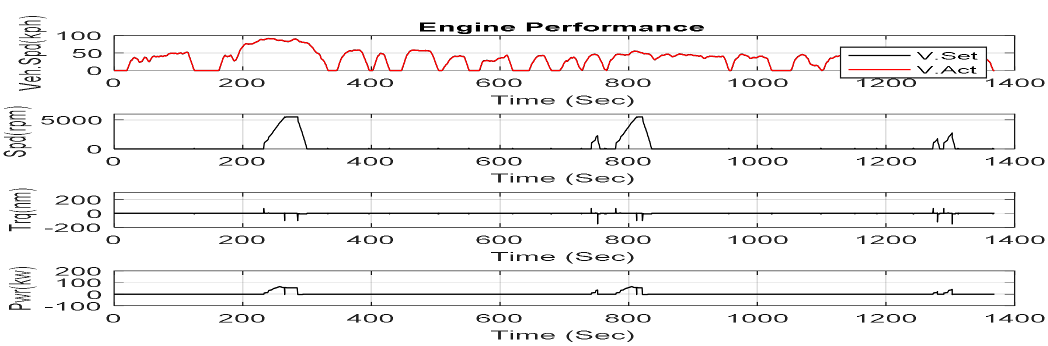

Figure18: Engine performance

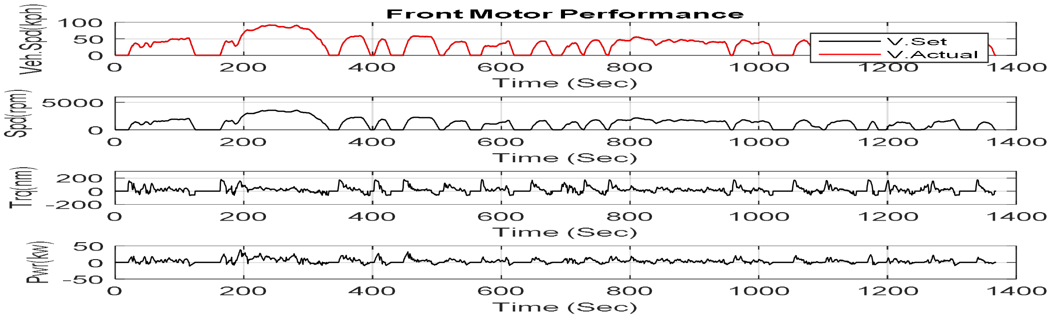

Figure19: Front E-Motor performance

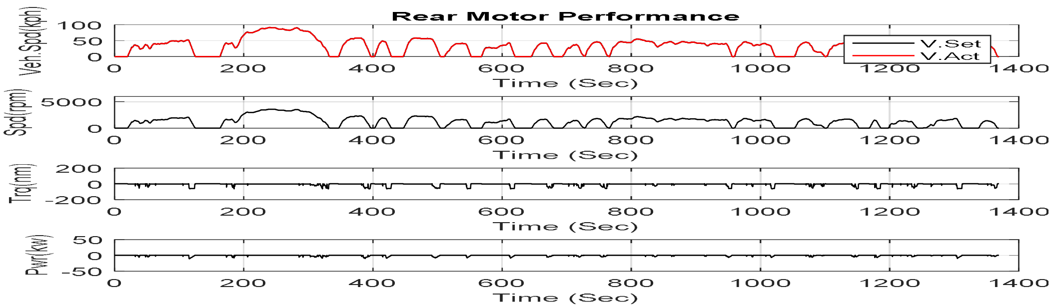

Figure20: Rear E-Motor performance

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