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Fuel Economy and Emissions of the Ethanol-Optimized Saab 9-5 Biopower

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ABSTRACT

Saab Automobile recently released the BioPower engines, advertised to use increased turbocharger boost and spark advance on ethanol fuel to enhance performance. Specifications for the 2.0 liter turbocharged engine in the Saab 9-5 Biopower 2.0t report 150 hp (112 kW) on gasoline and a 20% increase to 180 hp (134 kW) on E85 (nominally 85% ethanol, 15% gasoline). While FFVs sold in the U.S. must be emissions certified on Federal Certification Gasoline as well as on E85, the European regulations only require certification on gasoline. Owing to renewed and growing interest in increased ethanol utilization in the U.S., a European-specification 2007 Saab 9-5 Biopower 2.0t was acquired by the Department of Energy and Oak Ridge National Laboratory (ORNL) for benchmark evaluations. Results show that the vehicle's gasoline equivalent fuel economy on the Federal Test Procedure (FTP) and the Highway Fuel Economy Test (HFET) are on par with similar U.S.-legal flex-fuel vehicles. Regulated and unregulated emissions measurements on the FTP and the US06 aggressive driving test (part of the supplemental FTP) show that despite the lack of any certification testing requirement in Europe on E85 or on the U.S. cycles, the vehicle is within Tier 2, Bin 5 emissions levels (note that full useful life emissions have not been measured) on the FTP, and also within the 4000 mile (6400 km) US06 emissions limits. Emissions of hydrocarbon-based hazardous air pollutants are higher on Federal Certification Gasoline while ethanol and aldehyde emissions are higher on ethanol fuel. The advertised power increase on E85 was confirmed through acceleration tests on the chassis dynamometer as well as on-road.

INTRODUCTION

Ethanol fuel is receiving renewed interest as a means to displace petroleum fuel and potentially reduce greenhouse gas emissions. Multiple flexible-fuel vehicle (FFV) models are available in the U.S., capable of operating on conventional gasoline, or E85 (85% ethanol/15% gasoline) or any blend of the two. The majority of these offerings are "ethanol tolerant" gasoline vehicles, as E85 availability is still quite limited in the U.S., so there is little impetus for the manufacturers to optimize the vehicles for ethanol use. Due to the lower energy density of E85, these FFVs typically suffer a considerable loss in apparent fuel economy or "tank mileage" (miles per gallon of fuel, mpg) when running on E85, which results in a loss of vehicle range. Despite equivalent or slightly improved fuel efficiency (distance per unit energy), this range shortfall is considered a significant obstacle to wide-spread consumer acceptance.

Due to increasing interest in ethanol utilization in the U.S., a 2007 Saab 9-5 BioPower 2.0t was acquired by the Department of Energy and ORNL for benchmark evaluation. Current European regulations (Euro 4) only require vehicles 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 tank mileage on future vehicle designs. This paper provides results of fuel economy and emissions on the Federal Test Procedure (FTP), the Highway Fuel Economy Test (HFET), and the US06 aggressive driving test (part of the supplemental FTP). Both regulated and selected unregulated emissions compounds are reported for both Federal Certification Gasoline and an E85 blend containing nominally 12% by volume of the same Federal Certification Gasoline in denatured ethanol with 1% butane. Fuel economy on both fuels is compared to certification data available on U.S.-legal FFVs for model years 2000-2007. In addition, acceleration performance on E85 and gasoline is reported.

In 1988 the U.S. enacted the Alternative Motor Fuels Act to encourage the production and sale of alternative-fuel vehicles, in hopes of decreasing the nation's dependence on foreign oil[1]. The law allows a manufacturer to receive corporate average fuel economy (CAFE) credits for producing FFVs. Since 1999, the manufacturers have produced and sold some 6 million FFVs[2-3] in the United States (U.S.). In the U.S., ethanol is domestically produced from corn, a renewable source of energy, and could potentially be produced from cellulosic biomass such as trees and grasses[4-5]. On a net scale, an increase in the national production of ethanol could also lower the net CO_2 emissions to the atmosphere as the added feedstock to produce ethanol would recycle additional atmospheric CO_2[4-5]. Brazil has successfully adopted ethanol as an alternative source of energy[6].

In the United States, FFVs must be certified to applicable emissions regulations on both federal certification gasoline as well as on E85. In previous studies, FFVs have on average shown lower or equivalent emissions when operating with ethanol with the exception of ethanol, formaldehyde and acetaldehyde[7-12]. Ethanol and aldehyde emissions are common with E85 fueling due to unburned and partially oxidized fuel during combustion. Oxides of nitrogen (NOx), carbon monoxide (CO) and total hydrocarbons (THC) are generally reduced or unchanged with increasing content of ethanol in the fuel. Due to the lower energy density of ethanol, these FFVs typically suffer a considerable loss in fuel economy when running with added ethanol. However, ethanol's higher octane rating can help expand the performance envelop of the engine. Past FFVs have adjusted the engines' air/fuel ratio and spark advance timing to operate with different blends of ethanol typically ranging from 0% (E0) to 85% (E85) mixed with gasoline[13]. Aside from these engine parameters, optimizing the effective compression ratio to ethanol content of the fuel has also shown performance improvements[14].

Saab Automobile released the BioPower™ engines in 2006 that optimize performance when operating with ethanol fuel. As the engine control unit (ECU) detects ethanol content in the fuel, maximum turbocharger boost pressure is increased thereby increasing the mass air flow and ultimate engine power. Specifications for the 2.0t claim 150 hp (112 kW) on gasoline and a 20% increase to 180 hp (134 kW) on E85. The vehicle is equipped with components that are compatible with both fuels to prevent corrosion and premature wear[11,15]. Ethanol content in the fuel is detected by means of feedback control from the oxygen sensor in the vehicle's exhaust system. The sensor detects oxygen in the exhaust and allows the ECU to dither the air-to-fuel ratio slightly rich and slightly lean of stoichiometric[13,16].

EXPERIMENTAL

VEHICLE

A 2007 Saab 9-5 BioPower sedan was purchased from Sweden and delivered to ORNL in January 2007. The vehicle is equipped with a 2.0 liter turbocharged engine and 5-speed manual transmission. Curb weight is 3360 pounds (1525 kg). Rated power output is 150 hp (112 kW) at 5500 engine revolutions per minute (RPM) on gasoline, and 180 hp (134 kW) at 5500 RPM on E85. The vehicle is certified to the Euro 4 standard.

Catalyst Degreen and Certification Lab Emissions Tests

Upon receipt in Oak Ridge, the vehicle was shipped to Transportation Research Center (TRC) in East Liberty, Ohio for catalyst degreening using the Environmental Protection Agency (EPA) Accepted Mileage Accumulation Protocol[17]. Following 4000 miles (6400 km) of vehicle operation on the TRC track to degreen the catalysts and allow normal engine break-in, the vehicle was emissions tested with Federal Certification Gasoline (Unleaded Test Gasoline, 96 Research Octane, or UTG96, from Chevron-Phillips Chemical Company (CP-Chem)). Baseline tests consisted of duplicate Federal Test Procedure (FTP), Highway Fuel Economy Test (HFET), and US06 tests on UTG96. Following the UTG96 emissions tests, the vehicle fuel tank was triple-flushed with certification E85, also provided by CP-Chem, in which the added gasoline component was UTG96. With the vehicle fully adapted to E85, the FTP, HFET and US06 were repeated in duplicate. Because there was no scan tool available at that particular time to query the ECU for adapted ethanol content, a conservative triple flush procedure was used, and included adaptation of the ECU after each E85 fill. Results of the TRC tests will be discussed in the Results section.

The vehicle was then returned to ORNL for additional evaluations, including fuel economy and emissions on the same cycles with exhaust speciation and acceleration tests on a local track. As the vehicle arrived at ORNL with E85 in the tank and the ECU fully adapted to E85, the first set of experiments were run on ethanol fuel. After several days of cold-start FTP, HFET, and US06 tests, the vehicle was adapted to gasoline using the UTG96 federal certification gasoline. Gasoline tests were conducted over several days. The vehicle was then adapted back to E85 for a trip to a local track for acceleration tests. After acceleration tests on E85, the vehicle tank was drained on-site and refilled twice with premium pump gasoline for the gasoline acceleration tests. Emissions test weight (ETW) on the dynamometers at TRC and ORNL was 3625 pounds (1644 kg). Acceleration tests on the track were conducted at about 3900 pounds (1770 kg) (driver, passenger, full tank of fuel, and instrumentation).

Fuels

Selected fuel properties are shown in Table 1. The CP-Chem E85 used in this study was nominally 83.5% ethanol, as shown in Table 1. The ASTM standard for denatured fuel ethanol (D 4806) specifies that a minimum of 1.96 % by volume and a maximum of 5.0 % of natural gasoline, gasoline components or unleaded gasoline be added as a denaturant[19]. ASTM further specifies that E85 is a blend of nominally 75 to 85% by volume denatured fuel ethanol and 25 to 15 volume % hydrocarbons (D 5798)[20]. Three classes of E85 are specified for seasonal changes. Class 1 E85 can have

79-86% ethanol, while Class 2 and Class 3 can contain as low as 74% or 70% ethanol, respectively. Higher volumes of gasoline increase the vapor pressure of the fuel and improve starts and driveability in colder climates. Experiments at TRC and ORNL used Class 1 E85. CP-Chem blends denatured ethanol with 12% UTG96 and 1% butane for the finished fuel. The butane improves the RVP while using only 12% certification gasoline results in higher ethanol content (83-84%), but still within the Class 1 specification. The E85 blends for ORNL and TRC were ordered at the same time, but unfortunately were not of the same lot. The ORNL shipment was reportedly the last two drums of an older lot, while the TRC shipment was a new lot. The fuels were essentially the same except for a small difference in water content and RVP. Carbon mass fraction is the basis for fuel economy calculation and the two fuels were within 0.2%. Heating values were the same to 3 significant figures. Reasons for the difference in RVP are unknown.

Table 1. Selected Fuel Properties

Fuel Property	UTG96 Federal Certification gasoline Lot 6CPU9601	E85 CP-Chem lot 6KPE8501 (ORNL)	E85 CP-Chem lot 6KPE8502 (TRC)
Ethanol v/v %	--	83.4	83.7
Hydrocarbon v/v %	--	16.2	16.3
Carbon (mass %)	86.4	57.4	57.3
Hydrogen (mass %)	13.6	13.59	13.53
Oxygen (mass %)	0.0	29.33	29.44
Specific Gravity (60F)	0.741	0.784	0.784
Net Heat of Combustion (BTU/lb) [MJ/kg]	18,500 [43.0]	12,400 [28.8]	12,400 [28.8]
Net Heat of Combustion (BTU/gal) []	114,500 [31.9]	81,000 [22.6]	81,000 [22.6]
Water v/v%	--	0.86	0.64
Reid vapor Pressure (psi)	9.2	8.5	7.6
Motor Octane	87.8	NA*	NA*
Research Octane	96.4	NA*	NA*
Pump octane (R+M)/2	92.1	NA*	NA*

*Octane not reported by CP-Chem. Typical pump octane ((R+M)/2) for E85 is 105-110[21-22]

FACILITIES

The TRC chassis dynamometer is an AVL 48 inch (1.22 meter) Dual Axle 2-wheel drive/4-wheel drive motor/brake unit. Emissions are measured with Horiba 200 series analyzers. Carbon dioxide (CO2) and carbon monoxide (CO) are measured with non-dispersive infrared (NDIR) instruments. Oxides of nitrogen (nitric oxide (NO) and nitrogen dioxide (NO_2) collectively NOx) are measured by a chemiluminescence detector, and total hydrocarbons (THC) are measured with a flame ionization detector. Methane (CH_4) is measured with a Gas Chromatography analyzer.

Additional emissions evaluations were conducted at ORNL's Fuels, Engines, and Emissions Research Center (FEERC). The FEERC chassis dynamometer is of the twin-roll type (21.625 inch diameter (0.55 meter)) with an eddy current brake. Conventional emissions measurements are conducted with analyzers from California Analytical Instruments. NDIR is used to measure CO_2 and CO. Heated chemiluminescence detectors are used for NOx, and THC and methane are measured with a heated flame ionization detector with a methane cutter.

Emissions Speciation at ORNL

A Nicolet REGA 7000 FTIR (Fourier Transform InfraRed Spectrometer) was used to detect formaldehyde, acetaldehyde, ethanol, methanol, methane, 1,3 butadiene, ammonia, nitrous oxide, ethylene, and acetylene from the cycle-average Tedlar® bags of the driving cycles. The FTIR also sampled continuously from the dilution tunnel during the driving cycles. In addition, an INNOVA Photoacoustic Multi-gas Sensor (PAS) instrument was used to sample the bags for ethanol, methanol, and formaldehyde.

A Hewlett-Packard gas chromatograph mass spectrometer (GC/MS) with Entek Preconcentrator was used for identification and quantification of many other HC species from diluted samples collected in the bags. Evacuated stainless steel canisters are used to sample from the dilute bags.

Silica-gel cartridges treated with dinitrophenylhydrazine (DNPH cartridges) were used to sample for carbonyls such as formaldehyde and acetaldehyde[18]. Unless otherwise noted, reported values for aldehydes are from the DNPH cartridge-based measurements, as the bag levels were quite low for detection by FTIR or PAS.

RESULTS

FUEL ECONOMY

Fuel economy measurements from the 3 cycles (FTP, HFET, and US06) are shown in Figure 1. These TRC data show each individual run for each fuel (UTG96 and E85) and highlight the excellent repeatability at TRC as well as the expected 25-30% drop in “tank mileage” with the E85 fuel.

Figure 2 shows the average fuel economy of the TRC and FEERC drive cycle tests. Average fuel economies between the two laboratories were all within 4%, which is typical for lab-to-lab agreement. Comparisons of CO_2 emissions between the two labs were also within the same error, as expected, given that the fuel economy calculation is based on the collected carbon (CO_2, CO, and HC) in the exhaust. Figure 3 shows the same average fuel economies except that the E85 fuel economy has been converted to gasoline equivalent fuel economy (GE mpg). This calculation accounts for the differences in the energy density of the fuels by multiplying the E85 fuel economy by the ratio of the energy densities of the two fuels. Computing the gasoline equivalent fuel economy facilitates understanding any improvement in efficiency associated with operation on E85.

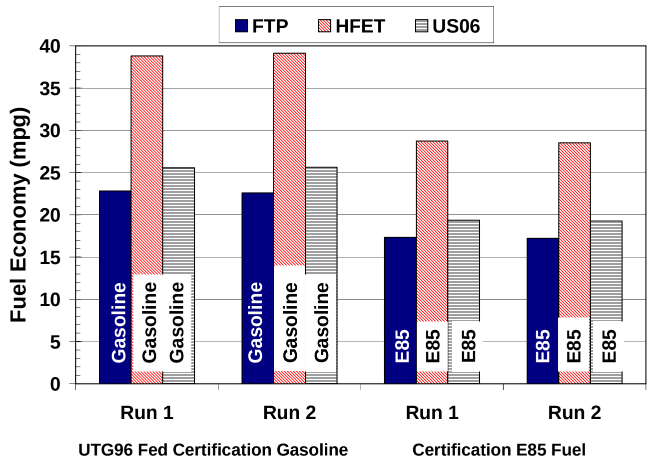


Figure 1. Drive cycle fuel economy for individual tests at TRC

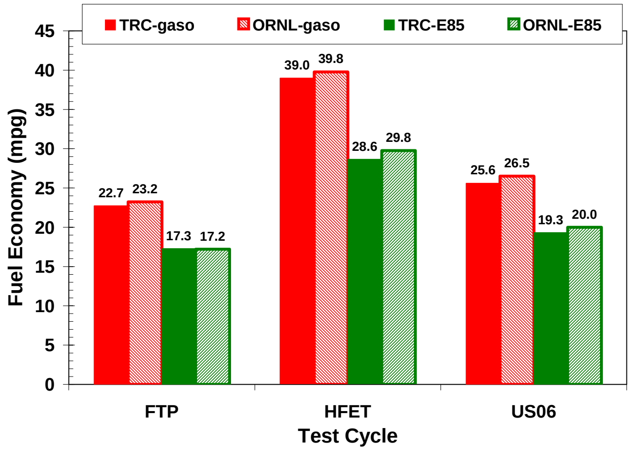


Figure 2. Drive cycle fuel economy for average of all tests at TRC and ORNL

EMISSIONS

Emissions measurements at TRC included NOx, CO, CO_2, THC, and methane. As no detailed HC speciation was conducted at TRC, non-methane organic gas emissions (NMOG) were not calculated. Detailed HC speciation was conducted at ORNL to look for hazardous air pollutants and to also enable computation of the NMOG emissions. Figure 4 shows the NMOG versus NOx emissions for the vehicle along with several relevant emissions standards. The applicable Euro 4 standard, in force through 2008, is the standard this car was required to meet (on the New European Driving Cycle, NEDC). Under Euro 4, the hydrocarbon emission limit is based on THC emissions. Euro 4 standards have been converted to g/mi to facilitate comparison with the U.S. standards in the figure (to convert g/mi to g/km, divide by 1.609 km/mi). The proposed Euro 5 standard is also shown (in this case as NMHC), along with the U.S. Tier 2, Bin 8 and Bin 5 standards (in terms of NMOG). Bin 8 is relevant as it is the maximum allowable standard for U.S.-legal light-duty vehicles in 2009, and Bin 5 is relevant as its NOx standard is the required fleet average for U.S.-legal light duty vehicles. The figure shows that the vehicle is within the Tier 2, Bin 5 level for 50,000 mile certification. Note that the vehicle had only accumulated some 4500 miles at the time of these emissions measurements, and full useful life has not been demonstrated. Nonetheless, the low emissions levels are extraordinary in that the vehicle was not certified on the U.S. cycles, nor was it certified on the NEDC on E85. If the ethanol and aldehyde emissions are ignored and NMHC is calculated from the THC and CH_4 emissions, the resultant NMHC emission is about half the NMOG emission. Emissions tests on the NEDC result in similar fuel economy as the FTP, with similar THC and NOx emissions. The NEDC begins with a cold start and very light load driving, which leads to higher CO emissions, at about 1.5 g/mi, very close to the 1.6 g/mi Euro 4 limit.

Carbon monoxide emissions for the vehicle were on the order of 0.5-0.6 g/mi for the FTP and largely undetectable for the HFET tests. At 0.5 - 0.6 g/mi, the CO emissions on the FTP are about 15-20% of the Tier 2 standard of 3.4 g/mi and about 35-40% of the Euro 4/Euro 5 standard of 1.6 g/mi.

Emissions on the US06 cycle are shown in Figure 5 as a fraction of the 4000 mile (6400 km) standard. Note the dramatic decrease in CO emissions on E85. The increase in available power from 150 to 180 hp (112 to 134 kW) no doubt has an effect on the level of enrichment required to follow the trace of this aggressive driving cycle. The NEDC has maximum accelerations below 2 mph/s (0.9 m/s^2) and a maximum speed of 75 mph (121 km/h). The US06 cycle has a maximum acceleration of 8 mph/s (3.6 m/s^2) and a top speed of 80 mph (129 km/h). As such, it is the most demanding emissions driving cycle from the commanded enrichment perspective.

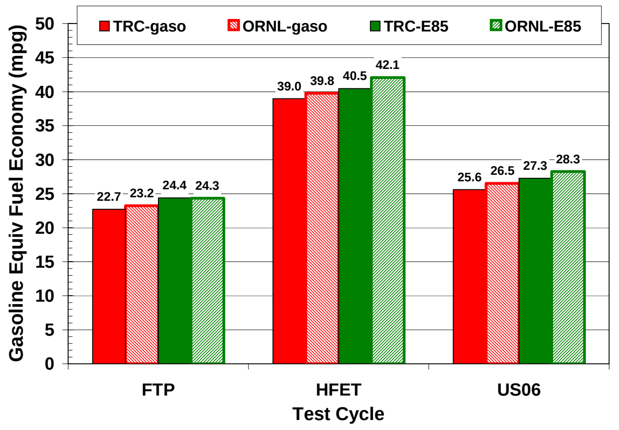


Figure 3. Gasoline equivalent drive cycle fuel economy for average of all tests at TRC and ORNL

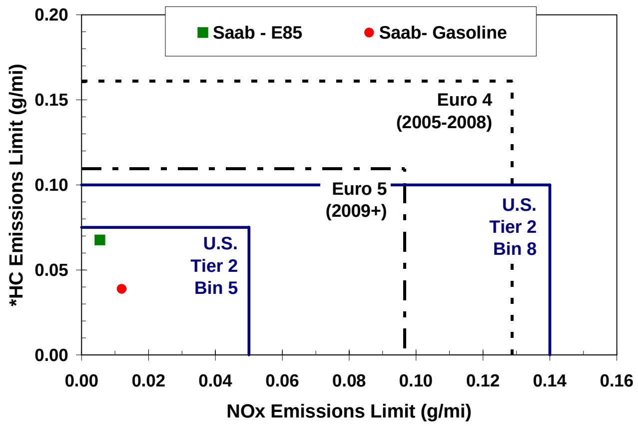


Figure 4. FTP NMOG versus NOx emissions for Saab FFV on gasoline and E85. Euro standards for NEDC test shown for reference. *Note that Euro 4 standard is for THC, Euro 5 standard is for NMHC, U.S. Tier 2 standards are for NMOG.

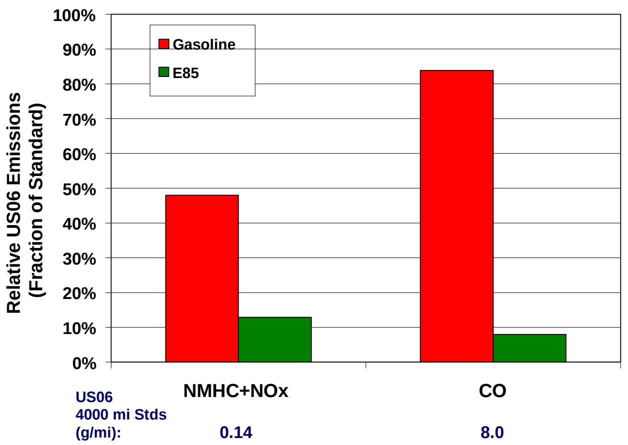


Figure 5. US06 Emissions for Saab FFV on gasoline and E85

Several individual species of interest were measured by GC/MS, FTIR, PAS, or by DNPH derivatization. Figure 6 shows several Hazardous Air Pollutants (HAPs) determined by GC/MS. Note that the hydrocarbon-derived HAPs are much higher for the gasoline case. Conversely, emissions of ethanol, formaldehyde, and acetaldehyde are higher for the E85 case on the FTP, as shown in Figure 7. Acetaldehyde emissions on the US06 were actually lower on E85 than on gasoline. The ethanol emissions were measured with the PAS, while aldehydes were from the DNPH cartridge method. Emissions of 1,3 butadiene were detected with the FTIR, and as expected, were higher for the gasoline case.

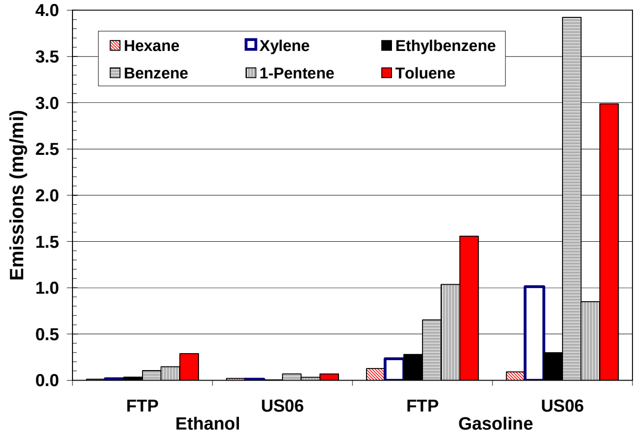


Figure 6. Selected hazardous air pollutant emissions for Saab FFV on FTP and US06

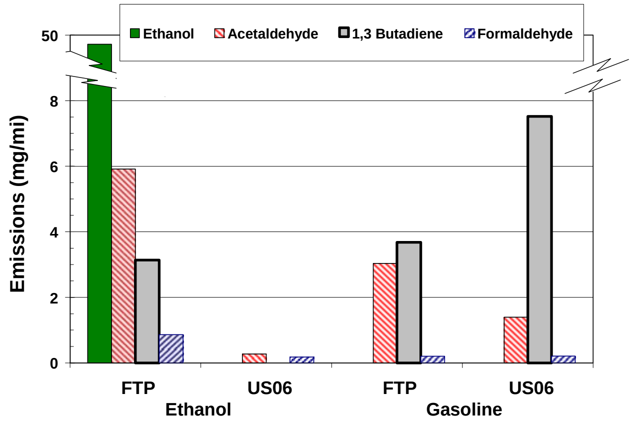


Figure 7. Ethanol, aldehyde, and 1,3 butadiene emissions for Saab FFV on gasoline and E85. Note the broken y-axis scale.

ACCELERATION PERFORMANCE

Fixed-gear accelerations were run on the chassis dynamometers at TRC and FEERC to ensure good lab-to-lab comparisons and also to highlight any performance advantage with E85 fuel. For a third gear wide-open-throttle (WOT) acceleration run, the vehicle is

2 seconds faster from 40 to 70 mph (64 to 113 km/h), as shown in Figure 8. This performance difference equates to over 1.5 car lengths over a 500 foot (152 m) acceleration.

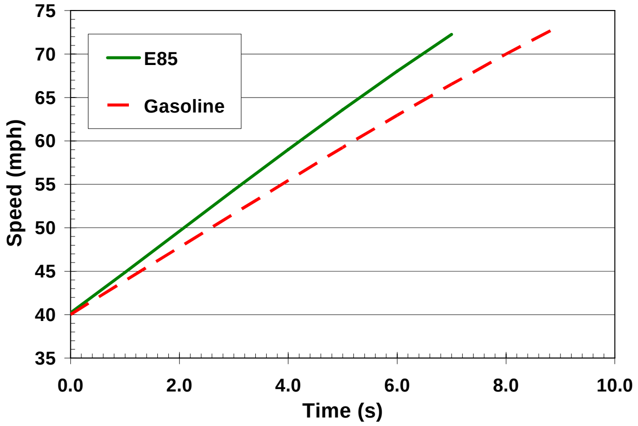


Figure 8. Wide-open throttle, fixed-gear acceleration for Saab FFV on gasoline and E85 (dynamometer)

The vehicle was instrumented and taken to a local test track for 0-60 mph (97 km/h) acceleration determination. Vehicle speed and distance were measured with a Datron Corrsys Davit Light Speed (DLS) sensor. Minimal wheel spin was used at launch and the clutch was used for lift-throttle shifts. With ethanol fuel, the vehicle is about one second faster to 60 mph (97 km/h). The vehicle reaches 60 mph (97 km/h) at its 6000 RPM redline in 2nd gear, so only 1 shift was used for each run. Best time for 0-60 mph (97 km/h) was 9.29 seconds with E85 fuel, and 10.22 seconds for premium gasoline (93 pump octane ((R+M)/2)), as shown in Figure 9. Published 0-100 km/h (62 mph) time for the 9-5 2.0t on gasoline is 9.8 seconds[23]. Performance on ethanol was cited at 8.5 seconds[23]. Details such as launch technique or shift speeds for these acceleration tests were not provided in the references. Given the faster acceleration times, it is likely that the vehicle was loaded with driver only and launched more aggressively. The results published here were for vehicle with a full tank of fuel, driver, passenger, and test instrumentation. The vehicle was weighed at 3910 pounds (1770 kg) before the acceleration tests. With driver only, the test weight would have been closer to 3700 pounds (1678 kg), and calculations suggest that the weight difference would enable about 0.5 second less time to 60 mph (97 km/h). In addition, the 2.0t engine is also available in a heavier Saab CombiSport wagon, with a curb weight of 3700 pounds (1680 kg). With the heavier test weight, the CombiSport's advertised 0-100 km/h (62 mph) time is 10.2 seconds on gasoline[23] which is on par with the ORNL results.

Collection of some relevant engine parameters during the acceleration runs was hampered by computer communications problems at the track. While the DLS and an Autoenginuity scan tool were communicating simultaneously with the notebook computer in the laboratory, upon arrival at the test track, both instruments would not communicate at the same time. As such, the DLS was used alone for vehicle speed and distance measurement, and then independent runs with the Autoenginuity tool were conducted to measure engine RPM, manifold pressure, spark timing, and vehicle speed. As the communications through the assembly line diagnostic link (ALDL) is relatively slow (serial at about 2 Hz for 2 parameters), these data cannot be accurately overlaid with the DLS data. Nonetheless, the parameters measured during the independent acceleration runs are of interest. Figure 10 shows manifold absolute pressure (MAP) and ignition timing versus time for two E85 runs and two gasoline runs at the track. Ignition timing is in degrees before top dead center (BTDC), and is also commonly known as spark advance. The ECU data show a maximum manifold absolute pressure (MAP) of 163 kPa for E85 and 152 kPa for gasoline (8.9 and 7.3 psig boost, respectively). In WOT runs on the dynamometer with an electronic pressure transducer installed and 10 Hz data collection, the maximum MAP on E85 recorded was 183 kPa versus 165 kPa for gasoline (11.8 and 9.2 psig boost, respectively). The ECU data from the test track also confirm the more advanced spark timing with E85 fuel.

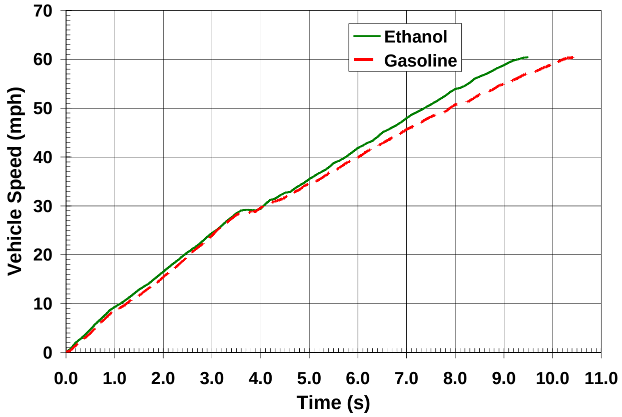


Figure 9. Vehicle speed versus time for 0-60 acceleration on test track

FFV FUEL ECONOMY ANALYSIS

Some 6 million FFVs have been sold in the U.S., and all were emissions certified on Federal Certification Gasoline and on E85. City (FTP) and Highway (HFET) fuel economy are determined on each fuel as well, and these data are available from the EPA[3]. These data are the basis of the window sticker fuel economies for new vehicles and the annual Fuel Economy Guide[24]. Data shown in the Fuel Economy Guide are typically adjusted to reflect fuel economy closer to what consumers might expect, and also rounded to an integer value. For the analysis described in this paper and the results from fuel economy evaluations at TRC or FEERC, the raw, unadjusted fuel economies have been used. Data from model years 2000-2007 were collected from the EPA website to develop a database of U.S. legal FFVs for comparison to the Saab FFV.

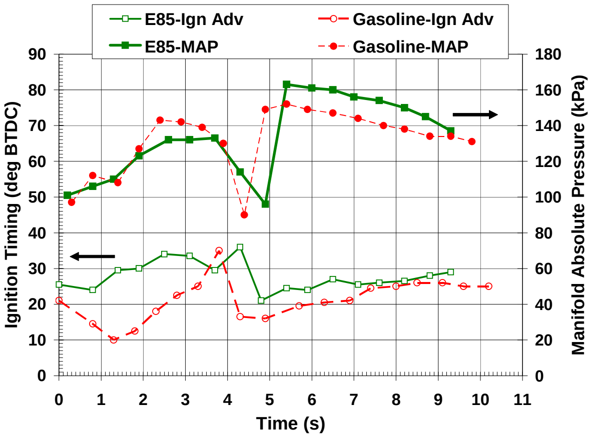


Figure 10. MAP and Ignition Timing for 0-60 acceleration on test track

The fuel economy data records for all vehicles evaluated on ethanol (E85) were located and matched with corresponding fuel economy data of the same vehicles (determined with identical vehicle identification numbers) tested with gasoline. The data collected had to include both ethanol and gasoline fuel economy in the same year on either the City or Highway driving cycles (but not necessarily both) with the same ETW and rated power. In several cases, multiple records were found for the same vehicle model with different test weights or power (e.g., multiple Ford Taurus models). For model years 2000-2007, ~90 city and highway fuel economy records of U.S. FFVs were located in the EPA database, consisting of ~20 passenger cars and ~70 trucks.

Figure 11 shows the city (FTP) and highway (HFET) fuel economy for the U.S. FFV fleet. Reported E85 fuel economy is plotted versus gasoline fuel economy. The slopes of the regressions indicate the expected 25-30% loss in tank mileage due to the lower energy density of E85. Measured values for the Saab FFV are also shown on this figure. It is noteworthy that the fuel economy for the vehicle is near the maximum for the U.S. FFV fleet on both city and highway driving cycles, but that the loss in tank mileage for the Saab appears to be comparable to the rest of the FFVs in the U.S. There are currently no turbocharged FFVs offered in the U.S., and the bulk of the engines offered are V6 and V8 configurations. About half of the FFV engines have displacements larger than 5 liters, while only about 25% are below 3 liters.

The fuel economy data were adjusted to a gasoline equivalent basis based on the assumption that the U.S. FFV ethanol fuel tests were conducted with 81% ethanol mixture (assumes 85% denatured ethanol (95% ethanol) blended with 15% Federal Certification Gasoline). Figure 12 shows the gasoline equivalent fuel economy data of the U.S. FFV fleet as a function of the vehicles' power-to-weight ratio, with comparable data from the Saab. This plot reveals a slight improvement of the fuel economy data between gasoline and ethanol (on a gas equivalent basis) for the U.S. FFVs. The Saab shows a significant adjustment on ethanol due to the substantial power increase on ethanol over gasoline. The fuel economy for the Saab compares favorably with other U.S. flex-fuel cars (such as the Chrysler Sebring and Ford Taurus). The Chevrolet Monte Carlo and Impala FFV have higher city and highway fuel economy (two data points in upper right corner of Figure 11).

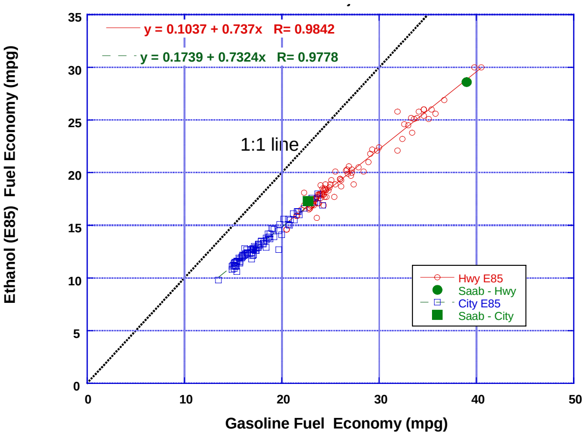


Figure 11. E85 Fuel Economy versus gasoline fuel economy for FFVs

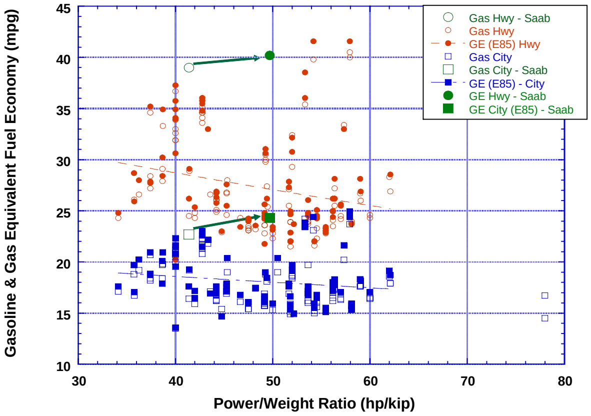
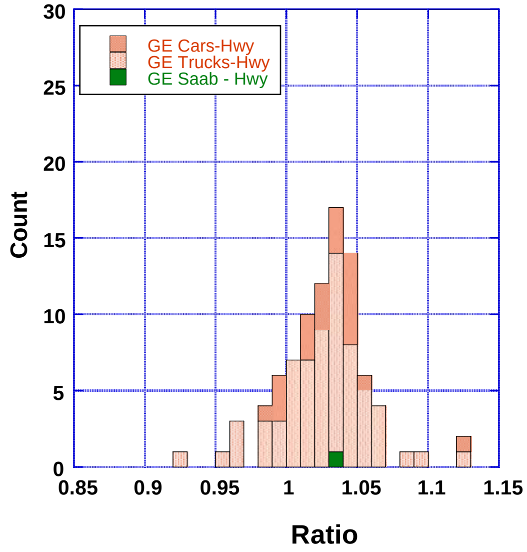


Figure 12. Gasoline equivalent fuel economy versus power-to-weight ratio

A Gasoline Equivalent Ratio (defined here as the ratio of the gasoline equivalent fuel economy on ethanol divided by the gasoline fuel economy) was computed for the Saab and each vehicle in the FFV database. This ratio indicates how much, if any, of the fuel economy loss is made up on an energy equivalent basis in switching to E85. Histograms of the Gas Equivalent Ratio for the US FFV fleet and the Saab are shown in Figures 13a and 13b for the Highway and City driving cycles, respectively. These data show that on ethanol, the US FFV fleet averages about a 3% increase in the gasoline equivalent fuel economy on both driving cycles (the mean Gasoline Equivalent Ratio for the highway and city cycles were both 1.03 ± 0.03). It is interesting to note that cars seemed to have a slightly higher Gasoline Equivalent Ratio than trucks; but no statistical correlations were noted with model year, vehicle manufacturer, or power-to-weight ratio. Figures 13a and 13b indicate that the Gas Equivalent Ratio for the Saab (1.04 for highway; 1.07 for city) is on-par with the rest of the US FFV fleet for highway fuel economy data, but is among the best in the US FFV fleet for the city driving test.

The Gasoline Equivalent Ratio on the US06 is also quite good for the Saab, showing a nearly 7% improvement in gasoline equivalent E85 fuel economy. Unfortunately, no US06 data for the U.S. FFV fleet were available for comparison.

(a) Highway



(b) City

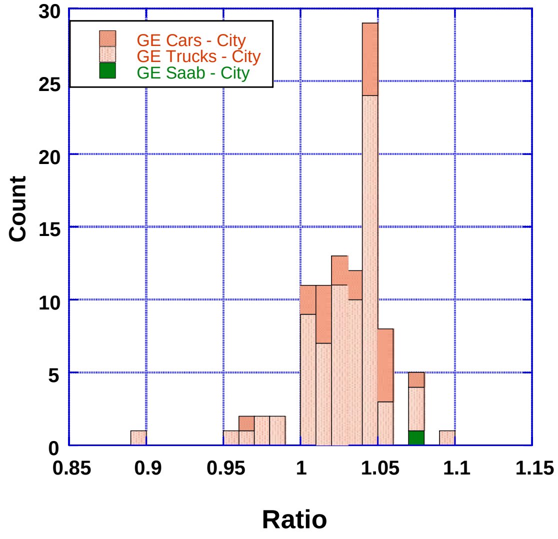


Figure 13. Histogram of gasoline equivalent ratio for FFVs on (a) highway (HFET) and (b) city (FTP)

CONCLUSIONS

Benchmarking the 2007 Saab 9-5 BioPower has led to several notable conclusions. Following 4000 miles (6400 km) of test track operation for engine break-in and catalyst degreening, driving cycle emissions and fuel consumption were measured on the chassis dynamometer, as well as vehicle acceleration on the dynamometer and on the track.

- The vehicle does produce more power on E85 than on gasoline, accelerating to 60 mph about 1 second faster on E85. The added power also leads to much lower CO emissions on the aggressive US06 driving cycle with E85 fuel. This power advantage may also provide additional consumer incentive to purchase an FFV and to then actually use E85 fuel when available.

- Saab BioPower emissions on U.S. cycles are below stringent Tier 2, Bin 5 levels (note that full useful life emissions have not been measured). These results are significant in that Europe does not require emissions certification on E85, and applicable Euro 4 emissions requirements are less stringent than the comparable Tier 2 levels. The vehicle's low emissions validate the BioPower as a reasonable benchmark for comparison to U.S. FFVs.

- Saab BioPower fuel economy is very good compared to the US FFV fleet, as it is among higher fuel economy FFVs available in the U.S. The Saab's gasoline equivalent fuel economy on E85 is on par with the U.S. fleet on the highway test (about 3% better than on gasoline). The gasoline equivalent fuel economy on E85 is slightly better on the city test (about 7% better than on gasoline, versus 3% for U.S. Fleet).

- Detailed exhaust speciation reveals ethanol and aldehyde emissions are higher on E85 while hydrocarbon-based hazardous air pollutants are higher on gasoline. Levels of these compounds on either fuel are very low.

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DISCLAIMER

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

AFR:	Air:Fuel ratio
ALDL:	Assembly Line Diagnostic Link, connector for communication with the ECU
ASTM:	American Society for Testing and Materials
BTDC:	Before Top Dead Center
CAFE:	Corporate Average Fuel Economy
CH_4:	Methane
CO:	Carbon monoxide
CO_2:	Carbon dioxide
DLS:	Davit LightSpeed, optical sensor for vehicle distance, speed, and acceleration
DNPH:	Dinitrophenylhydrazine
DOE:	U.S. Department of Energy
E85:	Nominally 85 volume percent denatured ethanol blended with 15 volume percent gasoline.
ECU:	Engine Control Unit (also known as Engine Control Module or ECM)
EPA:	Environmental Protection Agency
ETW:	Emissions Test Weight
FEERC:	Fuels, Engines, and Emissions Research Center at ORNL
FFV:	Flex-fuel vehicle, a vehicle capable of burning E85, gasoline, or any blend of the two
WOT:	Wide-open throttle
FTIR:	Fourier Transform InfraRed analyzer
FTP:	Federal Test Procedure for emissions certification and city fuel economy, also known as Urban Dynamometer Driving Schedule
HC:	Hydrocarbons
HCLD:	Heated chemiluminescence detector (for NOx)
HFET:	Highway Fuel Economy Test
HFID:	Heated Flame Ionization Detector (for HC)
HP:	Horsepower
km:	Kilometer (1000 meters)
kW:	Kilowatt
MON:	Motor Octane Number
NDIR:	Non-dispersive infrared, detector for CO and CO_2
NEDC:	New European Drive Cycle, for emissions certification in the European Union
NMHC:	Non-methane hydrocarbons ($THC-CH_4$)
NMOG:	Non-methane organic gases (includes oxygenates such as ethanol and aldehydes)
NOx:	Nitrogen oxides (NO and NO_2)
ORNL:	Oak Ridge National Laboratory in Oak Ridge, TN
Pump Octane:	Average of RON and MON ((R+M)/2)
RON:	Research Octane Number
(R+M)/2:	Average of RON and MON, also known as pump octane
RPM:	Revolutions per minute
TRC:	Transportation Research Center in East Liberty Ohio
US06:	Aggressive driving test for emissions certification