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Effect of E85 on Tailpipe Emissions from Light-Duty Vehicles

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ABSTRACT

E85, which consists of nominally 85% fuel grade ethanol and 15% gasoline, must be used in flexible-fuel (or "flex-fuel") vehicles (FFVs) that can operate on fuel with an ethanol content of 0–85%. Published studies include measurements of the effect of E85 on tailpipe emissions for Tier 1 and older vehicles. Car manufacturers have also supplied a large body of FFV certification data to the U.S. Environmental Protection Agency, primarily on Tier 2 vehicles. These studies and certification data reveal wide variability in the effects of E85 on emissions from different vehicles. Comparing Tier 1 FFVs running on E85 to similar non-FFVs running on gasoline showed, on average, significant reductions in emissions of oxides of nitrogen (NO_x; 54%), non-methane hydrocarbons (NMHCs; 27%), and carbon monoxide (CO; 18%) for E85. Comparing Tier 2 FFVs running on E85 and comparable non-FFVs running on gasoline shows, for E85 on average, a significant reduction in emissions of CO (20%), and no significant effect on emissions of non-methane organic gases (NMOGs). NO_x emissions from Tier 2 FFVs averaged approximately 28% less than comparable non-FFVs. However, perhaps because of the wide range of Tier 2 NO_x standards, the absolute difference in NO_x emissions between Tier 2 FFVs and non-FFVs is not significant (P = 0.28). It is interesting that Tier 2 FFVs operating on gasoline produced approximately 13% less NMOGs than non-FFVs operating on gasoline. The data for Tier 1 vehicles show that E85 will cause significant reductions in emissions of benzene and butadiene, and significant increases in emissions of formaldehyde and acetaldehyde, in comparison to emissions from gasoline in both FFVs and non-FFVs. The compound that makes up the largest proportion of organic emissions from E85-fueled FFVs is ethanol.

IMPLICATIONS

Ethanol production in the United States is rapidly approaching 10% of total gasoline usage. Ten-percent ethanol in gasoline is the highest concentration legally permitted for use in non-FFVs. The Energy Independence and Security Act of 2007 mandates renewable fuel levels of more than 10% of total gasoline consumption in the United States. Therefore, the ethanol surplus may result in an increase in the use of high-percentage ethanol fuels in FFVs, particularly E85, which currently represents only a small fraction of the U.S. fuel market. As the use of E85 increases, its impact on urban air emissions will be increasingly important.

INTRODUCTION

E85 is a motor vehicle fuel that is nominally 85% fuel-grade ethanol and 15% gasoline. Because fuel-grade ethanol contains denaturant, the ethanol content of commercial E85 ranges from as much as 79% in summer to as little as 70% in winter. More gasoline is used in winter months to improve cold starting by increasing volatility. A conventional light-duty vehicle cannot operate on E85; specially designed vehicles known as flexible-fuel or "flex-fuel" vehicles (FFVs) are required. An FFV can operate on any level of ethanol from 0 to 79%. Thus, the engine in an FFV must be capable of making automatic timing and air-to-fuel-ratio adjustments to optimize conditions for the different fuels and mixtures of them. There are some component differences between conventional vehicles and FFVs; the main ones are that FFVs require a higher volume fuel pump, larger diameter injectors, different fuel system plastics and elastomers, and a different engine controller calibration.

More than 100 different vehicle models capable of running on E85 have been certified by automakers with the U.S. Environmental Protection Agency (EPA) since 1998. There are an estimated 6 million FFVs on the road today,[1] and in 2006, Chrysler, Ford, and General Motors (GM) announced plans to double FFV production to 2 million vehicles per year by 2010.[2]

At present, E85 usage is limited by the current level of ethanol production and by the small number of E85 fueling stations. As of January 2009, there were 1700 E85 refueling stations in the United States;[3] in comparison, there were 121,000 U.S. gasoline refueling stations in 2002.[4] U.S. sales of E85 are expected to double in the next 10 yr,[5] and government policies that favor expanding the E85 distribution infrastructure and the sale of FFVs could cause E85 production and use to grow even faster. Because of the considerable impact of motor vehicle use on urban air pollutant inventories, changes in fuel usage may have significant environmental implications (not withstanding that tailpipe emission inventories are dominated by high emitting vehicles). Thus, a careful assessment is needed of the air quality impacts of expanded E85 use.

Studies considering the comprehensive environmental implications of using E85 have generally assumed that the differences in tailpipe emissions between E85 and gasoline are insignificant, because E85 vehicles are required to meet the same emissions standards as do other on-road vehicles.[6–8] However, using the ozone reactivity scale (maximum incremental reactivity [MIR]), Carter developed "reactivity adjustment factors" for emissions from alternatively fueled vehicles and found that E85 volatile organic compound emissions were two-thirds as reactive as California Air Resources Board (CARB) Phase 2 gasoline, on a weight basis.[9] More recently, predictive models were used to suggest that widespread E85 use in 2020 would increase ozone levels approximately 9% in Los Angeles.[10] The ozone increase was caused primarily by an estimated 30% reduction in tailpipe oxides of nitrogen (NO_x) emissions for E85 in comparison with those from reformulated gasoline, consistent with the results of recent studies.[11] Although this study modeled an extremely unrealistic scenario, ignored evaporative emissions, and made several controversial and questionable assumptions, it highlights the need for improved understanding of the air quality impact of introducing new fuels.

Here, we review published emission testing studies conducted since 1992 that compare E85 and gasoline, and we summarize the results of certification emission tests of FFVs that have been reported to EPA. Comparisons are presented for FFVs operating on E85 and gasoline, and between FFVs operating on E85 and comparable conventional vehicles operating on gasoline for carbon monoxide (CO), NO_x, non-methane organic gases (NMOGs) and other forms of hydrocarbon emissions, formaldehyde, acetaldehyde, benzene, and butadiene. Note that FFVs meet the same emission standards as conventional vehicles, and they do so when operating on either gasoline or E85.

Tailpipe emissions are the focus of this paper; however, the small dataset available for evaporative emissions with E85 are described in the next section.

Evaporative Emissions

Although evaporative emissions from motor vehicles play a significant role in urban emission inventories, information is limited regarding evaporative emissions from vehicles using E85. E85 has a Reid vapor pressure (RVP) that is typically less than that of gasoline. Assuming that other things are held equal, E85 would be expected to have a beneficial effect on evaporative emissions. However, the vapor pressure of pure gasoline and the gasoline fraction of E85 can be varied significantly by changing the relative proportion of component compounds. So, regulatory and specification limits are likely to determine actual differences in evaporative emissions. Other issues that could have an impact on emissions are permeation rates and the deterioration of elastomers in the presence of ethanol.

Black and coworkers[12] found evaporative emissions (NMOG) to be about one-third lower for E85 in the one FFV they tested, although the RVP of the E85 was higher than that of the reformulated gasoline (RFG) tested for comparison (7.15 vs. 6.85 psi). The Auto/Oil Air Quality Improvement Research Program (AQIRP) measured evaporative emissions of benzene, organic material hydrocarbon equivalent (OMHCE), NMOGs, and reactivity-weighted emissions (RWE, a measure of ozone-forming potential). Only the change in benzene emissions was statistically significant, with reductions of approximately 60%. This was based on E85 with an RVP of 6.5 psi, compared with RFG with an RVP of 6.8 psi.[13]

Kelly and co-workers[14,15] measured evaporative emissions from many vehicles, but only total hydrocarbons (THCs) were quantified. The initial paper states that the various fuels used were adjusted so that all achieved a nominal 7-psi RVP, which suggests that these results may not be representative of the typical vapor pressure differences between gasoline and E85. However, tabulated results in the paper show the E85 to have the expected lower RVP (6.15 vs. 6.9 psi for the gasoline). They found that THC evaporative emissions from vehicles using E85 were not significantly different from those from vehicles using gasoline.

LIGHT-DUTY EMISSION TESTING METHODOLOGY

Test Fuels

The E85 available at retail pumps is expected to meet ASTM Standard D5798 specifications,[16] although a recent survey has shown that retail fuel is frequently in violation of this specification.[17]

With one exception,[18] the literature studies and EPA certification data involved E85 specially blended for testing rather than for E85 retail sources. The fuel descriptions in these papers state that the tested E85 was approximately 85% ethanol. Because fuel-grade ethanol can contain up to 4.76 vol % denaturant[19] (generally a hydrocarbon known as natural gasoline), it is not clear in several papers whether the fuel tested was 80% ethanol (i.e., 85% fuel-grade ethanol) or 85% neat ethanol. For the EPA certification tests, the remaining 15% of the fuel (and the comparison gasoline test fuel) consisted of EPA unleaded certification fuel, which may represent a nationwide average retail gasoline. For most of the tests included in the literature, the gasoline fraction (and the baseline comparison gasoline fuel) is U.S. RFG or comparable California Phase 2 gasoline. The only exception is the study by de Serves conducted in Sweden using gasoline from Swedish sources.[20] The base gasoline used for comparison was Swedish summer quality gasoline, which includes 5% ethanol.

Test Procedures

Most of the studies discussed in this paper used the cold-start Federal Test Procedure (FTP). The only exceptions were the studies by de Serves,[20] which used several different driving cycles more commonly used in Europe, and by Black et al.,[12] which included the REPO5 cycle (a high-intensity cycle without a cold start) in addition to the FTP cycle. In all studies, steps were taken when switching fuels to ensure that the old fuel was completely purged from the system, including purging the evaporative control canisters with nitrogen gas and reconditioning the canister with test fuel; several fuel tank drain and fill sequences; and a succession of start-up, driving, and idle operations.

PUBLISHED EMISSION TESTING STUDIES

Table 1 summarizes the FFVs in the literature that have been emissions tested on both gasoline and E85.[12–15,18,20–23] Individual test results from these studies are presented in

Table 1. Summary of vehicles tested in the published literature.

Study	Test Cycles	Certification Level	Year	Make and Model	No. of FFVs
de Serves, 2005[a] [20]	5 cycles	Euro 4	2002/2003	Ford Focus	3
Chandler et al., 1998[18]	FTP	Tier 1	1996	Ford Taurus	2
Gabele, 1995[21]	FTP	Tier 1	1993	Chevrolet Lumina	1
Benson et al., 1996[13]	FTP	Tier 1	1992/1993	Chevrolet Lumina	3
		ND	1993	Ford Taurus	
		Tier 0	1993	Plymouth Acclaim	
Kelly et al., 1996[b] [14]	FTP	Tier 0	1992/1993	Chevrolet Lumina	21 at 2 mileages
NREL, 1999[22]	FTP	Tier 1	1998	Ford Taurus	1
Kelly et al., 1999[a] [15]	FTP	Tier 0	1993	Chevrolet Lumina Ford Taurus	24 at 3 mileages
		TLEV	1995		
Black et al., 1998[12]	FTP REP05	ND	1993	Chevrolet Lumina	1

Notes: [a]E85 vs. E5; [b]Some data overlap between two studies by Kelly et al.; NREL = National Renewable Energy Laboratory; TLEV = transitional low-emission vehicle.

Table 1 of the supplemental data (published at http://secure.awma.org/onlinelibrary/samples/10.3155-1047-3289.59.2.172_supplmaterial.pdf). The results of one study were omitted because of the high standard deviation; in most cases, the standard deviations for the emission tests were greater than the magnitude of the measurements.[24] With the exception of two studies by Kelly and coworkers,[14,15] the remaining datasets are small and included three or fewer vehicles. All duplicate tests were combined and the results averaged. However, if the same vehicle was tested twice, but at significantly different odometer readings (presumably as a result of continued on-road use), both results were included. Two studies included some of the same test results, and the repeated data were removed.[14,15] In total, there have been about 100 useful tests, each of which has included a measurement of NO_x, CO, and one or more representations of organic emissions. With the exception of the recent study by de Serves,[20] the vehicles tested are Tier 1 or earlier vehicles. The Ford Taurus and Chevrolet Lumina represent the vast majority of tested vehicles.

EPA CERTIFICATION DATABASE

The EPA certification tests are mandatory tests conducted on each new vehicle model, for all fuels that the vehicle is intended to use, to demonstrate compliance with EPA emissions standards. All new light-duty vehicles, including FFVs, sold in the United States must be certified to meet federal emission standards.[25] Manufacturers obtain certification under strictly regulated laboratory conditions on a sample preproduction vehicle. Testing is conducted at the vehicle manufacturers' test facilities, and results are reported to EPA. However, EPA audits data from these tests and performs its own tests on a small sample to confirm the manufacturers' results. All of the certification test data collected for model years 1979 through 2007 are available for review and analysis on the EPA website.[26] Both tailpipe and evaporative emissions are measured, although evaporative emissions have been included in the online database only since 2006. The database contains certification levels (projected emission levels for the end of useful-life odometer miles of the vehicle), deterioration factors used to compute the certification levels, and the certification standard for which the testing should qualify the vehicle.

Because of the small amount of in-use vehicle emission data available for FFVs, we examined this much broader certification dataset. Certification data are acquired under highly controlled conditions, and actual in-use vehicle emission impacts are likely to be somewhat different, especially when high-emission vehicles are considered. However, there is some precedent for using the certification emission database to assess the impact of fuel properties and vehicle technology on emissions.[27] In addition, the certification database makes up a complete dataset for all FFV models sold in the United States using a consistent testing protocol, whereas in-use testing to date does not even make up a representative sample. Although many different laboratories were used for testing, when an FFV was tested on gasoline and E85, or a similar non-FFV was tested using gasoline, all were tested in the same manufacturer's laboratory. All production vehicles must meet the emission standards, or the manufacturer could face expensive recalls; so, the manufacturer is motivated to test representative vehicles. Therefore, although certain caveats must be attached to any discussion based on certification data, this high-quality dataset is potentially more representative of E85 impacts on emissions than the limited in-use testing results published to date. Additionally, the certification data available from EPA are for Tier 2 vehicles, which are not represented in the literature data.

Each year's dataset contains about 2000 tested vehicles. Only a small fraction involve vehicle models run on E85; these range from two vehicle models for the 1999 model year, when the first FFVs were included in the database, to a high of 12 vehicles in the 2007 model year for a total of 70 different FFV vehicle models. Table 2 of the supplemental data presents a complete listing of those data. These FFVs were also tested using either EPA unleaded or CARB gasoline, depending on the area in which the vehicle would be sold, for some (but not all) of the same pollutants. In addition, non-FFVs that were similar to the FFVs but had a different engine family number were compared to show emissions changes that could occur if FFVs replaced similar vehicle models that ran only on gasoline. A vehicle was considered "similar" for this purpose only if it was the same model year, had the same or similar car line name (e.g., Taurus Wagon vs. Taurus

Wagon FFV), the same transmission, and the same weight (within 250 lb). It is possible that manufacturers have chosen different emission control strategies for FFVs and similar non-FFVs and so these comparisons do not strictly address the emissions differences between the different fuels, but they do show the what will happen if FFVs were to replace non-FFVs on the road on the basis of today's vehicle models.

The vehicles were tested using either the 2-day or 3-day FTP, which allows for a cold soak before tailpipe emissions testing. However, evaporative emissions data might not have been collected on these vehicles using E85, and no evaporative data were included in the certification database on the EPA website until the 2006 model year. Emissions are reported of CO, NMOGs, NO_x, THCs, non-methane hydrocarbons (NMHCs); and less frequently, formaldehyde, OMHCE, organic material NMHC equivalent (OMNMHCE), and CO from a cold-start test. More data were collected for CO, NMOGs, and NO_x than for any other pollutants. In numerous cases, the same data for the same car line and model year were reported more than once. The only apparent difference noted in these duplicate data points was the evaporative system number, the expected sales area, or the Tier 2 bin for which the vehicle was intended. In those cases, duplicates were deleted from the dataset for purposes of statistical analysis. Additionally, most vehicles had emissions reported at two mileages: 50,000 and either 100,000 or 120,000 mi, with mileage accumulations on gasoline. Emissions measurements at both mileages were retained. The measurements include 134 tests of FFVs (most of 68 different FFVs tested at two different mileages) for NO_x emissions from E85 and gasoline. One hundred and sixteen emissions tests were conducted on both fuels for NMOGs, and 138 for CO. Similar non-FFV vehicles were identified for NO_x 33 times; for NMOG, 26 times; and for CO, 35 times.

The certification testing program and EPA database were not developed for comparing E85 and gasoline emissions. Therefore, several caveats are associated with using the database for that purpose:

- E85 fuel for certification testing is not defined in the regulations. Although the fuel is nominally 85% ethanol and 15% either EPA unleaded certified fuel or CARB fuel, actual ethanol content may vary. It may contain some higher alcohols and some water, because ethanol exposed to the atmosphere will absorb water. Differences in the actual fuel used may contribute to differences in reported emissions.
- There is no information on the repeatability or representativeness of the testing. EPA works with vehicle manufacturers and other emissions testing laboratories to maintain consistency. However, the results of intralaboratory comparison testing have not been published.
- The number of significant digits reported for the same compounds varied between vehicles, and sometimes between tests on the same or similar vehicles.
- In some cases, the emissions data are entered with only one significant digit. Thus, small differences in actual emissions can be erased or appear to be more significant than they actually are.
- In several cases, the NO_x emissions and formaldehyde emissions were reported as zero, with no information on the detection limit used. Because the detection limit was not known, and the number of significant digits varied, normal methods of handling nondetections could not be applied. Moreover, it is possible that zero was reported when the test did not return a usable result. We decided to delete all zero results from this analysis.
- All of the tests begin when vehicles are new, and the vehicles are aged under controlled conditions. In contrast, urban emissions inventories are typically dominated by a small percentage of high emitters, as CARB first demonstrated in 1983[28] and which has been confirmed in many studies since then.[29] No information is provided on the fuel used during aging of the FFVs.

RESULTS

In both the literature and certification datasets, it is notable that measured emissions under the same standard vary considerably. However, every emissions result entered into the EPA database meets the certification standard, often by more than a factor of 2, so the emissions effects noted here are for very clean cars. With the exception of a few CO measurements,[14,15] all of the measured emissions reported in the literature were also within applicable regulatory requirements.

A percent change in emissions was computed for each paired comparison. Results for FFVs operating on E85 and gasoline were compared, as well as results for an FFV operating on E85 and a comparable conventional vehicle operating on gasoline, in cases where the second comparison was available. Geometric averages of the ratio between E85 emissions and gasoline emissions were considered more representative of the central tendency than arithmetic averages of percentage change. To demonstrate this by example, consider two tests—one that shows E85 causing an emission of 2 g/mi whereas gasoline resulted in 1 g/mi, and a second in which the results were reversed and E85 showed 1 g/mi and gasoline 2 g/mi. The percentage change would be 100% in the first case and −50% in the second case. The arithmetic average of the percentage change for these two cases would be +25%, suggesting that E85 is likely to cause an increase in emissions whereas, in fact, the results show it is equally likely to cause an increase or a decrease. Instead, if the geometric average of the ratio between the two values is used, the ratio of 1:1 or a 0% change shows the correct statistical relationship. All averages are shown with the 95% confidence level calculated around the geometric mean. Histograms of the percent change in emission results are included for NO_x and CO as Figures 1 and 2.

Paired *t* tests were performed to compare geometric average results between fuels for each pollutant. These *t* test results are reported as a *P* value for the two-tailed comparison; a low value of *P* indicated that the emission

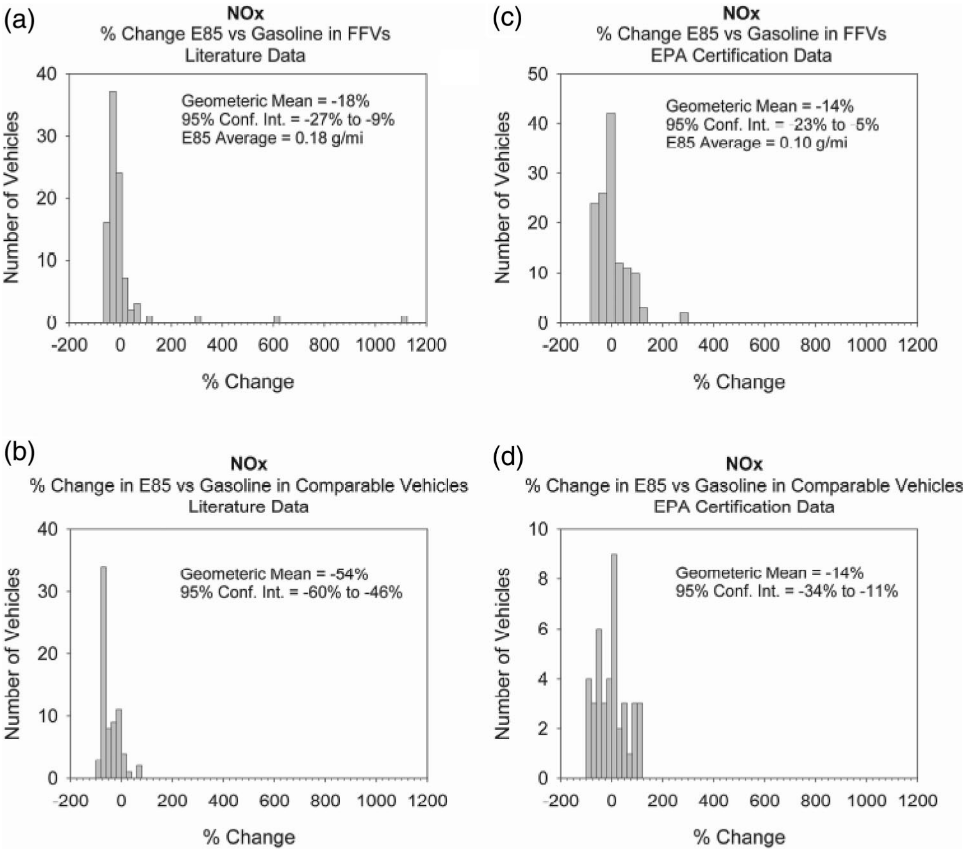

Figure 1. Histograms showing percent change in NO_x emissions for (a) E85 vs. gasoline in FFVs, literature data, (b) E85 in FFVs vs. gasoline in comparable vehicles, literature data, (c) E85 vs. gasoline in FFVs, EPA certification data, and (d) E85 in FFVs vs. gasoline in comparable vehicles, EPA certification data.

difference between the two groups is significantly different from zero. The results of these analyses are shown in Table 2 for literature values and Table 3 for the certification data.

Analysis of Emissions Results

Both the literature and certification data show that, on average, NO_x and CO emissions are reduced for E85, in comparison to gasoline. Nonetheless, the histograms show that there is a wide range in a fuel's effects on emissions from different vehicles. The variance for the comparison of the two fuels tested in the same FFV is smaller than for the E85 FFV compared with a similar non-FFV using gasoline.

In addition, the literature results suggest the following when comparing primarily Tier 1 FFVs operating on E85 with FFVs and standard vehicles operating on gasoline:

- NMHCs will be reduced by 10% (FFV) to 27% (non-FFV).
- CO will be reduced by approximately 20%.
- NO_x will be reduced by 18% (FFV) to more than 50% (non-FFV).
- Formaldehyde emissions will increase by approximately 50%.
- Acetaldehyde emissions will increase by a multiple of more than 20.
- Benzene and 1,3-butadiene emissions will decrease, perhaps in proportion to the amount of gasoline in the mixture; however, this observation is based on results for a small number of vehicles.
- Methane emissions will approximately double.
- Fuel economy will be adversely affected by approximately 25%.

Results recently presented by Whitney and Fernandez confirm these observations and show a significant reduction in emissions of particulate matter (PM).[30]

Tables 3 and 4 show certification test results for various classes of vehicles or test fuels. Not all of these comparisons are discussed; however, a forward-looking comparison could be limited to only Tier 2 vehicles. For FFVs running on E85 versus gasoline, the results are very close to those for the overall dataset: E85 relative to gasoline causes a reduction in NO_x of approximately 19%, a 28% increase in NMOGs, and a 20% decrease in CO. For the more relevant comparison of FFVs running on E85 with comparable non-FFVs operating on gasoline, we see no significant change in emissions of NMOGs, and a reduction in CO of approximately 15%. NO_x emissions from Tier 2 FFVs averaged approximately 28% less than comparable non-FFVs. However, when a P value is calculated to determine the significance of the absolute emission difference between FFVs and non-FFVs it suggests that the difference is not significant. This may be because vehicles certified to the Tier 2 standards were actually certified to a range of NO_x standards that varied by more than an order of magnitude.

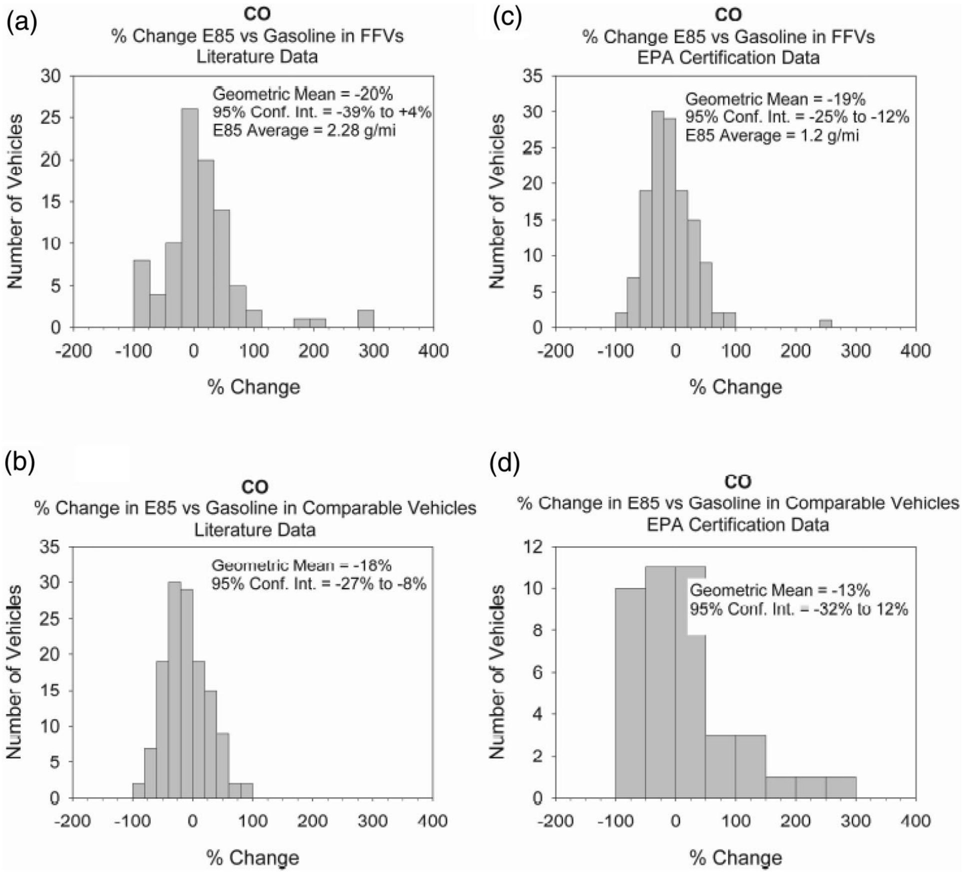

Figure 2. Histograms showing percent change in CO emissions for (a) E85 vs. gasoline in FFVs, literature data, (b) E85 in FFVs vs. gasoline in comparable vehicles, literature data, (c) E85 vs. gasoline in FFVs, EPA certification data, and (d) E85 in FFVs vs. gasoline in comparable vehicles, EPA certification data.

An interesting side note in these comparisons can be found in Table 3. The table suggests that Tier 2 FFVs operating on gasoline produced less NMOGs than comparable non-FFVs operating on gasoline. To investigate this further, we conducted a direct comparison of the average emission change between gasoline-operated FFVs and their similar non-FFV counterparts. The results are shown in Figure 3. There is a significant reduction (13%) in NMOGs in the FFVs; however, the limited data available do not show any significant effect on NMHCs, THCs, or formaldehyde emissions.

The measured organic pollutant emissions from the largest in-use study are compared in Figure 4.[14,15] For this study of Tier 1 vehicles, the total organic emissions from the gasoline-fueled FFVs were significantly less than the organic emissions from the non-FFVs, because the FFVs produced lower emissions of NMHC. Because fuel consumption, NO_x, and CO emissions of the two types of vehicles using gasoline are comparable, the difference in organic emissions may be due to differences in timing, calibration, or to the design of the catalyst or another emission control system component. Additionally, this figure shows that ethanol comprises most of the difference in emissions between E85 FFVs and the same or similar non-FFV vehicles run on gasoline. The results of Whitney and Fernandez[30] suggest that these ethanol emissions are primarily produced during cold starts.

Toxicity and Ozone-Forming Potential of Organic Emissions

The evidence gathered to date suggests that the use of E85 will reduce benzene and 1,3-butadiene at a rate approximately proportional to the amount of ethanol in the fuel, although this conclusion is based on tests of only seven vehicles. Acetaldehyde and ethanol emissions will increase by a large amount and formaldehyde by a lesser amount. On the basis of these results, others have concluded that total toxic compound mass emissions are likely to increase,[12,15] but potency-weighted toxicity will be reduced.[15] There may be no clear effect on cancer rates, because the greater toxicity of benzene and 1,3-butadiene is balanced by large increases formaldehyde, acetaldehyde, and ethanol emissions.[9]

Several researchers have estimated the tendency for organic emissions to react in the atmosphere to form ozone. These calculations do not take into account the atmospheric chemistry of any individual site, nor do they account for the fuel impact on NO_x emissions, both of which may affect ozone creation. Given these caveats, the results suggest that it is likely that E85 emissions will have lower specific ozone reactivity than those from RFG.[10,14] However, the quantity of ozone-forming emissions can differ between vehicles using E85 and those using gasoline, and the net effect on ozone creation will depend onthe multiplicative product of the quantity of emissions produced and its specific reactivity.[10,14]

Table 2. Percent change in emissions for E85 vs. gasoline: literature data.

Literature Results	Comparison	Geometric Mean (%)	95% Confidence Interval Range (%)		No. Tested	*P* Value for Paired *t* Test
THC	E85 vs. gasoline in same FFV	−8	−19	4	89	0.20
	E85 in FFV vs. gasoline in similar non-FFV	−18	−28	−7	71	0.00
NMOG	E85 vs. gasoline in same FFV	12	−56	182	6	0.43
	E85 in FFV vs. gasoline in similar non-FFV	−43	−43	−43	1	
NMHC	E85 vs. gasoline in same FFV	−10	−17	−3	72	0.03
	E85 in FFV vs. gasoline in similar non-FFV	−27	−37	−16	72	0.00
Methane	E85 vs. gasoline in same FFV	92	72	114	86	0.00
	E85 in FFV vs. gasoline in similar non-FFV	91	75	108	71	0.00
CO	E85 vs. gasoline in same FFV	−20	−39	4	93	0.30
	E85 in FFV vs. gasoline in similar non-FFV	−18	−27	−8	73	0.05
NO_x	E85 vs. gasoline in same FFV	−18	−27	−9	93	0.00
	E85 in FFV vs. gasoline in similar non-FFV	−54	−60	−46	73	0.00
PM	E85 vs. gasoline in same FFV	−34	−98	2395	3	1.00
	E85 in FFV vs. gasoline in similar non-FFV				0	
Fuel economy	E85 vs. gasoline in same FFV	−25	−26	−25	78	0.00
	E85 in FFV vs. gasoline in similar non-FFV	−27	−27	−26	72	0.00
Formaldehyde	E85 vs. gasoline in same FFV	63	51	75	92	0.00
	E85 in FFV vs. gasoline in similar non-FFV	56	39%	76	72	0.00
Acetaldehyde	E85 vs. gasoline in same FFV	1786	1424	2233	92	0.00
	E85 in FFV vs. gasoline in similar non-FFV	2437	2130	2786	72	0.00
Benzene	E85 vs. gasoline in same FFV	−70	−82	−50	6	0.16
	E85 in FFV vs. gasoline in similar non-FFV	−86	−86	−86	1	NA
1,3-Butadiene	E85 vs. gasoline in same FFV	−62	−83	−13	6	0.01
	E85 in FFV vs. gasoline in similar non-FFV	−91	−91	−91	1	NA

Notes: All studies showed the tested vehicles met the applicable emissions standards with the exception of two vehicles, which only slightly exceeded the CO standard. These tests did not include any high-emitting vehicles.

Gabele considered both the specific ozone reactivity and the quantity of emissions and calculated what he called a RWE rate.[21] He predicted that the RWE rate will be reduced when an FFV using E85 is compared with a non-FFV, but that it will increase slightly when compared with the same FFV using gasoline. Kelly and coworkers[15] also considered the specific ozone reactivity and the quantity of emissions, and they found no difference in the net ozone-forming potential between the E85-fueled FFVs and the gasoline-fueled non-FFVs. However, they also found that the FFVs using gasoline had a lower ozone-forming potential than either of the other two tested configurations. Black and coworkers[12] compared a Chevrolet Lumina FFV using gasoline with the same vehicle using E85 and found that, for the FTP cycle, the E85 tailpipe emissions had a lower specific ozone reactivity and a higher ozone-forming potential. It is interesting that, when the Chevrolet Lumina was tested on another cycle (the higher speed, higher acceleration REPO5 cycle, which does not include a cold start), the Lumina had a lower ozone-forming potential in the E85 case than in the gasoline case. The authors do not provide the specific reactivities for the REPO5 tailpipe emissions tests; however, they attribute the change in relative net ozone-forming potential to the elimination of the cold start in the REPO5 test. This suggests that organic emissions from FFVs using E85 are relatively more affected by cold starts (i.e., are higher) than the same vehicles using gasoline. On balance, these results suggest that there is no significant change in the ozone-forming potential of organic emissions as a result of the use of E85 in Tier 1 vehicles. To date, the data for Tier 2 vehicles are too limited to allow a conclusion to be drawn.

Analysis of Variance

Several studies in the literature used the statistical criteria established in AQIRP for determining whether duplicate or triplicate testing was required.[12,13,21] In the three studies cited, duplicate tests were performed on all vehicle/fuel combinations, and then a third (triplicate) test was added if the absolute value of the ratio of emissions between the first two tests exceeded the following values: 1.33 for THC, 1.70 for CO, and 1.29 for NO_x. The basis for these values is a statistical analysis on outliers conducted by Painter and Rutherford for AQIRP.[31] Using emissions data collected by AQIRP on vehicles operating on several different types of fuel, Painter and Rutherford calculated the ratios by setting the outlier level as those values outside of the 98.3% two-sided value of the distribution. Later authors, using these values for determining the need for triplicates, have assumed that the repeatability of their own testing was similar to that of the original AQIRP testing, and they have accepted the 98.3% level that determines which values are outliers. Because it has been more than 15 yr since the original analysis was performed, a reexamination of these criteria, on the basis of newer emissions measurement data, is warranted.

Two studies included numerous duplicates and numerous tests on different vehicles of the same make and model using the same fuel; these provided an opportunity to estimate the relative importance of testing precision

Table 3. Comparison of E85 and gasoline NO_x, NMOG, and CO emissions in EPA certification database.

		NO_x					NMOG					CO				
	Comparison	**Geometric Mean (%)**	**95% Confidence Interval Range (%)**		**No. Tested**	***P* Value**	**Geometric Mean (%)**	**95% Confidence Interval Range (%)**		**No. Tested**	***P* Value**	**Geometric Mean (%)**	**95% Confidence Interval Range (%)**		**No. Tested**	***P* Value**
Overall	E85 vs. gasoline in same FFV	−14%	−23	−5	134	0.51	26	17	37	116	0.00	−19	−25	−12	138	0.00
	E85 in FFV vs. gasoline in similar non-FFV	−14	−34	−11	33	0.15	−5	−13	3	26	0.36	−13	−32	12	35	0.27
Tier 1	E85 vs. gasoline in same FFV	18	0	41	20	0.17	−18	−33	0	4	0.15	−15	−26	−2	27	0.01
	E85 in FFV vs. gasoline in similar non-FFV	49	12	99	8	0.02	0	0	0	2	1.00	−7	−39	42	11	0.35
Tier 2	E85 vs. gasoline in same FFV	−19	−28	−9	114	0.00	28	18	39	112	0.00	−20	−26	−12	111	0.00
	E85 in FFV vs. gasoline in similar non-FFV	−28	−47	−3	25	0.28	−6	−14	4	24	0.36	−15	−39	16	24	0.06
EPA base fuel	E85 vs. gasoline in same FFV	−13	−22	−3	123	0.88	27	16	38	105	0.00	−18	−24	−11	127	0.00
	E85 in FFV vs. gasoline in similar non-FFV	−14	−34	11	33	0.15	−5	−13	3	26	0.36	−13	−32	12	35	0.27
CARB base fuel	E85 vs. gasoline in same FFV	−28	−47	−1	11	0.05	25	−1	56	11	0.07	−27	−50	7	11	0.02
	E85 in FFV vs. gasoline in similar non-FFV				0					0					0	
50,000 Miles	E85 vs. gasoline in same FFV	−13	−26	1	65	0.69	31	16	48	58	0.00	−18	−27	−8	67	0.00
	E85 in FFV vs. gasoline in similar non-FFV	−13	−41	30	15	0.33	−5	−17	9	13	0.60	−12	−40	28	16	0.55
100,000 or 120,000 Miles	E85 vs. gasoline in same FFV	−15	−27	−1	69	0.60	22	10	35	58	0.00	−19	−27	−11	71	0.00
	E85 in FFV vs. gasoline in similar non-FFV	−16	−41	20	18	0.30	−6	−16	6	13	0.47	−13	−39	23	19	0.37
LDV	E85 vs. gasoline in same FFV	−13	−34	15	38	0.73	24	10	41	38	0.00	−17	−28	−4	38	0.01
	E85 in FFV vs. gasoline in similar non-FFV	−44	−63	−15	16	0.11	−10	−19	0	16	0.09	29	4	59	15	0.06
LDT1	E85 vs. gasoline in same FFV	−1	−4	1	7	0.28	69	−3	195	6	0.68	−28	−37	−17	8	0.02
	E85 in FFV vs. gasoline in similar non-FFV				0					0					0	
LDT2	E85 vs. gasoline in same FFV	−26	−38	−13	47	0.00	30	14	49	42	0.00	−17	−26	−8	51	0.00
	E85 in FFV vs. gasoline in similar non-FFV	25	7	46	4	0.64	−9	−11	−8	2	0.11	−49	−72	−7	6	0.07
LDT3	E85 vs. gasoline in same FFV	9	−14	37	14	0.22	50	25	79	9	0.01	2	−12	17	14	0.14
	E85 in FFV vs. gasoline in similar non-FFV	49	−12	153	4	0.04	0	0	0	2	1.00	−21	−49	22	5	0.29
LDT4	E85 vs. gasoline in same FFV	−8	−20	7	28	0.53	5	−14	27	21	0.08	−29	−44	−10	27	0.03
	E85 in FFV vs. gasoline in similar non-FFV	21	−1	46	9	0.14	9	−13	37	6	0.47	−32	−66	37	9	0.69

Notes: Reported *P* values are for paired *t* test.

and the true variability between vehicles in causing the wide variations in emissions results.[14,15] The coefficient of variation (CV; equivalent to the standard deviation/average) for the duplicate tests were calculated and are included as Table 3 in the supplemental data. For most pollutants, the standard deviation was approximately 10% of the average measurement. Carbon dioxide and fuel efficiency could be measured with considerably more precision; the CVs were less than 1%. With the exception of acetaldehyde, the CVs for the E85 tests and the RFG tests were very similar. Counterintuitively, emissions of acetaldehyde appear to be measured with more precision

Table 4. Comparison of E85 and gasoline THC, NMHC, and formaldehyde emissions in certification database.

		NMHC					THC					Formaldehyde				
Engine	Comparison	Geometric Mean (%)	95% Confidence Interval Range on Geometric Mean (%)		No. Tested	P Value for Paired t Test	Geometric Mean (%)	95% Confidence Interval Range (%)		No. Tested	P Value for Paired t Test	Geometric Mean (%)	95% Confidence Interval Range (%)		No. Tested	P Value for Paired t Test
Overall	E85 vs. gasoline in same FFV	−43	−52	−32	12	0.00	−14	−24	−4	19	0.07	59	32	91	48	0.00
	E85 in FFV vs. gasoline in similar non-FFV	−37	−39	−35	4	0.00	−25	−35	−12	7	0.02	19	−8	53	12	0.15
Tier 1	E85 vs. gasoline in same FFV	−43	−52	−32	12	0.00	−21	−48	20	5	0.35	102	52	168	6	0.00
	E85 in FFV vs. gasoline in similar non-FFV	−37	−39	−35	4	0.00	−33	−33	−33	1	NA	−18	−45	21	2	0.50
Tier 2	E85 vs. gasoline in same FFV				0	NA	−12	−18	−6	14	0.00	54	24	89	42	0.00
	E85 in FFV vs. gasoline in similar non-FFV				0	NA	−23	−35	−9	6	0.03	28	−3	68	10	0.05

at lower levels; that is, the CV is lower for vehicles using RFG than it is for those using E85.

These studies also reported the CVs for tests on numerous vehicles of the same vehicle model conducted at the same laboratory and in the same year, as shown in Table 4 of the supplemental data.[14,15] The vehicles were approximately the same age and typically had odometer readings of less than 20,000 mi. The difference between the vehicle-to-vehicle CVs and the CVs for the duplicate tests represents the variability due to vehicle-to-vehicle variations within the same vehicle model. The CVs in vehicle-to-vehicle comparisons are in the range of 20–30% for most compounds, demonstrating why it is so difficult to determine small differences in emissions behavior between different fuels used in a large fleet of vehicles. Emission impacts vary considerably between different vehicles, even those that all meet emissions standard requirements, have the same engine model, and are tested in the same laboratory.

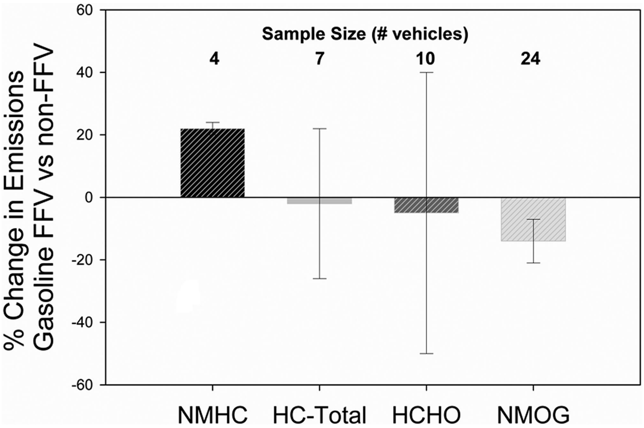

Figure 3. Average percent change in organic pollutant emission comparing FFVs using gasoline with non-FFVs using the EPA certification database. Error bars show the 95% confidence interval on the geometric mean.

DISCUSSION AND RESEARCH RECOMMENDATIONS

The evidence available to date suggests that there are wide variations in the effect of E85 on emissions from light-duty vehicles. On average, however, using E85 results in reduced NO_x, CO, benzene, and 1,3-butadiene emissions and increased ethanol, formaldehyde, and acetaldehyde emissions. NMHC emissions are reduced for Tier 1 vehicles, whereas NMOG emissions will likely be unaffected for Tier 2 vehicles. The overall toxicity of the emissions is likely to be unchanged and the ozone-forming potential could be slightly reduced. Previous assessments of the impact of light-duty gasoline vehicles on emission inventories have combined gasoline-fueled FFVs and non-FFVs without distinction. This analysis shows that, although the two types of vehicles have similar NO_x and CO emissions, Tier 2 FFVs operating on gasoline produced approximately 13% less NMOGs than non-FFVs operating on gasoline. The technology used to reduce tailpipe organic emissions in Tier 2 FFVs is apparently somewhat more effective than the technology used in non-FFVs. Research on emission control and catalyst technologies for reducing aldehyde and possibly ethanol emissions from FFVs should be a priority if the use of E85 becomes widespread.

The emissions tests described here were conducted almost entirely using only one test cycle, on a limited set of vehicles—primarily on a Tier 1 Chevrolet Lumina and Ford Taurus for the literature data—and on new Tier 2 vehicles for the EPA certification data. A much wider range of test conditions and vehicles should be investigated, particularly for older and high-emitting vehicles, different driving cycles, and hot and cold ambient conditions. Whitney and Fernandez have shown significantly different emission differences for E85 at low temperatures.[30]

In most scenarios in which the greater use of E85 is phased in, FFVs will have to be able to switch between E85 and gasoline when E85 stations are not available. As vehicles switch between these two fuels, the concentration

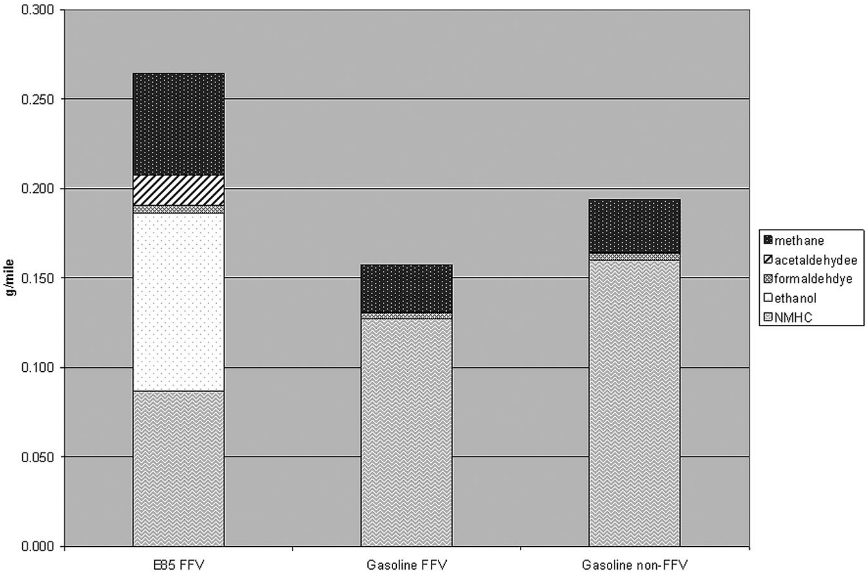

Figure 4. Organic pollutant emissions from testing of in-use vehicles reported by Kelly et al.[14,15]

of ethanol in the fuel may vary from 0% to close to 80%. Large, empirical emissions testing studies of new and in-use FFVs using E85, gasoline, and intermediate (commingled) blends are required to assess, more quantitatively, the impact of increased FFV and E85 use on emissions and emissions inventories.

Evaporative emissions were discussed in only a limited way in this paper. Further analysis of the available data and further evaporative emissions testing will be required to quantify the impact of E85 and FFVs on this significant contributor to urban emissions inventories.

An E85 certification test fuel specification should be developed for FFV certification and to promote repeatable testing between laboratories. The fuel should be representative of typical retail E85 so that laboratory tests can readily be applied to real-world modeling; that is, not using 85% ethanol but somewhere between 70 and 79% ethanol. As noted, the RVP of the finished E85 fuel is regulated. In addition to developing an E85 certification fuel, future studies should examine the emission impact of all E85 volatility classes.

The certification database could be improved with policies that require consistent reporting of significant figures on the basis of the precision of the testing procedure. Information on inter- and intralaboratory comparisons would make the data more valuable to scientists.

A more detailed understanding of the ozone reactivity of organic emissions from E85 of all three volatility classes, as well as comingled blends, is needed. Additionally, more detailed studies of toxic compound emissions are required. Historically, studies that have reported emissions of specific toxic compounds have focused on only four—acetaldehyde, formaldehyde, benzene, and 1,3-butadiene. If E85 is to make up a significant fraction of the fuel consumed in the United States or in certain airsheds, an expanded assessment of toxic compound and PM emissions will be required.

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NOMENCLATURE

AQIRP = Auto/Oil Air Quality Research Program
ASTM = ASTM International (a standards-setting organization)
CARB = California Air Resources Board
CO = carbon monoxide
CV = coefficient of variation (the standard deviation divided by the mean)
CFR = Code of Federal Regulations
DNPH = dinitrophenylhydrazine
E85 = a blend of nominally 85% fuel ethanol and 15% gasoline
EPA = U.S. Environmental Protection Agency
FFV = flexible-fuel (or flex-fuel) vehicle
LDV = light-duty vehicle
LDT1 = light-duty truck 1, less than 3750 lbs loaded vehicle weight
LDT2 = light-duty truck 2, greater than 3750 lbs loaded vehicle weight and less than 6000 lb gross vehicle weight
LDT3 = light-duty truck 3, less than 5750 lbs adjusted loaded vehicle weight and greater than 6000 lb gross vehicle weight
LDT4 = light-duty truck 4, more than 5750 lbs adjusted loaded vehicle weight and greater than 6000 lb gross vehicle weight
MIR = maximum incremental reactivity, a measure of ozone-forming potential
NMHC = non-methane hydrocarbon
NMHCE = non-methane hydrocarbon equivalent (NMHC adjusted for oxygenated hydrocarbons)
NMOG = non-methane organic gas
NO_x = oxides of nitrogen
OMHCE = organic material hydrocarbon equivalent (HC adjusted for oxygenated hydrocarbons)

OMNMHCE = organic material NMHC equivalent
psi = pounds per square inch
REPO5 = high-speed, high-acceleration-rate driving schedule
RFG = reformulated gasoline
RVP = Reid vapor pressure
RWE = reactivity-weighted emissions
THC = total hydrocarbons

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