Evaluation of Ethanol Blends for PHEVs using Engine-in-the-Loop

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Abstract – The easy availability, lower well-to-wheel emissions, and relative ease of use associated with existing engine technology have made ethanol and ethanol-gasoline blends a viable alternative to gasoline for spark-ignition (SI) engines. The lower energy density of ethanol and ethanol–gasoline blends results in higher volumetric fuel consumption than that associated with gasoline. On one hand, when higher-level ethanol blends are used, the higher latent heat of vaporization can result in cold-start issues. On the other hand, a higher octane number, which indicates resistance to knock and enables optimal combustion phasing, improves engine efficiency, especially at higher loads.

This paper compares fuel consumption and emissions for two ethanol blends with gasoline (E50 and E85) for conventional (nonhybrid), and series-type plug-in hybrid vehicles. Each vehicle configuration results in different engine operating regimes and multiple engine ON events. For each vehicle type, the sensitivities of fuel consumption and emissions to the three fuels are assessed. The impacts of ethanol blends on fuel consumption and emissions depend on the engine operating regime. The combined impact on fuel economy that results from low energy density (negative impact) and higher efficiency at high engine loads (positive impact) is assessed for the series PHEV. Changes to the vehicle energy management strategy for the series PHEV are proposed based on the differences in fuel consumption for the different blends.

In this study, Argonne's vehicle system simulation and control software AUTONOMIE was used to simulate the engine-in-the-loop process. This paper describes the process in the AUTONOMIE environment.

I. INTRODUCTION

Ethanol and ethanol-gasoline blends are being considered as an alternative to gasoline for SI engines. Ethanol-gasoline blends have some disadvantages when compared to gasoline, however. The lower energy density of the fuel mix results in higher volumetric fuel consumption, which decreases the vehicle range per tank of fuel. The higher latent heat of vaporization results in cold-start issues [1]. The issues are more pronounced when higher-level ethanol blends are used. At the same time, higher knock resistance results in better engine efficiency at higher loads [2]. Since the engine operates at higher loads in HEVs than in conventional vehicles [3], it is possible to lower the negative impact of fuel energy density because of the higher engine efficiency. Table I lists the relevant properties of ethanol-gasoline blends (compared to gasoline) and their potential engine and vehicle-level impacts.

TABLE I
ETHANOL-GASOLINE BLEND PROPERTIES AND ENGINE AND VEHICLE-LEVEL IMPACTS

Fuel Property of Ethanol-Gasoline Blend (Compared to Gasoline)	Engine-Level Impact	Vehicle-Level Impact
Lower energy density	Higher volumetric fuel flow for the same shaft power	Higher fuel consumption
Higher latent heat of vaporization	Unreliable cold start, especially for higher-blend ratios; low combustion temperature	High emissions because of failed combustion; issue might be aggravated for PHEVs with multiple cold starts
Better knock properties	Efficient high-load operation	Lower fuel consumption at high loads, which can be advantageous for hybrid operation

The increase in engine efficiency for the ethanol-gasoline blends at high engine loads can be attributed to the higher octane number of these fuels, which increases the knock-resistant properties of the fuel and enables optimal combustion phasing at higher loads (spark advance).

Flex-fuel vehicles now available in the market incorporate changes related to material compatibility for ethanol and calibration changes typically restricted to fueling requirements and injection timing. Further calibration changes and hardware modifications to the engine (higher compression ratios) could further exploit the higher octane number of ethanol blends [4] [5].

This paper studies the impact of different levels of ethanol-gasoline blends on the fuel consumption of a series PHEV to ascertain whether the increased engine efficiencies at high loads from using ethanol-gasoline blends result in lower fuel energy use by the hybrid than by the gasoline vehicle. While it is known that the lower energy density of the ethanol-gasoline blends results in higher fuel consumption for conventional vehicles [1], the combined impact on fuel economy that results from the low energy density (negative impact) and higher engine efficiency at high engine loads –

which is more pronounced for HEV applications (positive impact) – has not been evaluated so far. With changes in the ethanol-gasoline blend ratio, the fuel consumption changes as a result of variations in the properties listed in Table 1. The sensitivity of fuel consumption to changes in the blend ratio is compared for conventional vehicles and series PHEVs.

The experiment is conducted by using an engine-in-the-loop approach on a 2.2-L spark-ignition direct-injection (SIDI) engine with the ability to change engine control unit (ECU) parameters for different ethanol-gasoline blend ratios. The parameter changes to the ECU for the different fuels are restricted to fuel injection duration, to maintain stoichiometric combustion for the different blends. The ECU is equipped to change spark timing based on the detection of knock during a combustion event. As stated earlier, engines with higher compression ratios would show additional gains in fuel economy for the ethanol blends (and increased knock for gasoline), but such changes are not a part of this experiment.

The design of the experiment and engine-in-the-loop setup are described in the following sections.

II. ENGINE-IN-THE-LOOP SETUP

The block diagram for the engine-in-the-loop setup is shown in Figure 1.

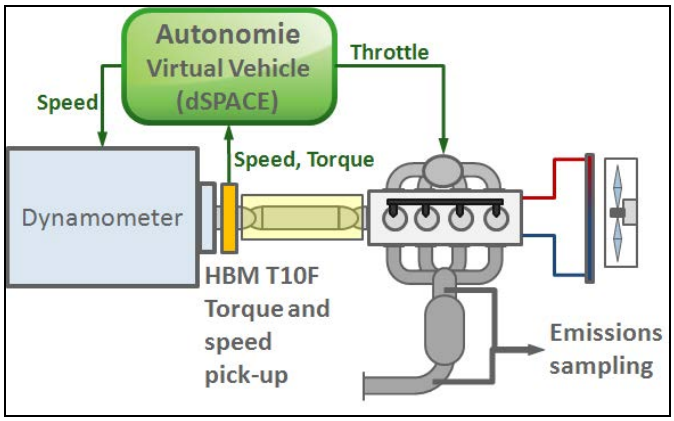

Fig. 1. Block diagram of the engine-in-the-loop setup

A vehicle simulation developed in AUTONOMIE [6] runs in real time on a dSPACE real-time computer with I/O. The simulation runs a vehicle model that follows a prescribed drive trace (drive cycle). The vehicle simulation (virtual vehicle) sends the throttle command to the engine on the basis of the engine torque demanded by the vehicle control unit and sends the speed command to the dynamometer on the basis of the expected engine speed at any given time. The HBM torque sensor measures the engine torque and is used as feedback to the virtual vehicle to provide engine propulsion torque to the virtual powertrain. The engine-in-the-loop experiment is set up and controlled in the AUTONOMIE environment [7].

The 2.2-L Ecotec Opel SIDI engine has the stock, close-coupled, three-way catalyst on the exhaust line. Emissions are sampled post catalyst and are analyzed by a Horiba MEXA Model 7100D exhaust gas recirculation (EGR) emissions analyzer. Hydrocarbons (HC), nitrogen oxides (NO_x,), and carbon monoxide (CO), measured as volumetric concentrations, are converted to emissions in g/mi by using the measured air and fuel flow to the engine. The engine coolant loop is set up to replicate an "in-vehicle" coolant loop, with a constant-speed fan blowing across the radiator, similar to the setup for chassis dyno tests of vehicles. Thus, the cold-start behavior of the engine is similar to the behavior of an in-vehicle [1]. Figure 2 shows a picture of the actual engine-dynamometer setup, with the coolant system, three-way catalyst (TWC), and HBM speed and torque sensor on the engine shaft. For the series hybrid PHEV operation, catalyst temperature is used as feedback to transition from a cold-start vehicle control strategy (focused on limiting cold-start emissions) to a hot control strategy (focused on maximizing fuel economy).

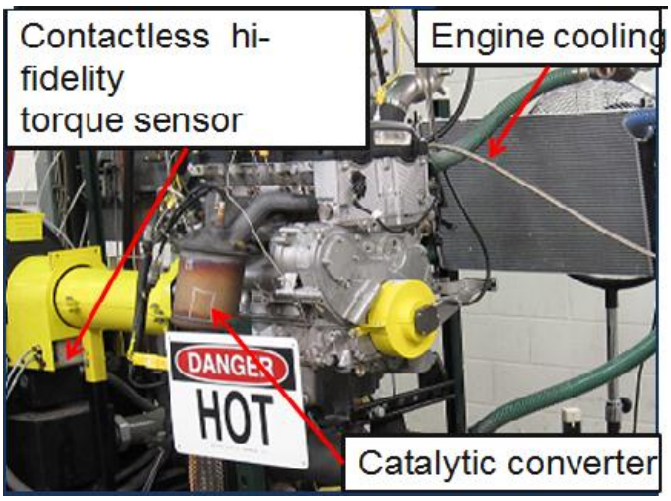

Fig. 2. 2.2-L Ecotec SIDI engine with TWC, vehicle-grade engine cooling, and HBM torque and speed sensor

III. DESIGN OF EXPERIMENT

There are two main objectives of this study:

1. Examine the impact of different levels of ethanol-gasoline blends on the fuel consumption of a conventional vehicle and a series hybrid PHEV.
2. Evaluate the impact of improved engine efficiency at high loads from using ethanol-gasoline blends on vehicle fuel consumption.

The design of the experiment is captured in Figure 3. The fuel consumed by the series PHEV and conventional vehicle is measured for gasoline (E0), E50, and E85. The conventional vehicle's fuel consumption is measured over a single urban dynamometer driving schedule (UDDS) cycle, while the series PHEV's fuel consumption is measured over five consecutive UDDS cycles. Table II lists some vehicle

parameters for the conventional vehicle and series PHEV. The size of the series PHEV is based on the automated sizing routine in AUTONOMIE: to provide about 20 miles in the electric (EV) range on the UDDS cycle.

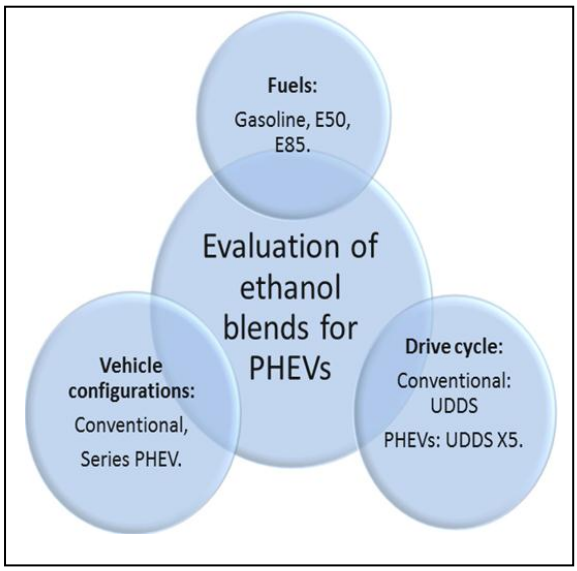

Fig. 3. Design of experiment matrix

The vehicle operates in charge-sustaining (CS) mode at a battery state of charge (SOC) of 30%. Both vehicles are sized for a small sport-utility vehicle (SUV) application. Although the engine of a series PHEV sized for this application would be smaller than the 2.2-L engine used for this experiment, available engine hardware dictated the use of the 2.2-L engine, thus slightly increasing the vehicle mass.

TABLE II
VEHICLE PARAMETERS FOR THE CONVENTIONAL AND SERIES PHEV (SMALL SUV)

Parameter	Conventional Vehicle	Series PHEV
Vehicle test weight (kg)	1,783	1,936
Motor power (kW)	NA	130
Generator power (kW))	NA	110
Battery energy capacity	NA	41 Ah, 10 kWh

The series PHEV is controlled to run in EV mode when charge-depleting for the UDDS cycle, and the engine turns on only in the CS phase. The conventional vehicle is the baseline against which the PHEV fuel consumption numbers are compared.

The focus of this study is to evaluate the impact of fuels (different ethanol-gasoline blends) on the fuel consumption of a conventional vehicle and PHEV. Therefore, for the PHEV, the vehicle control strategy is maintained across the different fuels. It was determined that the engine power does not change with changes in the blend ratio of ethanol to gasoline in the fuel [2]; therefore, for a certain torque demand from the engine (i.e., a certain throttle command), at a given speed, engine torque does not change with the fuel, provided the engine operates at stoichiometric conditions for all the fuel blends. As stated, the SIDI engine used for this study has an ECU that is fully accessible for calibration. Therefore, on the basis of the blend ratio, the injection duration for each combustion event was adjusted so as to provide stoichiometric operation for each fuel. Thus, from a vehicle perspective, the engine's shaft power/torque/speed at any instant in the cycle do not vary from fuel to fuel. What does vary are the amount of fuel consumed and efficiency of the engine in generating the power desired by the ECU. Since engine power (as a function of time) is consistent across the different fuels, battery consumption is also the same for the different fuel blends. Figure 4 shows the battery SOC and engine speed for the series PHEV subjected to five consecutive UDDS cycles.

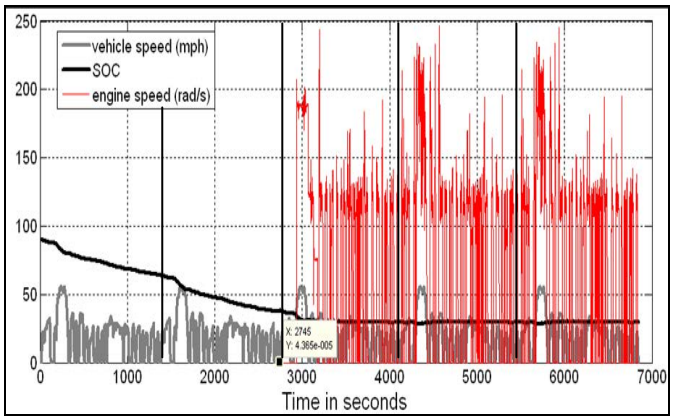

Fig. 4. Battery SOC and engine and vehicle speed for series PHEV

The solid vertical lines in Figure 4 represent the end of one UDDS cycle and the beginning of the next one. One can see that the first two cycles operate in EV mode. The third cycle is a transition from EV to CS mode and has an engine warm-up component to mitigate cold-start emissions. The engine warm-up can be seen in the form of the constant engine speed (180 rad/s) when the test time is around 3,000 seconds. The vehicle then maintains an SOC of about 30% in the CS mode for the final two UDDS cycles. Table III shows the battery energy consumption in Wh/mi for the five consecutive UDDS cycles for the PHEV for each fuel under consideration.

TABLE III
BATTERY ENERGY CONSUMPTION FOR THE FIVE UDDS CYCLES FOR THE DIFFERENT ETHANOL-GASOLINE BLENDS

Fuel	UDDS # 1 (EV)	UDDS # 2 (EV)	UDDS # 3 (Transition)	UDDS # 4 (CS)	UDDS # 5 (CS)
Gasoline	369.1	357.2	108	–6.5	–6.5
E50	369.1	357.2	107.3	–6.6	–6.6
E85	369.1	357.2	105.7	–6	–6.5

As the table shows, electrical energy consumption is the same for the three fuel blends. This fact implies that the engine power and energy usage are the same for the three fuels. As

stated, the differences are in the fuel consumption and efficiency for the same engine power.

IV. Results and Analysis

A. Conventional Vehicle

Figure 5 shows the fuel consumption results for the conventional vehicle. The fuel consumption increases with an increase in the ethanol content of the fuel. Tables IV and V list the percent increase in fuel consumption from using two ethanol blends as compared to using gasoline, and the engine cold-start penalty for each fuel, respectively.

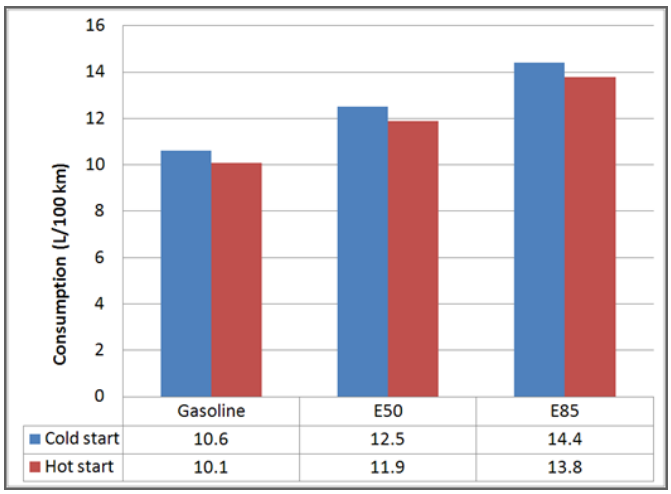

Fig. 5. Fuel consumed by a conventional vehicle for three fuel blends

TABLE IV
FUEL CONSUMPTION INCREASE FOR E50 AND E85 COMPARED TO GASOLINE

Start	E50	E85
Hot	18.6%	37.2%
Cold	18.4%	35.9%

TABLE V
ENGINE COLD-START PENALTY OVER ONE UDDS CYCLE

Fuel	Cold start penalty
Gasoline	5.1%
E50	5%
E85	4.5%

The increase in fuel consumption increase for both E50 and E85 is the same for hot and cold starts. The engine cold-start penalty is similar for all fuels. Since this experiment is performed by using the engine-in-the-loop approach, the cold-start penalty does not reflect the fuel consumption increase because of the additional losses in the rest of the powertrain (i.e., no additional cold-start losses of the transmission or drive line are taken into account).

B. Series PHEV

As stated in the previous section, fuel consumption by the PHEV is compared across five consecutive UDDS cycles, with the first two cycles being in EV mode, the third cycle being a transition cycle involving engine warm-up, and the fourth and fifth cycles being CS.

Figure 6 shows the fuel consumption for the transition cycle (UDDS # 3) and the two CS cycles (UDDS # 4 and # 5). As expected, as a result of the low energy density of the ethanol blends, fuel consumption increases with increases in the ethanol content of the fuel. Table VI shows the percent increase in fuel consumption for E50 and E85 and a conventional vehicle (hot start), and the two CS cycles for the PHEV. The fuel consumption increases with an increase in the blend ratio, similar to what happened in the conventional case.

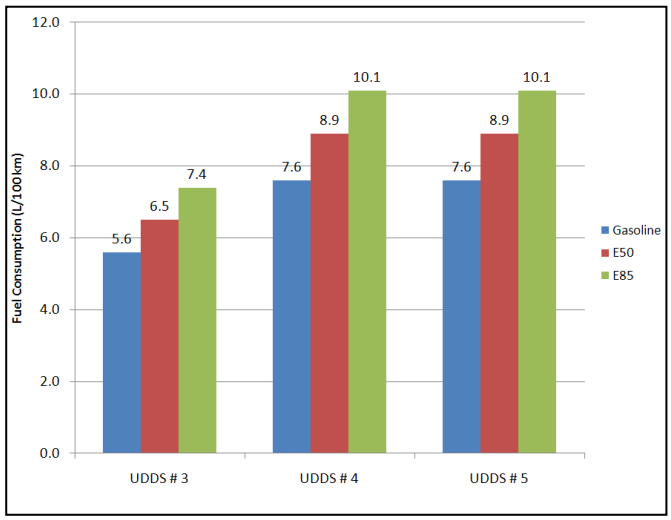

Fig. 6. Fuel consumed by the series PHEV – transition cycle and two CS cycles

TABLE VI
PERCENTAGE INCREASE IN FUEL CONSUMPTION COMPARED TO GASOLINE FOR THE TWO CS CYCLES AND THE CONVENTIONAL HOT START

Fuel	UDDS # 4	UDDS # 5	Conventional Hot Start
E50	17.7%	17.9%	18.6%
E85	33.1%	33.6%	37.2%

Table VI indicates that for E85, the increase in the amount of fuel consumed by a conventional vehicle that results from using E85 instead of gasoline is about 37%. But the fuel consumption penalty in the hybrid case is lower – about 33%. A similar reduction in the fuel-consumption penalty can be seen for E50 hybrid operation when compared with E50 conventional operation. The decrease in the fuel-consumption penalty or percentage increase in the fuel consumption of the hybrid vehicle is due to the increased efficiency of the engine at high load for the ethanol blends.

To isolate the impact of engine efficiency for the three fuel blends, the fuel energy used for the transition cycle (UDDS # 3) and the two CS cycles is shown in Figure 7.

As stated, the engine operates more efficiently for the ethanol blends at high loads, which is typically the case for hybrid operation. Thus for the same shaft power, the fuel energy consumed when E50 or E85 is used is less than that consumed when gasoline is used. Table VII shows the reduction (decrease) in fuel energy consumed for E50 and E85 for the two CS PHEV runs and conventional hot start.

Table VII indicates that for the E85 case, the decrease in fuel energy consumption is greater for CS operation of a PHEV than the conventional hot start. The effect is slightly less pronounced for E50, which has a less ethanol than E85.

Previous tests on the engine-in-the-loop system showed test-to-test repeatability of within +/–1%.

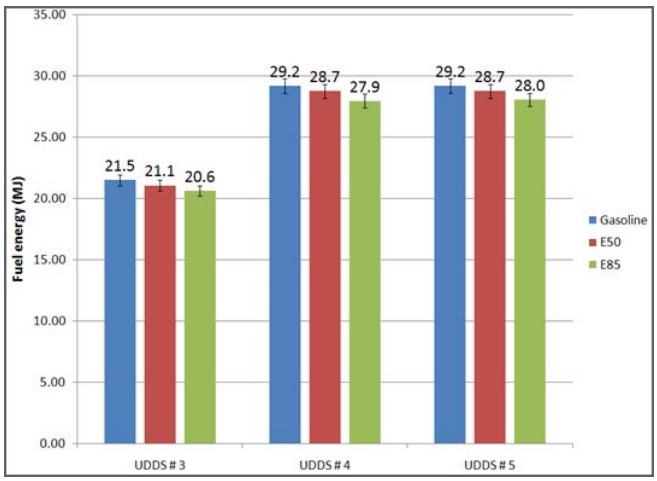

Fig. 7. Fuel energy consumption for the series PHEV – transition cycle and two CS cycles for gasoline, E50, and E85

TABLE VII
PERCENTAGE DECREASE IN FUEL ENERGY CONSUMPTION FOR E50 AND E85 COMPARED TO GASOLINE

Fuel	UDDS # 4	UDDS # 5	Conventional Hot Start
E50	1.4%	1.4%	0.7%
E85	4.2%	3.8%	1.2%

Figure 8 shows the percentage increase in engine efficiency for E85 in comparison to gasoline, in the form of a torque-speed engine map. The regions of improved engine efficiency at high loads can be clearly seen. At low loads, the difference between the gasoline and E85 efficiencies is minimal; at high loads, improvements in efficiency for E85 can be seen at speeds of about 200 to 400 rad/s and above 100-Nm torque.

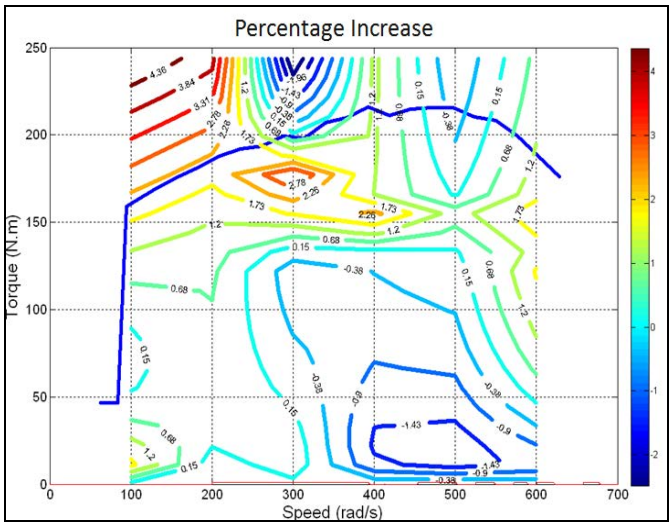

Fig. 8. Percent increase in engine efficiency for E85 over gasoline

Figures 9(a) and 9(b) show the exhaust gas temperature for gasoline, E50, and E85 when a PHEV operates in CS mode. Figure 9(a) shows that at high engine loads (indicated by the large vehicle acceleration and vehicle speed at around 1,600 seconds), the exhaust temperature for E85 is distinctly lower than that for E50 and gasoline, and that the exhaust temperature for E50 is lower than that for gasoline. Figure 9(b) shows that at low engine loads (indicated by the low vehicle speed and mild acceleration), the exhaust temperatures are close, which suggests that the use of E50 and E85 at low engine loads does not exploit the low knock and high efficiency possible with these fuels at high loads, resulting in engine efficiency comparable to that achieved when gasoline is used.

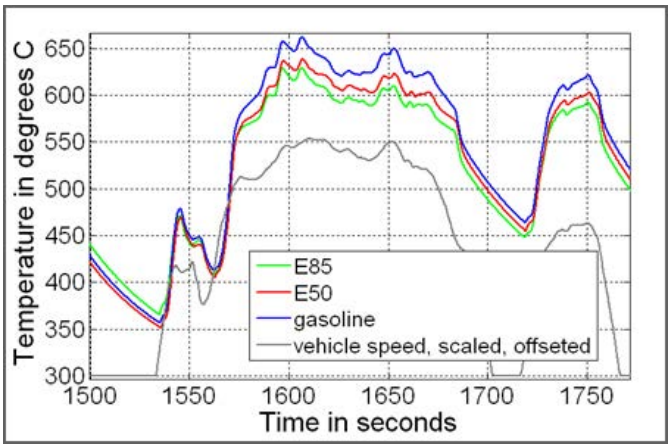

Fig. 9(a). Large difference in the exhaust gas temperature at high engine loads, suggesting more efficient operation results from using ethanol blends

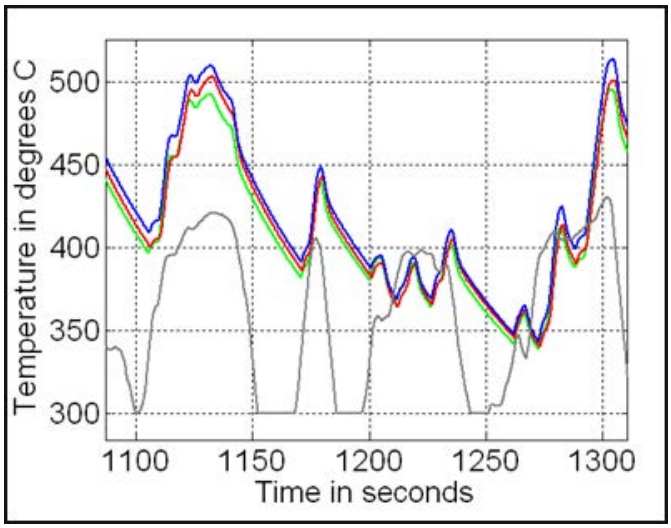

Fig. 9(b). Insignificant difference in exhaust temperatures at low engine loads

Figures 10(a) and 10(b) show the emissions for the series PHEV and the conventional vehicle cold start in g/mi. For the series PHEV, the emissions are for the third UDDS of the five-cycle test. As stated, the first two cycles for the series PHEV are in EV mode, and the third cycle has a warm-up routine to lower the emissions at startup. The figures show that there is no significant difference in the amount of emissions between the conventional vehicle and hybrid vehicle for a given fuel, or for different fuels for the same vehicle configuration.

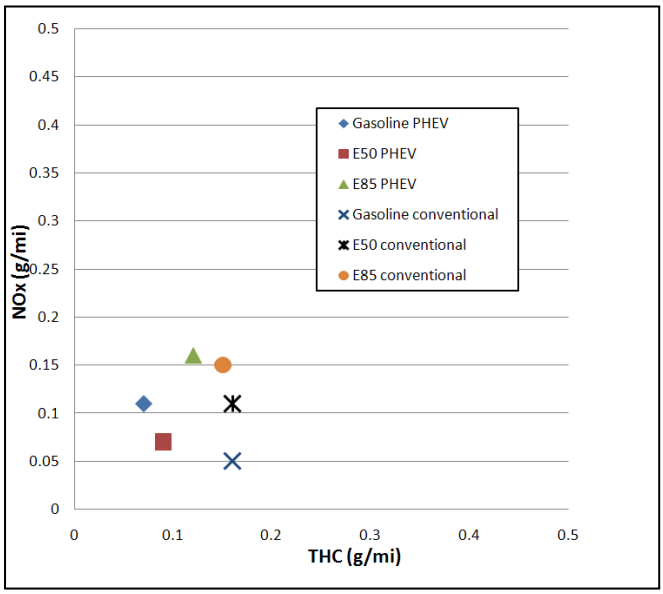

Fig. 10(a). NO_x and total HC emissions for the cold-start conventional and series PHEV transition cycle

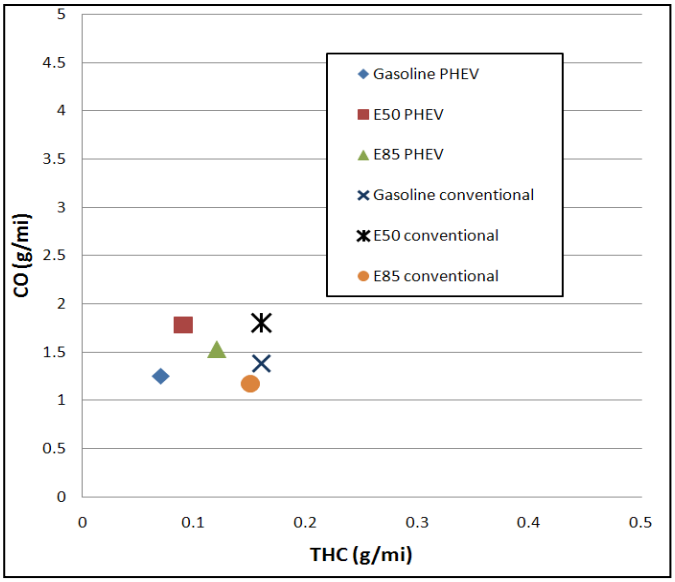

Fig. 10(b). CO and total HC emissions for the cold-start conventional and series PHEV transition cycle

V. VEHICLE SYSTEM OPTIMIZATION FOR FLEX FUELS

Figure 11 shows the percentage increase in engine efficiency for E85 when compared to gasoline in the form of a torque-speed map. Superimposed on the map are engine operating points for the three fuels. Note that the engine operation is the same for all of the fuels, as stated previously.

Figure 11 also shows that in order to exploit the better efficiency of E85, the engine operation could be moved to higher speeds, as indicated by the arrow. This would result in further improvements in PHEV fuel economy for E85. A similar assessment is possible for E50.

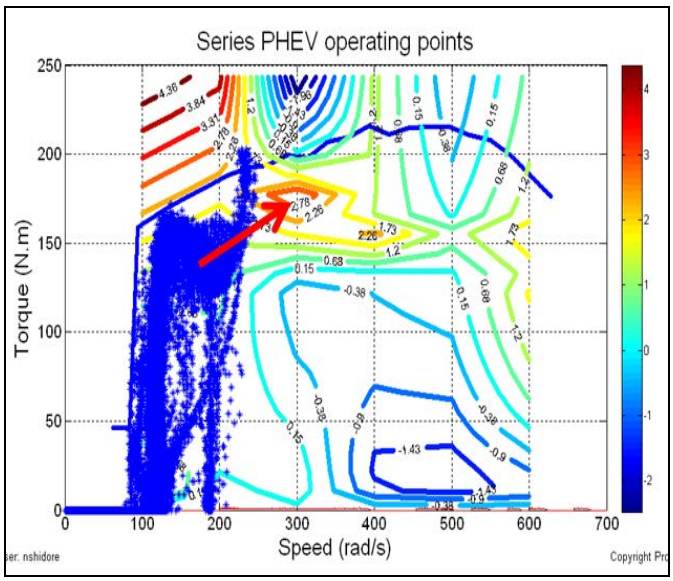

Fig. 11. Change in engine operating region could result in further improvements in fuel economy when E85 is used

To maximize vehicle fuel economy for the ethanol blends, the vehicle-level control strategy must be optimized. The E85/E50 efficiency maps should be used with the series generator efficiency map to ascertain optimal operating regions for the engine-generator combination. Operation of the engine at higher speeds and loads could also lead to higher emissions. Therefore, any such optimization would have to be an iterative process between simulation and the engine-in-the-loop, with simulation results being validated for fuel economy by the engine-in-the-loop process, while ensuring that emissions were meeting regulation standards.

VI. CONCLUSION

This paper compares the amount of fuel consumed by a conventional vehicle and a series PHEV for three ethanol-gasoline blends (gasoline, E50, E85). The energy density penalty on fuel economy is quantified for conventional vehicles. Hybrid operation when E50 or E85 is used has a lower energy-density impact, suggesting that the engine operates more efficiently as a result of the better knock properties of ethanol blends, resulting in spark advance at higher loads. There is no significant difference in the emission results for the different fuels. A comparison of the E50 and E85 efficiency maps to gasoline also indicates that further improvements in PHEV/HEV fuel economy for the ethanol blends would be possible if the vehicle system control for the said blends was optimized.

VII. FUTURE WORK

For different powertrain configurations, engine operating region and the engine ON time varies. To further analyze the impact of different fuels, we will compare the energy density penalty from using ethanol-gasoline blends for the series configuration with a single-mode power-split PHEV in the same vehicle class. We will compare the series and the power-split case with regard to the impact of improved engine efficiency at higher engine loads on fuel consumption. The current paper compares PHEV fuel consumption for different fuel blends. The fuel economy of a PHEV using E50 or E85 can be further improved by optimizing the vehicle system control for the said fuels. We will use engine maps for the ethanol blends in an AUTONOMIE simulation study to develop control strategies that maximize the potential of different fuel blends. We will validate the optimization results by using the engine-in-the-loop process, with an iterative process between the simulation and engine-in-the-loop process to ensure that emissions are below regulatory standards. When a series hybrid is used, since the engine speed as well as torque can be isolated from the vehicle speed and load demands, there is more freedom with regard to engine-generator optimization. When a single-mode power-split configuration is used, the engine is mechanically coupled to the wheel speed when the engine is ON; thus, there is less freedom with regard to engine operation.

Two important aspects with regard to using flex fuels rather than gasoline in engines is their cost at the pump and their overall life cycle cost. The fuel consumption results from the tests and simulation can be used to perform a net present value (NPV) analysis of operating costs and a life-cycle analysis by using Argonne's life-cycle analysis toolkit, GREET.

This study focuses on the fuel economy improvement for one driving trip. NPV analysis focuses on choosing a vehicle control strategy to minimize the vehicle's operating cost over its lifetime. With regard to PHEVs, an important aspect that affects the overall operating cost savings is battery life. Therefore, a comprehensive study that looks at maximizing the fuel economy from using ethanol blends by optimizing the vehicle system while considering minimizing the NPV (operating cost) and battery life, is possible.

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