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Diesel Hybridization and Emissions

A Report to DOE from the ANL vehicle systems and fuels team

For the U.S. Department Of Energy
Office of Advanced Automotive Technologies

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- EXECUTIVE SUMMARY -

Diesel Hybrid Testing Shows Impact of Control Strategy on Fuel Economy and Emissions

Description of the project

The CTR Vehicle Systems and Fuels team tested a diesel hybrid powertrain. The goal of this experiment was to investigate and demonstrate the potential of diesel engines for hybrid electric vehicles (HEVs) in fuel economy and emissions.

The test set-up consisted of a diesel engine coupled to an electric motor driving a Continuously Variable Transmission (CVT). This hybrid drive is connected to a dynamometer and a DC electrical power source creating a vehicle context by combining advanced computer models and emulation techniques.

The experiment focuses on the impact of the hybrid control strategy on fuel economy and emissions-in particular, nitrogen oxides (NO_x) and particulate matter (PM). The same hardware and test procedure were used throughout the entire experiment to assess the impact of different control approaches.

Exploration of different control approaches

Engine operation is key to hybrid vehicle control strategy, because it is directly related to fuel efficiency and gaseous emissions. The CVT parallel hybrid configuration provides tremendous flexibility in the choice of both engine torque and speed operation. The electric motor can replace, assist, or absorb the engine torque independently from driver expectations. In addition, the CVT allows decoupling between engine and wheel speeds.

Conventional vehicle operation provides experimental reference

To obtain a fuel economy and emissions reference, the first test results were produced by operating the vehicle in a conventional mode. Therefore, the electric motor was disabled, and the CVT acted as a manual transmission.

Hybrid vehicle control using best engine efficiency curve

The best efficiency curve describes the optimal engine operating point for each power demand from an energy point of view. Therefore, the engine torque and the CVT ratio are both controlled to operate the engine at the most efficient point while satisfying the power demand. However, when the engine operates on its best efficiency curve, it produces excessive NO_x emissions. CTR staff used simulation to design a trade-off between fuel economy and NO_x emissions.

Hybrid vehicle control using best engine trade-off curve

For each engine power demand, NO_x emissions and fuel consumption data were interpreted to define the best trade-off curve. The engine torque and the CVT ratio are controlled to operate the engine on this curve while satisfying engine power demand.

These figures display engine operating points during testing of the two hybrid control strategies. Color is based on duration of engine operation at a given operating point. Both curves were determined by using steady-state engine data. Control was developed in simulation and then implemented in the test set-up controller for experimental testing.

Experimental results, comparison, and analysis

Operating the engine with the best efficiency approach increases fuel economy by 57%. This efficient engine utilization results in a 35% increase in NO_x emissions. The best trade-off approach provides a 50% NO_x reduction, while improving the fuel economy by 41%. However, it also results in an increase in PM emissions

Fuel economy and NOx results summary

PM and NOx results summary

Those results refer to an emulated conventional vehicle, which is actually penalized by the inefficiency of a CVT acting as a manual transmission as well as the losses and inertia of a disabled electric motor.

Conclusion

This experiment demonstrates and quantifies the control strategy impact on fuel economy and emissions for diesel hybrid vehicles. To complete the evaluation of diesel hybrid technology, after-treatment devices should also be considered. At this time, particulate filter technology is more mature than a NO_x absorber. However, the development of an after-treatment control integrated to the vehicle control strategy would complete the demonstration of a diesel hybrid as a short-term bridge to a hydrogen economy.

Sponsor

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1 Description of the project

1.1 Objective and approach

The main objective of the project is to determine the impact of hybridization and powertrain system control on diesel engine emissions and efficiency. Argonne National Laboratory (ANL) completed the design and installation of a hybrid electric powertrain in the Advanced Powertrain Research Facility (APRF), consisting of a CIDI engine and electric motor in parallel driving through a continuously variable transmission (CVT). The components and the hybrid powertrain system are simulated using our in-house developed simulation tool (PSAT[®]), which is translated to the ANL control software (PSAT-PRO[®]) to control the components individually and as a system. Several control strategies were developed, tuned and tested. The powertrain test cell was used to study the trade-off between fuel economy and emissions using powertrain controls and validated Hardware-In-the-Loop (HIL) emulation technique.

1.2 Description of the tools

The Center for Transportation Research (CTR) offers a unique integrated process based on powerful simulation tools and experimental facilities to perform system-level tests quickly and cost-effectively. ANL's unique combination of capabilities, expertise, and facilities reduce wasted effort in progressing from simulation to control implementation, component emulation, testing, and validation by removing the barriers associated with communication, data transfer, unnecessary code generation, or software changes. CTR's integrated process is based on three advanced tools: PSAT[®] simulation, HIL emulation and APRF validation. [1]

The ANL-developed forward-looking vehicle modeling software PSAT[®] is used to optimize control strategies that will be further translated to PSAT-PRO[®] and integrated in a micro-controller for hardware control. [2][3]

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PSAT-PRO[®], designed for use in the APRF, is a Matlab[®]-based program that uses dSPACE[®] prototyper to link PSAT[®] control strategy and real hardware control. This direct connection between modeling and simulation software, control software, and the APRF offers the opportunity to streamline technology development through continual feedback and refinement. Control implementation bridges the modeling and experimental hardware testing programs. (Figure 1) [4] (APPENDIX 1)

Deleted: Therefore, the control of real components with the control strategy developed in simulation is effortless. PSAT[®] is capable of simulating wide range of HEV to provide fuel economy and emissions predictions. It is well suited for control development, which allows researchers to perform emissions reduction experiments by using an optimized control strategy [1].¶

Deleted: The purpose of PSAT-PRO[®] is to facilitate the development of system controllers. PSAT[®], the PSAT-PRO[®] companion for simulation, allows analysis studies and vehicle power management development. PSAT-PRO[®] offers the capability to use and to enhance the modeling work for control purposes. It allows the test of the power management system in a real environment [2].

Figure 1: Argonne's integrated vehicle system program

HIL is used at ANL as a unique advanced testing methodology combining hardware and computer models to emulate virtual components of the hybrid vehicle. HIL emulation provides a cost-effective way to validate technology.

The APRF is a flexible, controlled test environment that can be used to assess any powertrain technology, including engines, fuel cells, electric drives, and energy storage. State-of-the-art performance and emissions measurement equipment (listed below) are available to all component and vehicle test cells to support model development, HIL, and technology validation. [5] [6]

- Light- and heavy-duty dynamometers	- Ultra-fast (<5 ms) HC and NO _x measurement
- 2WD and 4WD chassis dynamometers	- Fast (10 Hz) direct fuel measurement
- Battery/fuel cell emulator (150 kW)	- Fast (10 Hz) particulate measurement;
- Precision-controlled environment	- Unique laser-induced incandescence (LII)
- SULEV emissions measurement capability	- Mini-dilution PM measurement
- Low-emissions raw emissions bench	- Scanning mobility particle sizer

1.3 Simulation: Hybridization of the baseline vehicle

In order to evaluate the performances of a conventional Diesel vehicle available in the market, we used a Mercedes C-class C 220 CDI as our baseline. The vehicle specifications are summarized in the table below:

Vehicle Parameter	Specification
Model Year	1999
Body Style	4-door sedan
Transmission	5-speed manual
Tires	P195/65R15
Engine Type	2.2 L I-4 intercooled turbo-diesel
Fuel System	Electronically controlled, high pressure common rail with pilot injection
Wheelbase	2,690 mm
Length/width/height	4,516 mm / 1,723 mm / 1,427 mm
Curb weight	1,410 kg
Top track speed	198 km/h (123 mph)
Acceleration 0-100km/h	10.5 sec
Rated Fuel Consumption (City + Highway)	6.1 l/100km (38.5 mpg)
Engine Parameter	
Cylinders / arrangement	4 / bank, 4 valves per cylinder
Displacement (bore x stroke)	2,151 cm ³ (88.0 mm x 88.4 mm)
Compression ratio	19.0:1
Rated output	92 kW (125 hp) @ 4,200 rpm
Rated torque	300 Nm @ 1,800-2,600 rpm
Aftertreatment	“Lean NOx” catalyst
Drivetrain Parameter	
Gear ratios 1 st / 2 nd / 3 rd / 4 th / 5 th / reverse	4.10 / 2.18 / 1.38 / 1.00 / 0.80 / 4.27
Final drive	3.07

The “lean NOx” catalyst after-treatment technology installed on this vehicle relies on low-sulfur fuel to be effective. Therefore, all our experiments have been performed using “California Low-Sulfur Commercial 2-D Diesel Fuel”.

The baseline vehicle (Mercedes C-class C 220 CDI) was simulated using PSAT and then tested in a 4wheel-drive chassis dynamometer environment at the APRF for validation purposes.

In order to assess the effect of hybridization and control on Diesel emissions, we hybridized in simulation the Mercedes-Benz C 220 CDI vehicle (including engine downsizing).

Using PSAT, a suitable hybrid version of the Mercedes C-class diesel has been studied. The Mercedes-Benz 2.2 L I-4 intercooled turbo-diesel engine used in the C-class vehicle has been downsized to a Mercedes-Benz 1.7 L engine from the same technology and generation. The engine power went from 92 kW (125 hp) @ 4,200 rpm for the conventional vehicle to 66 kW (88 hp) @ 4,200 rpm for its hybrid version. The engine downsizing corresponds to a power reduction of 26 kW (28%).

To compensate this power reduction, the simulation results recommend the addition of an electric motor of approximately 32 kW continue coupled to the engine shaft. This recommended power is slightly higher than the power reduction to keep the vehicle at iso-performances and compensate the weight gain.

The control strategy uses the motor as a prime mover when the engine is off. The battery must provide enough power to start moving the vehicle as an electric vehicle. Engine start/stop decision is based on battery state of charge (SOC). The power requirement and battery choice will depend of motor utilization. Simulation was used to select the most suitable battery for our application.

Since realistic vehicle performances are expected, utilization of commercially available existing battery technology is a requirement for the battery choice.

In simulation, custom-made battery pack can be design using existing commercially available battery cells which are available in PSAT. The number of cell is calculated to meet a minimum of 30 kW total pack requirement. The number of cells then sets packs characteristics (voltage, mass...). Battery capacity is also a key issue because it is directly related to engine utilization.

PSAT was used to design two battery packs matching our power requirement. The battery models are then submitted in simulation to the power profile extracted from test results.

Figure 2 and 3 show voltage, current and SOC variation of the batteries when submitted to test power profile.

Figure 2: Pack A - Cylindrical Ni-Mh from Panasonic (Japanese Prius cells technology)

Cell Characteristics: 1.2V / 6Ah / 200g

Pack: 240 Cells, 288V, 6Ah, 50kg

Figure 3: Pack B - Li-ion from SAFT

-Pack B: Li-ion from SAFT

Cell Characteristics: 3.8V / 6Ah / 550g (estimated)

Pack: 6 modules of 12 cells, 72 Cells total, 276V, 6Ah, 45kg

Those results show that the SAFT Li-Ion technology is more suitable to our application: The main advantage is better power and energy density and the higher available power to handle regenerative event. This battery gives more flexibility to motor utilization and therefore more options to design control strategy.

The components have been sized to eliminate any unnecessary constraints and limitations and ultimately to increase the possibility for the control of the system. For those reasons, a fixed ratio has been introduced between the engine shaft and the motor shaft. The ratio has been selected to adapt the motor speed range to the engine speed range. The maximum speed of the engine being 4,800 rpm and assuming a maximum speed of 8,000 rpm for the motor, this gives us a ratio of approximately 1.7.

Different type of transmission has been studied in simulation and it appears that a continuous variable transmission (CVT) provides more possibilities in terms of control than an automatic or a manual transmission. One of the benefits of using a CVT is that the engine speed is decoupled from the vehicle speed. The CVT ratio allows keeping the engine at a target operating speed. On the other hand, simulation results show that CVT have lower efficiency than manual transmission. As one of the objectives of the project is to demonstrate the impact of control in fuel economy and emissions, we decided to use a CVT and to modify it to increase its efficiency.

1.4 Emulation: Control and Assembly of the hybrid powertrain

To evaluate the potential of Diesel in a Hybrid Electric Vehicle (HEV) environment, we're using a unique advanced testing methodology combining hardware and computer models, providing a cost-effective way to validate technology. We can apply a PSAT[®] control strategy to efficiently use a diesel engine in a complex hybrid configuration while the battery and the vehicle will be emulated using Hardware-In-the-Loop (HIL).

The term HIL is derived from the common practice of testing an electronic control unit (hardware) with a real-time computer that behaves like system or vehicle (virtual) in a closed loop. [7]

HIL is often confused with rapid control prototyping or RCP, the practice of testing control software with a real system, because both often use the same control software development approach.

The confusion is easy in this project because we're actually using some elements of both HIL and RCP: We're using a real-time computer to control the dynamometer to react as a vehicle and a DC power source to act as a battery, but we also control the components of the hybrid powertrain.

The hybrid powertrain is controlled with PSAT-PRO[®]. Specifically, the computer-based PSAT-PRO[®] vehicle controller controls the torque of the powertrain to track a vehicle speed profile. The speed of the transmission output shaft (corresponding to the wheels) is measured. This measured speed feeds the vehicle model to determine the vehicle losses in these conditions. To simulate the torque losses that would be produced in reality by the vehicle's aerodynamics, the calculated vehicle losses are sent to the dynamometer as a torque command. The powertrain control computer is shown in Figure 4 and the overall concept is shown in Figure 5.

Figure 4: HIL hybrid powertrain control computer using PSAT-PRO[®]

Figure 5: Powertrain control concept using the ANL HIL computer system

A hydraulic friction brake was designed to provide the resisting torque that a vehicle would need during an aggressive driving cycle. Two calipers are used on the same disk so that no radial force is applied to the rotating shaft and the calipers team their effort. The calipers, disk, and master cylinder are automotive aftermarket units, typically used in racing applications. To translate this to a brake pressure (and resulting torque), an air control system was designed to operate the hydraulic automotive master cylinder. A high-precision pneumatic regulating valve takes the analog command from the PSAT-PRO[®] computer and provides a proportional air pressure output. The output pressure then enters a pneumatic cylinder that provides the mechanical force to the automotive hydraulic master cylinder. The hydraulic pressure from the master cylinder actuates the calipers. Figure 6

Figure 6: Disc Brake and Controller

Flywheels were added to one shaft of the both-ended dynamometer to provide the inertia required for the mass of the emulated vehicle. Figure 7 and 8

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Figure 7: Inertia flywheels

Figure 8: Layout of Major Components of the Hybrid Powertrain

The transmission is a modified Nissan CK-2 CVT, which uses a Van Doorne push-type belt that is commercially available in several Japanese production vehicles. Mechanical and electrical modifications were made to the CVT, both internal and external to the transmission. In stock trim, an off-board transmission control unit that controls torque converter lock-up, CVT ratio, and hydraulic pressure accompanies the CVT. In its original design, the mechanical hydraulic pump is connected to the engine thru the torque converter.

Hybridization requires disconnecting engine from transmission using a clutch, temporary allowing the electrical motor alone to propel the vehicle. The torque converter was replaced by a clutch. This benefits system efficiency because clutch efficiency is better than torque converter efficiency.

The reverse planetary gear was removed because HEVs with electric-only capabilities can use the electric motor for reverse.

All CVT control is done with the ANL developed PSAT-PRO[®] control software; additional hardware has been added to support this approach. But the main modification to the CVT was the removal of the internal high-pressure hydraulic pump. It was replaced with an off-board pump. The pump is a key component of the CVT as it provides adequate belt/pulleys clamping. By fitting an external pump, much higher power transmission efficiencies can be achieved because an electrically driven pump allows the optimal control of hydraulic clamping pressure condition by decoupling pump from transmission input shaft. Figures 9 and 10

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Figure 9:
Removal of the CVT oil

Figure 10:
Modified Nissan CVT

The supply clamping pressure is a key parameter for efficient use of this type of transmission: Ideally the pressure should always be minimized to allow efficient torque transmission while avoiding belt slipping (if pressure is too low) or overheating and abnormal wear (if pressure is too high).

For this reason, a dynamic control algorithm has been integrated in the powertrain controller allowing optimal CVT operation. This algorithm uses instantaneous CVT input shaft torque and ratio measurement to calculate optimum supply pressure and accordingly command hydraulic pump.

Figure 11 shows in parallel the CVT pressure, the input torque used to dynamically control the hydraulic pump and the vehicle wheel speed during a test.

Figure 11:
CVT pressure control

Test data are showing a substantial improvement of the transmission efficiency.

The hydraulic pump was instrumented to evaluate its energy use. This needs to be taken into account to validate the actual efficiency gain of the dynamic pressure control. Therefore, the power

consumed by the auxiliary pump was taken into account. The electric power consumed by the pump was drawn from the emulated battery to reflect its impact on fuel economy. Figure 12

Figure 12: Off-board hydraulic pump

Pump specifications were used to evaluate its instantaneous power. Manufacturer specifies pump shaft torque and speed according to operating pressure and flow. A constant efficiency is used to convert pump drive power into electrical power. The power is then drawn from the battery to discharge it and ultimately impact fuel economy, which is corrected according to battery state of charge.

The efficiency of the modified CVT was measured on the complete speed, torque and ratio range of the transmission. The results of this mapping are shown on the figure 13.

Figure 13: Modified CVT efficiency map

The figure 14 offers a comparison with a similar transmission commercially available in the Toyota Opa CVT. This vehicle has been previously tested at APRF for a different purpose but the vehicle was instrumented with an engine torque sensor and an axle torque sensor. Therefore, data could be extracted from the tests for CVT efficiency comparison. [8]

Figure 14: Toyota Opa CVT efficiency data

As seen earlier, the simulation study recommends an engine downsizing from 92 kW (125 hp) @ 4,200 rpm for the conventional vehicle to 66 kW (88 hp) @ 4,200 rpm for its hybrid version. A Compression-Ignition Direct-Injection (CIDI) engine from a Mercedes-Benz A170 CDI vehicle was removed from a research vehicle and prepared for testing as part of this HEV powertrain configuration. Figure 15.

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Figure 15: CIDI 1.7L engine

The motor, a 32 kW continuous (45 kW peak) DC brushless permanent magnet traction drive system from Unique Mobility (UQM), introduces the electrical torque into the powertrain by the use of a flat-toothed belt. The belt is a Woods QT Power Chain specifically made for high-torque applications. For greater accuracy in simulating the components in an actual vehicle, the components were designed to keep the inertia to a minimum. Figure 16

Figure 16: DC brushless permanent magnet electric motor

The battery was emulated using a DC power source (ABC150). Emulation was used to replace a real battery and to gain flexibility over the type of battery used.

Several options were available to emulate the battery but the more adapted is a power based constant voltage battery emulation.

With this option, the electric motor is powered using a constant nominal 180V. The current drawn and the voltage are used to calculate instantaneous electrical power. The predicted voltage from the battery model and the measured power give the current that would be drawn from the real battery. This calculated current is used to feed the battery model and predict voltage variations. Figure 17

Figure 17: Battery emulation principle

With this solution, the actual inverter DC voltage range does not limit battery choice and we can choose the battery totally independently from the inverter specifications. In addition, the SOC calculation is as realistic as the current measurement is accurate because there is no delay in the control of the ABC150. In fact, there is no need for a dynamic control of the DC power source. It is possible to argue about the fact that battery voltage is different from inverter voltage, but we can make the hypothesis that in an actual HEV, inverter hardware should be designed to interface/match motor and battery characteristics. Furthermore, inverter losses are still taken into account since the inverter is physically integrated in the test setup. Also it has been demonstrated that motor inverter efficiency is not significantly affected by DC voltage variation. The emulation is as realistic as the battery model. Therefore, adequate effort should be dedicated to the validation of the component models used for emulation.

1.5 Validation: Component models, fuel economy and emissions measurement

Components models validation is an integral part of the emulation process – providing the reality check between hardware development/testing and modeling. The enablers for the integrated process are the tools that ANL has developed to generate data, feed component models, analyze vehicle powertrain systems, perform testing using control tools, and produce results that validate the models. An important common thread of these tools is model validation. The usefulness of a model can only extend to the limits of confidence based upon rigorous validation of the models. [9][10][11][12]

We consider a vehicle model validated only when all the component model predictions are in agreement with the test data. To validate a single component, the data measured during a drive cycle are fed directly into the component model, and the simulated output is compared with the measured data. If there are errors in individual component models, this method will easily expose them.

Before using the battery model for emulation purposes, we validated the model using this methodology by tracking voltage and current throughout the drive cycle. The battery model predictions were compared to the actual battery data from the ANL Battery Test Facility using actual discharge profiles from the previously tested Toyota Prius.

Once the components have been validated independently, the last step is to integrate the control strategy developed with PSAT and compare the powertrain reactions to simulation results.

The whole drivetrain has been instrumented to allow this comparison. Three torque and speed sensors are necessary: one on the motor shaft, one on the input shaft of the CVT, and one on the output shaft of the CVT, as shown on Figure 18.

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To measure the CVT inputs without modifying the behavior of this component, we integrated a flat torque sensor. The bell housing of the CVT transmission had to be modified to mount the HBM T-10F flat torque sensor to measure CVT input torque. Flanges that mate to the splined shaft and the engine output are also machined. Figure 19

Figure 19: Instrumentation of the CVT

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¶ Figure 21: Instrumentation of the drivetrain

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The extensive instrumentation (listed in APPENDIX 2) is connected to a central Data Acquisition System (DAQ). The DAQ system consists of a National instrument chassis connected to a desktop computer. Instrument output signals are routed to the DAQ chassis and to the DAQ computer. An internally developed LabView program is running on the DAQ computer. The emission concentration bench is connected to the computer as well via series communication. The LabView program performs several functions. First the program graphical interface design allows the operator to monitor powertrain instrument and status during a test. The program also records over-sampled and averaged raw data at a 10Hz rate. Therefore the operator can record complete test phases while monitoring the powertrain behavior. At the end of each test phase, the program launches a post processing routines that automatically calculates and summarizes Fuel Economy and emission pollutants mass for the recorded phase.

Emission mass was preferred to evaluate control benefit of the pre-transmission diesel hybrid powertrain. The Pierburg 2000 emission bench provides emission sample concentration. But, to calculate total emission mass, it is necessary to monitor sample flow in addition to concentration. Initially, sample flow was evaluated based on mass conservation equation of intake airflow and fuel flow in order to evaluate exhaust gas flow. This method was not optimal because air and fuel flow are transient and depend on engine operating points. Therefore, accuracy of mass emission was highly dependant on fuel and airflow sensor accuracy as well as time response.

In order to address this issue, we designed a Constant Velocity Sampler (C.V.S.) associated with dilution of exhaust. The purpose of this device is to replace the previous transient flow calculation with a constant flow of diluted tailpipe exhaust and ambient air. As a result, total emission mass can be estimated more accurately. The design of the CVS is described step by step in the appendix 3.

In addition a port can be fitted in the CVS in order to get particulate mass on the same diluted sample using a Tapered Element Oscillating Microbalance (T.E.O.M.). This instrument will enhance exhaust sample analysis by providing particulate information.

The CVS system has been set up and all instruments have been calibrated. A propane injection test and an engine steady state test have been performed to validate the emission measurement system.

This test consists of injecting propane in the dilution tunnel using a calibrated flow meter. Therefore the mass of injected propane is known and can be compared to the CVS measured mass. This test will confirm that the CVS operates properly and especially that critical flow is correct.

CVS PROPANE TEST		
Propane Concentration	Venturi Number	Bag Flow Rate (Lpm)
99.99%		
CVS flowrate	0.157697311	Normalized cubic meters
Sample time	1.0	seconds
THC Sample	33.625092	ppm C3
THC Background	2.382933	ppm C3
Propane Shot Meas. THC	31.24	ppm C3
Barometric Pressure	29.02	inHg
Line Gage Pressure	59.0	psig
Panel Gage Pressure	50.0	psig
Orifice Temperature	74.4	Deg. F
Absolute Pressure	64.25	psia
CFO Propane Flow Rate	0.01018839	CFM
CVS Total Flow Rate	334.14	CFM Average
Calculated Concentration	30.49	ppm C3
System Error	2.463%	

The propane recovery indicates propane-injected mass within 2.5 %.

Concerning the engine steady state test, the emissions measurement system is used to calculate brake specific fuel consumption and pollutant mass emission while engine is operated at constant load and speed. The results of that test will be compared to publish reference values. The emission based calculated fuel consumption can also be compared to fuel scale measured value.

The engine speed is setup using the dynamometer, the engine load is setup using pedal position sensor. Once speed and torque are at desired levels (1900rpm, 68Nm), a warming up period allows all temperature to reach steady values.

The first step of the validation process consists of verifying that the dilute exhaust volume (V_{mix}) stays constant during the test. Figure20

Figure 20: Dilute exhaust volume during engine steady state test.

In order to have a constant V_{mix} , we will only use the data generated after the 500 first seconds of test.

V_{mix} is used to calculate the emitted mass of the pollutant in g/sec. Figure 21 shows the calculated mass of THC in g/sec from concentration in ppm.

Figure 21: From THC concentration to THC mass.

We can also calculate the diesel fuel rate from emissions data and compare it to measured fuel rate in order to validate our emissions measurement system. Figure 22 and Figure 23

Figure 22: Fuel Rate calculated from emissions data and fuel rate measured.

Figure 23: BSFC calculated from emissions data and BSFC measured.

The average brake-specific fuel consumption (BSFC) measured at this engine torque and speed is 244 g/kWh and 239 g/kWh for the calculated average. The difference of about 2% is consistent with the propane shot test. The following tables gives BSFC results for the same engine at the same operating point tested in different test cells. Our BSFC measurements are compared with those from Daimler, Oak Ridge National Laboratory (ORNL) and the engine and emissions research group at ANL. [13]

		ANL-HIL	ANL-Engine	Daimler	ORNL
Speed [RPM]	Torque [Nm]	BSFC [g/kWh]	BSFC [g/kWh]	BSFC [g/kWh]	BSFC [g/kWh]
1900	70	244 measured 239 calculated	245	230	247

The fuel used was “California Low-Sulfur Commercial 2-D Diesel”: the same than the Engine and Emissions Research group used at Argonne.

The CVS associated with the data acquisition system that supports it, provides transient emission readability and allows accurate calculation of pollutant g/mile. Both calculation of pollutant mass and fuel consumption calculation have been validated and are based on CFR 40 Part 86. The system successfully passed propane injection procedure and engine steady state testing result correlates. (APPENDIX 3 and 4)

Validation of the emissions and fuel measurement system provides confidence in the conclusions that will be drawn from the entire experiment. Similarly, component models validation was necessary to insure the authenticity of the emulated components reaction and to build trust in the hybridization effort performed in simulation.

2 Conventional Diesel

2.1 Conventional Diesel vehicle

Using emulation principle, we are able to evaluate the hybrid powertrain in the Mercedes-Benz C 220 CDI vehicle environment. However, the dynamic of our dynamometer controller is less than desirable to emulate the vehicle losses. Therefore, it is necessary to adapt the testing conditions and the simulation parameters to be able to compare simulation and testing results of the baseline vehicle to the results obtained on the hybrid powertrain. The appropriate process is to:

- Evaluate the actual losses being applied by the dynamometer emulating the vehicle
- Calculate the corresponding A, B, C coefficients
- Test and simulate the Mercedes-Benz C220 CDI with those coefficient
- Compare test and simulation results of the conventional vehicle to the hybrid powertrain where the exact same vehicle is emulated. Figure 24

Figure 24: A, B, C coefficients of the baseline vehicle are based on the emulated vehicle.

In order to simulate and test the vehicle and the powertrain under the same conditions, we need to define the A, B, C coefficients of the emulated vehicle, which could eventually be slightly different from the real baseline vehicle coefficients. A, B and C are the polynomial coefficients of the powertrain pound force curve. We don't measure the force losses but using coast down data, we can calculate those coefficients if we know the exact inertia of the emulated vehicle.

To measure the inertia, we're using the following procedure. The emulated vehicle is disconnected from the HIL hybrid powertrain by disengaging the torque limiter located after the transmission. Figure 25

Figure 25: Torque limiter is disengaged to evaluate inertia of the emulated vehicle.

A ramp up and down test is performed using the dynamometer to propel the emulated vehicle. The principle of the inertia calculation is showed in the figure 26.

Figure 26: Inertia principle

calculation

Dynamometer speed and torque are monitored. At point A, we have:
 $T_{\text{dyno_a}} - T_{\text{friction_a}} = J (dW/dt)_a$ (1)

$T_{\text{dyno_a}}$: Torque produced by the Dynamometer at point A
 $T_{\text{friction_a}}$: Friction torque at point A
 J : emulated vehicle inertia
 $(dW/dt)_a$: Rotational acceleration at point A

We can then write the same equation for B:

$$-T_{\text{dyno_b}} - T_{\text{friction_b}} = -J (dW/dt)_b$$
 (2)

$$(1)-(2) \text{ gives: } J = (T_{\text{dyno_a}} + T_{\text{dyno_b}}) / ((dW/dt)_a + (dW/dt)_b)$$

For repeatability purposes, we used this procedure on two different sets of data. Figure 27 and 28

Figure 27: Torque and speed measured during ramp up and down test 1.

$$(dW/dt)_a = 56.9 \text{ rpm/s}^2 = 6 \text{ rad/s}^2$$

$$T_{\text{dyno_a}} = 47 \text{ Nm (average)}$$

$$(dW/dt)_b = 57.5 \text{ rpm/s}^2 = 6 \text{ rad/s}^2$$

$$T_{\text{dyno_b}} = 34 \text{ Nm (average)}$$

$$J = 6.75 \text{ kg/m}^2 \text{ at dyno shaft}$$

$$J = 112.5 \text{ kg/m}^2 \text{ at wheel}$$

Figure 28: Torque and speed measured during ramp up and down test 2.

$$(dW/dt)_a = 63 \text{ rpm/s}^2 = 6.6 \text{ rad/s}^2$$

$$T_{\text{dyno_a}} = 54 \text{ Nm (average)}$$

$$(dW/dt)_b = 65.7 \text{ rpm/s}^2 = 6.9 \text{ rad/s}^2$$

$$T_{\text{dyno_b}} = 38 \text{ Nm (average)}$$

$$J = 6.81 \text{ kg/m}^2 \text{ at dyno shaft}$$

$$J = 113.5 \text{ kg/m}^2 \text{ at wheel}$$

$$\text{Calculated emulated vehicle inertia} = 113 \text{ kg/m}^2$$

The calculated emulated vehicle inertia can be used to calculate the pound force curve and the corresponding A, B, C coefficients from coast down test ($F = J/R^2 dV/dt$). Those coefficients were used in the entire study to set the simulation and testing parameters. For accurate comparison of the results and to maintain the integrity of our integrated program, it is crucial to use the same A, B, C coefficient in simulation, emulation and testing. (APPENDIX 5)

2.2 Conventional Diesel powertrain

In order to compare test setup prototype with baseline conventional vehicle it has been decided to operate the powertrain as if it would be a conventional vehicle powertrain. To do so, the electric motor has been disabled for the duration of this experiment. This 'Conventional Diesel Powertrain experiment' will also bring understanding for the CVT transmission operation and benefit hybridization of the powertrain. Vehicle controller must be implemented to automatically drive the powertrain over a complete driving cycle. Several components must be simultaneously controlled to achieve proper vehicle operation: Engine on/off, engine torque, clutch displacement, CVT ratio and mechanical brake. The same hardware setup has been used throughout the entire experiment.

2.2.1 Control development

-Engine on/off

Like in a conventional vehicle, the engine starts before the driving cycle and stops after completion. The controller uses a turn key system that automatically turns engine on before drive cycle starts. The engine keeps on idling as the vehicle comes to a stop. Physically ignition and starter commands are two voltage signals sent to the Engine Control Unit (ECU) by the vehicle controller.

-Clutch engagement: Vehicle launches and stops

The clutch realizes the coupling of the engine shaft with the CVT input shaft. It needs to be controlled to achieve proper vehicle operation. This function must be integrated in the vehicle controller as a part of the automated driving control. The clutch control intervenes for vehicle launch and when the vehicle comes to a stop. When the vehicle comes to a stop, engine shaft keeps idling while transmission input shaft stops. The algorithm that was implemented in the vehicle controller simply disengages the clutch, allowing engine to idle, when controller detect that transmission input shaft goes below idle speed during vehicle deceleration.

The clutch engagement process required at vehicle launch is more delicate: Vehicle launch is critical in the sense that CVT input shaft, linked to vehicle inertia, is initially stopped and the engine must provide launching power utilizing clutch friction. As a consequence, engine power and clutch engagement must be controlled simultaneously to achieve smooth vehicle launch without stalling the engine. The control algorithm engages the clutch and monitors engine speed. When this speed drops, because of initial clutch friction, the accelerator pedal is used to provide launching power that quickly accelerates the vehicle (clutch engagement is slower during this phase). Finally, when engine shaft and transmission shaft speeds are close and high enough for the engine to sustain torque, clutch engagement is completed. Physically, the vehicle controller sends a voltage that set the position of a servomotor connected to the clutch hydraulic command line. [14]

-Engine torque

For the vehicle to follow the driving cycle, the controller compares speed profile with instantaneous vehicle speed and uses Proportional Integral (PI) speed regulation. Physically, engine torque is controlled by sending voltage signal to the ECU that emulates pedal position sensor.

-Mechanical brake

Mechanical braking is necessary to meet driving cycle trace during deceleration phases. The PI speed regulation is used to operate brake actuator. This actuator is an air cylinder that pushes on brake master cylinder. Physically, the vehicle controller translates torque into voltage that regulates air cylinder pressure.

-CVT Ratio

Transmission ratio can be changed continuously during operation. The ratio ranges from 2.5 to 0.5 and is physically controlled using a stepper motor thru RS232 series communication. There are several possibilities to operate ratio during a driving cycle. The ratio control is a key parameter of the way the vehicle will perform on a given driving cycle. The ratio can be controlled to provide most efficient engine operation at all time.

Because the ratio can vary continuously, the engine speed is decoupled from the vehicle speed. This is illustrated on the figure 29.

Figure 29: Continuously variable ratio compare to discrete ratio

At each given vehicle speed, engine speed can be set to any value allowed by the ratio range. When for a manual or automatic transmission, discrete engine speed must be chosen among a limited number of gear set.

As a consequence, engine operating point (instantaneous engine torque and speed) can be set freely (within range limits) while the vehicle is being driven over a cycle. This is very advantageous as it can greatly benefit fuel economy and emissions. Adequate continuous control of CVT ratio can keep engine running in preferred efficiency operating range resulting in better fuel economy. This continuous ratio change may also limit transient operation of the engine thus lowering pollutant emission.

2.2.2 Baseline testing

For this experiment, the CVT is being operated at 5 discrete ratios; each ratio corresponds to one gear of the baseline vehicle manual transmission. An engine speed based shifting schedule is used to determine adequate ratio during the course of vehicle operation. Clutch is fully disengaged before and fully reengaged after a shifting event. Although shifting events duration are higher and CVT efficiency lower than those characteristic of an actual manual transmission (despite the torque converter removal), using this shifting approach recreates engine operation as it would be in a manual transmission vehicle context.

-Results

Test 103080/#	/11	/12	/13	Average	Standard Deviation	95% confidence interval
F.E. meas. (mpg)	36.47	36.77	37.84	37.03	0.42	[36.2;38.0]
F.E. calc. (mpg)	36.24	36.78	37.95	36.99	0.51	[36.0;38.1]
NOx (g/mile)	1.09	1.09	1.07	1.08	0.007	[1.06;1.11]
CO ₂ (g/mile)	277.73	273.54	265.28	272.18	3.66	[268.04;276.32]
CO (g/mile)	1.95	1.98	1.80	1.91	0.06	[1.84;1.98]
THC (g/mile)	3.03E-3	3.16E-3	2.67E-3	2.95E-3	1.47E-4	[2.78E-03;3.12E-03]

Test consist of a Federal Urban Driving Schedule (Duration 1372s, distance 7.45mile)

F.E. meas. denotes the fuel economy directly measured while F.E. calc. denotes the fuel economy calculated from emissions data. The average of the three tests will be used as a base for comparison during the entire study. The average provides an estimate but it is important to calculate the standard error from the mean to evaluate the dispersion from the mean. The 95% confidence interval gives an idea of how close the average is from the true value. With a 95% level of confidence, the actual value is within the given interval

independently from measurement variability. The interval calculation is made with an assumption of normal distribution around the average.

The figure 30 shows engine operating points from test data during a FUDS cycle while emulating a manual transmission with the CVT.

Figure 30: Engine operating point

The engine operates in low efficiency area ($< 28\%$) most of the time. Moreover, we can notice important speed and torque variations that have a negative impact on emissions. On the next experiment, we will use the CVT to maintain the engine at a constant speed and assess the impact of transients on emissions.

2.2.3 Impact of engine speed transients

In order to put a figure on the impact of engine speed transients on fuel economy and emissions, CVT ratio was being continuously operated to keep the engine at a constant operating speed of 2000 rpm during this experiment. Therefore, CVT ratio operation is proportional to vehicle speed during the cycle to minimize engine speed transients.

Results

Test 103080/#	/17	/19	/20	Average	Standard Deviation	95% confidence interval	% gain
F.E. meas. (mpg)	40.64	41.37	41.69	41.23	0.54	[40.6;41.8]	11%
F.E. calc. (mpg)	40.33	39.11	41.67	40.37	1.28	[38.9;41.8]	9%
NOx (g/mile)	0.90	0.87	0.89	0.89	0.02	[0.87;0.90]	-18%
CO ₂ (g/mile)	249.99	257.54	241.88	249.80	7.83	[240.94;258.67]	-8%
CO (g/mile)	1.47	1.67	1.49	1.54	0.11	[1.42;1.67]	-19%
THC (g/mile)	2.44E-3	2.68E-3	2.46E-3	2.53E-3	1.3E-4	[2.38E-3;2.68E-3]	-14%

Test consist of a Federal Urban Driving Schedule (Duration 1372s, distance 7.45mile)

% Gain compared to previous experiment

This experiment uses a very simple control algorithm which is not realistically applicable in a real vehicle context. However, the results show the impact of engine speed transients. We observed a gain of 10% in fuel economy and substantial emissions reduction. Limiting engine transients improves both fuel efficiency and emissions without trade-off. This inference will be used for the hybrid control strategy development because electric motor could compensate driver's high dynamics demands while limiting engine transients.

The figure 31 shows engine operating points from test data during a FUDS cycle while maintaining the engine speed constant.

Figure 31: Engine operating point – Constant speed operation

2.2.4 Impact of transmission efficiency

As described previously, the main modification of the CVT was to replace the mechanical hydraulic pump which was connected to the engine thru a torque converter. The pump is a key component of the CVT as it provides adequate belt/pulleys clamping. The torque converter has been replaced by a clutch and the CVT gear pump was replaced by an auxiliary electrically driven pump. This benefits system efficiency because clutch efficiency is better than torque converter efficiency and also because an electrically driven pump allows the optimal control of hydraulic clamping pressure condition by decoupling pump from transmission input shaft. Moreover, compared to the existing pump, an electrically driven pump can be operated when the engine is off and the vehicle is propelled electrically.

Transmission input torque, speed and ratio allow calculation of the optimal clamping pressure as described in “1.4 Emulation: Control and Assembly of the hybrid powertrain”. Closed loop control of the pump provides adequate clamping pressure.

Results

Test 103080/#	/14	/15	/16	Average	Standard Deviation	95% confidence interval	% gain	% gain cumul.
F.E. meas. (mpg)	43.30	43.56	43.04	43.30	0.26	[43.01;43.59]	5%	17%
F.E. calc. (mpg)	42.54	44.28	41.88	42.90	1.24	[41.50;44.30]	6%	16%
NOx (g/mile)	0.88	0.86	0.85	0.86	0.02	[0.85;0.88]	-3%	-20%
CO ₂ (g/mile)	236.24	227.30	239.88	234.47	6.47	[227.15;241.80]	-6%	-14%
CO (g/mile)	1.89	1.60	1.60	1.70	0.17	[1.51;1.89]	10%	11%
THC (g/mile)	2.68E-3	2.49E-3	2.52E-3	2.56E-3	1E-4	[2.45E-3;2.68E-3]	1%	13%

Test consist of a Federal Urban Driving Schedule (Duration 1372s, distance 7.45mile)

% Gain compared to previous experiment

% Gain cumul compared to baseline experiment

This experiment is the same than the constant engine speed operation with the exception of the control of the clamping pressure. In the previous experiment, the clamping pressure was set to a high value to avoid any belt slippage. On this experiment, we want to evaluate the benefit of operating the pump at lower pressure using our pump control algorithm. The % gain column represents the gain compare to the previous experiment while “%gain cumul.” is the percentage gain compare to the baseline experiment.

As expected, applying an optimal clamping pressure increases CVT efficiency and consequently improves fuel economy by 5%. We also can notice a general trend to improve NO_x and CO₂ emissions. Concerning CO and THC, the average results show higher level of emissions. However, because of the uncertainties associated with emissions data collection, we should also look at the confidence interval for an accurate comparison. The CO interval and THC interval for both experiments show an important superposition, demonstrating a limited accuracy of the averages comparison. In more details, if we look at the individual test data, the first test of the second experiment generated 1.89 g/mile of CO. This value is higher than the other tests and participated in the 10% increase of the average CO emissions. It would be erroneous to conclude that pressure control of the CVT causes an increase in CO emissions based on one single test. Because of its benefit on fuel economy, the control algorithm will be used for the rest of the study.

2.2.5 Impact of engine operation

As explained earlier, the CVT allows engine speed setting to any value within the ratio range. Thus, we have an additional degree of freedom (compared to a manual or automatic transmission) to operate the engine. During this experiment, in order to improve fuel economy, we applied a continuous control of CVT ratio to keep the engine running near its most efficient operating point for any given power demand.

Best efficiency operating area for each engine power demand gives the best engine efficiency curve shown in the figure 32.

Figure 32: Engine best efficiency operating curve

CVT offers additional control opportunities to maintain the engine on its best efficiency curve. However, for low power level requirement (below 15kW), the engine would have to operate at a low speed (below 1500rpm) to stay on the curve (point A). Thus, we need to impose a low engine speed limit where engine torque will be allowed to leave the curve in order to satisfy driver's demand. This engine speed limit has been selected using simulation and an example of the simulation analysis is discussed below for two different engine speed limits (1500rpm and 1900rpm).

If the minimum engine speed is set at 1500rpm, for an engine power below the intersection between 1900rpm and the best efficiency curve (point B) and above the intersection between 1500rpm and the best efficiency curve (point A), the engine is kept on the best efficiency curve. Figure 32

If the low engine speed limit is set at 1900rpm, for the same engine power requirement, the engine stays at a speed of 1900rpm and the torque decreases to match power demand. Engine operates between point B and C in figure 33. However, when comparing the area between A and B to the area between B and C, we can conclude that the difference in efficiency is not significant.

Figure 33: Selection of lower operating speed

Now, to complete the analysis, we can compare the efficiency in the low power area at 1500rpm to the low power area at 1900rpm (blue arrows in Figure 33). Similarly, the difference in efficiency is not significant and therefore, according to the simulation results, we should only expect a small fuel economy improvement by setting the low engine speed limit at 1500rpm compared to 1900rpm.

However, if we impose a low engine speed limit at 1500rpm, for low vehicle speed and low acceleration demand conditions, we will generate more engine torque transient than if the limit is set at 1900rpm. We can observe on figure 33 that it takes more torque variation to go from 10kW to 15kW if the engine is at 1500rpm than if the engine is at 1900rpm.

Even if the engine stays longer on its best efficiency curve with the low engine speed limitation is 1500rpm, the fuel economy impact is not significant. However, imposing a low engine speed limit at 1900rpm reduces engine torque transient in low vehicle power conditions. Therefore, for the rest of the study in conventional, we will operate the engine above 1900rpm.

The figure 34 shows engine operating points from test data during a FUDS cycle while maintaining the engine on its best efficiency curve.

Figure 34: Engine operating point – Best efficiency curve operation

The figure 34 shows that the control doesn't achieve to maintain the engine on its best efficiency all the time. This test was performed with a low engine speed at 1500rpm to confirm the impact of torque transient on emissions predicted by simulation. Therefore, when the power level required was below 15kW, the control reduces the engine torque and leaves the curve. Moreover, at high vehicle speed, the CVT ratio range becomes a constraint. At high vehicle speed, once the ratio reaches its minimum, the engine speed keeps accelerating with the vehicle speed. This becomes particularly problematic when the power demand decreases because we have to operate the engine in a low efficiency area. Moreover, if we are not limited by the CVT ratio range, we still have difficulties in controlling the ratio dynamically enough to follow the power variations.

Results

Test 103090/#	/01	% gain	% gain cumul.
F.E. meas. (mpg)	42.22	-2%	14%
F.E. calc. (mpg)	44.45	4%	20%
NOx (g/mile)	1.05	22%	-3%
CO ₂ (g/mile)	226.55	-3%	-17%
CO (g/mile)	1.49	-12%	-22%
THC (g/mile)	2.51E-3	-2%	-15%

Test consist of a Federal Urban Driving Schedule (Duration 1372s, distance 7.45mile)

% Gain compared to previous experiment

% Gain cumul compared to baseline experiment

This experiment demonstrates that we can achieve same fuel economy on operating the engine on its best efficiency curve than when the engine is kept at 2000rpm. We can assume that the higher efficiency operating point compensate from the transient effect on the fuel economy. However, NOx emissions increase. When performing the steady state emissions map of the engine, we notice that the best efficiency curve is located at very high NOx level. Nevertheless, looking at the measured engine operating point on Figure34, it is difficult at this point to assess if the 22% NOx increase is due to engine operating area or engine transients.

The figure 35 shows a summary of the study on the conventional powertrain.

Figure 35: Comparison between the different conventional powertrain control approaches

Those experiments introduce the notion of trade-off between fuel economy and emissions. They also demonstrate the limitations of the CVT in a conventional vehicle: limitation of the ratio range and limitation of the CVT dynamics.

Those issues can be addressed in a hybrid environment where the electric motor can compensate for the slow CVT dynamic and charge the battery to store energy when it is more efficient to operate the engine at a higher load.

3 Hybrid Diesel

The CVT parallel hybrid configuration provides a tremendous flexibility to the choice of both engine torque and speed operation. As a matter of fact, because of the engine and electric motor combination, engine torque can be replaced, assisted or absorbed by the electric motor independently from driver's expectations. As well the transmission continuous ratio variation allows decoupling the engine speed from wheel speed independently of power flow.

Engine operating point is a key parameter of the vehicle control strategy. The engine operation is directly related to fuel efficiency and gaseous emissions as demonstrated on the next experiment.

3.1 Control description

Each component of the hybrid powertrain is independently controlled using the control strategy developed in simulation. The control strategy can be described as the logic that supervises components depending on their status, and the driver input while the vehicle is being driven on a test cycle. The control strategy is critical as it manages energy resources (fuel and battery state of charge) and therefore impacts powertrain efficiency.

Driver has been automated and embedded in the control system as a driver model. The driver model function is emulating real driver using a PI control which compares actual vehicle speed to a driving trace. The driving trace consists of standard velocity vs. time driving cycle such as Federal Urban Driving Schedule (FUDS). The driver model outputs a wheel torque/power demand which may be positive or negative depending on instantaneous driving schedule variation. The torque/power demand is then interpreted by the vehicle control strategy to optimally operate each component while meeting the driving trace.

Battery State Of Charge (SOC) indicates availability of electrical energy stored in the battery and its preservation is a key feature of hybrid control strategy. Not only must the SOC be maintained so that motor torque is available to drive the vehicle but SOC must also allow energy recovery from the wheels during deceleration by regenerative braking. Battery life may be affected if state of charge goes out of a define range or instantaneous power exceeds theoretical limitations. Therefore in addition of the SOC preservation, the control strategy must ensure that electrical power flows are not affecting the battery life. This is performed thru constant monitoring and limitation of SOC and motor power and achieved thru motor torque limitations.

All vehicle launches are made using pure EV mode. EV mode will temporarily be used while cruising if driver demand does not require engine to supply power. When engine is on, motor can supply additional torque and to enhance vehicle performances. The motor can also absorb a part of the engine torque acting as a generator while cruising. This mode is used to charge the battery.

The electric motor allows recovery of the vehicle inertial energy during a deceleration. Regenerative braking energy stored in the battery may later be reused. Mechanical brake is used when motor cannot alone decelerate the vehicle. The mechanical brake is then operated to ensure that vehicle meet driving trace.

Because electric motor alone can temporarily supply power, the engine is not required at all time. The strategy must decide when engine must be fired or killed. This engine on or off decision is based on power demand. Engine will be fired when power demand exceeds acceptable level. Power demand is based on both driver input and battery state of charge. Similarly engine will be killed when its power is no longer required.

The control strategy logic is described in the figure 36 and in the table below.

Figure 36: Simplified control strategy logic

The following table describes the outputs of the strategy functions

Output	Logic	Description
Wheel torque demand	DRIVER LOGIC	Torque required at the wheel is calculated using closed loop Proportional Integral PI speed regulation
Driver power demand	DRIVER LOGIC	Power required for vehicle to follow the cycle is calculated using vehicle speed and wheel torque demand
SOC power demand	SOC LOGIC	Power required to maintain fixed SOC target is calculated using closed loop Proportional P regulation
Total power demand		Sum of both driver and SOC power demand
Engine ON command	ENG. ON LOGIC	If total power demand exceeds 20kW engine turns ON. If power demand is lower than -20kW engine turns OFF
Clutch command	CLUTCH LOGIC	Clutch is engaged when engine is ON. Clutch is disengaged prior engine shut off.
Engine torque command	ENG. TRQ. LOGIC	Engine torque command is calculated using engine target torque according to total power demand
Motor torque command	MOT. TRQ. LOGIC	Motor torque command is based o wheel torque demand engine measured torque and CVT ratio measured.
CVT ratio command	ENG. SPD. LOGIC	CVT ratio command is calculated using engine target speed according to total power demand
brake command	BRAKE LOGIC	Brake supplies negative torque at the wheel if motor torque reaches limits and to match wheel torque demand

(APPENDIX 6)

3.2 Impact of control on fuel economy

Engine brake specific fuel consumption data allows calculating engine efficiency. It is therefore possible to determine the most efficient engine operating point for each power. The best efficiency curve describes the optimal operation. When the engine is on, its torque and the CVT ratio are controlled to operate the engine at the most efficient point while satisfying engine power demand. Figure 37

Figure 37: Engine best efficiency curve

Hybridization brings a second degree of freedom compare to a conventional powertrain with CVT. The electric motor can compensate for the slow dynamic of CVT ratio change but also allows the engine to operate at a higher power than the driver power demand. The excessive power can be used to recharge the battery using the motor as a generator. If the battery state of charge (SOC) becomes too high or the driver power demand too low, we have the possibility to turn the engine off and propel the vehicle in electric. Consequently, the control of the engine is more accurate than with a conventional powertrain with CVT.

Figure 38 displays typical engine operation during a test that was performed with the best efficiency strategy. Engine power demand is calculated to match driver expectations as well as battery state of charge requirement. The engine power required is then interpreted by the control strategy in order to set engine torque command and CVT ratio command. This results in the engine operating near the best efficiency curve.

Figure 38: Engine operation point using the best efficiency strategy

The color density on this plot is proportional to the time spent by the engine on the operating area. Compared to the Figure 34, we can notice that the engine stays closer to the best efficiency curve. At high load and an engine speed above 2300rpm, the control reduces the engine torque because the motor cannot absorb all the excessive power generated by the engine. The motor being above its base speed, it is limited in maximum negative torque capacity. The driver power demand having priority on the best efficiency curve, the control has to leave the optimal (in terms of fuel consumption) mode of operation. We can also notice that we can operate the engine at a lower speed than in conventional and stay on the curve.

Results

Test 103110/#	/01	/02	/03	/06	/12	/15
F.E. meas. (mpg)	45.23	58.33	67.23	52.69	48.38	69.95
F.E. calc. (mpg)	44.50	61.19	69.39	55.63	50.69	76.08
Delta SOC (%)	+29.8	-1.91	-19.33	+9.71	+18.48	-21.06
NOx (g/mile)	1.77	1.29	1.12	1.59	1.84	1.13
PM (g/mile)	NA	NA	NA	0.086	0.087	0.061
CO ₂ (g/mile)	228.7	166.3	146.6	182.8	200.4	133.8
CO (g/mile)	43E-3	22E-3	29E-3	82E-3	#NV#	#NV#
THC (g/mile)	#NV#	3.3E-3	3.8E-3	9.4E-3	4.9E-3	9.4E-3

Test consist of a Federal Urban Driving Schedule (Duration 1372s, distance 7.45mile)

Both fuel usage and battery SOC must be taken into account when calculating or measuring the fuel economy (FE). The Figure 39 shows how to estimate the corrected FE (i.e.: what the fuel economy would be in case of SOC equalization over the test cycle).

Figure 39: Regression of Fuel Economy versus Delta SOC – Best efficiency strategy

This regression analysis studies how fuel economy varies across different tests indexed by delta SOC. It assumes that this relationship is linear on average. We need to estimate this linear relationship to make predictions (such as fuel economy prediction with SOC equalization). With the use of statistical theory, we can perform inferences about those predictions (such as confidence interval).

The concept is that the coefficients of the regression line are estimators of the real coefficients since we have a limited number of tests. The corrected FE is an estimate for the average fuel consumption. Thus, we can calculate its standard deviation and confidence interval in order to quantify the variability due to the test.

Results summary

Test 103110/ #	/01	/02	/03	/06	/12	/15	Corrected FE	Average	Standard Deviation	95% confidence interval	% gain	% gain cumul.
F.E. meas. (mpg)	45.23	58.33	67.23	52.69	48.38	69.95	58.2	57.0	1.4 for corrected FE	[54.4; 62.1] for corrected FE	38%	57%
F.E. calc. (mpg)	44.50	61.19	69.39	55.63	50.69	76.08	61.1	59.6	2.3 for corrected FE	[54.8; 67.3] for corrected FE	37%	65%
Delta SOC (%)	+29.8	-1.91	-19.33	+9.71	+18.48	-21.06	0	+2.62	NA	NA	NA	NA
NOx (g/mile)	1.77	1.29	1.12	1.59	1.84	1.13	NA	1.46	0.32	[1.20; 1.71]	39%	35%
PM (g/mile)	NA	NA	NA	0.086	0.087	0.061	NA	0.078	0.015	[0.066; 0.090]	NA	NA
CO ₂ (g/mile)	228.7	166.3	146.6	182.8	200.4	133.8	NA	176.4	35.1	[148.4; 204.5]	-22%	-35%
CO (g/mile)	43E-3	22E-3	29E-3	82E-3	#NV#	#NV#	NA	0.044	0.027	[0.023; 0.065]	#NV#	#NV#
THC (g/mile)	#NV#	3.3E-3	3.8E-3	9.4E-3	4.9E-3	9.4E-3	NA	0.0062	0.0030	[0.0037; 0.0086]	#NV#	#NV#

Test consist of a Federal Urban Driving Schedule (Duration 1372s, distance 7.45mile)

% Gain compared to previous experiment

% Gain cumul compared to baseline experiment

The 95% confidence interval for fuel economy is wider in hybrid mode because in addition to the test variability, we introduce a second variability by predicting the fuel consumption at a deltaSOC = 0 with a linear regression.

With the assistance of the electric motor, in hybrid, the engine operates closer to its best efficiency curve. As a consequence, the fuel economy increases by 38% compare to the same control principles used in a conventional mode with CVT and by 57% compare to the baseline 5-speed manual emulated conventional powertrain. This experiment is critical to demonstrate the potential of hybridization and control. The 57% fuel economy improvement denotes the impact of hybridization but the same components were used in both experiments (baseline and hybrid). The baseline powertrain uses all the components of the complete hybrid powertrain. In order to consider only the control aspect, the baseline is penalized by the CVT transmission operating as a manual (a manual transmission would be more efficient) and by the electric motor inertia and bearing losses.

Despite the fuel economy improvement, we can also notice a 39% increase in NOx emissions. We already observed this tendency in conventional operation but now that the engine is always operating on the best efficiency curve, we can correlate this NOx emissions increase to the engine operating point. Figure 40 shows the engine operating points on the NOx emissions map of the engine.

Figure 40: NOx emissions map based on steady state data

This map has been established using ANL test data of engine steady state. The best efficiency curve is located in high NOx emissions areas.

This experiment demonstrates the need for a trade-off between fuel economy and harmful NOx emissions.

(APPENDIX 7)

3.3 Trade-off between fuel economy and NOx emissions

Nitrogen Oxides NOx emission data allows definition of a minimal NOx curve that can be used to determine the lowest NOx production at each power. For each power, if several NOx minimums exist, the controller selects the most efficient operating point. The engine torque and the CVT ratio are controlled to operate the engine on this NOx / FE trade-off curve while satisfying engine power demand. Figure 41 shows the trade-off curve that has been calculated in simulation. (APPENDIX 8)

Figure 41: NOx / FE trade-off curve

The figure 42 displays typical engine operation during a test that was performed with the trade-off strategy. Engine power demand is calculated to match driver expectations as well as battery state of charge requirement. The engine power required is then interpreted by the control strategy in order to set engine torque command and CVT ratio command. This results in the engine operating near the trade-off curve

Figure 42: Engine operation point using the trade-off strategy (APPENDIX 9)

The color density on this plot is proportional to the time spent by the engine on the operating area. Compared to Figure 37, we can notice that the engine is operating at lower load and higher speed. Consequently, the motor is able to absorb the excess power generated by the engine and is not limited by its negative torque.

Each test consists of the Federal Urban Driving Schedule. The vehicle performs over several tests in order to check test repeatability. Initial and target battery SOC is changed before each test. This provides a range of SOC variation that will allows corrected FE calculation.

Results

Test 103110/#	/08	/10	/11	/16	/17
F.E. meas. (mpg)	51.97	50.36	42.97	59.98	60.25
F.E. calc. (mpg)	54.11	52.48	44.64	59.55	61.09
Delta SOC (%)	+1.26	+2.7	+21.53	-16.86	-17.33
NOx (g/mile)	0.521	0.559	0.819	0.407	0.409
PM (g/mile)	0.119	0.125	0.211	0.112	0.112
CO ₂ (g/mile)	187.2	193.4	227.4	170.3	165.6
CO (g/mile)	0.372	0.260	0.272	0.293	0.456
THC (g/mile)	80.7E-3	22.2E-3	24.3E-3	19.7E-3	76E-3

Both fuel usage and battery SOC must be taken into account when calculating or measuring the fuel economy (FE). The Figure 43 shows how to estimate the corrected FE (i.e.: what the fuel economy would be in case of SOC equalization over the test cycle).

Figure 43: Regression of Fuel Economy versus Delta SOC – Trade-off strategy

Results summary

Test 103110/ #	/08	/10	/11	/16	/17	Corrected FE	Average	Standard Deviation	95% confidence interval	% gain	% gain cumul.
F.E. meas. (mpg)	51.97	50.36	42.97	59.98	60.25	52.3	53.1	0.5 for corrected FE	[50.6; 54.0] for corrected FE	- 10%	41%
F.E. calc. (mpg)	54.11	52.48	44.64	59.55	61.09	53.7	54.4	0.9 for corrected FE	[50.8; 56.6] for corrected FE	- 12%	45%
Delta SOC (%)	+1.26	+2.7	+21.5 3	- 16.86	- 17.33	0	-1.74	NA	NA	NA	NA
NOx (g/mile)	0.521	0.559	0.819	0.407	0.409	NA	0.543	0.17	[0.395; 0.691]	- 63%	-50%
PM (g/mile)	0.119	0.125	0.211	0.112	0.112	NA	0.136	0.042	[0.099; 0.173]	NA	NA
CO2 (g/mile)	187.2	193.4	227.4	170.3	165.6	NA	188.8	24.5	[167.3; 210.2]	7%	-31%
CO (g/mile)	0.372	0.260	0.272	0.293	0.456	NA	0.331	0.083	[0.258; 0.403]	NA	NA
THC (g/mile)	80.7E -3	22.2E -3	24.3E -3	19.7E -3	76E-3	NA	0.0446	0.0309	[0.017; 0.071]	NA	NA

Test consist of a Federal Urban Driving Schedule (Duration 1372s, distance 7.45mile)

% Gain compared to previous experiment

% Gain cumul compared to baseline experiment

Compared to the previous experiment, we have a fuel economy penalty but NOx emissions are reduced. The figure 44 proposes a comparison analysis of the baseline experiment and the two hybrid modes of operation.

FE and NOx result summary chart
Figure 44: Comparison analysis

Hybrid operation PM and NOx summary

Operating the engine with the best efficiency approach increases fuel economy by 57%. This efficient engine utilization results in a 35% increase in NOx emissions. The NOx / Fuel Economy trade-off approach provides a 50% NOx reduction, while improving the fuel economy by 41%. However, it also results in an increase in PM emissions.

Those results refer to an emulated conventional vehicle, which is actually penalized by the inefficiency of a CVT acting as a manual transmission as well as the losses and inertia of a disabled electric motor. The NOx and PM emissions results are averages of the tests performed and are not SOC corrected. Consequently, the average delta SOC should be considered in order to interpret correctly the analysis.
(APPENDIX 10)

4 Conclusion

In this study, two different hybrid control strategies are presented. The objective of the study is not to optimize the control strategy but to assess the impact of hybridization and control and to demonstrate the potential of diesel to minimize fuel economy penalty while meeting emissions regulations. The figure 45 shows a comparison of our results for the experiments in conventional mode and figure 46 for the experiments in hybrid mode.

Figure 45: Comparison analysis for the conventional mode

This figure demonstrates that the control strategy has a limited impact on emissions for a conventional powertrain. In hybrid mode, we increase the degree of freedom and the potential for control impact on both emissions and fuel economy.

Figure 46: Comparison analysis for the hybrid mode

Figure 46 shows the trade-off between fuel economy and NO_x emissions. It demonstrates and quantifies the control strategy impact on fuel economy and emissions for diesel hybrid vehicles. To complete the evaluation of diesel hybrid technology, after-treatment devices should also be considered. Optimal control of the system would include engine calibration and advanced after-treatment devices such as particulate filters or NO_x absorber. At this time, particulate filter technology is more mature than NO_x absorber. However, the development of an after-treatment control integrated to the vehicle control strategy would complete the demonstration of a diesel hybrid as a short-term bridge to a hydrogen economy.

5 Recognition

This study has been made successful because of the Argonne's Center for Transportation Research flexible systems approach that links state-of-the-art testing and emissions measurement capabilities with accurate computer simulations (emulation) and component and vehicle testing (validation). The Advanced Powertrain Research Facility (APRF) is the U.S. Department of Energy's (DOE's) key laboratory for powertrain testing and validation.

The capabilities of our hybrid powertrain have been presented during the APRF dedication at a ribbon-cutting ceremony attended by 117 members of U.S. Congress, officials, and staff from DOE and Argonne, automobile manufacturers, the media, and others. U.S. Representative **Judy Biggert** (R-IL); DOE Deputy Assistant Secretary for Energy Efficiency and Renewable Energy (EERE) **Richard Moorer**; Argonne Laboratory Director **Hermann Grunder**; Argonne Associate Laboratory Director **Harvey Drucker**; and USCAR Executive Director **Bob Culver** gave opening remarks at the dedication. Others who attended the event included auto industry executives from Ford, General Motors, BMW, Honda, and DaimlerChrysler; DOE sponsors **Bob Kost**, Vehicle Systems Team Leader, Office of FreedomCar Vehicle Technologies, and **Lee Slezak**, who is a member of the team.

"This facility provides researchers with the tools needed to develop and evaluate vehicle components that will meet America's changing transportation needs," said DOE's Moorer. "The facility will help industry enhance energy efficiency and productivity by bringing clean, reliable and affordable energy technologies to the marketplace while reducing dependence on foreign supplies of oil. This will make a difference in the everyday lives of Americans by enhancing their energy choices and their quality of life."

Asserted Argonne's Grunder, "Argonne is an ideal place for this R&D to occur. We have one of the largest EERE transportation R&D budgets in the national laboratory system with 10 divisions actively participating in developing cutting-edge technologies in engines, fuel cells, batteries, advanced materials, heat exchangers, aerodynamic and thermal modeling, and fuel processing. We are centrally located for the automotive and truck industries, have unique scientific research facilities, and have excellent working relationships with many of the major industry players worldwide."

"This unique combination of analytical, development and testing experience provides DOE with the latest techniques to evaluate new vehicle technologies in both emulated and real-vehicle environments," said CTR Director **Bob Larsen**. "Argonne's long history in modeling, developing and testing advanced engines, hybrid-electric vehicle powertrains and control systems, traction batteries, fuel cells, and vehicles is a large part of making Argonne an important laboratory for vehicle technology development and validation."

This project was also presented to David Garman, Assistant Secretary for DOE's Energy Efficiency and Renewable Energy (EERE) Office, during a visit to Argonne National Laboratory. The demonstration of the Diesel hybrid powertrain showed how Argonne research supports DOE's work to reduce dependence on oil imports.

(Left to right) U.S. Rep. Judy Biggert (R-IL); Argonne Laboratory Director Hermann Grunder; DOE Deputy Assistant Secretary for Energy Efficiency and Renewable Energy Richard Moorer; and Argonne Associate Laboratory Director Harvey Drucker dedicate Argonne's Advanced Powertrain Research Facility (APRF).

(Left to right): Argonne's Harvey Drucker and Hermann Grunder with Chairman of the DuPage County Board Bob Schillerstrom; USCAR Executive Director Bob Culver; DOE's Richard Moorer; and U.S. Rep Judy Biggert.

(Left to right): Argonne's Hermann Grunder; Assistant Secretary for DOE's EERE Office David Garman; Argonne's Harvey Drucker.

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APPENDIX 1: PSAT-PRO[®] User Guide

INTRODUCTION

The purpose of PSAT-PRO is to facilitate the development of system controllers. PSAT, the PSAT-PRO companion for simulation allows analysis studies and vehicle power management development.

PSAT-PRO offers you the capability to use and to enhance your modeling work for control purposes. It allows the test of your power management system in a real environment or in Hardware-In-the-Loop (HIL). HIL is a technique for performing system-level tests in a quick and cost effective manner. HIL can be used to test Hybrid Electric Vehicle (HEV) components when they cannot be tested or instrumented easily in their operational environments.

SOFTWARE REQUIREMENTS

PSAT-PRO software has been developed in order to facilitate HEV control development. The software has been designed in order to optimize the link between modeling and prototyping, especially for the use and transfer of work from modeling to real world applications. It uses PSAT modeling software as a base and cannot be used independently. That's why PSAT modeling software is required to use PSAT-PRO control software.

PSAT-PRO is a Matlab based software using the following toolboxes:

MATLAB Toolbox	Version 5.3 (R11)	Version 6.1 (R12.1)
Simulink	Version 3.0 (R11)	Version 4.1 (R12.1)
Real-Time Workshop	Version 3.0.0 (R11)	Version 4.1 (R12.1)

PSAT-PRO INSTALLATION WITHOUT A PERSONAL MATLAB STARTUP

If you have never created a personal Matlab startup, then use the following procedure:

Open your explorer and select the drive where your installation source is located.
Double-click on the installation icon (PsatProInstall).

Acknowledge the PSAT-PRO Copyright disclosure and click 'OK'.

Enter the complete path where you want to install PSAT-PRO. By default, the software will be install under c:\ASAP\PSAT-PRO (ASAP stands for Argonne National Laboratory System Analysis Program).

PSAT-PRO uses PSAT models component library. It is necessary to characterize the location of PSAT; this needs to be done when first installing PSAT-PRO. This shall also be implemented if the PSAT location changes.

When the next window appears, select the location of the PSAT folder. Please, select only the PSAT folder and not the subdirectories.

Example:

Note: In this example, PSAT has been installed under C:\ASAP\PSAT and now, the user want to install PSAT-PRO under the same directory C:\ASAP\PSAT-PRO. But it is not necessary to install PSAT-PRO under the same directory than PSAT.

Wait until all the PSAT-PRO directories have been installed.

Congratulation, you are ready to start a PSAT-PRO session!

PSAT-PRO INSTALLATION WITH A PERSONAL MATLAB STARTUP

If you have a personal Matlab startup (particularly if you change the initial work directory), then you have to

Type `cd X:\psat_pro\root_pro; PsatProInstall` in your Matlab workspace:

This line will set the correct working directory and evaluate the installation file. You should replace **X** by the letter of the drive where your installation source is located.

Example:

Acknowledge the PSAT-PRO Copyright disclosure and click 'OK'.

Enter the complete path where you want to install PSAT-PRO. By default, the software will be install under `c:\ASAP\PSAT-PRO` (ASAP stands for Argonne National Laboratory System Analysis Program).

PSAT-PRO uses PSAT models component library. It is necessary to characterize the location of PSAT; this needs to be done when first installing PSAT-PRO. This shall also be implemented if the PSAT location changes.

When the next window appears, select the location of the PSAT folder. Please, select only the PSAT folder and not the subdirectories.

Example:

Note: In this example, PSAT has been installed under C:\ASAP\PSAT and now, the user want to install PSAT-PRO under the same directory C:\ASAP\PSAT-PRO. But it is not necessary to install PSAT-PRO under the same directory than PSAT.

Wait until all the PSAT-PRO directories have been installed.

Congratulation, you are ready to start a PSAT-PRO session!

PSAT-PRO FIRST START

Start a PSAT-PRO Session

To start using PSAT-PRO, you have to select it in the start menu located at the bottom of your Matlab workspace.

The start menu will appear at every Matlab session. If you want to use your personal Matlab startup program, it has been saved as startupsav.m. You can still launch it by selecting “username Matlab startup” in the start menu.

Acknowledge the PSAT-PRO Copyright disclosure and click ‘OK’.

Create a New Project

To create a new project, click on 'NEW'. If it is your first session, you can only choose 'NEW'. (The 'BROWSE' button is disabled because no project has been created before).

Choose a name for the project you are creating, you can mix numbers and letters. Please avoid space or special characters which may creates problem ('_' and '-' are ok). Then, Click 'OK'.

Warning messages may appear if the project name is not correct. In this case, you just have to follow the instructions.

Now you just have to choose the PSAT configuration you are interested in for control purposes. You can do this in the window: 'START A NEW PROJECT'. Select the right configuration using the popup menu and Click on 'START'.

The list is composed of PSAT saved and default configuration. You have the possibility to use the particular configuration you worked at in modeling using the PSAT graphical user interface. See: "6 - Create and Import a Specific PSAT Configuration p.10" for more details.

Now the Program will create your project and all requirements for you to be able to develop your own control system using PSAT-PRO. You should not interfere with the program while it is creating the project. It is recommended to wait until the PROJECT MANAGER window appears.

Congratulation, you are ready to work with PSAT-PRO!

Create and Import a Specific PSAT Configuration

Open a PSAT session.

Set up the vehicle configuration you are interested in with the first GUI window.

Click on the save button of the same window.

A saving window opens and you just have to give a name to your file:

Make sure to respect the convention **gui_*_in**.

Use the saving window browser to save the file.

Save it under your personal PSAT user folder or your personal PSAT-PRO user folder if it exists already (/psat_pro/root_pro/users/***username***).

Click on save.

You can close the PSAT Session, and start the creation of a prototyping project by starting a PSAT-PRO Session.

Open an Existing Project

To open an existing project, click on 'BROWSE'.

Select the project you want to work at, using the popup menu and click on 'OPEN'. The list is composed of the projects available on your user folder.

If you wish to open another existing project (created by another user), click 'Other...':

A browser window appears, use it to select the project folder you wish to open. And click open. The project you are interested in has been added to the popup menu list. You are now able to select and open it.

Note: Even if you can select this project from your popup menu, the project hasn't been saved under your user directory. You are working on the original project of another user. Any modifications to the project will be saved under the first user directory. This sharing work should be done with a lot of care and communication to avoid losing any work between the different users.

PSAT-PRO opens the latest version of the project you wish to work on.

PSAT-PRO DESCRIPTION

Work in a PSAT-PRO Project Environment

This is PSAT-PRO top-level Simulink window

The 'ptc' block (stands for PowerTrain Controller) is the controller of your system. Its only input is the measure bus, which is composed of signals coming from the vehicle model block in case of simulation, from your sensors otherwise.

The 'cond' block is a signal CONDitioning subsystem. It interfaces output signals from the 'ptc' controller block to the vehicle model or the real system.

The 'Vehicle_model' block is fairly similar to PSAT powertrain model. It is build, using the PSAT component model library. The input is the command signal bus and it outputs the simulated measure bus. The vehicle model features specific PSAT-PRO control functionalities.

The 'to_workspace' block declares all information the buses are made of, to Matlab workspace. This block also features signal plotting.

In the 'ptc' block, you can find all the functions necessary for the control of your system.

'sur' block detects all the potential default and send an appropriate warning to the 'emrg' block if necessary

'param' block transform the measure bus in a parameter bus where the variables are coming directly from the sensors or from a calculation.

'drv' block is a representation of a driver which can regulate the vehicle speed and follow a cycle.

'cstr' block calculates the constraints of each components of the system. This block is initially import from the PSAT environment.

'dmd' block represents the control strategy of your system. It optimizes the components commands. This block is initially imported from the PSAT environment.

'trs' block controls the component to respect the decisions taken in the 'dmd' block. This block is initially imported from the PSAT environment.

'input' block allows the user to switch between the commands coming out of the 'trs' block and his own commands.

'sat' block saturates the components commands by the constraints calculated in the 'cstr' block or by a constant value imposed by the user.

'emrg' block sends an emergency procedure to the system in accordance to the type of default detected.

Use the Model Browser

The model browser window on the left displays the architecture of the model. The model browser is a convenient way to navigate through the Simulink blocks.

Use the Project Manager Interface

This interface was kept simple to perform project management and remote simulation.

The project management consists of several main functionalities:

Update the different buses anytime during the development of your project. This function can be used after a modification of the bus system or when a signal has been added to a bus. See “**21 – Create a new Signal and its Selector p. 26**” for more details.

Saves all the blocks and information you modified in your project. This function opens the VERSION MANAGER interface, which propose saving and versioning of your work. See “**11 – Save and Manage the Different Project Versions p. 15**” for more details.

Allow you to access the different versions of your project. The project current version is displayed between the two push buttons. **It is possible to save modifications at the top version level only.**

Allow you to close the PSAT-PRO Session with or without saving the last modifications.

The simulation board consists of a popup menu to choose a standard driving cycle, but also Play, Pause or Stop the simulation.

PSAT-PRO PROJECT DEVELOPMENT

Save and Manage the Different Project Versions

Click on the save button of the PROJECT MANAGER Interface:

The next window appears:

-There is a check box for each block of your project.

-A disabled check box indicates that the corresponding blocks have not been modified since you last opened the project.

-Parameter, Survey, Vehicle and signal conditioning check boxes are never disabled in order to allow some of the PSAT-PRO Functionalities.

The use of the CANCEL button will close the VERSION MANAGER interface without saving any block.

The information bus system is checked and updated every time you save your project.

You can decide to select or not the check boxes.

When you click on save:

-Any block corresponding to an enable and blank check box will be save in its specific library under its current top version.

-Any selected block will be saved in its specific block library under a new block version.

If one or more check boxes are checked: The project version will be upgrade, otherwise, the project version remains the same. Only the modifications done on the project top version can be save.

Block versioning is hidden for the user, the user can only access project versioning. Which is displayed on the PROJECT MANAGER. It is recommended to use the versioning wisely by saving a new version at each big step of PSAT-PRO controller development. It is also highly recommended to save regularly your project under its current version (No check box selected).

Once you are satisfied with this block or even if you didn't finish this work, you can save it. By using the PROJECT MANAGER, you will be able to modify again this block in the present or

future PSAT-PRO session, at any step of the project development. See **“11 – Save and Manage the Different Project Versions p. 15”**.

Set up the Signal Survey

Use the model browser to open the 'ptc' block then the 'sur' block.

All the measured signals are surveyed in PSAT-PRO Controller. It is the purpose of each 'signal survey' block.

Double click on one of the 'signal survey' block:

Set the upper and lower limit of the signal using the interface: For each limit, you can choose to write a constant or check the external upper/lower input box to choose the constraint you want to survey the signal with. The constant values are displayed on the survey_block.

Choose the emergency level within the top popup menu. When a signal will cross one of the limits, the emergency block will react adequately.

This will allow for example to detect and react to a motor over speed. **You need to set the survey for each signal.**

Do not forget to save your work with the PROJECT MANAGER.

Set up the Signal Saturation

For safety purposes, all output signals of the PSAT-PRO controller must be saturated and inhibited by the emergency survey system. This will avoid sending wrong command to the components, which may result in damages or hazards.

To modify a saturated value:

Use the model browser to open the 'ptc' block.

Select the 'sat' block (the last but one block from the left) in the work area.

Right click and select 'Break library link'.

Use the model browser to open the 'sat' block.

Double-click on the block corresponding to the desired signal.

Set the upper and lower saturation limit of the signal using the interface: For each limit, you can choose to write a constant or check the external upper/lower input box to choose the constraint you want to saturate the signal with. The constant values are displayed on the survey_block.

Set the saturation for each signal.

You can now close the block and save your project.

Warning: The saturation block is protected and you have to break the library link to be able to modify it. It is the user responsibility to set the appropriate saturated values.

Set up the Emergency Signals

The emergency block allows the user to set the commands in case of a default. The block will output the commands corresponding to the right level of emergency detected in the survey block.

To set the commands in function of the emergency procedure:

Use the model browser to open the 'ptc' block.

Select the 'sat' block (the last but one block from the left) in the work area.

Right click and select 'Break library link'.

Double-click on the above block corresponding to the desired signal.

Set the HARD and SOFT emergency command values and click OK.

Repeat this to all signal present in the emergency block.

Don't forget to save your project.

Example: For the brake command, you may set the HARD emergency value to the max braking torque in order to stop your system motion as soon as possible, in case of SOFT emergency, you may set the brake command to zero, so your system will stop smoothly.

Warning: The emergency block is protected and you have to break the library link to be able to modify it. It is the user responsibility to set the appropriate emergency procedure.

Default detection will result in the interruption of the simulation within the next 2 seconds. It is then possible to check which signal cross its limit by going in the 'sur' block. A display shows the state off all the survey block output signals (1,2 and 3 for NONE, SOFT and HARD emergency stop).

You can also have a comprehensive plot to understand which error occurred and when it occurred by double-clicking on this push-button:

Note: For your records, the signals responsible for the emergency stop have been saved under EmrgStopHistFile.mat.

PSAT-PRO TOOLS DESCRIPTION

Plot the Signals

PSAT-PRO proposes an easy simulation signal-plotting tool. You can use it even during a simulation pause, and then keep on the simulation.

To plot a signal:

Use the browser to go in the 'to_workspace' block.

You can access all the project signals. Those signal are gathered within 3 busses of information in the three different blocks:

- In 'meas_space': You can access the measure signals
- In 'param_space': You can access the parameter signals
- In 'ptc_space': You can access the signal generated in the controller

Go in one of those blocks using the model browser:

Double click on the signal you wish to plot, double click on new figure to create a new plotting window.

If you double click many signals in a row, they will appear in the same figure.

Double click on auto scale if you want the signals to be sized at the same range.

Use the PSAT-PRO User Library

PSAT-PRO facilitates the control system development. Using state-of-the-art tools, you will be able to develop your own controller, to download it and to test it rapidly.

In order to have an easy access to the PSAT-PRO blocks developed under a particular project, the library of your project has been added to the Simulink library browser. Using the library of your project, you will be able to drag and drop any block created and saved in your project library.

To open the Simulink library browser, type “simulink” on the Matlab workspace.

Note: You may have to close and re-opened the Simulink library browser in order to update it.

Use the PSAT-PRO Selectors Library

A selector generates as output a selective element of the input bus.

Every selectors used in your model are included in your PSAT-PRO project library. This allows the user to re-use a signal created before.

There are two types of selectors: They can be related to the ptc bus or to the parameter bus. The ptc bus carries all the information generated by the powertrain controller and the parameter bus carries the measures and the calculated variables.

In the Simulink library browser, select your PSAT-PRO project library and then the right selector depending if you need a signal coming from the ptc bus or from the parameter bus.

Use the Selector Autoplug Function

Every selector used in the model, even those newly created by the user. (See “21 – Create a New Signal and its Selector p. 26”), can be plugged automatically to their related bus. This functionality avoids any mistake in the use of the variable buses.

By a simple double-click, the selector will be automatically plugged to its bus or to a feedback of the bus. In fact, you have the possibility to use a signal in a PSAT-PRO block before this signal has been generated. In this case, the selector will be plugged to a feedback of its related bus with a memory. The calculation will be performed using the step before value of the signal.

Example: You need to know what's the engine speed measured on your system and what's the torque command sent to the engine to develop your control strategy.

Use the model browser to open the ptc block.

Select the dmd block (which is dedicated to the control strategy) in the work area.

Right click and select 'Break library link'.

Use the model browser to open the dmd block.

Open your control strategy (strategy 2 on this example).

Open the PSAT-PRO selectors library browser.

Drag and drop the engine speed selector from the parameter bus.

Double-click on it and the link to the parameter bus input will appear.

Drag and drop the selector corresponding to the engine torque command sent out from the ptc bus.

Double-click on it and the ptc bus feedback with a memory block will appear.

Example: You want to add a new signal to the trs block.

As this signal has been calculated in the trs block, it has been added to the ptc bus. You can now use this signal anywhere in your system. You just have to drag and drop the selector that has been generated.

Example: Now, you want to saturate the new signal in the sat block. You need to select your signal from the coming ptc bus.

Drag and drop the selector corresponding to your signal from the appropriate bus.
Double-click on it and the link to the appropriate bus will appear.

Congratulation, your selector has been created and you have been able to use it!

APPENDIX 2: Instrumentation

MEASURE	PHYSICAL MEASUREMENT			
	Type	min	max	unit
DYNO SYSTEM				
DIGALOG SPEED CMD	SPEED	0	5000	RPM
DIGALOG TORQUE CMD	TORQUE	-542	542	Nm
DIGALOG SPEED	SPEED	0	5000	RPM
DIGALOG TORQUE	TORQUE	-814	814	Nm
AIR IN TEMP	TEMP	0	500	Deg. C
AIR OUT TEMP	TEMP	0	500	Deg. C
OIL PRESSURE	PRESSURE	0	500	PSI
CVT				
SUMP TEMP	TEMP	0	500	Deg. C
CASE TEMP	TEMP	0	500	Deg. C
OIL TEMP	TEMP	0	500	Deg. C
DRIVE PULLEY PRESSURE	PRESSURE	0	1000	PSI
DRIVEN PULLEY PRESSURE	PRESSURE	0	1000	PSI
SUPPLY PRESSURE	PRESSURE	0	1000	PSI
INPUT SPEED	SPEED	0	4500	RPM
OUTPUT SPEED	SPEED	0	2000	RPM
INPUT TORQUE	TORQUE	-500	500	N.m
OUTPUT TORQUE	TORQUE	-5000	5000	N.m
EXHAUST				
PRE TURBO	TEMP	0	1000	Deg. C
PRE CATALYST	TEMP	0	500	Deg. C
MID CATALYST	TEMP	0	500	Deg. C
POST CATALYST	TEMP	0	1000	Deg. C
FUEL & EMISSION				
VOLUME	VOLUME	0	60	L/h
AMBIANTE TEMP	TEMP	0	500	Deg. C
CO2	CONCENT.	0	1000000	ppm
CO	CONCENT.	0	1000000	ppm
O2	CONCENT.	0	1000000	ppm
CH4	CONCENT.	0	1000000	ppm
NOX	CONCENT.	0	1000000	ppm
THC	CONCENT.	0	1000000	ppm
CVS PRESS.	PRESSURE	-20	20	PSI
CVS TEMP.	TEMP.			Rankine

MEASURE	PHYSICAL MEASUREMENT			
	Type	min	max	unit
ENGINE				
SPEED	SPEED	0	4500	RPM
COOLANT RETURN TEMP	TEMP	0	500	Deg. C
COOLANT SUPPLY TEMP	TEMP	0	500	Deg. C
AIR INTAKE TEMP	TEMP	0	500	Deg. C
OIL TEMP	TEMP	0	500	Deg. C
MANIFOLD AIR PRESSURE	PRESSURE	0	100	PSI
OIL PRESSURE	PRESSURE	0	100	PSI
PRE-TURBO PRESSURE	PRESSURE	0	100	PSI
POST-TURBO PRESSURE	PRESSURE	0	100	PSI
PRE INTERCOOLER TEMP	TEMP	0	500	Deg. C
POST INTERCOOLER TEMP	TEMP	0	500	Deg. C
FUEL SUPPLY TEMP	TEMP	0	500	Deg. C
FUEL RETURN TEMP	TEMP	0	500	Deg. C
AIR INTAKE MASS FLOW	AIR FLOW	0	530	SCFM
BRAKE				
COMMAND	TORQUE	0	400	Nm
PRESSURE	PRESSURE	0	1000	PSI
PAD TEMP	TEMP	0	500	Deg. C
UQM				
FIRST TEMP	TEMP	0	500	Deg. C
SECOND TEMP	TEMP	0	500	Deg. C
COOLANT IN TEMP	TEMP	0	500	Deg. C
COOLANT OUT TEMP	TEMP	0	500	Deg. C
INVERTER IN TEMP	TEMP	0	500	Deg. C
INVERTER OUT TEMP	TEMP	0	500	Deg. C
SPEED	SPEED	0	8000	RPM
TORQUE	TORQUE	-200	200	N.m
INVERTER CURRENT	CURRENT	-300	300	A
VOLTAGE	VOLTAGE	0	200	V
CLUTCH				
COMAND SIGNAL	POSITION	0	1	Deg. C
FALK 4:1 Speed increaser				
TEMP	TEMP	0	500	Deg. C
OIL PRESSURE	PRESSURE	0	50	PSI

APPENDIX 3: Design of the Constant Velocity Sampler

Critical flow venturi

Constant velocity sampling is achieved when emission sample is extracted out of a constant and homogeneous flow; the known flow and the concentration readings gives emission flow mass. A Critical Flow Venturi (C.F.V.) will be used to achieve constant velocity sampling: The CFV is a specially designed orifice with a smoothly curved geometry shown figure 1

Figure 1: Critical Flow Venturi

The property of the CFV is to ensure constant flow at the throat when the pressure or vacuum of the outlet reaches a certain level. When the critical flow is reached, the venturi is operating in choked mode and ensures sonic flow. The flow value can be calculated accurately using venturi geometry related calibration constant and the pressure and temperature affecting fluid density at the inlet of the venturi.

The CFV that will be used for the design of the CVS is a stainless steel HORIBA design recovered from decommissioned CVS-40 equipment. The Throat diameter of the venturi is 1.2865'' (32.7 mm)

The flow can be calculated as follow: $V_{mix} = (C1 \cdot P_{in}) / \sqrt{T_{in}}$

V_{mix} : Choked flow in Standard Cubic Feet per Minute (SCFM)

$C1$: Calibration constant: $10.631 \text{ SCFM} \cdot \text{R}^2 \cdot \text{mmHg}^{-1}$

P_{in} : Inlet pressure in millimeter of mercury (mmHg)

T_{in} : inlet Temperature in Degree Rankin (R)

Under standard conditions $P_{in} = 760 \text{ mmHg}$ and $T_{in} = 527.69 \text{ R}$, the venturi standard flow is $V_{mix_std} = 350 \text{ SCFM}$

The main issue with CFV is to make sure that the blower pulls enough air resulting in chocking the venturi. The manufacturer usually provides CFV operating pressure conditions. Those conditions are usually a vacuum level at the venturi outlet and/or a pressure differential ratio between inlet and outlet. Another way to verify that venturi is choked is to verify that pressure inlet the venturi is not affected by pressure change at the venturi outlet. When choked, the flow at the venturi is constant and pressure in the dilution tunnel shall only depend on dilution tunnel geometry.

A propane shot calibration test will certify that CFV is choked because sonic flow is used to recalculate injected propane mass. If sonic flow is not achieved, propane shot test result will be irrelevant.

Dilution tunnel

It is necessary that both exhaust gas and dilution air are being well mixed in order to have meaningful concentration reading of a homogeneous sample. To do so a dilution tunnel collects and mixes both exhaust and dilution air before the sample is routed to an analyzer. The dilution tunnel consists of a pipe connected to the venturi inlet on one side and collecting exhaust flow and dilution air on the other side. A mixing device is installed on the collecting side of the tunnel. This ensures dilution of exhaust in air by creating turbulences. The sample probes shall be placed closer from the venturi where mixing turbulences are dampened by their travel throughout the tunnel and where sample will most likely be homogeneous. The general rule of thumb for dilution tunnel dimensioning is that the length separating mixing device and sample probe shall be at least ten times tunnel diameter. Figure 2 and Figure 3

Figure 2

Figure 3

The tunnel diameter should be approximately the venturi inlet diameter for assembly compatibility. In order to simplify design, tunnel shall be a straight pipe; in addition this will minimize loss of particulates that are more likely to be trapped in a complex geometry. A mixing device will create turbulences near the location of tailpipe gases and ambient dilution air inlet.

Mixing device and collecting funnel

The mixing device is an aluminum build, reduced diameter choking plate that is fitted near the inlet of the dilution tunnel. The diameter is 1'' smaller than dilution tunnel inside diameter. The plate has been secured in place with rivets. The reduced diameter of the mixing device creates a pressure drop at the inlet of the CFV. It is important that reduced diameter remains bigger than venturi throat diameter or Venturi flow might be disturbed. Figure 4

Figure 4

Propane shot calibration procedure demonstrated the importance of mixing device. Propane was first injected in dilution tunnel without mixing plate. Then injection was performed with mixing device in place. The next illustration demonstrates how mixing device affect stable concentration readability. Figure 5

Figure 5

A collecting funnel has been installed to reduce air speed flowing along the tailpipe. This way the funnel helps maintaining near atmospheric pressure at the tailpipe. If the tailpipe were directly inserted in tunnel, exhaust gases would be non-realistically pulled from exhaust line because tailpipe and tunnel diameter are fairly close.

Sampling probes

The Pierburg probe collects a sample to read dilute sample gas concentration. The probe is plumbed using stainless steel line to the end of line filter. The Pierburg line is heated between end of line filter and concentration bench. Figure 6 and Figure 7

Figure 6

Figure 7

Ideally, the TEOM probe should be designed to have iso-kinetic PM mass measurement sampling. This means that dilute sample would enter the TEOM probe at the same speed that sample is flowing in the tunnel. This way, the sample probe would collect particulate species without creating turbulences in the flow. Iso-kinetic sampling can be achieved in the following condition: $Q_s / Q_t = (R_s / R_t)^2$

Qs: Flow of the TEOM sampling
Qt: Flow of the dilution tunnel
Rs: Radius of the TEOM probe inlet port
Rt: Radius of the dilution tunnel

In addition collecting probe shall be at list ½” diameter. Because of the tunnel diameter and Qs/Qt ratio value, iso-kinetic could not be achieved with the developed setup. However, a design effort has been made to minimize travel between inlet port and TEOM analyzer. Reducing this travel contribute to decreasing amount of particulate losses on the inside wall of the line. The final probe design makes the particulate travel thru a single smooth 90 degree curve and less than a foot of line to the instrument. Figure 8

Figure 9

Emission mass and fuel consumption calculation

The Pierburg 2000 emission bench provides dilute emission concentration in Particles Per Million (PPM). The critical flow will be used to calculate emission mass in grams. The calculation will be processed on line using the data acquisition system based on **CFR 40 Part 86** calculation theory.

The emitted masses are calculated according to the following equation:

$$M_i = V_{mix} * Q_i * C_i / 1000000$$

M_i : Mass of exhaust pollutant

Q_i : Density of the pollutant g/l at standard temperature and standard pressure

C_i : Pollutant concentration expressed in particles per million (p.p.m.)

V_{mix} : Corrected dilute exhaust volume corrected to standard conditions

The data acquisition system is connected to the Pierburg 2000 concentration bench thru RS232 series interface so the mass of each pollutant can be calculated online during powertrain operation. Exhaust gas is diluted using ambient air, so background pollutant concentration is collected while engine is not operating. At each sample time the program computes pollutant and background concentration values, sample temperature and pressure that gives instantaneous pollutants g/s for the following species: CH₄, THC, CO₂, CO, O₂ and NO_x.

At the end of a test, all data are saved and post processed using integrated instantaneous vehicle speed (driving distance). Finally, pollutant emissions in g/miles are used to calculate vehicle fuel consumption in mpg using the following formula:

$$\text{Diesel fuel consumption (mpg)} = 2778 / (0.866 * \text{HC} + 0.429 * \text{CO} + 0.273 * \text{CO}_2)$$

HC: Total hydrocarbon mass g/mile
CO: Total carbon monoxide g/mile
CO₂: Total carbon dioxide g/mile

APPENDIX 4: Data Acquisition Code to Calculate g/miles Emissions

```
/*                               CSV THEORY                               */

float C1;

// float NOXbckgnd; float CObckgnd; float THCbckgnd; float CH4bckgnd;
// float CO2bckgnd; float O2bckgnd;
float QNOX;float QCO; float QTHC; float QCH4; float QCO2; float QO2;
float SCFM2LPS; float QFuel; float gallon2L; float V; float Vmix; float DF;
float NOXcorrected; float COcorrected; float THCCorrected; float CH4corrected; float CO2corrected; float
O2corrected;
float Fuelgallonsec;

/*Declares constants*/

QNOX=1.913;QCO=1.164;QTHC=0.5768;QCH4=0.6672;
QCO2=1.83;QO2=1.3136;QFuel=837;

SCFM2LPS=28.316847/60;
gallon2L=3.785412;
C1=10.631;

/*Calculates total flow in venturi*/

V=(C1*DilPress)/sqrt(DilTemp); /* Venturi SCFM */
Vmix=V*SCFM2LPS; /* Venturi choke flow in L/s */

/*Calculates the dilution factors */

DF=13.4/((CO2+THC+CO)/10000);

/*Calculates corrected concentrations*/

NOXcorrected      =   NOX   -   NOXbckgnd   *(1-(1/DF));
Cocorrected       =   CO    -   CObckgnd    *(1-(1/DF));
THCCorrected      =   THC   -   THCbckgnd   *(1-(1/DF));
CH4corrected      =   CH4   -   CH4bckgnd   *(1-(1/DF));
CO2corrected      =   CO2   -   CO2bckgnd   *(1-(1/DF));
O2corrected       =   O2    -   O2bckgnd    *(1-(1/DF));

/* Mass of emissions */

NOXg=Vmix*QNOX*NOXcorrected/1000000;
COg=Vmix*QCO*COcorrected/1000000;
THCg=Vmix*QTHC*THCCorrected/1000000;
CH4g=Vmix*QCH4*CH4corrected/1000000;
CO2g=Vmix*QCO2*CO2corrected/1000000;
O2g=Vmix*QO2*O2corrected/1000000;

/* Calculates fuel flow measured using fuel scale signal*/

FuelgsecMeas=FuelIN*QFuel/3600;

/* Calculates fuel flow using emission concentrations */
```

```
Fuelgallonsec=(0.866*THCg+0.429*COg+0.273*CO2g)/2778; /* gallon per sec */  
FuelgsecCalc=Fuelgallonsec*gallon2L*QFuel;
```

APPENDIX 5: A, B, C coefficients calculation

Powertrain Specifications:

We estimated the powertrain rotational inertia at 139 kg/m², which would correspond to a vehicle of 1410 Kg (Curb Weight) with an assumed wheel radius of 0.316 m.

Mercedes-Benz C 220 CDI Vehicle Specifications:

Curb Weight: 1410 Kg

Wheel Radius: 0.316 m (estimated from tires specifications 195/65 R 15 H)

Frontal Area: 2.09 m²

The rolling coefficient depends on the road surface, vehicle speed and type of tires used. Simulation tools have been used in order to demonstrate the important impact of the rolling coefficient.

The following simulated coasts down have been performed for two different values in order to demonstrate the important impact of the rolling coefficient.

$f = 0.01$ for low-rolling resistance car tire on dry pavement

$f = 0.015$ for ordinary car tire on dry pavement

A coast down of the powertrain was performed to compare with the simulation results and determine the corresponding rolling coefficient value for the powertrain. The curves clearly show that the performances of a Mercedes C220 CDI with a rolling coefficient of 0.015 can be accurately compared to the performances obtained with the hybrid powertrain.

The following curve has been generated by simulation using a model of the Mercedes C220 CDI with a rolling coefficient of 0.015. This curve allows the calculation of the A, B, C target coefficient of the chassis dynamometer using a polynomial fit algorithm.

A, B, C Target Calculation From Simulated Vehicle Data with $f = 0.015$

The polynomial fit algorithm gives:

$$A = 46.64$$

$$B = 0.00$$

$$C = 0.02$$

$$\text{with } P = A + B.v + C v^2$$

The same process was applied for a vehicle with a rolling coefficient of 0.01.

A, B, C Target Calculation From Simulated Vehicle Data with $f = 0.01$

The polynomial fit algorithm gives:

$$A = 31.10$$

$$B = 0.00$$

$$C = 0.02$$

$$\text{with } P = A + B.v + C.v^2$$

The previous A, B, C calculations were obtained from simulation of a Mercedes C220 CDI with different rolling coefficients. Those A, B, C coefficients were used as target for the emulated vehicle. But we would not be completely accurate if we were using the same coefficient during the vehicle testing because of the potential gap between the target and the actual emulated vehicle A, B, C: We need to measure the emulated vehicle losses that could be different from the target A, B, C.

APPENDIX 6: Different Mode of Operation of the Powertrain

DRIVING MODE	MODE	SPEED	SOC	ENGINE
<p>EV Mode Accel.</p>	EV1	Increases	Decreases	Disabled
<p>EV Mode Decel.</p>	EV2	Decreases	Increases	Disabled
<p>HEV Mode Accel.</p>	HEV1	Increases	Decreases	Enabled
<p>HEV Mode Decel.</p>	HEV2	Increases	Increases	Enabled

APPENDIX 7: Engine Torque and Speed over a FUDS Cycle Using Best Efficiency Control

APPENDIX 8: NO_x Emissions Results from Engine Steady State Tests

APPENDIX 9: Simulation Results Trade-off Control Operation

The simulation results show a good ability for the control to keep the engine on the trade-off curve.

As for the best efficiency curve, it is more accurate to use the engine torque measured in order to determine the speed target that will allow the engine to operate at the desired operating point.

Improvements to the CVT model have been done to take into account the dynamic of the CVT, to represent more realistically the behavior of the transmission and to correlate the test results.

APPENDIX 10: Engine Torque and Speed over a FUDS Cycle Using Trade-off Control

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perform testing leveraging ["word missing?] control		
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alidating a vehicle model is not only		
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to be validated. But this higher degree of validation is		
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comparing its fuel consumption results with simulations		
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we		
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. Because PSAT is able to perform analysis studies at a detailed component level, the component models also have		
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s also have		
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Figure 15:

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dataEngine torque comparison between measured and simulated data		
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Basically, we have to collect the input and output data from each studied component to be able to validate their model.		
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