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A Comparative Analysis of Emissions Deterioration for In-Use Alternative Fuel Vehicles

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ABSTRACT

Although there have been several studies examining emissions from in-use alternative fuel vehicles (AFVs), little is known about the deterioration of these emissions over vehicle lifetimes and how this deterioration compares with deterioration from conventional vehicles (CVs). This paper analyzes emissions data from 70 AFVs and 70 CVs operating in the federal government fleet to determine whether AFV emissions deterioration differs significantly from CV emissions deterioration. An analysis is conducted on three alternative fuel types (natural gas, methanol, and ethanol) and on four pollutants (carbon monoxide, total hydrocarbons, non-methane hydrocarbons, and nitrogen oxides). The results indicate that for most cases studied, deterioration differences are not statistically significant; however, several exceptions (most notably with natural gas vehicles) suggest that air quality planners and regulators must further analyze AFV emissions deterioration to properly include these technologies in broader air quality management schemes.

INTRODUCTION

Since passage of the Alternative Motor Fuels Act of 1988, the Clean Air Act Amendments of 1990, and the Energy Policy Act of 1992, an increased number of urban air quality managers are considering the use of alternative fuel vehicles (AFVs) to meet air quality goals.[1] When certified to stringent emission standards (e.g., clean fuel vehicle standards), AFVs can often provide emissions benefits while avoiding many of the problems surrounding other, more controversial mobile source control schemes (e.g., inspection and maintenance programs, employee trip reduction programs).

Although an estimated four million AFVs will be on the road by 2005,[2-4] planners who wish to use AFVs as a means for meeting air quality goals still face several obstacles. In particular, when integrating AFV technologies and programs into air quality plans, planners must have information on how AFV emissions *and* their deterioration compare with conventional vehicles (CVs). Without this information, planners will find it difficult to perform appropriate impact assessments for AFV technologies and programs.

Because of the need for such data, the U.S. Department of Energy (DOE) is currently collecting emissions data on AFVs operating in the U.S. federal fleet. From this database, researchers are becoming more confident about emissions values for various AFVs. Studies conducted by the National Renewable Energy Lab on this data,[5-7] as well as several independent studies,[8-10] have quantified emissions values for heavy- and light-duty vehicles operating on fuels such as compressed natural gas, methanol, ethanol, propane, and reformulated gasoline (RFG).

However, understanding how emissions values *change* over AFV lifetimes remains an elusive problem. Static studies on AFV emissions can give valuable baseline data for estimating air quality impacts of AFV use, but dynamic studies that measure emissions with respect to vehicle lifetimes are necessary for understanding the long-term effects of AFV use.

The purpose of this paper is to present the results of a statistical study conducted to compare emissions deterioration from AFVs and CVs currently operating in the federal fleet. Data from the National Alternative Fuels Data Center (AFDC) are analyzed, including emissions testing results for 70 AFVs distributed among three different fuel

IMPLICATIONS

Alternative fuel vehicles (AFVs) offer possible solutions to many of the air quality problems in urban areas. To incorporate AFV programs into air quality management plans, decision-makers must determine AFV emissions values and emissions deterioration over vehicle lifetimes. This study examines how emissions deterioration from in-use AFVs compares to deterioration from conventional vehicles operating on reformulated gasoline. If deterioration from AFVs is significantly different from deterioration from conventional vehicles, regulators and policy-makers must take appropriate actions to include these differences in air quality management strategies.

and vehicle model types. Emissions deterioration from these vehicles is compared to 70 reformulated gasoline (RFG) control vehicles of identical model type. The results of this analysis provide important inputs into assessments of the future role of AFVs in air quality management plans.

The purpose of this study is *not* to calculate precise deterioration factors for these vehicles (such precision is not yet possible with current data). Instead, this study answers the following question: *Are there significant **differences** in emissions deterioration between vehicles of the same make and model, but operating on different fuels?*

THE IMPORTANCE OF AFV EMISSIONS DETERIORATION

Mobile source deterioration factors (DFs) are correctional factors that government and industry use to help predict vehicle tailpipe emissions over the life of a vehicle. The U.S. Environmental Protection Agency (EPA) expresses these values as multiplicative "correctional factors" that are a function of accumulated vehicle mileage. EPA uses DFs for two primary purposes: demonstration of emissions compliance and mobile source emissions modeling.

For compliance purposes, vehicles that undergo tailpipe emissions testing must meet emissions standards that are adjusted (usually upward) for vehicle deterioration. EPA maintains DFs for each engine family. For example, for a 1996 Dodge Spirit to comply with emissions standards, emissions test results are compared to a base emissions value adjusted using the 1996 Dodge Spirit DF. Manufacturers can determine DFs for each engine family by either running a series of tests on a representative vehicle from that family or (if qualified as a "small-volume manufacturer") using DFs assigned by the EPA.[11]

For modeling purposes, EPA does not use the above-mentioned "certification" DFs, but instead applies a different set of DFs determined through more realistic mileage accumulation and operating conditions (certification DFs tend to be lower than those used in mobile source emissions modeling). EPA uses these values in their well-known MOBILE5 mobile source emissions model.[12] Because MOBILE5 models a "fleet" of vehicles of different makes and models, EPA determines MOBILE5 DFs using various statistical analyses on actual emissions data of selected vehicle populations. MOBILE5 then uses these DFs to predict emissions from aging vehicle fleets.

An increased use of AFVs, spurred predominately by regulatory mandates and new market incentives, raises the possibility of using AFVs as air quality management tools. But without reliable DFs for AFVs, lifetime emissions from these vehicles are difficult to quantify. Thus, regulators and planners need to determine whether AFV emissions deterioration is significantly different that that of CVs. If AFV deterioration is significantly different, then researchers must begin to collect the data needed to calculate new DFs for AFV technologies. This paper examines whether statistically significant differences do, in fact, exist between AFVs and their CV counterparts.

ANALYTICAL APPROACH

Data

In 1991, the National Renewable Energy Laboratory (NREL) was charged with collecting emissions data on a number of light duty AFVs operating in the federal fleet. Phase I of this program consisted of testing 18 vehicles at the three following labs: EPA's facility in Ann Arbor, MI; EPA's facility in Research Triangle Park, NC (operated by ManTech Environmental Technologies); and Environmental Research and Development (ERD) in Washington, DC. NREL tested each vehicle using the EPA's Federal Test Procedure (FTP) at odometer readings of approximately 4,000 miles, 10,000 miles, and every 10,000 miles thereafter. These vehicles were "in-use" vehicles. Mileage accumulation represented a variety of typical driving conditions and operations.

Phase II of NREL's program began in 1993 and covers nearly 300 federal AFVs. Testing facilities for Phase II vehicles include ERD, Automotive Test Laboratories (ATL) in Ohio, and ManTech in Colorado. Similar to Phase I, NREL tests these Phase II vehicles at odometer readings of 4,000 miles, 10,000 miles, and every 10,000 miles thereafter. These vehicles are also "in-use" vehicles used to support the everyday missions of their respective agencies. The general test procedures, emissions test driving profiles, hydrocarbon speciation, and other facts about this program are reported in other publications.[5-7] The National Alternative Fuels Data Center (AFDC), located in Golden, CO, collects and reports data from these emissions tests.

The emissions deterioration analysis presented here was conducted by extracting emissions values from the AFDC database for six different fuel–model combinations. The pollutants examined include carbon monoxide (CO), total hydrocarbons (HC), nitrogen oxides (NO_x), and non-methane hydrocarbons (NMHC). Table 1 provides information about the vehicles, their fuels, and their sample sizes. AFV/model combinations were chosen that had reformulated gasoline (RFG) vehicle counterparts and also had adequate sample sizes for statistical analysis. The alternative fuels included compressed natural gas (CNG), methanol-gas mixtures of 85% methanol (M85), and ethanol-gas mixtures of 85% ethanol (E85). All the CNG vehicles are dedicated Dodge Ram Vans, all the M85 vehicles are flexible-fuel Dodge Spirits, and all the E85 vehicles are flexible-fuel Chevrolet Luminas. Note that all vehicles are original equipment manufactured (OEMs) vehicles (i.e., none of the vehicles is an alternative fuel "conversion").

Table 1. Vehicle types analyzed, including sample size by model year.

Vehicle Type	N (by model year)
Dedicated Original Equipment Manufactured CNG	14 (1992)
Dodge Ram B250 Van (CNG/Ram)	3 (1994)
• 5.2 liter V-8 engine configuration	
• Multi-point fuel injection	
• 4-speed automatic	
• 11.1-15.7 equivalent gallon fuel capacity	
• 6,400 lbs Gross Vehicle Weight	
• LEV-Certified	
RFG Dodge Ram B250 Van (RFG/Ram)	7 (1992)
• 5.2 liter V-8 engine configuration	9 (1994)
• Multi-point fuel injection	
• 4-speed automatic	
• 35 gallon fuel capacity	
• 6,400 lbs Gross Vehicle Weight	
Flexible Fuel Ethanol Chevrolet Lumina	3 (1992)
(E85/Lumina)	6 (1993)
• 3.1 liter V-6 engine configuration	
• Multi-point fuel injection	
RFG Chevrolet Lumina (RFG/Lumina)	13 (1993)
• 3.1 liter V-6 engine configuration	
• Multi-point fuel injection	
Flexible Fuel Methanol Dodge Spirit (M85/Spirit)	44 (1993)
• 2.5 liter, in-line 4 cylinder	
• Multi-point fuel injection	
RFG Dodge Spirit (RFG/Spirit)	41 (1993)
• 2.5 liter, in-line 4 cylinder	
• Multi-point fuel injection	

For this study, vehicles were chosen that were FTP tested several times at different odometer readings. In cases where multiple tests were conducted on a single vehicle at a constant odometer reading (many vehicles were tested three times per test visit), the weighted average of the multiple test results, as reported in the AFDC database, was used.

Vehicle model year (MY) was not part of the data filtration process. Although all M85/Spirits and their RFG counterparts are MY 1993, the CNG/Rams are skewed towards MY 1992, while their RFG counterparts are split evenly between MY 1992 and MY 1994. The E85/Luminas are also skewed towards an older model year, with one-third being from MY 1992 and the remainder from MY 1993; their RFG counterparts are entirely from MY 1993. Although baseline emissions values can be slightly affected by model year improvements, vehicles within 1-2 model years of each other are not expected to exhibit different emissions deterioration characteristics.

The M85 and E85 vehicles are operable on a range of fuel mixtures. NREL tested these vehicles on fuels that include RFG, E50/M50, and/or E85/M85. However, only the E85 and M85 test data were used because these are the fuels on which the vehicles operate most frequently, if not entirely. In addition, M85 and E85 are the only mixtures found at fueling stations throughout the country, so these are the fuels that typical consumers will access.[13] More detailed data on fuel composition and vehicle attributes are presented in other studies.[5-7]

Table 2. Final data set sample sizes, including range of odometer readings.

Model	Fuel Type	# Vehicles	Odometer Readings (miles)
Lumina	E85	9	8218-27282
	RFG	13	2903-28290
Ram	CNG	17	2121-29585
	RFG	16	3527-36629
Spirit	M85	44	3704-38506
	RFG	41	4339-61638

Comparing Emissions Deterioration

This analysis compares CNG, M85, and E85 automobiles with same model RFG vehicles. Aside from the above data set restrictions, only those vehicles that had initial emissions tests conducted after at least 2,000 miles of driving were selected. This criterion was included to address the "green catalyst" phenomenon whereby catalytic converter efficiencies are extremely high when a vehicle is new and degrade very quickly for the first 2,000 or 3,000 miles. It should be noted that only 7 of the 140 vehicles analyzed had initial odometer readings less than 4,000 miles. In addition, only those vehicles that had differences in odometer readings (between the first and last tests) of at least 3,000 miles were included in the data set.

Table 2 provides the final subset of vehicles upon which the analysis and conclusions are based. The fourth column of this table shows the minimum and maximum odometer readings for a given fuel–model

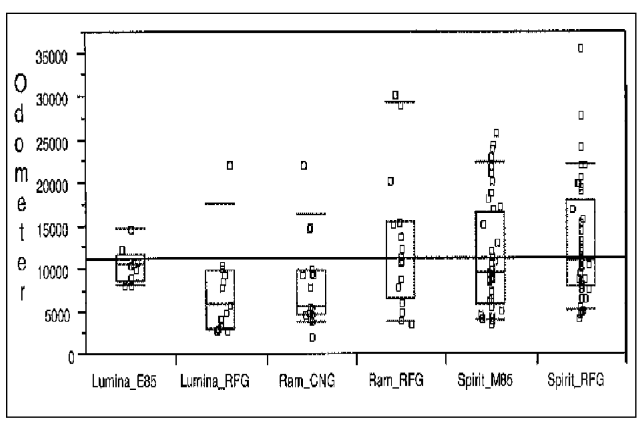

Figure 1. Comparison of first test odometer reading for six fuel/model combinations.

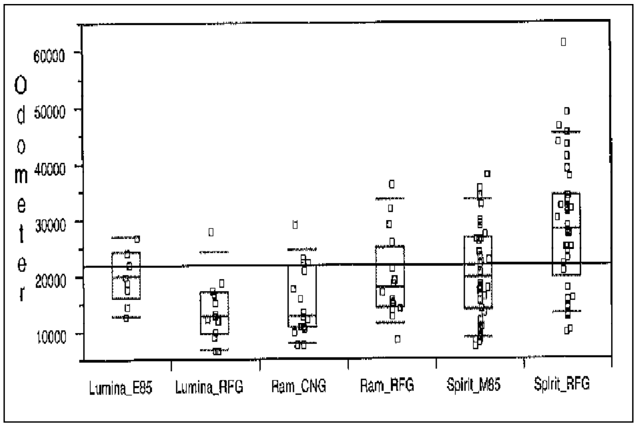

Figure 2. Comparison of last odometer reading for six fuel/model combinations.

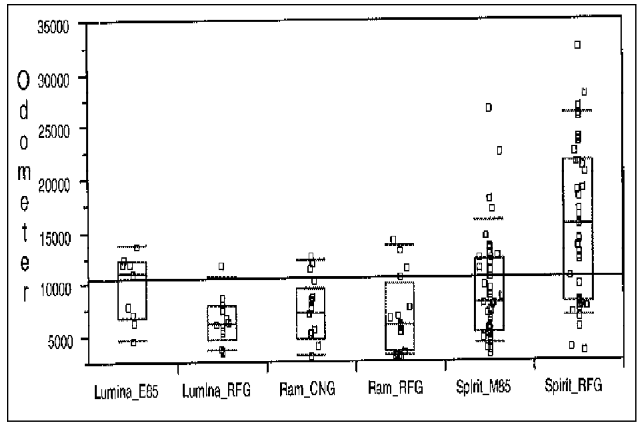

Figure 3. Comparison of difference in first and last odometer reading for six fuel/model combinations.

combination. These data allow a meaningful comparison of each alternative fuel with its RFG counterpart. Comparisons between alternative fuel types are not possible because a different vehicle model is used for each of the alternative fuels.

In addition, Figures 1-3 present data on the odometer readings of the vehicles tested. These figures show the first odometer reading, last odometer reading, and difference in odometer readings, respectively, for the six fuel/model combinations analyzed. The data show that more than 50% of the vehicles tested had initial test odometer readings greater than about 14,000 miles, and only 2.5% had odometer readings less than 3,700 miles. From the figures, it should be noted that RFG/Lumina vehicles and CNG/Ram vehicles may exhibit some low mileage deterioration concerns. These concerns are addressed in the results section of this paper. In all, the "green catalyst" phenomenon will likely affect only a small percentage of vehicle tests.

To compare emissions deterioration between AFVs and their RFG counterparts, the deterioration rate for each automobile, expressed in grams/mile deterioration per 10,000 miles, was calculated. Let ED_{ij} stand for the value of this quantity for pollutant type i and vehicle j. ED_{ij} is proportional to the slope of the regression model in which emissions is expressed as a function of odometer reading. If only two emissions tests are run (the case in approximately 75% of the vehicles in the data), then this value is calculated as follows:

$$ED_{ij} = \frac{E_{ij}^{\max} - E_{ij}^{\min}}{OD_j^{\max} - OD_j^{\min}} \times 10{,}000 \qquad (1)$$

where $E_{ij}^{\max}$ and $E_{ij}^{\min}$ are the emissions test results in grams/mile for pollutant type i and fuel/model type j at the maximum and minimum odometer readings, respectively, and $OD_j^{\max}$ and $OD_j^{\min}$ are the maximum and minimum odometer readings, respectively. These deterioration rates are the metrics used for comparing each alternative fuel to RFG.

The statistical comparison between each alternative fuel and RFG was based on the median test, attributable to Brown and Mood.[14] This test is known to be superior to the two-sample t-test whenever data come from a distribution that is nonsymmetric and prone to outliers. Previous studies suggest that such features are common in AFV emissions measurements.[5-7,9,10]

The median test aggregates all vehicles of a particular automobile model (e.g., CNG/Ram and RFG/Ram) and generates the median deterioration rate among those vehicles. Under the null hypothesis that there *is no difference* in deterioration rates between the two fuel types, the proportion of vehicles from the alternative fuel that fall above the median should be close to 0.5. If the actual proportion is substantially different than 0.5, the null hypothesis is rejected in favor of the alternative hypothesis that there *is a difference* in deterioration rates between the two fuel types. The p-value for determining statistical significance is approximated using a chi-square distribution.

Table 3. Median test results for carbon monoxide.

Model	Fuel	Total Sample Size (N)	Median Deterioration Parameter for Each Fuel/Model Combination (g/mi per 10k miles)	Number Above Median	Prob > ChiSq
RAM	CNG	17	-0.20	6	0.124
	RFG	16	0.80	10	
LUMINA	E85	9	0.37	4	0.672
	RFG	13	1.01	7	
SPIRIT	M85	44	0.34	23	0.587
	RFG	41	0.31	19	

DISCUSSION OF RESULTS

Tables 3–6 present the results. These tables include results from the median test for each of the pollutants examined. Each table shows the median value of the deterioration parameter for each fuel/model combination, the number of points above the median for each combination, and the probability that rejecting the null hypothesis will lead to error. Data are grouped in rows by model to easily compare AFV/model combinations with their RFG/model counterparts. At probabilities less than 0.05, the null hypothesis can be rejected with 95% confidence (these points are denoted with an asterisk). In these cases, the differences in the emissions deterioration parameter values are statistically significant at the 95% confidence level.

The results of this analysis provide a number of useful insights into the emissions deterioration of AFVs as summarized below.

- Table 3 shows that differences observed in CO deterioration parameter values are not statistically significant for any fuel–model pair at the 95% confidence level.
- Table 4 shows that differences observed in HC deterioration parameter values between the CNG/Rams and their RFG counterparts are statistically significant at a 95% level of confidence. The CNG/Rams are shown to have a *higher* deterioration parameter. Differences for other fuel–model pairs are not significant at the 95% confidence level.
- Table 5 shows that differences observed in NO_x deterioration parameter values between the CNG/Rams and their RFG counterparts are statistically significant at a 95% level of confidence. The CNG/Rams have a *higher* deterioration parameter. Differences for other fuel–model pairs are not significant at the 95% confidence level.

Table 4. Median test results for total hydrocarbons.

Model	Fuel	Total Sample Size (N)	Median Deterioration Parameter for Each Fuel/Model Combination (g/mi per 10k miles)	Number Above Median	Prob > ChiSq
RAM	CNG	17	0.24	12	0.010*
	RFG	16	0.056	4	
LUMINA	E85	9	0.012	3	0.204
	RFG	13	0.045	8	
SPIRIT	M85	44	-0.00040	19	0.237
	RFG	41	0.0066	23	

* Probability of Type I error is less than 5%.

Table 5. Median test results for nitrogen oxides.

Model	Fuel	Total Sample Size (N)	Median Deterioration Parameter for Each Fuel/Model Combination (g/mi per 10k miles)	Number Above Median	Prob > ChiSq
RAM	CNG	17	0.31	12	0.010*
	RFG	16	0.077	4	
LUMINA	E85	9	0.028	4	0.672
	RFG	13	0.034	7	
SPIRIT	M85	44	0.0069	18	0.106
	RFG	41	0.039	24	

* Probability of Type I error is less than 5%.

- Table 6 shows that differences observed in NMHC deterioration parameter values between the CNG/Rams and their RFG counterparts are statistically significant at a 95% level of confidence. The CNG/Rams have a *higher* deterioration parameter.
- Table 6 also shows that differences observed in NMHC deterioration parameter values between the M85/Spirits and their RFG counterparts are statistically significant at a 95% level of confidence. The M85/Spirits have a *lower* deterioration parameter. (However, these values are so close to zero that these results have little practical significance).

The results of this analysis are somewhat contrary to current belief. One might expect the cleaner burning properties of alternative fuels to result in lower deterioration values than conventional fuels. One would think this especially true for gaseous fuels (e.g., CNG).

One possible explanation for CNG/Rams' poor performance is shown in Figures 1-3, where the CNG/Ram vehicles are shown to have *slightly* lower odometer readings than the RFG/Ram vehicles; thus a "green catalyst" phenomenon may be at work (although the odometer differences remain slight). (Another possible explanation explored by the authors was whether the catalytic converters on the CNG/Ram vehicles were standard three way catalytic (TWC) systems, as CNG is known to perform poorly on standard TWC systems. However, the catalytic converters on these dedicated CNG/Ram vehicles are specially made for dedicated CNG operation).

One might also expect the alcohol fuels (M85 and E85) to have higher deterioration factors because of their corrosive properties when operating in a flexible-fuel system. This analysis has challenged these beliefs by demonstrating that M85 actually has lower deterioration and E85 shows no significant difference in deterioration when compared to their respective RFG counterparts.

Table 6. Median test results for non-methane hydrocarbons.

Model	Fuel	N	Median Deterioration Parameter for Each Fuel/Model Combination (g/mi per 10k miles)	Number Above Median	Prob > ChiSq
RAM	CNG	17	0.19	12	0.010*
	RFG	16	0.046	4	
LUMINA	E85	9	0.0089	4	0.672
	RFG	13	0.041	7	
SPIRIT	M85	44	-0.0013	16	0.013*
	RFG	41	0.0058	26	

* Probability of Type I error is less than 5%.

CONCLUSIONS

In this paper, emissions deterioration among several AFV and CV fuel–model combinations is compared. The results indicate that only in a few cases are emissions deterioration likely to differ significantly between AFVs and CVs. In those cases, movement to conduct appropriate tests to determine actual AFV deterioration factors for use in modeling and certification is appropriate. However, such tests may not be required for all AFV types; deterioration factor estimates based on current conventional vehicle data may suffice for the short term until the market identifies a clear AFV "winner."

There are at least two important caveats that must be highlighted regarding the analysis presented in this paper. First, the vehicles tested are all "in-use" vehicles operating in the federal fleet. These vehicles have a tendency to be driven over short distances. Such severe driving may lead to rapid aging of engine components and exhaust systems. Thus, the deterioration comparisons above are actually for vehicles in severe service. Second, the data are limited to a small number of vehicles with limited mileage accumulation. Over the next several years, more and better data will be generated that can be used to refine this analysis.

In fact, more data will help to actually quantify *deterioration factors* for alternative fuels. This paper's analysis is limited because actual DFs are not calculated (the data are not yet adequate for this exercise). Further, only three fuel–model combinations are considered. As more data are collected, more appropriate analyses will be conducted to determine AFV DFs under a variety of fuel–model combinations. When possible, analyses should be performed using current EPA analytical procedures (e.g., regression analysis).

Lastly, one should recognize that there are improvements each year in both conventional and AFV emissions control systems. This is particularly true in the AFV industry, which is still advancing along a steep learning curve. These advancements have the potential to improve deterioration rates over time at a level not expected from conventional vehicles.

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