V.8 Enhanced Ethanol Engine and Vehicle Efficiency

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Objectives

- Enable reduction of petroleum imports through more efficient use of ethanol.
- Address the market barrier of reduced fuel economy with ethanol use in flexible-fuel vehicles (FFVs).
- Exploit properties of ethanol for more optimized engines.

Accomplishments

- Demonstrated 3-6% fuel economy improvement in preliminary lean-burn experiments on a Dodge Caravan FFV.
- Imported and baselined a European-spec Saab BioPower FFV, the first FFV optimized for E85.
- Mined EPA database to compare Saab fuel economy and emissions to U.S.-legal FFVs.
- Initiated lean-burn experiments with the Saab vehicle in lean-burn mode with a novel hydrocarbon selective catalytic reduction lean NOx catalyst.
- Established new Cooperative Research and Development Agreement (CRADA) with Delphi on high-efficiency ethanol engines.

Future Directions

- Establish fuel economy and emissions limits of homogeneous-charge, spark-ignition, lean-burn engines with the Saab vehicle with prototype lean NOx catalysts installed.
- Explore additional technologies for enhancing efficiency, such as direct-injection, cylinder deactivation, variable valve timing, boosting, etc.
- Determine optimum compression ratio for prototype CRADA engine.

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Introduction

Increased use of ethanol to displace petroleum fuels is receiving renewed priority within the Department of Energy as well as nationally. In the U.S., FFVs can operate on gasoline or E85 (85% ethanol, 15% gasoline), or any blend of the two. Traditionally, these vehicles are optimized for gasoline and made to be ethanol tolerant. That is, the manufacturers have not tuned the engines to take advantage of some of ethanol's favorable properties. Power output for current FFVs on E85 fuel is typically on par with the gasoline rating, and the vehicles suffer a considerable 25-30% loss in driving range when running on E85 due to its lower energy density. Despite equivalent or slightly improved fuel efficiency (distance per unit energy), this range shortfall is considered a significant obstacle to wide-spread consumer acceptance of FFVs. Ethanol has several properties that make it attractive as a spark-ignition engine fuel, such as high octane, flammability limits at leaner air:fuel ratios than conventional gasoline, high latent heat of vaporization, and it is a very effective reductant for certain types of lean-NOx catalysts. Engines specifically designed to take advantage of ethanol's properties should be capable of improved thermal efficiency, and thus improved vehicle fuel economy, thereby reducing the driving range loss with E85 use, as well as further reducing petroleum imports.

Saab recently introduced the BioPower engines in the European market. The BioPower vehicle is an FFV than can burn gasoline or E85, but it is optimized for use with E85. Through higher turbocharger boost pressures and more advanced spark timing (enabled by E85's higher octane rating), the engine's power rating is 20% higher with E85 fuel. ORNL acquired a new Saab BioPower for benchmark evaluation in 2007. Current European regulations (Euro 4) only require FFVs to meet emissions standards on gasoline. As this vehicle is reportedly performance-optimized for E85 operation, there was interest in determining what effect, if any, this performance tuning had on emissions or fuel economy, and whether such tuning might be the basis for improved ethanol driving range on future vehicle designs. Following the benchmark exercise, the Saab became the platform for researching means to improving FFV fuel economy through lean-combustion.

Approach

Chassis dynamometer experiments are being conducted to accomplish this work. The vehicle is driven over standard transient drive cycles such as the Federal Test Procedure (also known as Urban Dynamometer Driving Schedule), the Highway Fuel

Economy Test, and the high-speed, high-load US06 test (part of the Supplemental Federal Test Procedure). Emissions and fuel consumption on each of these cycles is measured for both gasoline and E85 fuel, and results can then be compared with data from similar tests on other, comparable vehicles.

Lean-burn experiments were conducted on the vehicles by forcing their engine control units (ECUs) to command less than the necessary fuel for stoichiometric operation. Modern vehicles operate in a closed-loop mode most of the time, by monitoring oxygen content in the exhaust. The "switching type" oxygen sensor detects rich or lean conditions in the exhaust and the ECU dithers the air:fuel ratio slightly rich to slightly lean, maintaining a net stoichiometric air:fuel ratio. To operate the Dodge Caravan lean, the oxygen sensor was disconnected, which forced the engine into an open-loop mode that mimics the most recent closed-loop operation. With fixed fueling, the fuel rail pressure was decreased to decrease fuel addition and bring about lean operation.

Lean-burn experiments on the Saab were conducted in a more sophisticated closed-loop mode. A wide-range oxygen sensor was installed next to the factory switching sensor. The factory sensor signal to the ECU was intercepted and replaced with a biased signal based on the wide-range sensor. In this way, a desired air:fuel ratio could be achieved and controlled in a closed-loop mode by the factory ECU. The air:fuel ratio is on a mass basis (grams air per gram of fuel), but a non-dimensional term is often preferred, called lambda, also known as the excess air factor. Lambda is defined as the actual air:fuel ratio divided by the stoichiometric air:fuel ratio; thus lamda-1.0 is stoichiometric, and lambda>1.0 indicates the degree of enleanment.

In a separate but related CRADA project with Delphi, ORNL will conduct research on an advanced direct-injection engine platform designed by Delphi. Experiments will focus on efficiency improvements in stoichiometric engines.

Results

Initial lean-burn experiments in 2006 were conducted with a Dodge Caravan FFV. Figure 1 shows the fuel economy under steady cruise conditions for stoichiometric operation on gasoline, on ethanol fuel, and for the lean ethanol experiments. The modest 3-6% improvement would likely be improved with a greater level of engine control (for example, spark timing, exhaust gas recirculation). These proof-of-concept experiments were conducted with limited resources, but achieved the goal of justifying further study.

In 2007, a Saab 9-5 BioPower was imported and benchmarked against U.S.-legal FFVs under the auspices of the Office of the Biomass Program. The Saab is shown

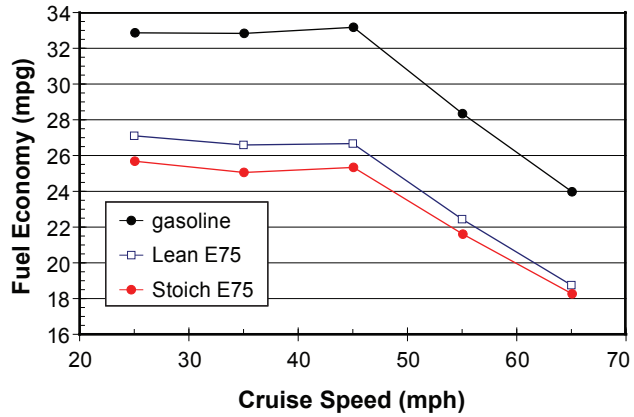

FIGURE 1. Steady Cruise Fuel Economy for the Dodge Caravan FFV

in Figure 2 on the chassis dynamometer at ORNL. A comprehensive discussion of the benchmarking of this European FFV is too detailed to discuss here, but can be found in a recent SAE publication [1]. In summary, the vehicle emissions were found to be within U.S. limits (although not tested at full useful life), the relative fuel economy on E85 and gasoline was found to be on par with, or slightly better than U.S.-legal FFVs, and the 20% power increase with E85 was confirmed and found to offer about a 1 second quicker acceleration to 60 mph over that with gasoline fuel.

Following the completion of the Saab benchmark, modifications to the vehicle were made to enable closed-loop lean operation. The intercept control system developed successfully allows the vehicle to operate in a closed-loop mode at a target lambda other than 1.0. Initial drive cycle experiments have been successfully run with lambda as high as 1.4. Figure 3 shows the first 500 seconds of the FTP driving cycle for two experiments, one with factory air:fuel ratio control at stoichometry (lambda=1.0), and a second demonstrating

FIGURE 2. Saab 9-5 BioPower Vehicle

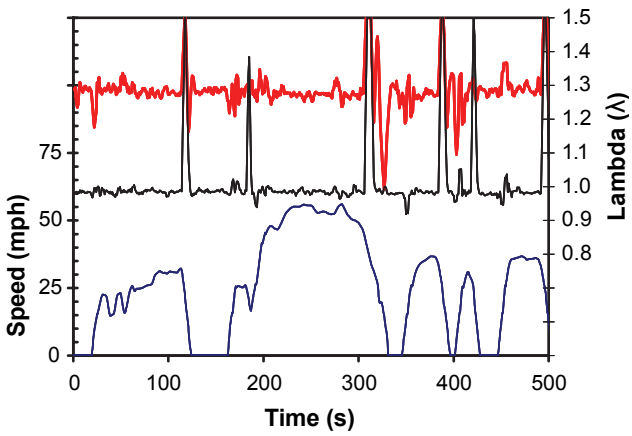

FIGURE 3. Segment of LA4 Driving Cycle Showing Factory Closed-Loop Control at Stoichiometry and Intercept Control at Lambda 1.3

the closed-loop operation at lambda 1.3. Fuel shut-off during deceleration is evident in both curves when lambda goes above 1.5 (lambda actually goes to infinity, but the sensor is setup to read only to 1.5).

In addition, a novel lean-NOx catalyst was procured through an industrial partner (Catalytic Solutions). This silver-alumina (Ag/Al_2O_3) formulation is known to be particularly well-suited to NOx control in lean environments with ethanol or other alcohols as reductants [2,3]. The catalysts have been canned and will be installed for experiments in FY 2008.

Conclusions

- Preliminary lean-burn experiments on a Dodge Caravan FFV show 3-6% fuel economy improvement with limited engine control. Greater improvement is expected with improved control.
- A Saab BioPower FFV was imported and compared to U.S.-legal FFVs. Findings include:
  - Power increase with E85 confirmed through acceleration tests.
  - E85 fuel efficiency slightly better than U.S.-legal FFVs on the city test.
  - Emissions on U.S. cycles are within Tier 2, Bin 5 levels.
- The methodology for operating the Saab engine in the lean regime is sound and will be used in FY 2008 experiments with advanced lean-NOx catalysts.

References

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