Zhai, H., H.C. Frey, N.M. Rouphail, G.A. Gonçalves, and T.L. Farias, "Fuel Consumption and Emissions Comparisons between Ethanol 85 and Gasoline Fuels for Flexible Fuel Vehicles," Paper No. 2007-AWMA-444, Proceedings, 100th Annual Meeting of the Air & Waste Management Association, Pittsburgh, PA, June 26-28, 2007

Fuel Consumption and Emissions Comparisons between Ethanol 85 and Gasoline Fuels for Flexible Fuel Vehicles

Extended Abstract # 2007-A-444-AWMA

Haibo Zhai, [1] H. Christopher Frey, [1] Nagui M. Rouphail, [2] Gonçalo A. Gonçalves [3] and Tiago L. Farias [3]

[1] Department of Civil, Construction and Environmental Engineering, North Carolina State University, Campus Box 7908, Raleigh, NC 27695-7908, USA
[2] Institute for Transportation Research and Education, NCSU, Centennial Campus, Campus Box 8601, Raleigh, NC 27695-8601, USA
[3] Department of Mechanical Engineering, Instituto Superior Técnico, Av. Rovisco Pais, 1, 1049-001Lisbon, Portugal

INTRODUCTION

Ethanol-based fuels may offer advantages of reduced national dependence on imported petroleum. Since ethanol is an oxygenated fuel, the use of ethanol may offer environmental benefits such as reduction in emissions of products of incomplete combustion (namely carbon monoxide) as well as total hydrocarbons (THC).[1] However, there is some concern that E85 is associated with higher emissions of some hydrocarbon species, such as aldehydes[2]. Ethanol can be blended with gasoline to create E85, a blend of 85% ethanol and 15% gasoline by volume. The objective of this research is to evaluate differences in fuel consumption and emissions of flex fueled vehicles (FFVs) operated on E85 versus gasoline powered vehicles.

Second-by-second fuel consumption and emissions from one FFV Ford Focus fueled with E85 and gasoline were measured under real-world traffic conditions in Lisbon, Portugal using a portable emissions measurement systems (PEMS), that was developed by Instituto Superior Técnico.[3] Furthermore, emissions data and test results for Ford Taurus and Chevrolet Lumina FFVs were available from the Alternative Fuel Data Center (AFDC) of the U.S. Department of Energy.[4] Carbon dioxide (CO_2), CO, and nitric oxide (NO) emissions were measured in both types of tests, and THC emissions were measured in dynamometer tests. Empirical analysis was based upon these two databases.

METHODOLOGY

Fuel consumption and emissions were compared for a given vehicle when operated on each of E85 and gasoline fuels based upon theoretical and empirical analyses.

Theoretical Ratios of Fuel Use and CO_2 Emissions: E85 versus Gasoline

When comparing fuel use and emissions for a given vehicle, the theoretical ratios of fuel use and CO_2 emissions for E85 versus gasoline were estimated by assuming that the same amount of energy was required (i.e. same engine efficiency was assumed). The complete combustion reactions for gasoline and ethanol are, respectively:

Equation 1.

$$CH_{1.875} + 1.469(O_2 + 3.76N_2) \rightarrow CO_2 + 0.938H_2O + 5.523N_2$$

Equation 2.

$$CH_3O_{0.5} + 1.5(O_2 + 3.76N_2) \rightarrow CO_2 + 1.5H_20 + 5.64N_2$$

Based on fuel chemical properties summarized in Table 1, the ratio of the lower heating value for one gallon of fuel gasoline versus E85 is 1.41. The theoretical mass-based ratio of fuel use for an equivalent amount of energy is 1.49 for E85 versus gasoline.

For the same amount of energy released from E85 and gasoline, the theoretical ratio of CO_2 emissions for E85 versus gasoline is 0.98.

Table 1 Fuel Chemical Properties [5]

Fuel	Equivalent Molecular Formula	Equivalent Molecular Weight (g/gmole C)	Density (kg/m^3)	Lower Heating Value (Btu/gallon)	Lower Heating Value (MJ/liter)
Gasoline	$CH_{1.875}$	13.875	737	115,500	31.76
Ethanol	$CH_3O_{0.5}$	23	790	76,000	21.07
E85	-	21.63	782	81,925	22.67

VSP and Modal Average Fuel Consumption and Emission Rates

Vehicle specific power (VSP) has been identified as a useful exploratory variable for emissions. Based on coefficient values for a generic light duty vehicle, VSP is calculated using the following equation:[6-7]

Equation 3.

$$VSP = \mathrm{v} \times [1.1 \times a + 9.81 \times (\sin(\mathrm{atan}(\varphi))) + 0.132] + 0.000302 \times \mathrm{v}^3$$

Where: VSP = vehicle specific power (m^2/s^3); v = vehicle speed (m/s); a = acceleration (m/s^2); φ = road grade.

Fourteen VSP discrete modes were defined for light-duty vehicles in a previous study.[6] These modes are applied to FFVs for both types of fuels. Using the second-by-second speed profile, and acceleration and road grade, VSP was computed from Equation (3) and then categorized into the VSP modes. Thus, modal average fuel consumption and emission rates for both types of fuels were estimated based on the PEMS database. The ratios of fuel use and emissions for E85 versus gasoline were calculated for each VSP mode. Equally weighted average modal ratios and their 95 percent confidence intervals were estimated.

Dynamometer Test Fuel Consumption and Emissions Analysis

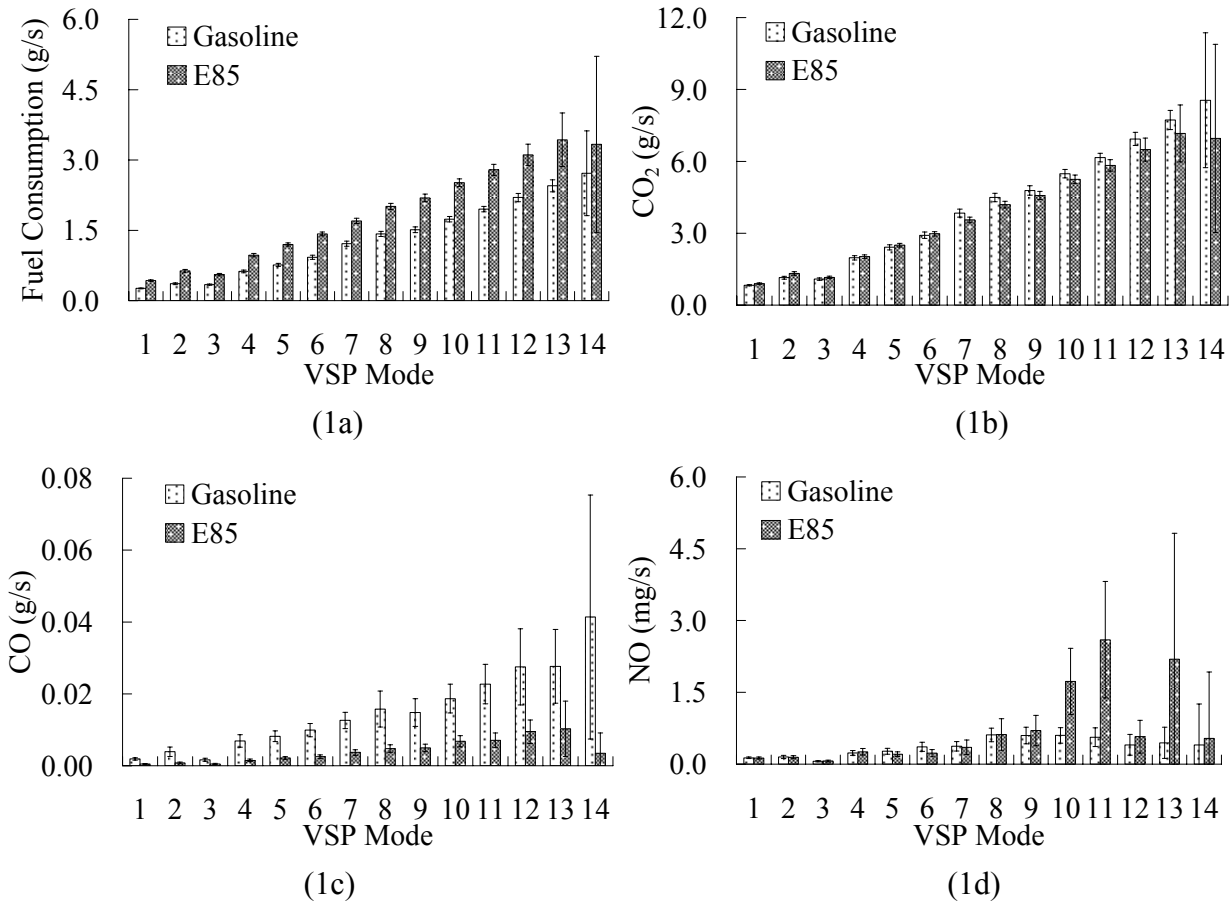
Average fuel consumption and emission dynamometer test results are available for the FTP-75 driving cycle.[4] Average fuel consumption and emission rates were categorized by vehicle model and odometer reading (mileage accumulation). The ratios of fuel use and emissions for E85 versus gasoline were calculated for the same driving cycle, vehicle model, and range of mileage accumulation. In addition, an equally weighted average ratio was estimated based upon all ranges of mileage accumulation for each vehicle model.

RESULTS AND DISCUSSION

Modal average fuel consumption and emission rates based upon PEMS data are shown in Figure 1. In general, there is an approximately monotonic increase in fuel consumption and emission rates with respect to VSP modes for both fuels. There are wider confidence intervals for higher

VSP modes because there are few samples available. Fuel consumption and emission rates are reported in units of grams per second. For a given VSP mode, the E85-fueled vehicle consumed more mass of fuel than the gasoline-fueled vehicle; compared with gasoline, the E85-based emissions were similar for CO_2 and much lower for CO, and higher for NO, especially for higher VSP modes. In both cases THC emissions were very close to the lower detection limits of the analyzer used.

Figure 1 Modal Average Fuel Consumption and Emission Rates of a European 2006 Ford Focus based upon PEMS Data



Dynamometer test results are given in Table 2. Comparisons of dynamometer tests for E85 versus gasoline are based upon fuel consumption rates in gallons per mile and emission rates in grams per mile. The fuel consumption rate of E85 was greater than that of gasoline for both vehicles. The average ratios of fuel economy for gasoline versus E85 are 1.31 for the Taurus and 1.38 for the Lumina, which are close to the expected theoretical ratio of 1.41. CO_2 emission rates were similar for both fuels. For the Taurus, CO and NO_x emission rates from the E85-fueled vehicle were typically slightly lower than those from the gasoline-fueled vehicle, but THC emission rates from the E85-fueled vehicle were higher. However, for the Lumina, CO, NO_x and THC emission rates from the E85-fueled vehicle were all significantly lower than those from the gasoline-fueled vehicle.

Mileage accumulation did not have a significant effect on fuel economy, but appeared to have more effect on emissions. For example, emissions of NO_x and THC increased with mileage

accumulation for the E85-fueled Taurus. However, these trends were not consistently observed for the gasoline-fueled tests for the Taurus or for the Lumina on either fuel.

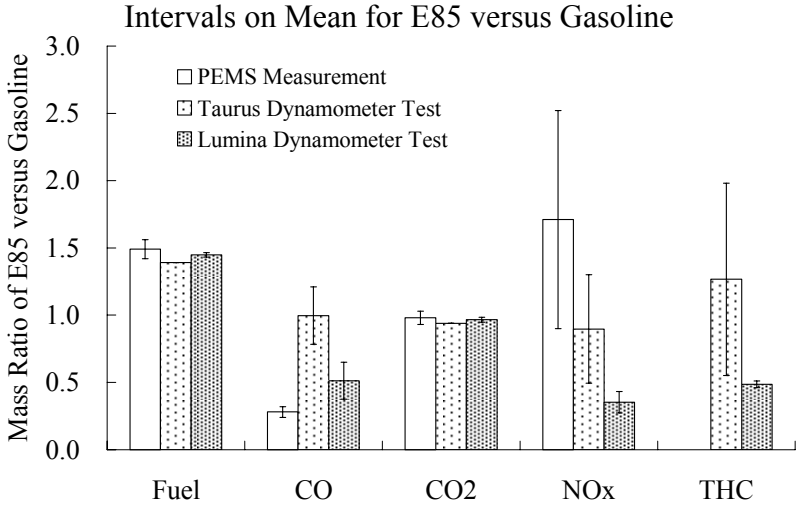
The mass ratios of fuel consumption and emission rates for E85 versus gasoline are shown in Figure 2. The ratios of fuel consumption and CO_2 emissions for real-world measurement and dynamometer tests were close to the theoretical ratios. However, the ratios of CO, NO_x and THC emissions varied by vehicle model.

Table 2 Average Fuel Consumption and Emission Rates based upon FTP75 Dynamometer Tests[a]

Vehicle Model	Fuel Type	No. of Vehicle Tests	Mileage Accumulation (miles)	Fuel Economy (mpg)	Fuel Consumption (gallon/mile)	Emission Rate (g/mile)			
						CO	CO_2	NO_x	THC
Taurus	E85	12	0-5000	15.4	0.065	1.13	405	0.100	0.107
		11	5000-10000	15.4	0.065	1.35	402	0.117	0.135
		5	10000-15000	15.4	0.065	1.28	397	0.119	0.153
	Gasoline	15	0-5000	20.0	0.050	1.15	431	0.100	0.103
		10	5000-10000	20.0	0.050	1.46	429	0.120	0.116
		12	10000-15000	20.4	0.049	1.17	423	0.168	0.096
Lumina	E85	15	10000-15000	13.9	0.072	2.46	448	0.184	0.125
		6	15000-20000	14.1	0.071	2.50	438	0.254	0.132
		6	20000-25000	13.9	0.072	3.27	443	0.192	0.135
		4	25000-30000	14.3	0.070	2.88	429	0.212	0.142
	Gasoline	12	10000-15000	19.6	0.051	4.26	447	0.645	0.258
		8	15000-20000	19.6	0.051	4.72	445	0.635	0.263
		4	20000-25000	18.9	0.053	5.58	461	0.641	0.285
		2	25000-30000	19.2	0.052	6.86	446	0.590	0.288

Notes: Different vehicles were tested for each fuel for a given vehicle model, fuel type, and mileage accumulation. The E85 tests were with Flexible Fuel Vehicles (FFVs) and the gasoline tests were with conventional vehicles.[2]

Figure 2 Ratios of Average Fuel Consumption and Emission Rates, with 95% Confidence Intervals on Mean for E85 versus Gasoline



SUMMARY

Empirical ratios of fuel consumption and CO_2 emissions for E85 and gasoline fuels agreed within a margin of error compared to the theoretical expectations. From the PEMS data, CO emissions appeared to be typically lower but NO emissions were higher when comparing E85 to gasoline. From the dynamometer data, CO and NO_x emissions were lower but THC emissions could be either higher or lower, depending on the vehicle. These results imply that the use of E85 in place of gasoline may reduce CO emissions, as expected, but that the effect on THC and NO_x emissions is more variable. The data analyzed here did not include speciated hydrocarbons.

ACKNOWLEDGEMENTS

The work at North Carolina State University was supported by U.S Environmental Protection Agency STAR Grant R831835 via the University of North Carolina- Chapel Hill and by National Science Foundation Grant No. 0230506. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the EPA and NSF. The work at Instituto Superior Técnico was supported by MMSAFU project (POCI/ENR/57450/04) funded by the Fundação para a Ciência e a Tecnologia as well as FLAD (Luso–American Foundation). The authors also would like to acknowledge the support of Ford Lusitana and TOTAL Portugal.

REFERENCE

1. Guerrieri, D.A.; Caffrey, P.J.; Rao, V. Investigation into the vehicle exhaust emissions of high percentage ethanol blends. SAE Special Publications, n 1095, Gasoline: Additives, Emissions, and Performance, 1995, p 85-95.
2. Kelly, K.; Eudy, L.; Cobum, T. *Light-Duty Alternative Fuel Vehicles: Federal Test Procedure Emissions Results*. NREL/TP-540-25818, Prepared by National Renewable Energy Laboratory. September 1999.
3. Gonçalves, G. A. and Farias, T. L., On-Road Measurements of Emissions and Fuel Consumption of Gasoline Fuelled Light Duty Vehicles, Clean Air 2005, 27-30 June 2005, Lisboa, Portugal.
4. Alternative Fuel Data Center of the U.S. Department of Energy Home Page. See fttp://www1.eere.energy.gov/vehiclesandfuels/avta/light_duty/afv/emissions_data.html (accessed on December, 2006).
5. Wang, M., GREET 1.5- Transportation Fuel-Cycle Model Volume 1: Methodology, Development, Use, and Results. Argonne National Laboratory, ANL/ESD-39, 1999.
6. Frey, H.C.; Unal, A.; Chen, J.; Li, S.; Xuan, C. *Methodology for Developing Modal Emission Rates for EPA's Multi-Scale Motor Vehicle & Equipment Emission System*; EPA420-R-02-027, Prepared by North Carolina State University for U.S. Environmental Protection Agency, Ann Arbor, MI. August 2002.
7. Frey, H.C.; Rouphail, N.M.; Zhai, H. Speed- and Facility-Specific Emission Estimates for On-Road Light-Duty Vehicles based on Real-World Speed Profiles, *Transportation Research Record: Journal of the Transportation Research Board*, Paper No. 1987, 2006,pp128-137.

KEY WORDS

Ethanol 85, Gasoline, Flex Fueled Vehicles, Fuel Consumption, Emissions, Portable Emissions Measurement Systems, Dynamometer Test, Theoretical Ratios, Empirical Ratios