

Control Analysis under Different Driving Conditions for Peugeot 3008 Hybrid 4

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ABSTRACT

This paper includes analysis results for the control strategy of the Peugeot 3008 Hybrid4, a diesel-electric hybrid vehicle, under different thermal conditions. The analysis was based on testing results obtained under the different thermal conditions in the Advanced Powertrain Research Facility (APRF) at Argonne National Laboratory (ANL). The objectives were to determine the principal concepts of the control strategy for the vehicle at a supervisory level, and to understand the overall system behavior based on the concepts. Control principles for complex systems are generally designed to maximize the performance, and it is a serious challenge to determine these principles without detailed information about the systems. By analyzing the test results obtained in various driving conditions with the Peugeot 3008 Hybrid4, we tried to figure out the supervisory control strategy. The engine of the vehicle is mostly turned on or off on the basis of the SOC, demand power, and vehicle speed according to the driver mode. If the engine is turned on, the front axle driven by the engine generally provides all propulsion power. Further, when the engine is on, the generator torque is controlled to satisfy the desired battery power, while the power is determined by SOC according to the driver mode. The control targets for the vehicle components are basically determined by these concepts. Several additional analysis results are provided such as creep torque control, engine on/off under different thermal conditions, and the energy consumption of the electrical accessories. The information provided in this paper should be helpful in understanding the system behavior of the Peugeot 3008 Hybrid4.

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INTRODUCTION

Transportation Technology Research and Design Center (TTRDC) at Argonne National Laboratory (ANL) has been doing testing, modeling, validation for advanced vehicles such as Hybrid Electric Vehicles (HEVs) and Battery Electric Vehicles (BEVs), which has been driven by Department Of Energy (DOE). [1][2][3] Therefore, providing informative analysis results to help other researcher in automotive industry is one of duties of the research center. In this study, Peugeot 3008 Hybrid4, a hybrid vehicle that has multiple modes are tested, and the control concepts are analyzed. The tests did not aim to analyze the control concepts in detail but instead to understand overall behaviors and energy consumptions. Therefore, we did not fully install all available measuring instruments or obtain all possible signals from the vehicle tests, so this study is limited to a preliminary analysis.[1] However, the analysis was conducted under a standard process developed for analyzing the full control strategy, and the study includes all necessary processes to understand the supervisory control strategy, although the analysis used alternative signals and approaches. This will be helpful for following researchers to analyze or understand control concepts for other advanced vehicles.

TEST DESCRIPTION

Vehicle Description

The Peugeot 3008 Hybrid4 is a crossover hybrid vehicle, which has dual-axle architecture. The front axle is similar to the conventional vehicle powertrain that has an engine, but a generator recuperates energy from the engine and charges the battery, as shown in [Figure 1](#). [1]

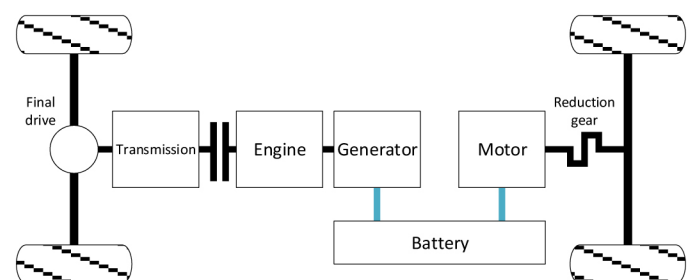


Figure 1. Schematic of the powertrain configuration of 3008 Hybrid4

The Peugeot 3008 Hybrid4 offers four operating modes:

In the “Auto” mode, the electronics automatically control the entire system, including transitions between the diesel engine and the electric motor. This arrangement allows optimal driving with a mix of low fuel consumption and dynamics drivability. The electric motor is mainly used for boosting or for gearshift compensation.

- The “ZEV” mode (zero emission vehicle) provides access to an all-electric mode. Engine start is avoided unless the driver requires high power.
- The All-Wheel Drive mode (e-AWD) instructs both power trains to operate together as far as possible; the rear wheels are then driven by the electric motor and the front wheels by the diesel engine. This arrangement enables the vehicle to take off on low adherence ground and with high slope (Peugeot claims 25% incline).
- The “Sport” mode tries to have quicker gear changes at higher engine speeds than the normal mode and a high level of dynamics.

The stop-and-start function can also be disabled by the driver using a special button on the dashboard. Other functionalities are available, such as creeping using the rear electric motor.

Test Conditions

Vehicle chassis dynamometer testing for this study was done at ANL's APRF using a four-wheel drive chassis (4WD) dynamometer and associated thermal test chamber. For well over a decade, APRF has been testing a wider range of advanced technology vehicles for the U.S. Department of Energy (DOE) and related research partners. Although not unique to this facility, the 4WD capability (i.e., separately controlled front and rear axles) is particularly helpful for evaluating a wider range of vehicles than can be tested using a single-axle dynamometer. [5], [6] The 4WD nature of the 3008 Hybrid4 requires both separately controlled front and rear axles. The dynamometer used in the APRF has two separate 48-in. roll sets as specified in the Code of Federal Regulations (40 CFR 86.108-79). Figure 2 shows the 3008 Hybrid4 vehicle mounted in the APRF.



Figure 2. 3008 Hybrid4 Being Tested in Advanced Powertrain Research Facility (APRF)

Argonne's chassis dynamometer facility was designed to perform research-oriented testing. As a result, a custom data acquisition and control system was built around the needs for hybrid vehicle testing. The custom design also allows integration with new measurement systems as the various vehicles are tested in the APRF. Data are sent from analog or frequency signals in the test facility and are digitized by a “real-time” PXI computer. This computer controls the facility emissions equipment and sampling system. Data are received from the emissions equipment through several serial data connections.

Pre-Calculation for Control Analysis

In most case, not enough signals are obtained from the test data to analyze the control strategy because we cannot capture all physical signals of the vehicle. However, by calculating missing signals and screening signals, we can improve upon the raw information obtained from the test. Our typical processes to treat the signals prior to the analysis are introduced in this section.

Signal Alignment

The test signals come from several measuring systems. For example, wheel output torque and speed are captured by the dynamometer, whereas input torque is measured by torque sensors installed between the final drive and the wheel. Furthermore, a number of signals come between controllers from the Controller Area Network (CAN) bus. Although the reference times of the signals are synchronized in the testing facility, sometimes, accurate signal alignments are needed for control analysis.

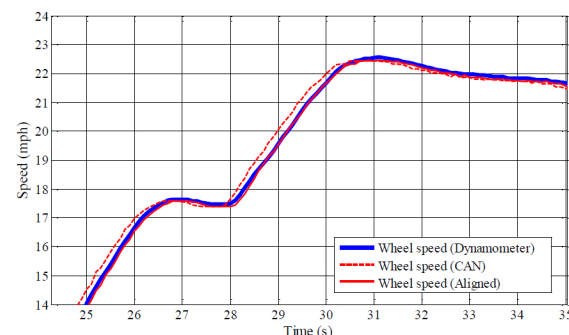


Figure 3. Wheel speed determined by different methods correlated as function of time.

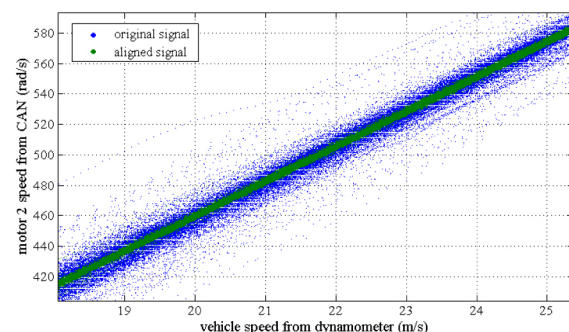


Figure 4. Aligned signal based on cross-correlation of original signals

For the alignment, we selected several reference signals that are assumed to have strong cross correlations. For example, the wheel speed obtained from the CAN bus was selected as a reference for all CAN signals, while the wheel speed obtained from the dynamometer was selected for all dynamometer signals (Figure 3). At the next step, an alignment time, or a shifting time t_{shift} , that maximizes the cross-correlation coefficient between the two selected signals, x_1 and x_2 , was calculated from the following equation:

$$t_{shift} = \arg \max_t \int_{-\infty}^{\infty} x_1(\tau) \cdot x_2(t + \tau) d\tau \quad (1)$$

By shifting all CAN signals with t_{shift} , we could synchronize the time of the two signal groups and enhance the quality of the signals when we analyze the control strategy (Figure 4). For example, when we obtain motor 2 speed from the CAN bus and vehicle speed from the dynamometer, the original signal data in Figure 4 show some discrepancy in the two signals. The aligned signal data show the two signals matching well, indicating that the CAN signals are well aligned, so we can make reliable correlations of CAN signals with the other signals from dynamometers or installed sensors.

Calculating Missing Signals

Not only is it nearly impossible to obtain all available CAN signals because the information is proprietary to the original equipment manufacturer (OEM), but it is also difficult to install a large number of sensors in the vehicle to measure all relevant physical values such as torque, speed, and temperature. Therefore, common practice is to measure important signals and calculate the other signals based on the obtained signals. In this analysis, we prefer to use signals obtained from the testing facility as opposed to manipulated signals calculated based on assumptions like transfer efficiency. Therefore, if the real signal is obtained from another test, the results can be updated based on the new signal. The same approach is used to validate the signals. For example, the power flow can be calculated from power sources or from the dynamometer. The two calculations should show reasonable energy balance of the system. If not, we assess which signals are more reliable than other signals by comparing alternative signals, and only use the feasible signals for control analysis.

Signal Screening

Signal screening or windowing is widely used in our analysis, though is not commented upon in most of the following sections. The screening process is crucial because system behaviors by the control target and by the transient control are mixed in the signals obtained from the testing facility.

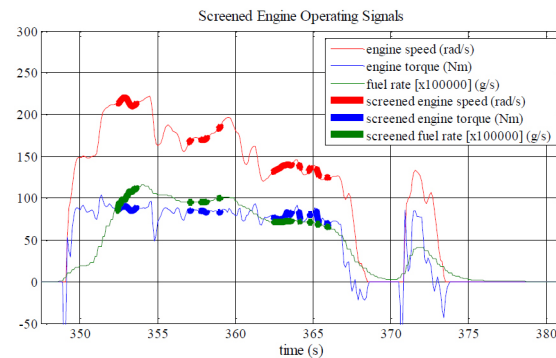


Figure 5. Signal screening for engine speed, engine torque, and fuel rate.

Figure 5 shows an example of signal screening, which can be used to determine engine control targets. The engine torque and speed might not be the desired torque and speed from a supervisory controller because the controller should add a transient control torque to obtain the desired speed. Furthermore, the correlation between the engine operating points and the fuel rate is also affected by the transient behavior, so we need to screen, or selectively use, the obtained signals to determine the exact control behavior and characterize the performance of the components. In this analysis, we use a number of screening functions that extract signals under specific conditions such as temperature, speed, or demand.

SUPERVISORY CONTROL ANALYSIS

A supervisory controller generates high-level control signals that determine overall system behavior of the vehicle being tested. [7] The role of the supervisory controller is occasionally limited to the mode decision and power distribution, but all available analyses used to understand the major control behavior, including the gear shifting event, will be introduced in this section. Based on the analysis, we will be able to understand the overall control behavior of the vehicle. Prior to addressing the main analysis results, we need to carefully define the meaning of the different concepts for the driver and operating modes. The vehicle typically has four driver modes, such as Auto, ZEV, 4WD, and Sport, which are manually selected by the driver. Somewhat differently, hybrid electric vehicles (HEVs) generally have different operating modes according to the operation of the power sources. To avoid terminological confusion, Table 1 lists the definitions used in this study for the different modes.

The driving status can be characterized by one of the driver modes and one of the operating modes. For example, we will introduce analyzed results that are obtained under the EV mode when the vehicle is tested under Auto mode. Therefore, the operating mode should be distinguished from the driver mode.

Table 1. Terminology for vehicle driver and operating modes with brief description

Mode	Available mode	Description
Driver mode (Manually selected driver)	Auto	Automatically controls the entire system
	ZEV	Provides access to all-electric driving
	e-AWD (4WD)	Makes both powertrains operate together as far as possible
	Sport	Favors quicker gear changes for better accelerating performance
Operating mode (Determined by operating condition)	Engine Driving	Provides propulsion power only by engine
	HEV	Uses both power sources to drive the vehicle
	EV	Only operates motor 2 (rear wheel) to drive the vehicle
	Regenerative Braking	Recuperates the braking energy from motor 2

Operating Mode Control (Engine On/Off)

At the supervisory control level, the engine on/off actually determines the operating mode because we can generally conclude that the vehicle has entered the HEV mode from the EV mode if the engine is turned on, or vice versa. On the other hand, although the engine is turned off at a certain positive power demand, it is not easy to determine the exact points of the engine-off condition because, for example, the engine is turned off when a driver suddenly takes the foot off the acceleration pedal whereas the engine is turned on when a driver continuously pushes the pedal. The data in Figure 6 indicate that the engine is turned off mostly when the wheel torque drops below zero, which means that this vehicle also has a simple off-control: the engine is turned off if there is no acceleration pedal signal, which had been generally experienced in analyses for other HEVs. Therefore, our analysis focused on the engine-on rather than the engine-off points.

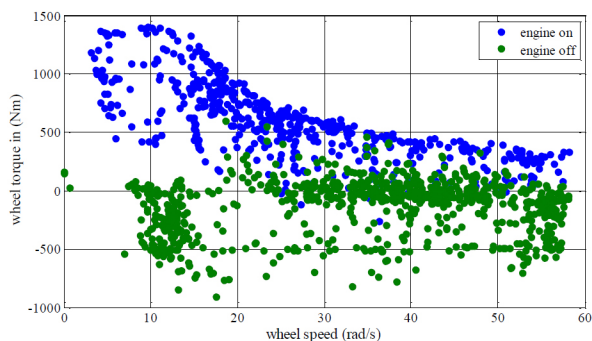


Figure 6. Engine on/off points of 3008 Hybrid4 according to wheel speed and torque under Auto mode.

Figure 7 shows all operating points according to the engine state for all driver modes-the engine-on points, however, are only for the Auto and ZEV modes. The y-axis reflects the summation of both front wheel torque and rear wheel torque from the dynamometer, which is assumed to be, at least close to, a demand torque. The red points show the vehicle speed and wheel torque when the engine is on, and the blue points

show the status when the engine is off. Engine-on points, white circles in the figure, indicate values obtained when the engine is turned on. From the figure, we conclude that: i) Above a certain power, the engine should be turned on. This condition could be because of the maximum power of the electric system, or it could be a control threshold. ii) At low vehicle speed, the engine should be turned on if high torque is demanded. This condition is desired because the motor is not able to continuously provide high torque. iii) The engine is not allowed to be turned off over 18 m/s - the data actually show that the engine is not turned on over 18 m/s, but they sufficiently proved that the engine is turned on before 18 m/s because the motor does not have enough power to solely provide the required power over the speed. The gray points in the figure indicate that the engine is not turned off over 18 m/s, although the engine does not provide propulsion power. Instead, the engine keeps operating on a specific speed, so that the engine is able to provide power as soon as it is desired.

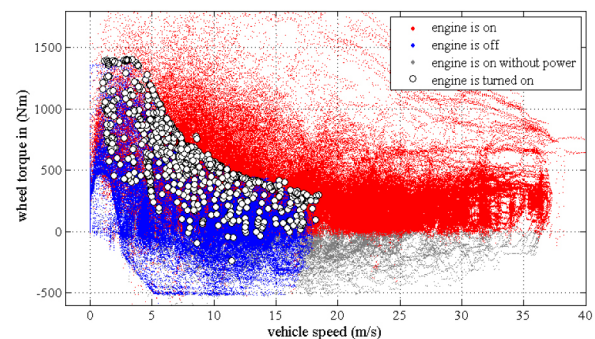


Figure 7. Engine-on and -off points according to vehicle speed and wheel torque. The engine-on points in this figure are the same as those in Figure 6. The gray points indicate when the engine has positive speed but generates retarding torque on high vehicle speed. (Engine-on points for e-AWD and Sport modes are not shown in this figure because they not meaningful. See the following section)

For detailed analysis, we need to examine the control strategy according to the driver modes because the tested vehicle clearly has different control strategies for the driver modes. The engine on/off control is thus analyzed for each driver mode.

Engine On/Off under e-AWD and Sport Mode

Because the engine on/off strategies for these two modes are simple, we discuss the controls for these modes first. The engine is not turned off if a driver selects the e-AWD mode, as shown in Figure 8. However, it is not that the engine provide the power all the time. The engine is on idle state with zero torque when the vehicle is stopped at zero speed. (See Figure 9) Under the Sport mode, the vehicle also has a simple engine on/off strategy.

The curves in Figure 10 show that the engine is turned on as soon as the driver takes the foot from the braking pedal, not