

Economy Mode for Electrified Vehicles

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ABSTRACT

Hybrid and Electric vehicles present special challenges when developing a customer-selectable Economy Mode, as the vehicles are already energy-efficient by design. This paper analyzes the sources of sub-optimal fuel economy in: energy generation, vehicle usage, and customer usage. The paper first reviews the effects on customer acceptance from other implementations of Economy Mode, using “Things Gone Wrong” data from customer surveys on competitive vehicles. This information was used as lessons learned for the new design. The paper then discusses which changes to vehicle functionality could be implemented to improve fuel economy while maintaining acceptable vehicle performance, along with acceptable noise, vibration, and harshness objectives. The vehicle parameters studied in this paper include: 12 V loads, engine operating commands of torque and speed, EV operating limits, customer demand inputs, regenerative braking, cruise control operation, and climate control function. Measures of the fuel economy improvements were developed, as were tests to represent real-world driving conditions. The final package of potential fuel economy changes was tested on several Ford Hybrid vehicles with results demonstrating the net improvement to vehicle fuel economy. The Economy Mode functionality was deemed to be effective and it entered vehicle production during the 2016 model year on the Ford Fusion Hybrid, Ford C-MAX Hybrid, and Lincoln MKZ Hybrid vehicles under the name of EcoSelect.

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INTRODUCTION

The fuel economy rating of a vehicle is regulated by governmental agencies around the world using a variety of specific test methods. This is the fuel economy listed on the vehicle label. Some customers consider fuel economy as an important attribute in their selection of a vehicle, whether they wish to reduce their fuel expense, extend their time between vehicle refuel events, or for other reasons. Customer dissatisfaction may occur, however, if the customer experiences lower fuel economy during their real-world driving than what the label indicates. Conventional vehicles have employed an Economy Mode, or ECO Mode, that attempts to coach the driver to accelerate more slowly and requests quicker upshifts on manual transmissions. The question is what to do when the vehicle itself is designed to achieve optimal fuel economy, as Hybrid electric vehicles do? These vehicles employ both a conventional internal combustion engine (ICE) and one or two electric motors, combined with an energy storage system, such as a high voltage battery pack. This paper contains the solution that the Ford Motor Company Electrification team employed on the model year 2016 Fusion, C-MAX, and Lincoln MKZ Hybrid vehicles. The goal was to offer average customers a solution to improve fuel economy over what they achieved using the “normal” vehicle operating mode while still maintaining an acceptable driving experience. Maintaining an acceptable driving experience was considered crucial if the customer is to use the Economy mode function in their daily driving.

The paper begins the discussion with what has been employed on other vehicles, conventional and Hybrid. Benchmarking was conducted to attempt to determine what changes were made when ECO Mode was engaged, and the tradeoffs to the customer driving experience. Part of this benchmarking process included an analysis of Things Gone Wrong (TGW) data to attempt to identify lessons the team could learn to avoid customer dissatisfaction. The paper then covers many aspects of Hybrid vehicle operation, looking at which tradeoffs may be made in order to further improve fuel economy over the current vehicle design. The paper then discusses various strategies and calibration changes that were studied over the course of this Economy Mode design, along with their tradeoffs for:

- Vehicle response
- Engine noise, vibration, and harshness (NVH),
- Emissions
- Climate comfort

Following this, tests were developed and refined to determine which changes improved fuel economy and to determine the limits of customer acceptability. Finally, the entire package of changes was tested on a custom-designed on-road test, using multiple drivers and trips to assess the net impact of these fuel economy changes.

POWER SPLIT HYBRID VEHICLE INTRODUCTION AND BACKGROUND

The Economy Mode described in this paper was developed on the Ford Fusion and Ford C-MAX Hybrid Electric vehicles. These vehicles contain Ford's 3rd generation of the electrification technologies that Ford has named the Power Split. The main driving components of the Power Split electrification architecture are described as follows.

The main powertrain components of the Power Split system are shown in [Figure 1](#). The Power Split system contains an internal combustion engine and two electric machines (the Generator and the Motor), connected together by a single planetary gear set and other reduction gears. The system also contains a high voltage traction battery that stores and delivers energy to the two electric machines. The Motor can both propel the vehicle using electrical energy, and can decelerate or brake the vehicle, sending electrical energy back into the HV battery and other high voltage electrical components. The engine uses fuel (gasoline, in the case of the Fusion and C-MAX) to provide torque and power to the system. The Generator is used to start and stop the engine, generate electricity from the engine, help propel the vehicle, and dissipate energy by spinning the engine unfueled to simulate engine compression braking, which is useful on downhill grades. The engine, Generator, and Motor are connected to each other through a single planetary gear set. The Motor drives the wheels and also turns the ring gear. The engine is connected to the planetary carrier, and the Generator to the sun gear. The combination of the engine speed and the Generator speed matches the planet carrier speed at all times. This configuration allows the engine speed during operation to vary widely versus vehicle speed by changing the generator speed. The engine in the Fusion and C-MAX may remain off and not spinning up to a vehicle speed of 137 kph, and the engine can spin at a speed of at least 3,000 RPM while the vehicle is stationary. Because of this wide-range of possible engine speeds versus the vehicle speed, the transmission is also known as an electrically continuously variable transmission, or e-CVT. The ability to select an engine speed independent of the vehicle speed opens up many opportunities for efficient engine operation. This combined with the use of a late-intake valve closing and high numerical compression ratio engine design, commonly known as the Atkinson design, also improves the potential for excellent fuel economy.

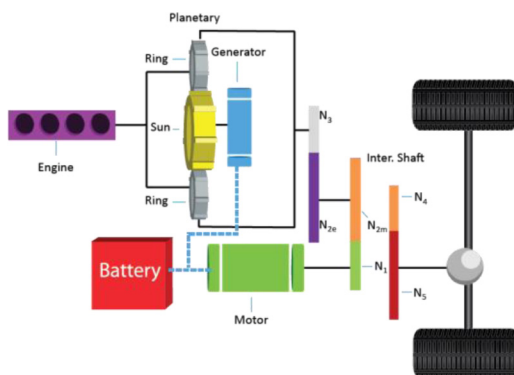


Figure 1. Power Split Vehicle Architecture

[Figure 2](#) shows an X-ray view of the essential Hybrid components. Along with the Inverter System Controller and high voltage battery pack, the Power Split Hybrid has an electric DC/DC converter and an electric Air Conditioning (A/C) compressor. The DC/DC converter replaces a conventional vehicle alternator, converting the HV battery voltage (at 200V to 300 V) to 12 V to 14.5 V, permitting all of the vehicle electrical systems to function as they would in a conventional vehicle. The vehicle A/C compressor is normally belt-driven from the engine Front End Accessory Drive, or FEAD. For maximum performance in the Hybrid, it is more efficient to run the A/C compressor with the engine off, so the A/C compressor is driven electrically from the HV bus. Since the A/C compressor is electric, the speed and power consumption of the compressor may be set independent of the engine and vehicle speed. This provides flexibility in the rate of cabin cooling not offered in a conventional vehicle. Another component of the Hybrid design is the regenerative braking system. Regenerative braking means that the vehicle is decelerated using the electric drive motor, which generates electricity that would otherwise be dissipated as heat in the vehicle brake pads and rotors. Regenerative braking can occur when the customer operates the brake pedal, but also whenever the vehicle is moving and the accelerator pedal is not applied. This is called lift pedal regenerative braking, and hybrids commonly use some of this to match the deceleration provided by the conventional vehicle due to engine drag while coasting.

In summary, the essential elements that improve fuel economy over a conventional vehicle are:

- Shutting off and stopping the engine when not needed for propulsion.
- Operating an electric drive system using stored electrical energy from a battery, when propulsion is needed at low power levels and where it is not efficient to operate the internal combustion engine.
- Operating the engine at an efficient operating point when it is running (measured as Brake Specific Fuel consumption in grams of fuel per kWhr of delivered energy, or BSFC in g/kwh).
- Operating an efficient internal combustion engine, possibly using the Atkinson cycle.
- Recapturing vehicle braking energy to store in the HV battery for use in future propulsion or for operating electrical systems such as the DC/DC converter and the A/C compressor.
- Using HV electrical devices that use stored HV battery energy instead of conventional FEAD belt-driven devices for the support of the vehicle 12 V loads (DC/DC Converter) and the cabin climate control (Electric A/C Compressor).

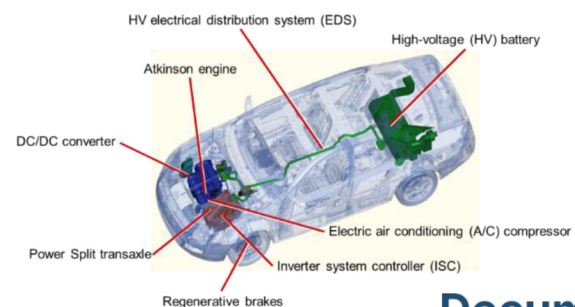


Figure 2. Location of Electrified Components

ANALYSIS OF ECO MODE

Electrified Vehicles: Tradeoffs in Efficiency versus Other Attributes

While all vehicles manufacturers optimize their products for best fuel economy their powertrain can deliver while maintaining all other drivability attributes, ECO Mode biases toward better fuel economy, negotiating against other attributes. The key word for ECO Mode is *efficiency*. Running the system at the best efficiency points of its components (e.g. engine, motors, HV Battery, etc.) would increase the overall system efficiency. Doing that could impose some adverse effects on some other attributes such:

- Engine Response
- Vehicle acceleration performance
- Vehicle NVH
- Climate control response and performance

Review of Competitive Economy Mode Offerings in the Industry and Lessons Learned

As part of the development of the ECO Mode for hybrids, the team looked at the ECO Modes implemented in competitive vehicles in the industry. The team especially wanted to understand what the customers were dissatisfied about, and design out the dissatisfaction concerns to the extent possible. An analysis was made using data on Things Gone Wrong (TGW) from the competitive vehicles. Three main complaints or issues surfaced from the data:

1. The Driver being required to select ECO Mode before each drive (ECO Mode settings were not retained at ignition off.)
2. The climate control function was degraded too far.
3. The accelerator pedal was too unresponsive.

To address the retention issue between drives, the team decided that the ECO Mode shall persist between key cycles. The primary reasoning is that the customer is willingly making a performance trade-off for better fuel economy, so the choice is honored until they change it.

With regard to the climate control dissatisfaction, the climate control team used competitive data to determine how to adjust the heating and cooling; the results are discussed later in this paper. In addition, the ECO Mode climate changes are overridden when the customer is using the maximum performance modes of Defrost and Max A/C.

Finally, to address the issue of an unresponsive pedal, the calibration team tested multiple versions of the accelerator pedal mapping to find an optimum solution.

DISCUSSION OF FUNCTIONAL CHANGES INVESTIGATED

Engine Operating Efficiency

A normal gasoline engine loses over 62% of the fuel's energy due to friction, air pumping losses in both the intake and exhaust, and heat generation into the exhaust and engine coolant. The engine efficiency

map is referred as BSFC map, (Brake Specific Fuel Consumption), and it is the rate of fuel consumption divided by crank power produced. So the smaller the BSFC number, the higher the engine efficiency. In Power Split hybrid, the e-CVT transmission behavior allows a wide range of possible engine speeds in order to operate the engine in an efficient BSFC.

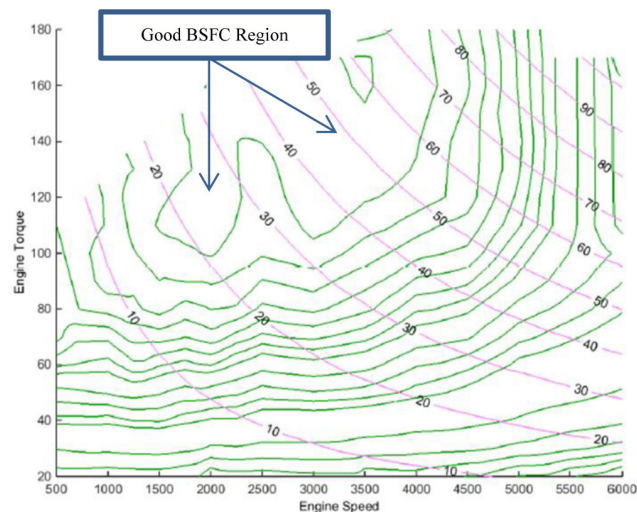


Figure 3. Sample Internal Combustion Engine Brake Specific Fuel Consumption (BSFC) map.

Engine and Traction Battery Optimal Power Usage

In a hybrid vehicle, energy can be stored or released by the traction battery, so system energy optimization plays a major role in defining the optimum engine operation point. Discharging and charging the traction battery can help the engine remain in the optimal BSFC target zone, as shown in Figure 3. For example, if driver demanded propulsion power, added with the power usage of the accessories, is less than the optimal BSFC power, the energy management function can bias the engine toward a more optimum BSFC power by storing some energy in the traction battery (charging). However, that may mean running the engine at a higher speed than what it would run at without charging the traction battery. At a low vehicle speed, this relatively high engine speed may appear out-of-place to a driver, making the engine feel like it is racing. Most drivers tend to like a uniform increase with engine speed and power with the accelerator pedal input increase, so the engine speed changes at low vehicle speed must be limited so that it is acceptable to the driver.

As an example of how the use of ECO Mode biases the engine power toward a good BSFC is shown in Figure 4.

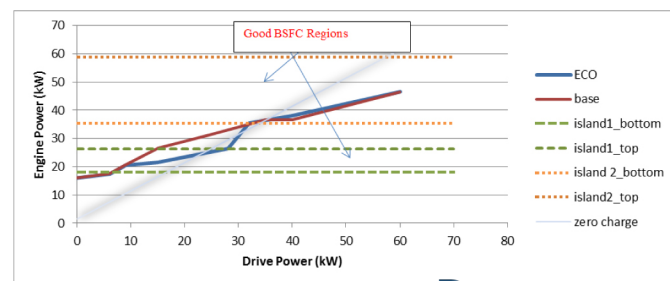


Figure 4. Engine power versus Drive power describing the Engine Power Biasing (Battery Optimal) table.

In Figure 4, there are two low BSFC islands, or ranges. The area between island 1 and island 2 is a less efficient operating range for the engine. The “base” line represents the normal mode, and it provides the driver with smoothly increasing engine power with an increasing drive power demand, so the power line operates in the less efficient range. For ECO Mode, changes have been made to the energy management system to bias towards one of the two islands, depending on the total vehicle power demand and the HV battery state of charge. Changes have also been made to shorten the time the engine spends while transiting from one island to the other. This short time between islands results in a quicker increase of engine power and engine rpm relative to vehicle power demand change or increase. The quicker change of RPM versus the change in driver pedal position would be non-intuitive for many drivers. In addition, the higher RPM at low power or low vehicle speed might create an NVH concern with the increased engine audible and vibration presence, and this is why the strategy was not implemented in normal mode. With ECO Mode, biasing for better fuel economy, the engine speed and power is allowed to move between the two efficient operating islands quickly, trading off the engine sound for improved total vehicle efficiency. The BSFC island strategy was incorporated into ECO Mode. [1]

Accelerator Pedal Mapping Function

The accelerator pedal is one of the main controls the driver uses to communicate to the powertrain. The pedal position and current vehicle speed is converted by the engine management computer into a drive torque or to a drive power request, often referred to as “driver demand.” Allocating more power to a specific pedal position and vehicle speed will result in more acceleration and quicker response. The higher the acceleration, the more energy consumption per distance, and the lower the resulting vehicle fuel economy.

An internal study of different driver’s behavior has shown that at the initial vehicle acceleration from a stop, a majority of drivers tend to tip in at 35% to 50% of the pedal movement, then gradually releasing the pedal as vehicle starts moving to settle at an acceleration they desire. This behavior can be explained by the fact that when depressing the pedal, the pedal spring force pushes back against the driver’s foot. This spring force is not constant, however, and the Ford accelerator pedal has a force peak designed to be maximum at around 50% of the total pedal travel. This means the driver tends to tip in to a comfortable position at less than 50% pedal travel to avoid the high spring force region.

As shown in Figure 5, the change in pedal movement during initial acceleration to 40% of travel will be reflected into acceleration response and energy usage of generally the same shape.

For ECO Mode, the acceleration rate versus the accelerator pedal position and vehicle speed was modified to provide less torque and power at low to medium pedal positions. The resultant vehicle response is now slower, resulting in a reduction in fuel consumption, as long as the customer still presses the accelerator pedal to 50% or less of total travel, as shown in Figure 6. This means that the amount of fuel economy benefit in ECO Mode vs normal mode will be different from customer to customer, depending on their acceleration habits.

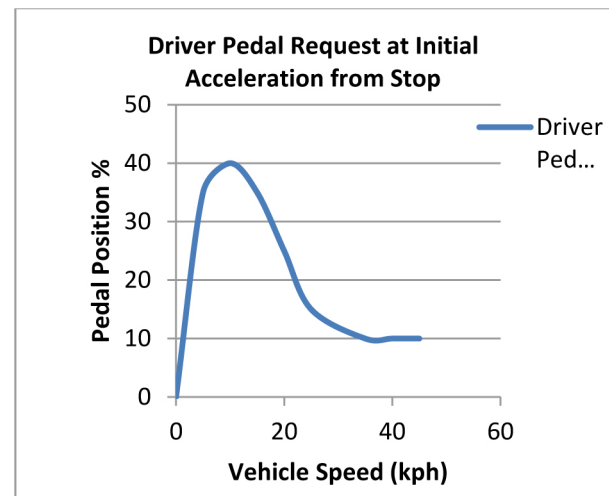


Figure 5. Driver’s Accelerator Pedal Position during Acceleration from Stop.

Knowing that the power or energy required to propel the vehicle at a given speed is the same regardless of mode selection, the ECO Mode pedal map changes will only provide a benefit during acceleration to reach the given speed. If the driver presses the accelerator pedal for maximum performance, the altered accelerator pedal mapping will still provide full performance, and the pedal change will not benefit fuel economy. Thus, the ECO Mode accelerator pedal map, in addition to being an efficient driving mode, is a training mode where the customer can become accustomed to a smoother, slower response. This slower response to the accelerator pedal position provides an additional benefit to a driver who tends to make a lot of quick changes to the accelerator pedal position during driving, sometimes called a “noisy” pedal. This driver keeps changing between over and under acceleration, which causes the powertrain to constantly change power delivery, using additional energy. The revised accelerator pedal provides less response to these movements, helping the driver find the correct pedal position and acceleration level. A final note is that the change in the accelerator pedal map will not provide any benefit for the official fuel economy tests. These tests have a prescribed vehicle speed versus time trace, which results in standard acceleration and deceleration profiles. The accelerator pedal must be actuated to meet the trace, so an ECO pedal map has no effect. This accelerator pedal map change only provides a benefit in on-road operating conditions.

The accelerator pedal map change was tested in combination with other changes in the final evaluation, described elsewhere in this paper. This change was incorporated into ECO Mode.

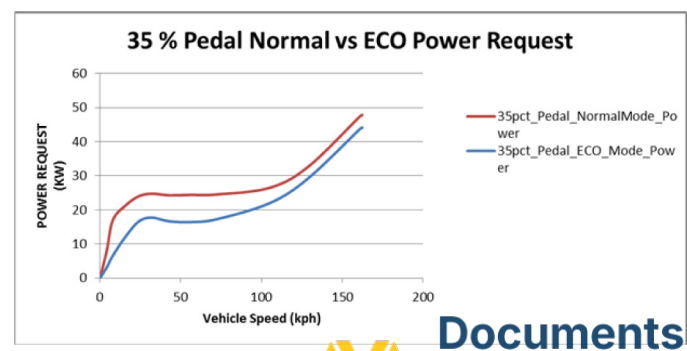


Figure 6. Normal versus Eco Power request