Fuel economy improvement and emission reduction of 48 V mild hybrid electric vehicles with P0, P1, and P2 architectures with lithium battery cell experimental data

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Abstract
This paper intends to provide design selections of hybrid powertrain architectures in 48 V mild hybrid electric vehicles. Based on the location of the electric machine in the driveline, the hybrid powertrain architectures can be categorized into five groups, P0, P1, P2, P3, and P4. This paper uses simulation software to investigate the fuel economy improvements and emission reduction of 48 V mild hybrid electric vehicles with P0, P1, and P2 architectures. A baseline conventional and a 12 V start/stop vehicle models based on the production vehicle are built for comparison. The 48 V battery pack model is based on experimental data including open-circuit voltage and internal resistance of a 20 Ah lithium polymer battery cell. Four standard driving cycles are used to assess the fuel economy and emissions of the vehicle models. With features of engine idle elimination, electric power assist, and regenerative braking, the 48 V P0 and P1 respectively gains average 13.5% and 15.5% simulated fuel economy compared to baseline vehicle. The 48 V P2 enables feature of electric launch/driving and improves the fuel economy by average 18.5% better than baseline vehicle. The 48 V mild hybrid system seems to be one of the promising techniques to meet future fuel economy standards and emission regulations.

Keywords
48 V battery, belt integrated starter generator, crankshaft integrated starter generator, hybrid powertrain architecture, mild hybrid electric vehicle, start stop

Introduction
Due to Corporate Average Fuel Economy (CAFE) standards and emission regulations getting stringent, electrified vehicles are gaining market share. Based on the electrification levels, electrified vehicles can be classified to micro hybrid or start/stop, mild hybrid, full hybrid, plug-in hybrid, and pure electric. Hybrid electric vehicles (HEVs) are one means of increasing propulsion system efficiency and decreasing pollutant emissions. The hybrid vehicle utilizes two propulsion systems in its powertrain. The word hybrid refers to the fact that these propulsion systems use two different forms of energy as a source. This energy is transformed into the mechanical energy that moves the vehicle. Among micro hybrid, mild hybrid, and full hybrid powertrains which do not require external recharge, the...
mild hybrid powertrain is becoming popular due to their competitive cost to performance ratio.\textsuperscript{3,4} The simplest hybrid systems, or mild hybrids, provide limited hybrid functions, such as engine stop/start and regenerative braking. The rated electric power for these systems typically does not exceed approximately 10 kW. Nowadays, most Mild Hybrid Electric Vehicles (MHEV) use 48 V electrical system as the industry standard.\textsuperscript{5,6} Compared to high voltage battery and traction system, the 48 V system can be less-expensive, safer, and easier implemented in the existing vehicle powertrains. Additionally, the 48 V systems are compact and lightweight so they have little effects on the vehicle’s weight and interior space.\textsuperscript{7,8} The fuel economy, performance, and cost of hybrid electric vehicles are significantly influenced by the powertrain architectures. Based on the location of the electric machine within the powertrain or driveline, the hybrid powertrains architectures can be categorized into five groups as P0, P1, P2, P3, and P4,\textsuperscript{9} as shown in the Figure 1. The P0 architecture is mainly for engine start/stop function (engine idle elimination) while utilizing 12 V Starter-lighting-Ignition (SLI) battery. The P0 and P1 architectures become mild hybrid when implementing higher voltage battery (36, 48 V, or more) and electric machine.\textsuperscript{10–18} The electric machines in the P0 and P1 architectures are on the engine side without the possibility of mechanical disconnection between engine and the electric machine. Engine friction loss makes the motor power assist and regenerative braking not efficient. The P2, P3, and P4 architectures are also called driveline side electric machine architectures. They have better energy flow efficiency, mainly because the electric machines in these architectures are installed subsequently the driveline connecting device (clutch or torque convertor). Also, the P2, P3, and P4 architectures enable the pure electric launch/driving and much energy recapture.\textsuperscript{3,7}

The P0 architecture is also known as Belt-Integrated-Starter-Generator (B-ISG) or Belt-Alternator-Starter (BAS)\textsuperscript{10–14} has an ISG mounted in the front of engine through accessory drive belt. The ISG is an electric machine with the combined functions of motoring (starter) and generating (generator or alternator). This ISG directly replaces alternator and requires minor modifications to the belt and tensioner. Compared to other architectures, the P0 has minimum impact on the existing powertrain of conventional vehicle and low integration cost.\textsuperscript{11} The P0 architecture is mainly for engine start/stop function, while with limited motor power assist and regenerative braking due to belt slip, belt durability, and torque capability of the electric machine.\textsuperscript{12–14} The P1 architecture, Crankshaft-ISG (C-ISG) or Flywheel-Alternator-Starter (FAS), replaces the conventional starter motor and alternator with a larger electric machine located between the engine flywheel and transmission.\textsuperscript{15–18} A P1 architecture typically utilizes conventional transmissions with significant packaging changes to accommodate the increased envelope of the electric machine. The electric machine in the P1 architecture may be packaged around torque converter (using a ring type motor) such as,\textsuperscript{16} or between the engine and the transmission where the torque converter is removed, such as Honda Integrated-Motor-Assist (IMA) system.\textsuperscript{17,18} The electric machine serves as the engine starter, as a motor to provide power boost during vehicle acceleration, and as a generator to provide regenerative braking during vehicle deceleration.\textsuperscript{19} Because there is no belt connection which causes slip, the electric motor in P1 architecture can provide higher torque than the B-ISG. However, the biggest drawback of the P1 architecture is the impact on the existing vehicle powertrain and higher integration cost.\textsuperscript{20} In the P2 architecture, the electric machine is mounted between the engine and transmission input shaft with clutches. Comparing to P0 and P1, the P2 architecture has higher energy recapture efficiency because there is no engine friction loss when the driveline clutch is disengaged. The P3 architecture has the electric machine connected to the output shaft of the transmission, and P4 architecture has an electric machine connected to the rear axle drive or the wheel hubs. The P3 and P4 architectures have the highest energy recapture efficiency since both friction loss from engine and transmission are eliminated when the driveline is disconnected. The P4 architecture can enable the all-wheel-drive with engine drives the front wheels and electric machine drives the rear wheels. However, a higher torque electric machine is necessary in P3 and P4 architectures to enable pure electric drive since the torque from the electric machine is not amplified by the transmission.\textsuperscript{3,7,9,20}
This paper uses simulation software GT-ISE to investigate the fuel economy improvements and emission reduction of 48 V MHEVs with P0, P1, and P2 architectures with experimental battery cell data. Based on the model year 2018 Ford Focus 2.0L, a baseline conventional vehicle model and a 12 V micro hybrid vehicle model with start/stop function are established for comparison. The 48 V battery pack model is based on experimental data including open-circuit voltage (OCV) and internal resistance of a 20 Ah lithium polymer battery cell. The fuel economy and emissions of the vehicle models during four standard driving cycles (WLTP, UDDS, HWFET, and US06) are assessed and compared.

Vehicle simulation models

Five vehicle simulation models are built in the GT-ISE platform: conventional vehicle (Case 1 as baseline) and 12 V micro hybrid vehicle (Case 2) based on the 2018 Ford Focus 2.0L, 48 V MHEV with P0, P1, and P2 powertrain architectures (Case 3, Case 4, and Case 5). These five cases have the same vehicle parameters in dimensional sizes, frontal area, aerodynamic drag coefficient, and tire rolling resistance coefficient. The only differences among five cases are vehicle curb mass, the use of motor/generator with 12 or 48 V battery pack and the architecture of them. All five cases are simulated under the same environment (weather) and road conditions.

Baseline vehicle model

Case 1 which serves as the baseline is a 2018 Ford Focus 2.0L conventional vehicle. Actual vehicle specifications\(^{21,22}\) including vehicle mass, frontal area, drag coefficient, tire size, and transmission gear ratios are inputs to the model. The model utilizes a standard 2.0L naturally aspirated engine map from the GT-Suite library. Figure 2 shows the connections between the engine, ICE-controller, clutch, driver, and vehicle module/subassembly. Inside the vehicle module, driving power goes from transmission output shaft through the driveshaft, differential, axle, and finally to the front wheels. The “Driver signal,” located close to the brakes in the vehicle module, receives braking signal from the driver and sends it to the brakes. Connection ports on the transmission and vehicle body (“Car-1”) are used to connecting them to the driver and engine. A clutch is connected between engine flywheel and input shaft of the transmission. Inputs from the vehicle module to the driver are vehicle speed, transmission gear number/gear ratio, and shift indicator. The driver’s output to the vehicle module is the requested gear number. The driver receives the engine speed information from the engine and sends accelerator pedal position and clutch pedal position signal to the ICE-controlled and clutch, respectively. The driving cycles are included in the driver module. In Case 1, a shift strategy profile is generated by the “Shift Strategy Generation” and “Vehicle Kinematic Analysis” objects. Vehicle mass, aerodynamics, rolling resistance, powertrain output, and transmission gear ratios are taken into account when the software generates the shift strategy. The generated upshift and downshift strategies are stored in two tables. The vehicle speed (km/h) at which the shift occurred depends on the different shifts (such as first gear upshift to second gear, or third gear downshift to second gear) and accelerator pedal positions. The generated shift strategy profile is used by the “Driver” module.

Battery cell experiments

Battery cell experimental data, including open-circuit voltage (OCV) in charge and discharge mode and internal resistance, of the EiG ePLB-C020B Lithium-Nickel-Manganese-Cobalt-Oxide (LiNiMnCoO\(_2\)) based cell is used to build the 12 V battery pack in Case 2 micro hybrid vehicle model and the 48 V battery pack in Case 3, 4, and 5 MHEV models. The cell has 20 Ah
nominal capacity and 3.6 V nominal voltage. This type of cell is widely used in hybrid electric and pure electric vehicles. The Digatron charge/discharge unit (cycler) controlled by Digatron Battery Manager software, as shown in Figure 3, is used to charge and discharge the battery cell. All tests are performed in the temperature chamber with controlled interior temperature at 25°C.

To obtain the OCV in charge and discharge mode, the pulse current tests with state-of-charge (SOC) resolution of 5% are performed. During each pulse charge or discharge, 5% of the cell’s total capacity is charged into or discharged from the cell. A three-minute rest time with no current is between each two pulses. The OCV at each SOC is measured at the end of each rest time. The pulse charge and discharge current (C-rate) used in the experiments are respectively 2C and 3C-rates. To achieve 100% SOC or 100% DOD, control voltage method is applied. The battery cell is charged or discharged using a continuous constant 1 C-rate current to the upper (4.2 V) or lower (2.5 V) voltage limit, respectively. After reaching the voltage limit, the cycler reduces the charging or discharging current gradually to keep the voltage at upper or lower voltage limit, respectively. The charging or discharging process stops once the charging or discharging current reduces to 0.1 C-rate, which marks the point of 100% SOC or 100% DOD, respectively.

Figure 4 shows the cell terminal voltages and OCV during pulse discharge and pulse charge tests. The first orange dot represents OCV at 10% depth-of-discharge (DOD) and 10% SOC in the left and right figures, respectively. The last orange dot represents OCV at 90% DOD and 90% SOC in the left and right figures, respectively. To determine the cell internal resistance, the OCV in discharge mode is compared with the 20 A (1 C-Rate) discharging voltage, as shown in the left plot in Figure 5. The OCVs at 0% and 100% DOD are measured after the cell is completely charged and discharged, respectively. A voltage difference between the OCV and discharging voltage at the 1 C-Rate is the voltage drop caused by the cell internal resistance. The voltage drop divided by the discharging current (20 A) is the internal resistance which is a function of DOD as shown in the right plot in Figure 5. It clearly shows...
that the internal resistance increases rapidly when the DOD is reaching 100%.

**12 V P0 micro hybrid vehicle model and 48 V P0, P1, and P2 MHEV models**

One 12 V micro hybrid model with P0 architecture (Case 2) and three 48 V MHEV models with architectures P0 (Case 3), P1 (Case 4), and P2 (Case 5) are shown in Figure 6. The connections of “Vehicle” modules in Case 2, 3, 4, and 5 are very similar to Case 1 except that “Transmission” module is moved out from the “Vehicle” modules in Case 2, 3, 4, and 5. These micro hybrid and mild hybrid cases have the same vehicle parameters (frontal area, drag coefficient, and tire size) as well as mechanical components (engine map, transmission gear ratios, driveshaft, differential, and axle) as Case 1 baseline vehicle, a 2018 Ford Focus 2.0L. The vehicle mass of Case 3, 4, and 5 has additional 50 kg representing 48 V battery pack, electric machine, powertrain electronics, and cables. Case 2 and Case 3 have the same powertrain layout and they both have a B-ISG motor attached to the engine accessory belt. The differences between Case 2 and Case 3 are the sizes of the B-ISG and battery pack. Case 2 uses a 10 kW B-ISG with a 12 V SLI battery and Case 3 uses a 15 kW B-ISG with a 48 V battery pack. Case 2 only features engine start/stop function while Case 3 has additional features of motor assist and regenerative braking. In Case 4, a 20 kW motor is connected to the engine crankshaft. In Case 5, a 25 kW motor is connected between engine and transmission with two clutches. The transmission shifting strategies are also generated by the software for the Case 2, 3, 4, and 5 separately.

In Case 2, four cells are connected in series to form a 12 V SLI battery which has 14.4 V nominal voltage and 20 Ah capacity. Case 3, 4, and 5 use 14 series-connected cells to form the 48 V battery pack which has 50.4 V nominal voltage and 20 Ah nominal capacity. The resistance of the connecting bars between cells is neglected. The designed battery pack’s 20 Ah capacity is sufficient powering MHEV architectures ranging from P0 to P4 according to Refs. 6,23,24 which indicated a typical 48 V MHEV has around 10 Ah battery pack capacity. The battery pack operating SOC range is defined 40%–85% and the targeted SOC is set at 60%. If the SOC is below 60%, the electric machine charges the battery pack when engine is running. The initial SOC of the battery pack is set to 75% before any simulations. In Case 3, 4, and 5, the lower vehicle speed limit for regenerative braking is 8 km/h, meaning no regenerative braking when vehicle speed is lower than 8 km/h. The P2 (Case 5) is capable of electric launch/driving when the battery pack SOC is higher than 60% and gentle acceleration. The vehicle speed limit for pure electric driving is 35 km/h.

**Simulation results and discussion**

To investigate the impacts of the 48 V mild hybrid on the vehicle fuel economy and emission, simulations of all five cases are performed under (Worldwide harmonized Light vehicles Test Procedures (WLTP),25 Urban Dynamometer Driving Schedule (UDDS),26 Highway Fuel Economy Test (HWFET),27 and US0628 driving cycles. This study applies Class 3b cycle of WLTP which contains four phases of driving conditions in urban, suburban, rural, and highway. The WLTP cycle duration is 1800 s and total distance driven is 23,266 m. The UDDS represents the urban driving condition with frequent stops. The time duration of UDDS is 1372 s and the total distance driven is 12.07 km. The HWFET runs for 765 s with 16.45 km total distance driven. The US06 test schedule simulates the aggressive driving behavior with high acceleration/deceleration and rapid speed fluctuations. The US06 has 596 s time duration and 12.8 km total driving distance.

The fuel economy of Case 1 baseline vehicle, 2018 Ford Focus 2.0L, is 26 mile-per-gallon (mpg) in city and 36 mpg on highway published by Driverside.21
Case 1 simulation result shows a 28.6 mpg for UDDS and 38.1 mpg for HWFET driving cycles, which are very close to the EPA published data. Table 1 summarizes the fuel economies of all five cases during different driving cycle runs. The percentages shown in the parentheses are the fuel economy improvements over the baseline vehicle (Case 1). The engine start/stop function in Case 2 improves the average fuel economy about 2.3% compared to the conventional vehicle in Case 1. The engine start/stop function can improve the fuel economy about 5% in WLTP driving cycle because the vehicle is in stationary for long time in WLTP cycle, such as between 99 and 137 s, 445 and 511 s, 567 and 600 s, 986 and 1026 s, and 1452 and 1478 s. However, Case 2 has the same fuel economy as the Case 1 in HWFET cycle because the vehicle is always moving and engine is always operating. The simulation results show that 48 V mild hybrid system has the largest fuel economy improvement in city driving. During UDDS driving cycle, the Case 3, 4, and 5 have respectively 21%, 23%, and 28% fuel economy improvement over the Case 1. The 48 V mild hybrid system with P0, P1, and P2 architectures improve the fuel economy respectively by 18%, 21%, and 27% in the WLTP Class 3b driving cycle which consists of much urban driving condition. The fuel economy of highway and aggressive driving cycles is increased as well while the improvements are not so significant. Table 1 also clearly shows that the gas mileage of city driving gets the largest benefit from P2 over P0 and P1, while the gas mileages of P0, P1, and P2 architectures during highway and aggressive driving do not have much difference.

The SOC variations of the 12 V SLI battery in Case 2 and 48 V battery pack in Case 3, 4, and 5 during driving cycle simulations are examined. WLTP Class 3b driving cycle is used for the battery SOC investigation because it contains almost all driving conditions, ranging from low-speed urban driving with frequent stops to high-speed highway driving. Figure 7 shows the battery SOC variations in Case 2, 3, 4, and 5. The Case 2 has 12 V SLI battery SOC increasing once the engine is running. This is due to that 12 V P0 architecture does not have motor assist feature to consume much electricity. Cross-checking the SOC variations and engine fuel consumption in Case 2, it can be seen that the battery SOC increasing rate is proportional to the engine fuel consumption rate. Higher fuel consumption rate usually means engine has higher rpm. The B-ISG spins faster and charges much the battery as the engine in higher rpm. For the 48 V cases, the vehicle speed limit...
Table 1. Average fuel economy of five cases during different driving cycles.

|       | Baseline (Case 1) (mpg) | 12 V P0 (Case 2)         | 48 V P0 (Case 3)         | 48 V P1 (Case 4)         | 48 V P2 (Case 5)         |
|-------|-------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| WLTP  | 30.5                    | 32.0 (+5%)               | 36.1 (+18%)              | 37.0 (+21%)              | 38.7 (+27%)              |
| UDDS  | 28.6                    | 29.5 (+3%)               | 34.5 (+21%)              | 35.1 (+23%)              | 36.6 (+28%)              |
| HWFET | 38.1                    | 38.1 (+0%)               | 41.6 (+9%)               | 41.9 (+10%)              | 42.2 (+11%)              |
| US06  | 29.8                    | 30.1 (+1%)               | 31.7 (+6%)               | 32.1 (+8%)               | 32.2 (+8%)               |
| Average% increase | 2.3% more than Case 1 | 13.5% more than Case 1 | 15.5% more than Case 1 | 18.5% more than Case 1 |

Figure 7. SOC of 12V SLI battery in P0 architecture and 48V battery pack in P0, P1, and P2 architectures during WLTP simulations.
for motor assist in Case 3 (P0) is much lower than those in Case 4 (P1) and Case 5 (P2). The overall SOC variation trend in Case 3 is increasing after 600 s when the WLTP cycle starts to enter higher vehicle speed region. The battery SOC variation in Case 4 (P1) is small (between 70% and 74%) before 1100 s, which indicates that electrical energy consumed for motor assist is almost equal to the electrical energy generated from regenerative braking and generator charging during urban and suburban driving conditions.

Figures 8 shows the engine fuel consumption rates of all five cases during the WLTP Class 3b driving cycle. The Case 1 baseline vehicle does not have engine idle start/stop, so the fuel consumption rate is always more than 0. Case 2 has zero engine fuel consumption when the vehicle is in stationary because Case 2 is equipped with engine start/stop function. The Case 3 and Case 4 also feature engine start/stop function with zero fuel consumption when vehicle is not moving. The duration of the zero fuel consumption of Case 5 is much longer than that of Case 2, 3, and 4. Thanks to earlier shut-off engine during vehicle deceleration and electric launch/driving to certain speed, the Case 5 has much duration of zero fuel consumption. Early engine shut-off and pure electric launch provide much fuel shut-off time, which results in better fuel economy. From Case 2 to Case 5, the engine fuel consumption rate becomes slightly lesser and lesser during most time of the driving cycle. This trend is attributed to the increasing of motor power assist duration from Case 2 to Case 5.

The simulations of carbon dioxide emissions during different driving cycles are studied. Table 2 summarizes
the simulated results. The Case 1 baseline vehicle has an average 179.4 g/km carbon dioxide emission. This simulated data is close to the real vehicle carbon dioxide emission data, 200 g/km, published by Natural Resources Canada.29 Table 2 also shows that each case has higher carbon dioxide emissions in UDDS and US06 driving cycles, and the lowest emissions in HWFET driving cycle. In the WLTP driving cycle which has long duration of vehicle in stationary, the engine start/stop feature of Case 2 reduces the carbon dioxide emission by 8.7 g/km compared to Case 1. This indicates that engine idle elimination contributes much to emission reduction in heavy traffic driving. Compared to the conventional vehicle (Case 1), 48 V MHEVs with P0, P1, and P2 architectures reduce the average carbon dioxide emissions by 21.5, 23.9, and 27.6 g/km, respectively. To meet the US EPA’s requirement on the carbon dioxide emissions below 89 g/km by 2025, the 48 V mild hybrid system seems to be one of the promising techniques.

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