

Regulatory Impact Analysis: Renewable Fuel Standard Program

Chapter 3 Impacts on Emissions from Vehicles, Nonroad Equipment, and Fuel Production Facilities

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Chapter 3: Impacts on Emissions from Vehicles, Nonroad Equipment, and Fuel Production Facilities

As described in Chapter 2, there are a large number of potential fuels that qualify as renewable. However, only two are expected to be used in significant volumes by 2012: ethanol and biodiesel. Of these, ethanol use is expected to predominate. In particular, ethanol is expected to dominate the “growth” in renewable fuel use between now and 2012. Thus, our primary focus here will be on the impact of the use of ethanol on emissions in spark-ignited vehicles and equipment. We will more briefly touch on the impact of biodiesel fuel use on emissions.

Similarly, we expect that the bulk of the impact of ethanol use on emissions and air quality will be associated with emissions from spark-ignited vehicles and equipment using low level ethanol-gasoline blends. We expect the use of high level ethanol-gasoline blends, like E85 to be relatively small in comparison. Thus, the discussion here will focus on emissions from the use of low level ethanol blends. We will more briefly discuss the per vehicle impacts of use of high level ethanol-gasoline blends relative to gasoline.

Finally, we present estimates of the emissions related to the production and distribution of both ethanol and biodiesel. The emissions related to the production and use of ethanol can be significant relative to the emission impacts of the use of ethanol blends, due to the significantly increase in the volume of ethanol expected to be produced in the future.

3.1 Effect of Fuel Quality on Onroad Spark-Ignited Vehicle Emissions

Ethanol belongs to a group of gasoline additives commonly referred to as oxygenates. The two most commonly used oxygenates are ethanol and MTBE, though TAME has been used in significant volumes, as well. All oxygenates have relatively high levels of octane (i.e., greater than 100 R+M/2). Both ethanol and MTBE have been used historically to meet the gasoline oxygen requirements for oxyfuel and RFG. Historically, MTBE was the predominant oxygenate used in gasoline in the U.S. Over time, MTBE use has decreased in the U.S, while ethanol use has increased, to the point where ethanol use now predominates. This trend appears to be accelerating, to the point where it appears that essentially all MTBE use will cease in the U.S sometime in 2007.

The impact of oxygenate use on emissions from motor vehicles has been evaluated since the mid-1980's. Several models of the impact of gasoline quality on motor vehicle emissions were developed in the early 1990's and updated periodically since that time. We use the most up-to-date versions of these models here to estimate the impact of changes in oxygenate use on emissions. Still, as will be described below, significant uncertainty exists as to the effect of these gasoline components on emissions from both motor vehicle and nonroad equipment, particularly from the latest models equipped with the most advanced emission controls. Assuming adequate funding, we plan to conduct significant vehicle and equipment testing over the next several years

to improve our estimates of the impact of these additives and other gasoline properties on emissions. The results of this testing are not available for inclusion in this analysis. We hope that the results from these test programs will be available for reference in the comprehensive evaluation of the emission and air quality impacts of all the fuel-related requirements of the Energy Act required by Section 1506. A draft of this study is required to be completed in 2009. As we discuss the emission impacts of increased ethanol use below, we identify the areas where current estimates appear to be the most uncertain and where we hope to obtain additional data prior to the 2009 study.

3.1.1 Low Level Ethanol and MTBE-Gasoline Blends

EPA has developed a number of emission models relating the impact of gasoline quality on emissions from motor vehicles. In 1993, EPA published the Complex Model, which predicts the effect of gasoline quality on VOC, NO_x and air toxic emissions from 1990 model year light-duty motor vehicles (i.e., Tier 0 vehicles). This model is used to determine refiners' compliance with RFG and anti-dumping standards. The Complex Model also contains estimates of the impact of gasoline RVP on non-exhaust VOC emissions. These estimates were taken from the then-current version of the MOBILE emissions model, MOBILE5.

In 2001, in responding to California's request for a waiver of the RFG oxygen mandate, EPA performed a new analysis of the impact of gasoline quality on exhaust VOC and NO_x emissions from Tier 0 vehicles. This analysis included essentially all of the data used to develop the Complex Model, as well as some additional data developed since 1993. It also used more advanced statistical tools, such as a mixed statistical model, which were not available in 1993. These VOC and NO_x models are referred to here as the EPA Predictive Models. Thus, in terms of both supporting data and modeling tools, the EPA Predictive Models represent an improvement over the Complex Model, at least for exhaust VOC and NO_x emissions. Because the criteria for granting California a waiver of the oxygen requirement focused on ozone and PM impacts, EPA did not develop a similar model for toxics or CO emissions.

In roughly the same timeframe, EPA developed its latest motor vehicle emission inventory model, MOBILE6. Some of the fuel-emission relationships from the Complex Model were incorporated into MOBILE6. These included the effect of selected gasoline properties on exhaust VOC and NO_x emissions and the fraction of VOC emissions represented by several air toxics (benzene, formaldehyde, acetaldehyde, and 1,3-butadiene). The EPA Predictive Models were not available in time for their incorporation into MOBILE6. MOBILE6 also contains estimates of the effect of certain gasoline parameters on CO emissions, namely RVP and oxygen content. The effect of RVP on non-exhaust VOC emissions contained in MOBILE6.2 represents an update of the MOBILE5 and Complex Model estimates.

We desire in this RFS analysis to utilize the most up to date estimates of the impact of gasoline quality on emissions currently available. No one model currently contains the most up to date estimates for all the pollutants of interest. Therefore, we have broken up the remainder of this sub-section into six parts. The first discusses emissions of VOC and NO_x, as the EPA Predictive Models address these pollutants. The second discusses CO emissions, as neither the Complex Model nor the EPA or CARB Predictive Models address this pollutant. The third

section addresses emissions of air toxics, as a combination of models represents the best estimate of the impact of fuel quality on these emissions. The fourth section addresses non-exhaust VOC emissions. The fifth section addresses PM emissions. The sixth section addresses emissions of aromatic hydrocarbons. The seventh and final section presents the impact of ethanol and MTBE blending on per mile emissions from gasoline-fueled motor vehicles.

3.1.1.1 Exhaust VOC, CO and NO_x Emissions

In this section we evaluate the various models available which predict the impact of gasoline quality on exhaust VOC, CO and NO_x emissions. Several such models have been developed over the past 15 years. We first discuss the EPA Complex Model, the EPA Predictive Models and the CARB Predictive Models due to the wide range of fuel parameters which they address and their similar form. We next describe the fuel effects contained in EPA's MOBILE6.2 emission inventory model, as this model addresses CO emissions, which the other models do not. These models best predict emissions from Tier 0 vehicles, as most of the emission data upon which they were based were from these vehicles. A number of fuel effects test programs which tested later model year vehicles have been performed since the above emission models were developed. We summarize these studies below and develop emission projections based on consistent statistical procedures. Finally, we select which model best predicts the effect of fuel quality for each pollutant. Due to the uncertainty involved with predicting the impact of fuel quality on emissions from Tier 1 and later vehicles, we develop two alternative approaches to making such predictions for the purpose of this rule.

3.1.1.1.1 EPA Complex Model and CARB and EPA Predictive Models

In 1993, EPA published the Complex model to investigate the effects of changing gasoline fuel parameters on the exhaust emissions of Tier 0 and older vehicles. This model predicts the effect of gasoline quality on exhaust VOC, toxics and NO_x emissions and non-exhaust emissions of VOC and benzene. The Complex Model is used to determine compliance with the emissions performance requirements for federal RFG by comparing the predicted emissions of a candidate fuel to that of a baseline fuel for common baseline vehicle technology. The baseline fuel and the baseline vehicle technology represent those fuels and vehicles included in the 1990 US light duty vehicle fleet (Tier 0 technology).

In 1999, the state of California petitioned EPA for a waiver of the oxygen requirement in RFG. The reasoning behind the waiver request centered on the California Air Resources Board's (CARB) analysis which showed that reducing the amount of oxygen in RFG would lead to reduced NO_x exhaust emissions. The model that CARB developed to support their claim was called the Phase 3 predictive model^{ZZ}. This model differed from the previous version of CARB's predictive model (the Phase 2 model) in a number of ways. The most significant difference included a substantially expanded database, mainly for model year 1986 and newer vehicles, as well as an improved version of the statistical analysis software package used to develop the model (SAS® PROC MIXED). According to CARB, the Phase 3 predictive model displays a steeper NO_x/Oxygen response than the Phase 2 Predictive model as a result of eliminating the RVP by Oxygen term which the previous model had erroneously included. This caused an increase in the NO_x exhaust emissions predicted, and for many areas this increase

would lead to NO_x levels exceeding those set by National Ambient Air Quality Standards (NAAQS).

According to the 1990 Clean Air Act, EPA can waive the RFG oxygen requirement if it prevents compliance with a NAAQS. In order to properly perform an environmental impact analysis in response to this waiver request, EPA considered using both its Complex Model, as well as CARB's Phase 3 Predictive Model to estimate the impact of gasoline quality on emissions. The EPA Complex model, while considered statistically robust due to the large number of vehicles comprising the dataset, was not considered to be adequate for a number of reasons. First, the Complex Model was based on an emissions database which did not include several studies that have since been published. Second, the EPA Complex Model was developed using a fixed effects statistical modeling approach⁴². In contrast, both the CARB Phase 2 and 3 models were mixed models, employing a more sophisticated statistical approach than was available at the time of development of the Complex model.

EPA also rejected using CARB's Phase 3 Predictive Model in its analysis of the waiver request. While CARB had developed a very detailed protocol for developing the Phase 3 model, it rejected the results of this protocol because the resulting model differed too substantially from the Phase 2 model. Thus, EPA decided to create its own "predictive models" for exhaust VOC and NO_x emissions which combined the protocols used to develop the Complex Model with the expanded database and improved statistical tools which were now available. EPA relied on existing EPA models for evaporative VOC emission effects. However, these latter estimates were augmented with recent data indicating that ethanol increased permeation emissions, as well as the consideration of several commingling models and associated assumptions about drivers' refueling behavior.

One main conclusion drawn by EPA in the California Oxygen waiver analysis was that insufficient data existed at that time to conclusively determine the response of Tier 1 and newer vehicles to fuel parameters other than sulfur.⁴³ Some data indicated that oxygen increased NO_x emissions from Tier 1 and later vehicles, while other data contradicted this. Due to this inconsistency, EPA assumed that oxygen did not affect exhaust VOC, NO_x or CO emissions from Tier 1 and later vehicles in its analysis of CARB's request for a waiver of the RFG oxygen mandate.

⁴² A "fixed effects" model of this kind makes no attempt to estimate the error introduced by sampling from some larger population of vehicles or fuels. The model just describes quantitatively the relationships among variables that are present in the dataset that was analyzed. A "mixed" model, as was used by CARB in both the Phase 2 and Phase 3 predictive models' construction, attempts to go beyond description of the available data to make statistical inference to some larger population from which the available data were sampled. In this case CARB treated the vehicle effects as random (assuming that the test vehicles were sampled from some larger fleet) while fuel effects were treated as "fixed" (assuming that all fuels of interest were represented in the data). Such a modeling approach makes it possible to estimate the probable error in modeled effects in a way that is not possible with a fixed effects model. The approach, moreover, improves the accuracy of the significance measures used to decide which terms to include in the model.

⁴³ At the time of that 1999 analysis, sufficient data existed on the emissions effects of Sulfur on Tier 1 vehicles to be modeled. However, sulfur levels were not expected to change as a result of the removal of oxygen from RFG in California, so the effect of sulfur was moot in this situation.

None of the three models discussed above (i.e., the Complex Model, the CARB Predictive Model, and the EPA Predictive Models) address CO emissions. Historically, this is because the RFG program did not mandate a specific reduction in CO emissions and the lesser role of CO emissions in forming ambient ozone. The CARB Predictive Model considers the impact of fuel oxygen content beyond 2 wt%, but does not address the full range of oxygen levels on CO emissions, nor the impact of other fuel parameters. The only EPA model which predicts the impact of fuel quality on CO emissions is MOBILE6.2, which is discussed in the next section.

3.1.1.1.2 MOBILE6.2

The exhaust emission effects contained in MOBILE6.2 often differ for normal and high emitting vehicles. They can also vary by model year. As it is difficult to determine the fraction of emissions coming from each model year's vehicles in MOBILE6.2, as well as normal and high emitters, it is not feasible to predict outside of the model how a specific fuel is going to affect in-use emissions. In addition, the split between normal and high emitters varies depending on the presence and type of inspection and maintenance (I/M) program applicable in a particular local area. Thus, the effect of a specific fuel on emissions can vary to some degree from one county to another.

In order to quantify the effect of various fuel parameters on exhaust emissions in MOBILE6.2 under the conditions existing in the 2012-2020 timeframe, we compared the changes in emissions predicted by the NMIM modeling described in Chapter 4 of the Draft RIA with the changes in fuel quality occurring in the ethanol use scenarios. Specifically, we first determined the percentage change in exhaust VOC, CO and NO_x emissions by county for the base and 7.2 Minimum RFG Use scenarios evaluated for the NPRM. We then performed a series of linear regressions of these ratios against the change in fuel RVP, ethanol content and MTBE content. We did this for the 2012, 2015 and 2020 emission projections separately. For each combination of county and calendar year, the only property that changed was fuel quality. All other parameters relevant to emissions (e.g., the distribution of vehicles by age and class, VMT, ambient temperature, etc.) were otherwise identical. The results are summarized in Table 3.1-1.

Table 3.1-1. Fuel-Exhaust Emission Effects in MOBILE6.2

	RVP (% / psi)	Ethanol (% / Vol %)	MTBE (% / Vol%)	Adjusted r-Square
2012 (fleet average)				
VOC	7.1%	-1.1%	-0.7%	0.83
NOx	0.6%	0.0%	0.0%	0.95
CO	12.7%	-0.75%	-0.4%	0.36
2015 (fleet average)				
VOC	7.0%	-1.2%	-0.7%	0.85
NOx	0.6%	0.0%	0.0%	0.95
CO	12.7%	-0.73%	-0.4%	0.36
2020 (fleet average)				
VOC	6.7%	-1.2%	-0.7%	0.87
NOx	0.6%	0.0%	0.0%	0.95
CO	12.6%	-0.67%	-0.4%	0.39

For comparative purposes, the effect of RVP, ethanol and MTBE on exhaust VOC and NOx emissions from the EPA Predictive Models are shown in Table 3.1-2. The base fuel is a typical non-oxygenated, summertime, conventional gasoline, with 8.7 RVP, 30 ppm sulfur, 32 vol% aromatics, 13 vol% olefins, T50 of 218 F, T90 of 329, and no oxygen.

**Table 3.1-2.
Fuel-Exhaust Emission Effects per the EPA Predictive Models**

	RVP (% / psi)	Ethanol (% / Vol %)	MTBE (% / Vol%)
VOC	1.1%	-0.16%	-0.17%
NOx	1.1%	0.75%	0.36%

As can be seen, the exhaust emission effects contained in the EPA Predictive Models differ quite dramatically from those in MOBILE6.2. Regarding the effect of RVP, both models predict that an increase in RVP will increase both exhaust VOC and NOx emissions. However, MOBILE6.2 predicts that an increase of 1.0 psi will increase exhaust VOC by roughly 7%, while the EPA Predictive Models predict only a 1% increase. Regarding NOx emissions, the EPA Predictive Models predict the larger effect (1%), while the effect in MOBILE6.2 is smaller (0.6%). While the ratio of these two effects is significant, the absolute difference (0.4%) is very small.

Regarding the addition of ethanol, the two models again predict very different results. MOBILE6.2 predicts roughly 7 times the exhaust VOC reduction per volume percent of ethanol added, with no increase in NOx. The EPA Predictive Models project a significant increase in NOx emissions. The relative differences are similar for the addition of MTBE to gasoline, though the difference between the two estimates of exhaust VOC reduction is smaller.

Regarding CO Emissions from Tier 0 vehicles, MOBILE6.2 projects that a 3.5 wt% oxygen fuel (i.e., E10) will reduce CO emissions from normal emitters by 11% and those from

high emitters by 19%.⁴⁴ For Tier 1 and later vehicles, MOBILE6.2 projects that a 3.5 wt% oxygen fuel (i.e., E10) will have no effect on CO emissions from normal emitters and will reduce CO emissions from high emitters by the same 19% estimated for Tier 0 vehicles. This latter projection was based on a similar assumption to those made during EPA's review of California's request for a RFG oxygen waiver due to the same lack of relevant emission data. We estimate that the fraction of CO emissions coming from high emitters is 64.8% based on the overall effect of 6.7% in 2020 shown in Table 3.1-1 for 2020, when the fleet is entirely Tier 1 and later vehicles. This produces a fleet wide CO emission reduction for an E10 blend of 13.8% for Tier 0 vehicles and 6.7% for Tier 1 and later vehicles. MOBILE6.2 does not project any impact of the other relevant fuel parameters (aromatics, olefins, T50, and T90) on CO emissions for either Tier 0 or Tier 1 vehicles.

Since that time, the results of several test programs have been published. Given the dwindling numbers of Tier 1 vehicles on the road, these more recent studies have focused on vehicles certified to California's low emission vehicle (LEV), ultra low emission vehicle (ULEV), and super ultra low emission vehicle (SULEV) standards, as well as federal LEV and Tier 2 standards. The results of these more recent studies, as well as the few available in 2001, are discussed in the following section.

3.1.1.1.3. CRC E-67 Study

3.1.1.1.3.1 Overview

In early 2006, the Coordinating Research Council (CRC) published the results of their E-67 study investigating the effects of three fuel parameters, ethanol, T50 and T90, on exhaust emissions from recent model year vehicles.² The twelve vehicles tested included both cars and light trucks, certified to California LEV, ULEV and SULEV standards, with model years ranging from 2001 to 2003. A matrix of twelve (12) fuels was tested in this program, with varying levels of ethanol, T50, and T90. Each fuel parameter (ethanol, T50, and T90) was tested at each of three levels. However, a full factorial matrix of 27 test fuels was deemed unnecessarily large due to subtle differences between fuels that may not have yielded statistically significant results, or due to practical considerations regarding the fuels that could be blended using existing refinery streams.

The E-67 report presents the results of emission testing for each fuel, as well as a mixed statistical model created from the emission data. The model indicates that each of the three fuel parameters always has a statistically significant effect on both NMHC⁴⁵ and NOx emissions. In addition, significant interactions between the three fuel parameters are also often present.

The first step in our analysis of the CRC E-67 model was to compare the emissions changes predicted by the CRC mixed model to the actual emissions changes observed for each

⁴⁴ A normal emitter is generally a vehicle whose emissions are no more than twice its certification emission standards. A high emitter is a vehicle whose emissions exceed this level.

⁴⁵ NMHC is essentially equivalent to VOC for our purposes in this study.

fuel in the test program. We calculated average NMHC and NO_x emissions over the Federal Test Procedure for all twelve vehicles on each fuel. The CRC mixed model predicts the percentage change in emissions for each fuel relative to another fuel. These changes in predicted exhaust emissions for each fuel were applied to the measured emissions for fuel “H” in order to create a set of absolute emission levels for each fuel. We then compared the emissions predicted by the CRC E-67 model to the measured emission levels to observe how well the model predicted the effects of each fuel. The fuel properties of the CRC E-67 test fuels are listed in Table 3.1-3^{AAA}, below, and in greater detail in Table 3A-1 of Appendix 3A. We selected CRC fuel “H” as the “base” fuel since its properties are the closest to a national average non-oxygenated conventional gasoline (0% Ethanol, 215°F T50, 330 °F T90). (See Table 2.2-6 in Chapter 2 for data pertaining to gasoline survey results across the U.S.)

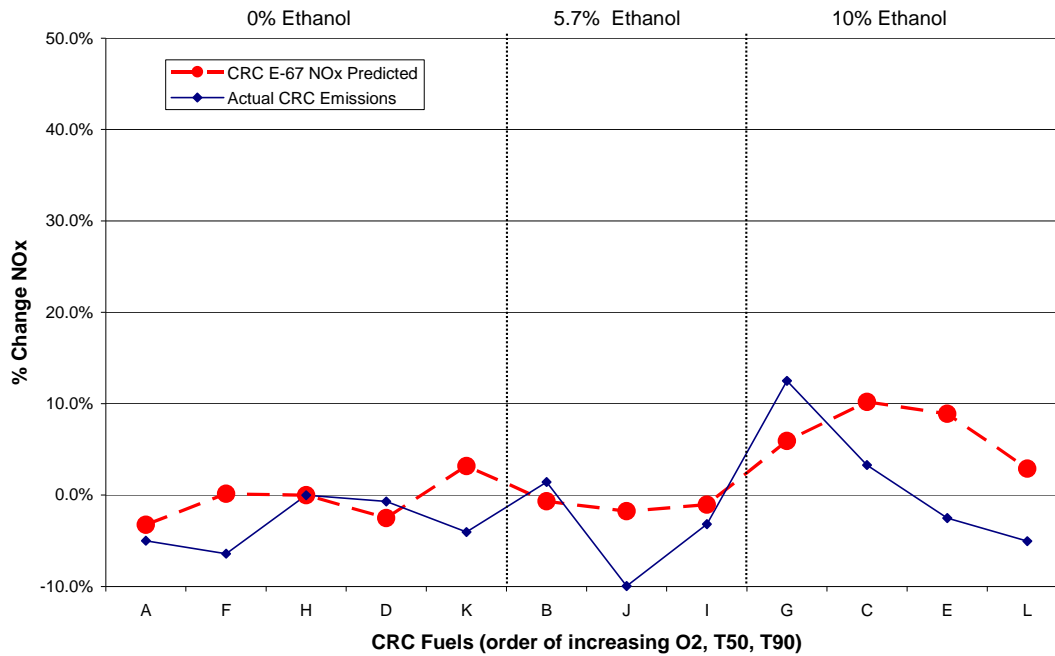
Table 3.1-3. CRC E-67 Test Program Fuels Properties^a

Fuel	Target Properties for Design Variables			Actual Values		
	T50 (°F)	T90 (°F)	Ethanol (%)	T50 (°F)	T90 (°F)	Ethanol
A	195	295	0	195	294	0
B	195	295	5.7	191	290	5.6
C	195	330	10	193	329	10.4
D	195	355	0	199	355	0
E	195	355	10	198	352	10.3
F	215	295	0	217	295	0
G	215	295	10	212	291	10.1
H	215	330	0	216	327	0.1
I	215	355	5.7	216	354	5.9
J	235	330	5.7	237	329	5.9
K	235	355	0	236	355	0
L	235	355	10	233	349	10.5

^aSee Table 3A-1 in Appendix 3A for detailed properties of all E-67 test fuels

The comparison between predicted and measured NO_x emissions is shown in Figure 3.1-1. The fuels are shown to indicate a trend in ethanol content, from the lowest levels on the left to the highest levels on the right. Within a constant level of ethanol content, the fuels are then shown in order of their level of T50 (lowest again on the left and highest on the right). The y-axis scale in this figure is set to match that for NMHC emissions, which will be presented and discussed next.

Figure 3.1-1. CRC E-67 Predicted vs. Actual Emissions
 Relative NOx Emissions Change from Base (CRC H: 215 T50, 330 T90, 0% EtOH)

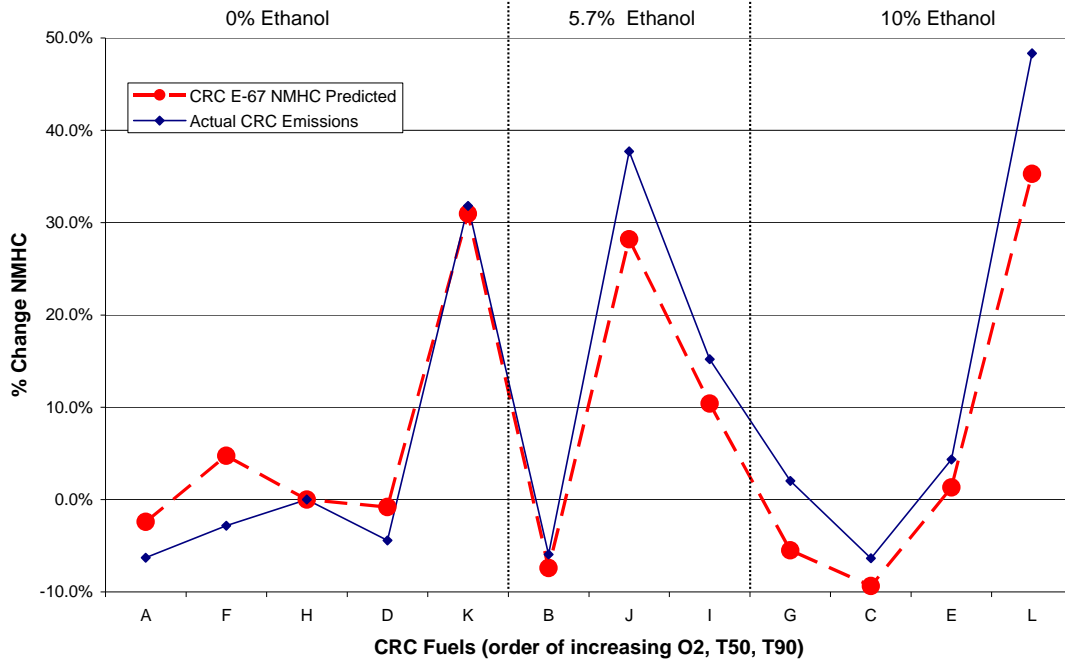


As shown in Figure 3.1-1, the CRC model for NOx emissions predicts the general trend in the emission data, which roughly indicates an increase in NOx emissions with increasing ethanol content. However, the model clearly does not reflect many of the fuel to fuel differences indicated by the actual emissions data. One example of this is the change between fuels G and C – two 10% ethanol blends with relatively low distillation temperatures. In changing from fuel G to fuel C, the CRC E-67 model predicts a 4.3% increase in NOx emissions whereas the actual test data clearly shows a 9.2% decrease. This likely indicates the existence of interactions between the fuel parameters which are more complex than those which could be included in the model. While fuel parameters other than ethanol, T50, and T90 were held as constant as possible among all the test fuels, the level of specific compounds (such as toluene or the various xylenes) could not be held constant. It is possible that some of these compounds are affecting NOx emissions and confounding the ability of the model based just on ethanol, T50, and T90 to predict the observed changes.

Figure 3.1-2 repeats this comparison for NMHC.

Figure 3.1-2. CRC E-67 Predicted vs. Actual Emissions

Relative NMHC Emissions Change from Base (CRC H: 215 T50, 330 T90, 0% EtOH)



First, it is very apparent that NMHC emissions are much more sensitive to fuel quality than NOx emissions. The largest increase in NMHC emissions relative to Fuel H is three times that for NOx emissions. Except for Fuels A and F (and of course Fuel H), the CRC model generally under-predicts the measured NMHC data. Directionally, however, the predicted emissions changes are very consistent with those observed in the test results. For this dataset at least, the effect of fuel quality on NMHC emissions are much more predictable than NOx emissions.

The fuels studied in this test program were varied independently at low, medium, and high levels of T50, T90, and Ethanol. If you include all the possible linear, quadratic, and interactive terms, there are a total of possible 10 combinations. The CRC E-67 models included 8 out of the 10 possible fixed effects for the NOx, NMHC, and CO models. These terms were: T50, T90, ethanol (EtOH), T50 squared, T90 squared, EtOH squared, T50 by EtOH, and T90 by EtOH. The excluded terms were T50 by T90, and T50 by T90 by EtOH, which CRC excluded from consideration since previous studies had indicated that these terms had little effect on emissions.

Also, several of the terms that were included in the CRC model had p-values greater than 0.1, indicating that those terms are less than marginally significant.⁴⁶ Specifically, the EtOH by EtOH term in the NMHC model and the T90, T90 by T90 and T90 by EtOH terms in the NOx model all had p-values above 0.10. In developing both the Complex Model and the EPA

⁴⁶ Using the widely accepted criteria of a 95% confidence interval, $p \leq 0.05$ is considered to be statistically significant, $0.05 < p \leq 0.10$ is marginally significant, and $p > 0.10$ is not considered statistically significant.

Predictive Models, our procedures would normally exclude the least significant term. A new regression would then be performed without this term being included in the model. This process would be repeated until all the remaining terms were statistically significant.⁴⁷

We desired to determine how these statistically insignificant terms might be affecting the predicted emission changes. This, plus the discrepancies between the CRC E-67 model and the actual emissions data, especially for the NOx model, prompted us to create our own NOx and NMHC models using the CRC E-67 dataset. Conducting our own modeling also provides us with the opportunity to apply a wide range of statistical tests in order to better understand the role of various fuel parameters in affecting emissions from these vehicles. The following sections provide details pertaining to the verification of the CRC model and the motivation for constructing a new model from this data.

3.1.1.1.3.2. Development of a New Mixed Model: The EPA E-67 Model

Using the E-67 dataset provided by the CRC, EPA first verified the coefficients and p-values of the CRC E-67 model using the full E-67 dataset (no outliers were removed) with the same 8 fixed fuel effects that were included by CRC. This was successful and the coefficient and p-values resulting from this modeling are shown in Table 3.1-4.

Table 3.1-4. CRC E-67 Model P-Values and Coefficients

CRC E-67 Effect	NMHC		CO		NOx	
	P-Value	Coefficient	P-Value	Coefficient	P-Value	Coefficient
Intercept	<.0001	-3.2942	0.0001	-0.7966	<.0001	-2.6183
T50	<.0001	0.0063	0.3099	0.001227	0.8939	-0.00013
T50*T50	<.0001	0.000176	0.0428	0.000099	0.2182	-0.00006
T90	0.0541	0.001685	0.0051	-0.0045	0.762	0.00024
T90*T90	0.0035	0.000058	0.0815	0.000045	0.1163	0.000043
EtOH	0.1124	0.005679	0.0174	-0.01581	0.0504	0.00571
EtOH*EtOH	0.2816	0.000722	0.0005	0.003118	0.0861	0.001622
T50*EtOH	0.084	0.000195	0.0182	0.000355	0.0414	-0.00032
T90*EtOH	0.0004	0.000244	0.0534	0.000174	0.99	-1.19E-06

EPA then created a new model starting with all combinations of T50, T90, and EtOH along with their squares, cross products, and the interactive terms T50 by T90 by EtOH for a total of 10 fixed effects. From this “full model”, variables were eliminated in order to improve the fit statistics between the model and the test data until a “final model” was created that contained 7 fixed fuel effects for NMHC and CO, and 6 fixed fuel effects for NOx. Table 3.1-5, on the following page, shows the p-values and coefficients for the fixed effect terms of each model.

⁴⁷ One exception to this process is that the linear form of a variable, such as ethanol, would always be retained in the model if a second order term included ethanol (e.g., the ethanol by T90 term).

Table 3.1-5. EPA E-67 Model P-Values and Coefficients

EPA E-67 Effect	NMHC		CO		NOx	
	P-Value	Coefficient	P-Value	Coefficient	P-Value	Coefficient
Intercept	<.0001	-3.2773	0.0002	-0.7684	<.0001	-2.6418
T50	<.0001	0.006272	0.5815	0.00066	0.687	-0.00037
T50*T50	<.0001	0.000168				
T90	0.0498	0.00172	0.0059	-0.00437	0.7761	0.000224
T90*T90	0.0039	0.000057			0.0735	0.000047
EtOH	0.101	0.005892	0.0111	-0.01726	0.062	0.005393
T50*EtOH	0.0987	0.000186	<.0001	0.003843	0.0446	0.001854
T90*EtOH	0.0002	0.00025	0.0299	0.000178	0.0426	-0.00031
T50*T90			<.0001	0.000126		
T50*T90*EtOH			0.0003	0.000023		

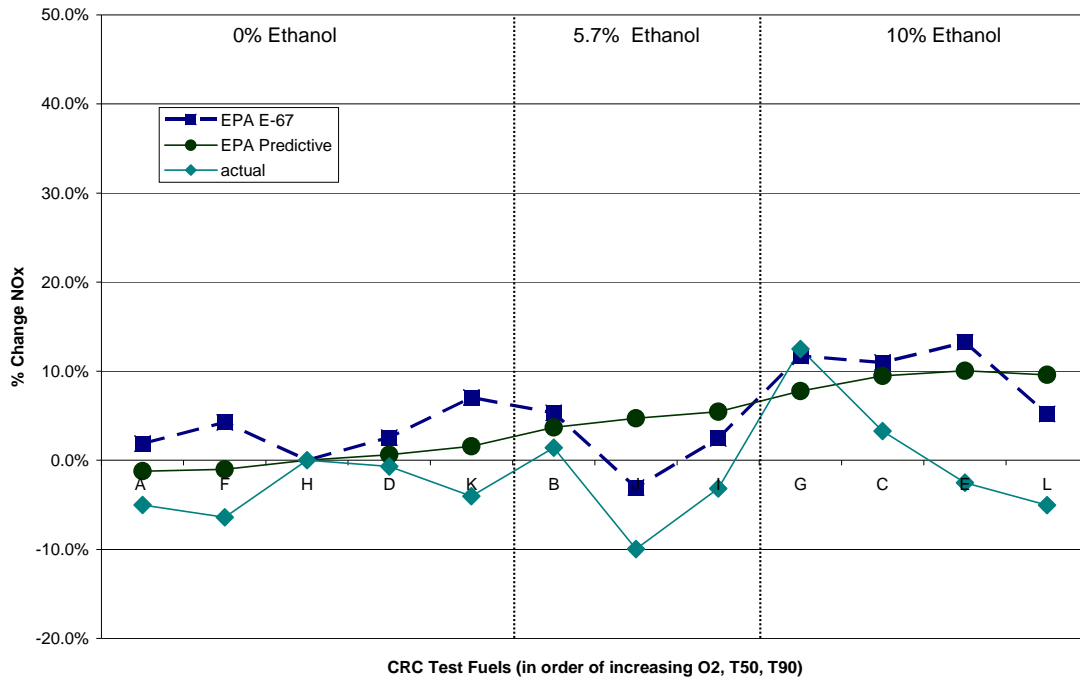
As shown in Table 3.1-5, the EPA E-67 Model does not include terms with p-values greater than 0.10 (except for linear terms included in statistically significant higher order terms). Statistical tests show that these two models are not significantly different from one another. The null hypothesis in this case is that EPA E-67 fits the data just as well as the original CRC E-67 model based on a chi-squared test. However, based on several fit statistics (AIC, AICC, and BIC) the EPA E-67 model provides a slightly better fit to the test data than either the original CRC E-67 model or the full model with all 10 terms included. The next step is to compare the EPA E-67 model predictions to both the E-67 data and the predictions of the EPA Predictive Models, which reflect the emission effects for older vehicles.

Both the EPA E-67 and EPA Predictive models are mixed models that predict the relative changes in exhaust emissions due to carefully controlled changes in gasoline quality, including the addition of an oxygenate such as ethanol. The models are not intended to be accurate at predicting absolute emission levels, but rather the difference in emissions when fuel properties are varied. The goal of this analysis is to determine if the EPA Predictive models, which were developed using data from Tier 0 and earlier vehicles, predict the same relative changes in emissions as the Tier 1 vehicles used for the EPA E-67 model.

A key difference between the models is that there are only three fuel parameters used as inputs for the EPA E-67 model: T50, T90, and ethanol content. The EPA Predictive Models use these three properties along with RVP, aromatic content, olefin content, and sulfur content as fuel parameter inputs to the model.

We ran the EPA E-67 and EPA predictive models with the 12 fuels used in the CRC test program, inputting the applicable fuel properties used in each model. Following the same procedure as outlined above, CRC test fuel H was selected as a “base” fuel in order to compare relative changes between this fuel and others with varying amounts of ethanol, T50, and T90. The NOx emissions predicted by the EPA E-67 and EPA Predictive models, together with the actual E-67 study data, are shown graphically in Figure 3.1-3, below.

Figure 3.1-3. EPA E-67 and EPA Predictive vs. Actual Emissions
 Relative NOx Emissions Change from Base (CRC H: 215 T50, 330 T90, 0% EtOH)

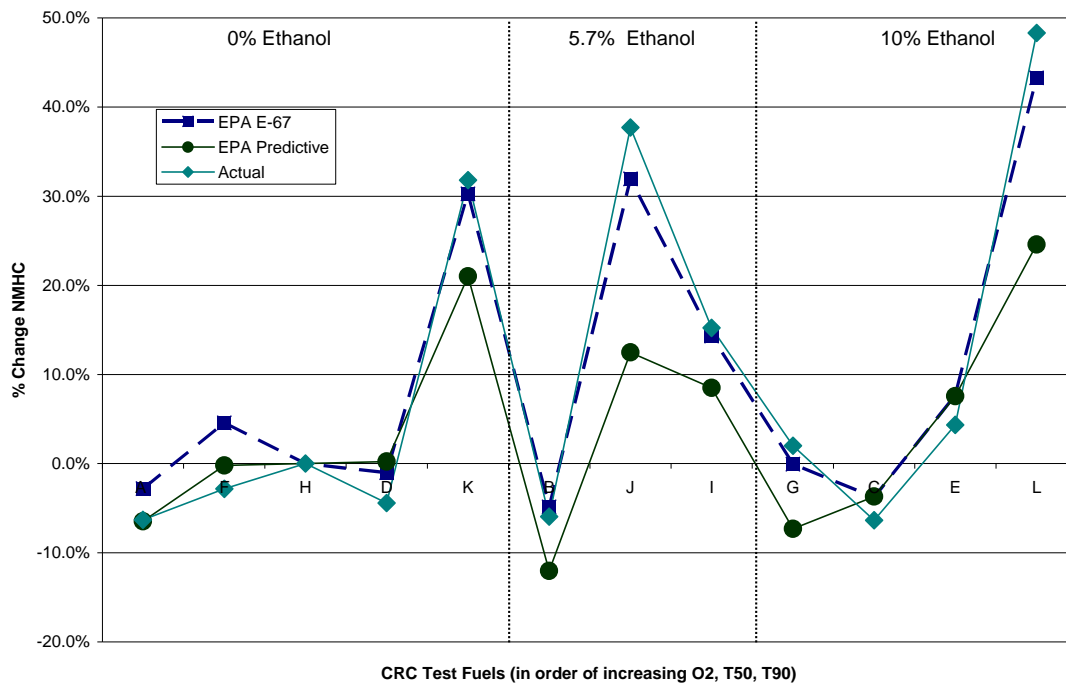


As shown in Figure 3.1-3, neither model predicts the actual test data with complete accuracy. The EPA E-67 shows the same general relationship to the emission data as did the CRC E-67 NOx model. Thus, removing the statistically insignificant terms had little impact on the relative fit of the model to the data. The EPA Predictive NOx models, on the other hand, appear to be primarily sensitive to ethanol, with T50 and T90 playing very limited roles in affecting NOx emissions. In contrast, the E-67 model shows sensitivities to all three parameters.

Overall, the E-67 study indicates that NOx emissions from recent model year vehicles (LEVs, ULEVs and SULEVs) are still sensitive to at least several fuel parameters. As indicated by the inability of either the EPA E-67 model or the EPA Predictive Models to accurately predict all of the changes seen in the E-67 data, this study is very valuable in identifying the continued sensitivity of LEV and cleaner vehicles to changes in fuel quality.

Figure 3.1-4, below, shows the comparison of NMHC emissions predicted by the EPA E-67 and Predictive models together with the E-67 study data.

Figure 3.1-4. EPA E-67 and EPA Predictive vs. Actual Emissions
 Relative NMHC Emissions Change from Base (CRC H: 215 T50, 330 T90, 0% EtOH)



From Figure 3.1-4, it is apparent that both models do a better job at predicting changes in NMHC emissions than was the case for NOx emissions. The EPA E-67 model is clearly the more accurate of the two models. However, this is to be expected given it was based on the data being depicted. The ability of the EPA Predictive Model to predict the general trend of nearly all the CRC E-67 test fuels is impressive, given it is based on data from Tier 0 vehicles with 5-10 times the NMHC emission levels of the vehicles in the E-67 test program. Overall, it appears that NMHC emissions from LEVs and cleaner vehicles are even more sensitive to changes in fuel quality than NMHC emissions from Tier 0 vehicles.

The preceding figures illustrate the differences between the models for all 12 fuels included in the E-67 test program. Some of these fuels are more practical, or likely to be commercially produced, than others. Based on the results of AAM fuel surveys presented in Chapter 2, summertime E10 blends will generally have levels of T50 and T90 that are about 29 °F and 7 °F lower than non-ethanol blends. Thus, it could be useful to focus on sets of fuels in the CRC E-67 study which reflect these differences.

The fuel pair which most closely reflects these differences are CRC fuel “C”, a 10 vol% ethanol blend, and CRC fuel “H”, a non-oxygenated fuel. Both fuels have a mid-range level of T90. A second, more complex set of fuels involve those with higher levels of T90. The CRC “E” fuel contains 10 vol% ethanol and has the high level of T90. However, there is not a good match to this fuel which is non-oxygenated. Yet two non-oxygenated fuels (“D” and “K”), when considered together, represent a reasonable match to fuel “E. Fuel D reflects no change in T50 relative to fuel E, while fuel K reflects slightly more than a typical drop in T50. Thus, by averaging the emissions for fuels K and D and then comparing this to the emissions with fuel E,

we are able to generate a second direct indication of the impact of ethanol blending on emissions from these low emitting vehicles. The general properties of these five fuels and the emissions changes predicted by the two models are shown in Table 3.1-6 below.

**Table 3.1-6.
Predicted NOx and NMHC Emissions Changes
for EPA E-67 and Predictive Models⁴⁸**

Fuel Changes	H to C	K to E	D to E
T50 (°F)	Mid - Low	High – Low	Low - Low
T90 (°F)	Mid - Mid	High – High	High - High
Oxygen (vol%)	0 - 10	0 – 10	0 - 10
Change in Emissions			
EPA Predictive Model NOx	9.5%	8.4%	9.4%
EPA E-67 NOx	11.0%	5.8%	10.4%
Actual E-67 Data	3.3%	1.6%	-1.8%
EPA Predictive Model NMHC	-3.7%	-11.1%	7.3%
EPA E-67 NMHC	-3.8%	-17.3%	8.8%
Actual E-67 Data	-6.3%	-21.0%	9.2%

As shown in Table 3.1-6, the two models agree quite closely on the effect of fuel C relative to fuel H on both NMHC and NOx emissions. However, that said, both models tend to overestimate the impact of fuels C and E on NOx emissions and underestimate the impact of these fuels on NMHC emissions.

Regarding the comparison of fuel E to fuels K and D, the two models tend to agree on the effect of fuel E to fuel D, but differ more with respect to the effect of fuel E to fuel K, particularly for NMHC emissions. One reason for the difference in the latter comparison is that the EPA E-67 NMHC model is more sensitive to very high levels of T50 than the EPA Predictive Model for NMHC.

Overall, the results of the E-67 study suggest that our assumption that Tier 1 and later vehicles would not be sensitive to fuel parameters such as ethanol, T50 and T90 (made in our consideration of California’s request for a waiver of the RFG oxygen requirement) may not be valid. The observation that NMHC emissions from LEVs, *et. al.* could actually be more sensitive than Tier 0 vehicles (on a percentage basis), particularly challenges our assumption. While the effect of fuel quality on NOx emissions from low emitting vehicles is still not clear from the recent test data, these emissions do appear to be sensitive to fuel quality.

⁴⁸ For an additional comparison between the models with an expanded set of fuels to be used later in this analysis, refer to Table 3A-2 in Appendix 3A.

3.1.1.1.3.3. Effect of Oxygen Content Alone on Emissions: CRC E-67 Study

In order to provide an estimate of fuel-emission effects comparable to those of the other studies of the effect of fuel quality on emissions from LEV and later vehicles, we selected three pairs of fuels tested in the CRC E67 study where the only change in fuel properties was oxygen content. One pair of fuels compared non-oxygenated fuel versus E6 (fuels A and B). Two pairs of fuel compared non-oxygenated fuel versus E10 (fuels D and E and fuels F and G). We applied mixed univariate statistical models to the logarithm of the emission data from fuels A and B and to fuels D, E, F and G, with vehicle as a random variable and fuel type as a fixed variable. Table 3.1-7 presents the results in terms of the percentage change in emissions between the non-oxygenated fuel and the ethanol blend in each pair.

**Table 3.1-7.
Matched Fuel Pair Results from the CRC E-67 Study: Effect of Oxygen Alone**

	NMHC	CO	NOx
	% Change	% Change	% Change
6 vol% ethanol vs. no oxygenate (Fuels A and B)	-4.5%*	-7.5%	2.6%
10 vol% ethanol vs. no oxygenate (Fuels D, E, F and G)	4.7%	-18.1%	9.5%

* Bold type indicates the difference was significant at a 90% confidence level.

As can be seen, the addition of 6 vol% ethanol increased NOx emissions, while decreasing NMHC and CO emissions. None of the effects were statistically significant at a 90% confidence level. The addition of 10 vol% ethanol decreased CO emissions, while increasing NMHC and NOx emissions. All three pollutant effects were statistically significant at a 90% confidence level.

3.1.1.1.4. AAM-AIAM Sulfur and Oxygenate Study

AAM, together with AIAM and Honda, performed a test program in 2001 to evaluate the effect of fuel sulfur and oxygen on emissions of CARB Tech 5 vehicles (i.e., LEV and later vehicles)^{BBB}. This program was performed at the request of the CARB in conjunction with the MTBE ban and new Phase 3 Cleaner Burning Gasoline regulations. The first of the program's two distinct goals was to evaluate the emissions of very low sulfur fuels at 1, 30, and 100 ppm sulfur, with other fuel parameters held constant. Part two was to compare the emissions effects of MTBE and ethanol blended fuels to non-oxygenated fuel, again with other parameters held as constant as possible. The fuel specifications for the oxygenated fuel matrix are shown in Table 3.1-8. (The sulfur-related testing is not relevant here, so the fuels which only reflect a change in sulfur are not shown.)

**Table 3.1-8.
AAM Fuel Properties for Oxygenated Test Fuels**

Test Fuel	Non-Oxy	MTBE	E10
RVP (psi)	7.1	6.9	7.1
Arom (vol.%)	24.6	22	21.6
Olefins (vol.%)	4.6	3.4	4.1
T50 (°F)	210	202	205
T90 (°F)	297	294	291
MTBE/EtOH (vol.%)	0	11.3	11.5
Sulfur (ppm)	35	31	28

The sulfur effects portion of this study tested 13 TLEV, LEV, and ULEV vehicles while the oxygenate phase of the study used 8 and 2 of phase 1's LEV and ULEV vehicles, respectively. These vehicles were a mixture of light and medium duty passenger cars and trucks of undisclosed make and model year. The FTP 75 was selected as the drive cycle, with regulated data collected both at the tailpipe and engine out for a subset of vehicles to evaluate catalyst efficiency.

The sulfur related testing found a clear relationship between the level of sulfur in the fuel and the natural log of emissions (CO, NO_x and NMHC). Bag weighted emissions of NO_x, CO, and HC emissions were reduced by 16%, 12%, and 11% (respectively) when fuel sulfur levels were reduced from 30 to 1 ppm. The effects found in the oxygenate portion of the study were less clear, since some results were not statistically significant. Average bag weighted emissions of HC and CO tended to decrease with increasing oxygen content. Both oxygenated fuels showed a decrease in NO_x emissions, with MTBE having slightly lower emissions than ethanol. The details of the statistical procedures applied to the data were not described in the documentation.

In order to provide a consistent basis for comparing the results of this study to the other studies of the effect of oxygenate on LEV and later vehicle emissions, we applied a mixed univariate statistical model to the logarithm of the emission data from the AAM-AIAM oxygenate study, with vehicle as a random variable and fuel as a fixed variable. Table 3.1-9 presents the results in terms of the percentage change in emissions between the 11 vol% MTBE blend, the 11 vol% ethanol blend and the non-oxygenated fuel.

**Table 3.1-9.
Fuel Effects from the AAM-AIAM Oxygenate Study: EPA Mixed Model**

	NMHC	CO	NO _x
	% Change	% Change	% Change
11 vol% MTBE vs. no oxygenate ^a	-15.3% ^b	-23.7%	-12.7%
11 vol% ethanol vs. no oxygenate	-12.6%	-24.6%	-6.6%
11 vol% ethanol vs. 11 vol% MTBE	-1.4%	-5.7%	25.2%

^a Fewer vehicles were tested on the MTBE blend.

^b Bold type indicates the difference was significant at a 90% confidence level.

As can be seen in Table 3.1-9, the addition of 11 vol% MTBE was found to significantly reduce the emissions of all three pollutants by 10% or more relative to the non-oxygenated California RFG. The addition of 11 vol% ethanol was also found to significantly reduce the emissions of all three pollutants relative to the non-oxygenated California RFG. However, the reductions were smaller than those of the MTBE blend for all three pollutants. Also, the reduction in NOx emissions was not statistically significant at a 90% confidence level. When we compared the emissions with the ethanol blend to those with the MTBE blend, we found that the increases were all statistically significant at a 90% confidence level.

Based solely on this single study of seven vehicles and three fuels, it appears that adding ethanol to a severely reformulated gasoline while holding other properties constant tends to reduce NMHC, CO and NOx emissions. However, replacing MTBE with the same volume of ethanol tends to increase these emissions. Focusing on just this one study, the effect of increased ethanol use could differ in RFG areas, where MTBE has traditionally been used, and conventional fuel areas, where no oxygenate has traditionally been used. However, this one study is not a sufficient basis to draw a firm conclusion regarding the effect of ethanol blending on exhaust emissions.

3.1.1.1.5. ExxonMobil Study of Oxygenate Type and Content

In the fall of 1999, ExxonMobil (Mobil Oil at that time) conducted a test program to investigate the emissions effects of MTBE and ethanol on LEV and ULEV vehicles. The information which follows was made publicly available on the CARB website^{CCC} and is taken directly from a presentation posted on that webpage. The vehicles tested are listed in Table 3.1-10.

Table 3.1-10. Vehicles Tested in 1999 ExxonMobil Study

Make/Model	Emissions		Fuel
	Calibration	Engine	System
1999 Dodge Stratus	LEV	2.4L	MFI
1999 Chevrolet Malibu	LEV	3.1L	PFI
1999 Mazda Protégé	ULEV	1.6L	MPF
1999 Ford Crown Victoria	LEV	4.6L	SFI
1998 Honda Accord	ULEV	2.3L	MFI

Four test fuels were developed with varying MTBE and ethanol content, with other parameters controlled as tightly as possible. The fuel specifications are listed below in Table 3.1-11.

Table 3.1-11. ExxonMobil Test Fuel Specifications

Test Fuel	M1	M2	M3	M4
RVP, psi	6.5	6.4	7.3	7.2
T50 (°F)	192	191	198	203
T90 (°F)	279	272	274	282
MTBE (vol%)	0	10	0	0
Ethanol (vol%)	0	0	7	10
Aromatics (vol%)	21	21	21	21
Olefins (vol%)	<1	<1	<1	<1
Oxygen (wt%)	0	1.82	2.436	3.48

Vehicles were tested in duplicate over the FTP 75 drive cycle, and composite weighted emissions for regulated pollutants reported. The average results for all vehicles, based on least squares means from the analysis of variance, is shown in Table 3.1-12., below. The oxygenate effect is the percent change in emissions between a given fuel and the base fuel M1.

Table 3.1-12. Average Exhaust Emissions: ExxonMobil Study (all vehicles)

Fuel	Oxygenate	Exhaust Emissions, g/mi			Oxygenate Effect ^(a)		
		HC	CO	NOx	HC	CO	NOx
M1	None	0.058	0.70	0.187			
M2	10% MTBE	0.058	0.72	0.198	0%	3%	6%
M3	7% EtOH	0.059	0.66	0.213	1%	-6%	14%
M4	10% EtOH	0.061	0.66	0.239	5%	-6%	28%

(a) Bold font represents statistically significant ($\alpha=0.1$)

The bold numbers in the above table represent statistically significant differences in emissions at the 90% confidence level. Only the effect of ethanol on NOx emissions was found to be statistically significant while the effects on other criteria pollutants were not. As was the case for the AAM-AIAM study, the presentation to CARB did not describe the statistical analysis applied to the detail in sufficient detail to replicate the results. Thus, we applied a mixed univariate statistical model to the logarithm of the emission data from the ExxonMobil oxygenate study, with vehicle as a random variable and fuel type as a fixed variable. Because of the greater number of fuels in this study, we applied two different types of mixed models. One set of models compared emissions between various pairs of fuels (e.g., M1 and M2). We applied five models of this type. A sixth model used oxygen content as the fuel variable and considered the significance of the square of oxygen content, as well. The upper half of Table 3.1-13 presents the results in terms of the percentage change in emissions between the various fuel pairs. The bottom half of Table 3.1-13 presents the estimated emission effects for 2.1 wt% and 3.5 wt% oxygen fuels using the results of the fuel oxygen content based model.

Table 3.1-13. Fuel Effects from the ExxonMobil Oxygenate Study

	THC	CO	NOx
	% Change	% Change	% Change
Two Fuel Comparisons			
10 vol% MTBE vs. no oxygenate	-2.5% ^a	-5.1%	-0.4%
7 vol% ethanol vs. no oxygenate	-0.9%	-11.3%	9.3%
10 vol% ethanol vs. no oxygenate	3.6%	-11.6%	20.3%
10 vol% ethanol vs. 10 vol% MTBE	6.3%	-7.6%	21.1%
Oxygen Content model			
2.1 vol% Oxygen	-2.0%	-9.1%	2.9%
3.5 vol% Oxygen	3.5%	-15.2%	17.3%

^a Bold type indicates the difference was significant at a 90% confidence level.

As can be seen, the results of our statistical analysis differ from those performed by ExxonMobil. This may have been due to our focus on the logarithm of emissions or the use of a mixed model. As shown in Table 3.1-13, the addition of 10 vol% MTBE was found to reduce the emissions of all three pollutants relative to the non-oxygenated California RFG. While the differences tended to be substantial in magnitude on average, they were not statistically significant at a 90% confidence level. The addition of 7 vol% ethanol to the non-oxygenated California RFG (with an increase of roughly 1.0 psi RVP) was also found to reduce the emissions of all three pollutants. Again, the reductions in NMHC and NOx emissions were not statistically significant. While the reduction in CO emissions was slightly smaller on average than that for MTBE, the effect was more consistent across vehicles and statistically significant at a 90% confidence level. The addition of 10 vol% ethanol to the non-oxygenated California RFG (again with an increase of roughly 1.0 psi RVP) was also found to reduce emissions of NMHC and CO, but increased NOx emissions slightly. Like that for the 7 vol% ethanol blend, only the CO emission effect was statistically significant at a 90% confidence level. Finally, the substitution of 10 vol% ethanol for 10 vol% MTBE was found to increase emissions of THC and NOx substantially, while reducing CO emissions slightly. None of the effects were significant at a 90% confidence level, though the NOx increase was nearly so (e.g., 89% confidence).

With respect to the model using oxygen content to describe the four fuels in the study, the effect of oxygen on emissions was found to be statistically significant for all three pollutants. In addition, the square of the oxygen content was statistically significant at the 90% confidence level for THC and NOx emissions. The predictions shown in Table 3.1-13 utilize the square of oxygen content for these two pollutants, but not for CO emissions. As can be seen, a 2.1 wt% oxygen fuel (e.g., an 11 vol% MTBE or 6% ethanol blend) is predicted to decrease THC and CO emissions, but increase NOx emissions. A 3.5 wt% oxygen fuel (e.g., a 10% ethanol blend) is predicted to decrease CO emissions, but increase THC and NOx emissions.

The two modeling approaches produce markedly different predictions for a 10 vol% ethanol blend, especially for THC and NOx. The direct comparison of the clear fuel and the E10 blend shows the E10 blend to reduce THC and NOx slightly. In contrast, the oxygen content approach predicts that the E10 blend will increase both THC and NOx emissions. This

underlines the need for more data to accurately predict the emission effect of various types and levels of oxygenate on modern vehicles.

3.1.1.1.6. Toyota Study of MTBE and Ethanol Blends

Toyota Motor Company of Japan performed a small study, presented in 2000, evaluating the effect of MTBE and ethanol blended gasoline on exhaust emissions of nine LEV, TLEV, ULEV vehicles.^{DDD} The model years for these vehicles were not presented.. Three test fuels were evaluated in this study: Phase 2 California RFG containing MTBE, a matched RVP E10 and a higher RVP E10. However, exhaust emission testing was only performed on the MTBE fuel and the higher RVP ethanol fuel. The fuel properties for these test fuels are listed in Table 3.1-14, below:

Table 3.1-14. Fuels Tested in the Toyota Oxygenate Test Program

Fuel Parameter	MTBE Blend	Matched RVP Ethanol Blend	Higher RVP Ethanol Blend
RVP (psi)	6.8	7	7.6
Arom (vol.%)	24	23	24.1
Olefins (vol.%)	5	5	3.4
T50 (°F)	156	208	212
T90 (°F)	290	294	297
MTBE (vol.%)	11.1	0	0
EtOH (vol.%)	0	11.2	8.9
Sulfur (ppm)	30	29	30

As can be seen in the above table, aromatics, olefins, and sulfur were held relatively constant while other parameters varied. The emission test cycle used was not stated. We assume it was the FTP 75 test. Only regulated emissions results are provided.

The study found that, on average across all vehicles and tests, NO_x emissions increased by 5% for E10-B relative to MTBE. Correspondingly, CO emissions were reduced by 6% and NMHC emissions were decreased by 0.6% for E10-B relative to MTBE.

Again for comparison purposes, we applied a mixed univariate statistical model to the logarithm of the emission data from the Toyota oxygenate study, with vehicle as a random variable and fuel type as a fixed variable. Table 3.1-15 presents the results in terms of the percentage change in emissions between the 11 vol% MTBE and the 9 vol% ethanol blends.

Table 3.1-15. Fuel Effects from the Toyota Oxygenate Study

	NMHC	CO	NO _x
	% Change	% Change	% Change
9 vol% ethanol vs. 11 vol% MTBE	-0.8% ^a	-6.1%	3.8%

^a Bold type indicates the difference was significant at a 90% confidence level.

As can be seen, the substitution of 9 vol% ethanol for 11 vol% MTBE in a RFG-type blend was found to reduce the emissions of NMHC and CO, but increase NOx emissions. None of the emission effects was found to be statistically significant at a 90% confidence level.

Based solely on this single study of nine vehicles and three fuels, it appears that replacing MTBE with roughly the same volume of ethanol in reformulated gasoline while holding other properties constant (except RVP) tends to reduce NMHC and CO, and increases NOx emissions. It is not possible to separate the effect of ethanol from RVP in this study.

3.1.1.1.7. Mexican Petroleum Institute Fuel-Emission Effects Study

In 2006, the Instituto Mexicano del Petroleo (hereafter referred to as Mexican Petroleum Institute) published a paper on a recently conducted research program investigating the effects of gasoline properties on exhaust and evaporative emissions on 30 light duty cars and trucks, ranging in model year from 1993 to 2002.^{EEB} The fuel quality parameters investigated include RVP, oxygen, Sulfur, olefins, aromatics, and distillation parameters. The results of this study were used to develop a statistical model for predicting emissions based on fuel quality for use in guiding national air quality improvement program policy. In their analysis, a comparison was made between the “predictive model,” developed based in this test data, and EPA’s Complex model. The end result is a general qualitative agreement with the EPA Complex model, with some quantitative differences pertaining to the vehicles and fuels used in each model’s development. Selected properties of the test fuels are shown below in Table 3.1-16.

Table 3.1-16. Fuel Tested in the Mexican Petroleum Institute Fuel Effects Study

Fuel	Aromatics (vol%)	Olefins (vol%)	Oxygen^a (wt%)	Benzene (vol%)	RVP (psi)	T50 (°F)	T90 (°F)	Sulfur (ppm)
1	19.1	6.6	0	0.86	6.8	224	325	411
2	19.3	6.6	0.98	1.09	6.8	222	324	412
3	18.8	6.5	2.03	0.9	6.9	216	324	406
4	20.6	6.7	2.1	1.13	7	227	326	386
5	19	6.6	1	1.15	8.6	213	323	423
6	18.7	6.9	1.03	0.98	10.7	199	325	387
7	40.2	6.9	0.98	2.26	6.6	233	324	402
8	20.7	15	1.07	1.31	10.9	197	322	415
9	35.8	15.5	1.06	1.25	10.8	209	326	403
10	19.8	5	1.03	0.6	6.6	220	335	89
11	20	7.4	0.98	0.8	6.7	223	321	209
12	19.8	6.1	1.05	0.75	6.6	222	321	817
L-S	40.3	4.8	1.14	1.06	8.1	232	324	34
Ref	28	13.5	0.34	1.14	8.9	207	332	724
ZM	24.1	9	1.21	1	7.7	213	326	403

^a Oxygenate is MTBE, except fuel 4 (Ethanol)

The base fuel from which other fuel parameters were varied to form additional fuels is indicated as fuel 2 in the above table, and is a low-level MTBE fuel blended to represent a composite average of all brands of commercially available Mexican gasoline. The reference fuel for comparative fuel effects purposes, fuel “Ref”, is a fuel blended to have refinery average levels of sulfur, benzene, RVP, aromatics, olefins, and distillation properties for the year 2000.

The technology groups investigated were referred to as either “Tier 0” and “Tier 1” vehicles, which is a bit of a misnomer as these vehicles were not equipped with on-board diagnostic equipment (OBD), nor were they subject to emissions durability standards⁴⁹. Rather, each technology class acts as a surrogate for emission control technologies with the certification standards shown in Table 3.1-17.

Table 3.1-17. Certification Standards of Test Vehicles by Technology Class

Technology class	# of Vehicles	Model Years	CO (g/km)	NMHC (g/km)	NOx (g/km)
"Tier 0"	12	1993-1998	2.1	0.25 (THC)	0.62
"Tier 1"	14	1999-2002	2.1	0.156	0.25

Vehicles were tested on a chassis dynamometer over the FTP-75 test. Regulated emissions, as well as speciated hydrocarbons and carbonyls, were collected for each test. The procedures and statistical methods employed to develop the predictive model for this test program were similar to those used to construct the complex models for exhaust VOC and NOx emissions.

The emissions test results were separated into “Tier 0” and “Tier 1” categories, and reported as mean emissions rates for all vehicles of that type on each test fuel. The natural logarithm of emissions was then regressed to develop a predictive model, using a statistical approach that is “similar to the techniques used to construct the complex model for exhaust VOC and NOx emissions” (Schifter et al, 1275). The report then goes into details on the experimental vs. model predicted results, as well as a validation of their model which will not be discussed here. The model predicted percent changes in emissions (for both vehicle fleets) for the Mexican Petroleum Institute predictive model and EPA Complex model are shown in Figures 3.1-5 and 3.1-6, below.

⁴⁹ The Mexican Environmental Agency currently mandates emissions durability certificates to be issued on new vehicles

Figure 3.1-5. Emissions Effects Predicted by EPA Complex Model

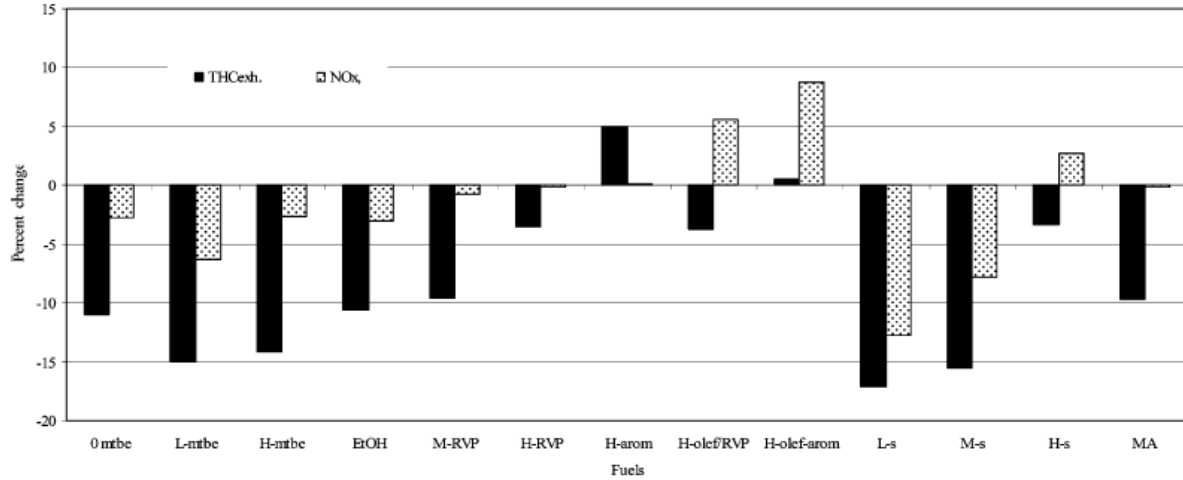
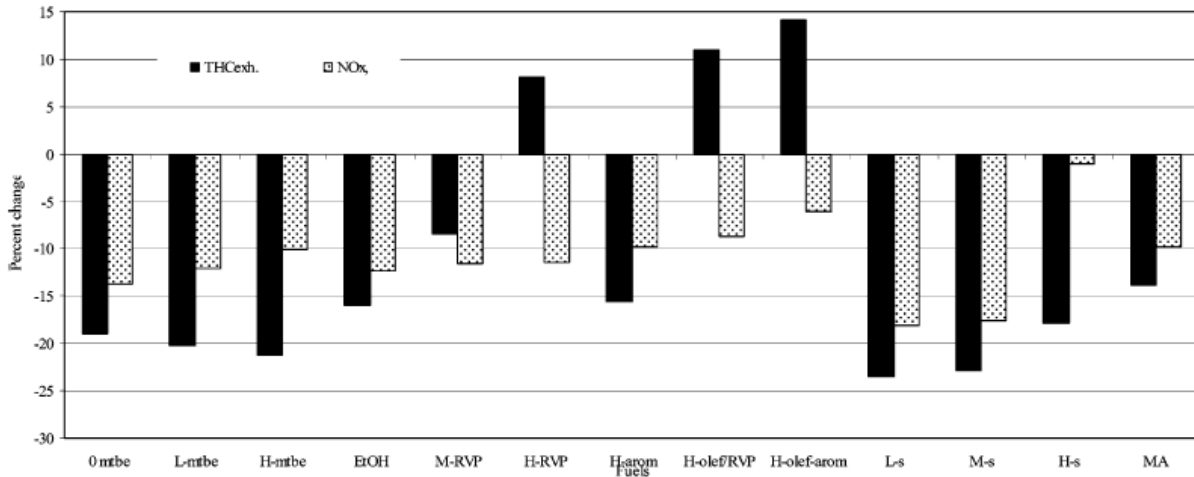


Figure 3.1-6. Emissions Effects Predicted by Mexican Petroleum Institute “Predictive” Model



The values above represent average emissions across both vehicle technology fleets considered together, and with the industry average fuel (“Ref”) as a baseline for predicted changes in emissions. As you can see, their model predicts an even greater reduction in exhaust THC and NOx emissions with ethanol (and MTBE) than the complex model, along with directionally inconsistent results for fuels with high aromatics, RVP, and olefins. This is partly due to differences in the fuels and vehicles used to develop each model (along with the properties of the base fuel selected) and speaks to the fact that there is a high degree of uncertainty and sensitivity to consider when extrapolating the results of a fuel effects model to the larger vehicle and fuel population.

As with the other studies, we applied a mixed univariate statistical model to the logarithm of the emission data from the Mexico fuel study, with vehicle as a random variable and fuel type as a fixed variable. We restricted the vehicles to those which had NOx emissions of 0.20 g/mi or

less on the low sulfur fuel (30 ppm) included in the test matrix. This resulted in the inclusion of seven vehicles (numbers 9, 15, 25, 27, 28, 29, and 31). Table 3.1-18 presents the results in terms of the percentage change in emissions between the non-oxygenated base fuel, the 5.5 vol% and 11 vol% MTBE blends and the 6 vol% ethanol blend.

Table 3.1-18. Fuel Effects from the Mexico Fuels Study

	NMHC	CO	NOx
	% Change	% Change	% Change
5.5 vol% MTBE vs. no oxygenate	11.1% ^a	-5.5%	-3.1%
11 vol% MTBE vs. no oxygenate	-11.1%	-9.7%	10.0%
6 vol% ethanol vs. no oxygenate	3.9% ^a	-6.3%	27.2%
6 vol% ethanol vs. 6 vol% MTBE	-5.8%	-0.9%	32.8%
6 vol% ethanol vs. 11 vol% MTBE	19.5%	4.0%	14.2%

^a Bold type indicates the difference was significant at a 90% confidence level.

As can be seen, the addition of 5.5 vol% MTBE to a low-RVP type fuel at constant RVP was found to increase the emissions of NMHC and CO, and decrease NOx emissions. The addition of 11 vol% MTBE to a low-RVP type fuel at constant RVP was found to increase the emissions of NOx and CO, and decrease NMHC emissions. Only the NMHC reduction was found to be statistically significant at a 90% confidence level. The addition of 6 vol% ethanol to a low-RVP type fuel at constant RVP was found to reduce the CO emissions, and increase NMHC and NOx emissions. Only the NOx emission increase was statistically significant at a 90% confidence level.

The substitution of 6 vol% ethanol for 11 vol% MTBE at constant RVP and oxygen content was found to decrease NMHC emissions and increase NOx emissions. CO emissions were essentially unchanged. Only the NOx emission increase was statistically significant at a 90% confidence level. The substitution of 10 vol% ethanol for 11 vol% MTBE was found to increase emissions of all three pollutants. Only the NMHC emission increase was statistically significant at a 90% confidence level.

Based solely on this single study of six vehicles and three fuels, it appears that either MTBE or ethanol blends with roughly 2 wt% oxygen increase NOx emissions, while the effect on NMHC and CO emissions are inconsistent. Substituting ethanol for MTBE at the same oxygen content appears to increase NMHC, CO and NOx emissions.

3.1.1.1.8. Overview of LEV and Later Vehicle Studies

The differences in the details of the various studies prevent a simple quantitative comparison of their results. However, we have performed a qualitative comparison by simply determining whether the study found an increase or a decrease in emissions of 2% or more and whether the effect was statistically significant at 90% confidence or not. The results of this determination are shown in Table 3.1-19 below for a number of fuel pairs.

Table 3.1-19. Summary of Oxygenate Emission Effects: LEV and Later Vehicles

	THC/NMHC		CO		NOx	
	Lower	Higher	Lower	Higher	Lower	Higher
10/11 vol% MTBE	AAM-AIAM Mexico ExxonMobil*		AAM-AIAM Mexico ExxonMobil		AAM- AIAM Mexico	
E6/E7	Mexico CRC E67		Mexico ExxonMobil CRC E67			Mexico ExxonMobil CRC E67
E10/E11	AAM-AIAM	CRC E67 ExxonMobil	AAM-AIAM ExxonMobil CRC E67		AAM- AIAM	ExxonMobil CRC E67
E10/11 vs. MTBE	Toyota AAM-AIAM	ExxonMobil	ExxonMobil AAM-AIAM		Toyota	AAM-AIAM ExxonMobil

Starting with MTBE, none of the three studies which tested both non-oxygenated and MTBE fuels found MTBE to increase the emissions of any of the pollutants. One to two studies found statistically significant reductions in THC/NMHC, CO and NOx emissions with the use of MTBE.

Three studies tested a non-oxygenated fuel and a 6-7 vol% ethanol blend. Ethanol blending at this level likely reduces CO emissions and increases NOx emissions. Two of the three studies showed an increase in NMHC emissions, but neither result was statistically significant at a 90% confidence level. Thus, the effect of E6 on NMHC emissions is particularly unclear.

Three studies tested a non-oxygenated fuel and a 10-11 vol% ethanol blend. Ethanol blending at this level likely reduces CO emissions, as all three studies showed a statistically significant reduction. Two of three studies found an increase in NOx emissions, while one found a decrease, all statistically significant at a 90% confidence level. Again, the effect of ethanol blending on exhaust NMHC emissions is not clear. Two of three studies found an increase in THC/NMHC emissions, while one found an increase. The results of one of the two studies finding an increase and those of the study finding a decrease were statistically significant at a 90% confidence level.

Finally, three studies tested both MTBE and 10-11 vol% ethanol blends. Ethanol blending at this level appears to reduce CO emissions relative to MTBE. The effect on the other two pollutants is less clear. Two of three studies found a decrease in THC/NMHC emissions, though the one study finding an increase was the only one where the result was statistically significant at a 90% confidence level. Two of three studies found an increase in NOx emissions and both of these were statistically significant at a 90% confidence level.

3.1.1.1.9 Selection of Models for Exhaust NMHC, CO and NOx Emissions

3.1.1.1.9.1 Exhaust NMHC and NOx Emissions

For Tier 0 vehicles, the EPA Predictive Models are based on more data and the most advanced statistical tools. Therefore, we will use these models here to project the effect of increased ethanol use and decreased MTBE use on exhaust VOC and NOx emissions.

For Tier 1 and later vehicles, the choice is much less clear. In our analysis of California's request for an RFG oxygen waiver, we assumed that there was too little data upon which to project the effect of fuel quality on the emissions of these vehicles. Substantially more data exist on the effect of oxygenates on LEV and later vehicle exhaust emissions than did in 2001. However, as indicated by the summary of these results shown in Table 3.1-19, there does not appear to be sufficiently consistency to confidently predict the impact of oxygenate type and content on exhaust NMHC and NOx emissions.

For the NPRM, we developed two separate sets of predictions: a primary analysis assuming no effect of oxygen on NMHC and NOx emissions from Tier 1 and later vehicles, and a sensitivity analysis which applied the Predictive Model effects to Tier 1 and later vehicles. The qualitative summary shown in Table 3.1-19 supports a continuation of this approach. The effect of ethanol blending on NMHC emissions is unclear in Table 3.1-19. This is reasonable bracketed by the primary and analysis, which assumes no effect and the sensitivity analysis which assumes a reduction. Table 3.1-19 also indicates that five out of six studies found that 6-10 vol% ethanol blends increased NOx emissions from LEV and later vehicles. This is also reasonable bracketed by the primary and analysis, which assumes no effect and the sensitivity analysis which assumes an increase. Given the uncertainty in the fuel-emissions effects for Tier 1 and later vehicles, there is also some value in maintaining consistency with our analysis conducted in response to California's request for an RFG oxygen waiver. The primary analysis does this.

The varied results across these studies indicate the need for additional test data. It may also be possible in the future to combine the emission data from all such studies (as was done for the Complex and Predictive Models) in order to develop a more robust estimate of the impacts of oxygenate blending on emission from late model year vehicles.

3.1.1.1.9.1 Exhaust CO Emissions

For Tier 0 vehicles, MOBILE6.2 is the standard modeling tool for estimating the effect of fuel quality on CO emissions. Therefore, we will use that model here to project the effect of increased ethanol use and decreased MTBE use on CO emissions.

Regarding later vehicles, the five studies of LEV and later vehicles all found that increasing oxygen content in terms of MTBE or ethanol reduces CO emissions. This is consistent with both the primary and sensitivity analyses, as both approaches include a reduction in CO emissions.

The five studies of LEV and later vehicles all tested normally emitting vehicles. MOBILE6.2 estimates that an E10 blend will reduce CO emissions from Tier 0 vehicles by 11%. The quantitative results of the five studies generally support this degree of reduction (Toyota, ExxonMobil, Mexican Petroleum Institute) or perhaps a larger degree of reduction (CRC E67, AAM-AIAM). Due to the absence of an EPA Predictive Model for CO emissions, for the NPRM, we did not develop a sensitivity case for CO emissions. However, given the possibility that the CO emission reduction is larger than that currently estimated by MOBILE6.2 for these vehicles, it appears reasonable to include a sensitivity analysis for CO emissions, as well as NMHC and NOx. An approach analogous to that taken for NMHC and NOx emissions appears reasonable. That is, for the primary analysis, we will continue to use MOBILE6.2 to project the effect of fuel properties on CO emissions. This means essentially a 6.7% reduction in CO emissions from Tier 1 and later vehicles for an E10 blend. For the sensitivity analysis, we will apply the MOBILE6.2 CO emission reduction of 13.8% for Tier 0 vehicles to Tier 1 and later vehicles.

As discussed above, the five studies of LEV and later vehicles are not sufficient for use in quantitatively projecting the impact of fuel quality on emissions from these vehicles. Additional data must still be collected over a broader set of vehicles, fuel changes, and conditions.

3.1.1.2 Exhaust Toxic Emissions

Two EPA models project the impact of fuel quality on exhaust toxic emissions: the Complex Model and MOBILE6.2. The Complex Model projects the impact of fuel quality on toxic emissions directly. That is, any impact of fuel quality on total exhaust VOC emissions (which includes the air toxics) is implicitly included in the model's predictions. MOBILE6.2 separates the process into two steps. Total exhaust VOC emissions are projected first, in part based on fuel quality. Then, the fraction of VOC represented by each air toxic is estimated, in part based on fuel quality.

The effect of fuel quality on exhaust VOC emissions in MOBILE6.2 was already discussed above. The effect of fuel quality on the fraction of exhaust VOC emissions represented by each air toxic in MOBILE6.2 is based on the projections contained in the Complex Model. These Complex Model's effects of fuel quality on exhaust toxic emissions were used with the effect of fuel quality on exhaust VOC emissions backed out. Thus, with respect to the effect of fuel quality on the fraction of exhaust VOC emissions represented by each air toxic, the Complex Model is the basis of both the Complex Model and MOBILE6.2 predictions.

With respect to exhaust VOC emissions, we already decided above that the EPA Predictive Models represent the best estimate for Tier 0 vehicles. For Tier 1 and later vehicles, we assume in our primary analysis that these vehicles' exhaust VOC emissions are unaffected by fuel quality. As a sensitivity analysis, we decided to extend the impacts indicated by the EPA Predictive Models to all vehicles.

We follow the two-step process taken in MOBILE6.2 here in modeling the impact of fuel quality on exhaust toxic emissions. We will use the EPA Predictive Models to project the impact

of fuel quality on exhaust VOC emissions, as discussed above. We will use the effects of fuel quality on the toxic fractions of exhaust VOC emissions contained in MOBILE6.2.

3.1.1.3 Non-Exhaust Emissions

Both the Complex Model and MOBILE6.2 evaluate the effect of gasoline quality on non-exhaust VOC emissions. However, the effects in the Complex Model were taken from an older version of MOBILE, as was mentioned above. Therefore, MOBILE6.2 represents the better of the two estimates of the effect of gasoline quality on non-exhaust VOC emissions. The EPA Predictive Models do not address non-exhaust emissions, so they are not applicable here.

In EPA's second analysis of California's request for a waiver of the RFG oxygen requirement, we enhanced the estimate of non-exhaust emissions in MOBILE6.2 by adding additional permeation emissions related to the use of ethanol.^{FFF} Recent testing at that time indicated that ethanol increases the rate of permeation of hydrocarbons through plastic fuel tanks and elastomers used in fuel line connections, as well as permeating ethanol itself. Subsequent testing has confirmed this effect. Therefore, we have added the effect of ethanol on permeation emissions to MOBILE6.2's estimate of non-exhaust VOC emissions in assessing the impact of gasoline quality on emissions here.

Air Improvement Resource, Inc. for the American Petroleum Institute, recently summarized the available test data on the effect of ethanol on permeation emissions and developed a methodology for estimating in-use permeation emissions in several U.S. cities.^{GGG} This study provides a useful starting point for incorporating these emissions into this RFS analysis.

Before examining this study, it is useful to point out that the non-exhaust emission estimates in MOBILE6.2 include permeation emissions for non-oxygenated gasoline. Typical extended diurnal emission tests (e.g., those lasting 2-3 days) automatically include any emissions permeating through plastic and elastomeric fuel system components. However, since the emission tests used as the basis of the MOBILE6.2 estimates of non-exhaust emissions primarily were performed with non-oxygenated gasoline. Those tests that did include ethanol blends only exposed the vehicle to this fuel for a few days. The CRC study of ethanol-related permeation indicates that it takes at least a week or two for the effect of ethanol to fully develop. Therefore, it is very unlikely that the tests performed by EPA and others to assess the impact of ethanol and other fuel components on non-exhaust emissions included the effect of ethanol on permeation emissions. In those cases where a vehicle may have been exposed to an ethanol blend for some time prior to testing, the increased permeation emissions likely were still present when the vehicle was tested on a non-oxygenated gasoline, still masking the effect. Therefore, our task here is to develop an estimate of the incremental impact of ethanol use on permeation emissions, and not an estimate of total permeation emissions with and without ethanol.

The primary source of ethanol permeation emission data is the CRC E-65 study.^{HHH} This study tested 10 vehicles, 6 cars and 4 light trucks, ranging in model year from 1989 to 2001. Permeation emissions were measured using two fuels, a non-oxygenated gasoline and a 6 vol% ethanol blend like that commonly sold in California. AIR placed these vehicles into three

groups, based on a combination of model year and applicable evaporative emission standards. The vehicles in the test program were certified to two distinct evaporative emission requirements. The older vehicles were certified to EPA's or California's 2 gram hot soak plus diurnal emission standard based on an accelerated one-hour diurnal test. The three newest vehicles were certified to the enhanced evaporative emission requirements first implemented in the 1996 model year, which included an extended two or three day diurnal test. In addition, the data indicated that the three pre-1990 model year vehicles had much larger incremental ethanol permeation emissions than the later pre-enhanced evaporative emission vehicles. Therefore, AIR split the pre-enhanced evaporative emission category into two groups, pre-1990 model year vehicles and 1990 and later model year vehicles. We believe that this is appropriate and apply this split here, as well.

Since the earliest calendar year during which emissions are assessed in the RFS analysis is 2012 and MOBILE6.2 only considers vehicles which are 24 years old or newer, at most only two model years of pre-1990 vehicles are present in our analysis. Due to accumulated scrappage, these vehicles comprise a very small percentage of the on-road fleet in 2012 and disappear from our analysis by 2015. Therefore, we decided to ignore the pre-1990 model year data here.

AIR estimated the average incremental ethanol permeation emission rates for the 1990 and later model year pre-enhanced evaporative emission vehicles to be 0.86 gram per day (g/day), while that enhanced evaporative emission vehicles was 0.80 g/day. Given the small number of vehicles tested and the variability in the rates measured for individual vehicles, for the purposes of this analysis, we consider these two levels to be generally equivalent. Therefore, we use an average incremental ethanol permeation emission rate of 0.8 g/day for all vehicles. A follow-on study performed by CRC indicates that the permeation emissions associated with a 10 vol% ethanol blend could not be distinguished statistically from those of the 6 vol% blend.^{III} Therefore, we use the 0.8 g/day incremental permeation emission rate for both 6 vol% and 10 vol% ethanol blends here.

Beginning with the 2004 model year, EPA and California implemented further enhancements to their evaporative emission standards. The EPA "Tier 2" requirements include accumulating mileage on durability data vehicles with an ethanol blend. However, actual emission testing is still performed using non-oxygenated gasoline. We believed that this combination of requirements would incorporate any effects of ethanol on emissions, including potential permeation effects. Because of these and other aspects of the 2004 and later standards, AIR estimated that the permeation emissions due to ethanol would be reduced to 0.43 g/day for these vehicles.

We believe that it is likely that permeation emissions for non-oxygenated blends will be lower for these vehicles, due to the fact that the diurnal emission standard was reduced from 2 g/day to 0.95 g/day and lower in some cases. However, as mentioned above, the effect of ethanol on permeation emissions takes about 2 weeks to fully develop and to fully disappear. Therefore, it is possible to accumulate mileage on a certification vehicle using an ethanol blend, change the fuel to the emission test fuel, wait two weeks and then test the vehicle. In this case, the effect of ethanol on permeation will have disappeared during the certification testing. Thus,

until EPA requires certification emission testing with ethanol blends, we have no assurance that manufacturers will modify their vehicle designs to address the effect of ethanol on permeation. Thus, for the purposes of this analysis, we maintain the estimate of 0.8 g/day for Tier 2, and earlier vehicles.

Permeation emissions vary significantly with ambient temperature, with emissions increasing with increases in temperature. The 0.8 g/day emission estimate applies at an average temperature of 95 F. The literature indicates that permeation varies exponentially with temperature. The CRC testing indicates that permeation emissions double with every increase in temperature of 18 F. Vice versa, permeation emissions drop 50% with every decrease in temperature of 18 F. We apply this relationship in Chapter 4 in developing incremental ethanol permeation emissions for each hour of the day in each county in the U.S.

We plan to update our projections of the effect of gasoline quality on non-exhaust VOC emissions from Tier 1 and later model year vehicles based on additional testing which is expected to begin in 2007. Additional testing of permeation emissions is already underway with the CRC E-77 test program. These updated projections will be used in the comprehensive assessment of the impact of the fuel-related provisions of the Energy Act which due in 2009.

Non-exhaust emissions are a function of ambient temperature and temperatures vary across the nation. Therefore, it is not as simple to determine the effect of RVP and other fuel qualities on non-exhaust emissions on a per vehicle basis as it is for exhaust emissions. Therefore, we performed a regression of the non-exhaust VOC and benzene emissions developed in Chapter 4 as a function of fuel properties in order to estimate these effects on a per vehicle basis. Specifically, we regressed the ratio of non-exhaust VOC and benzene emissions in each county in July between two fuel scenarios (the RFS case and the base case) against the change in RVP, ethanol content and MTBE content. The results are summarized in Table 3.1-20.

Table 3.1-20. Fuel-Non-Exhaust Emission Effects in MOBILE6.2: 2012

	RVP (%/psi)	Ethanol (%/Vol %)	MTBE (%/Vol%)	Adjusted r-Square
VOC	11.8%	0.3%	0.0%	0.53
Benzene	2.0%	1.0%	-0.5%	0.50

Non-exhaust emissions of benzene are estimated in MOBILE6.2. MOBILE6.2 adjusts these emissions for RVP, benzene fuel content, MTBE fuel content, temperature and the total non-exhaust VOC emissions produced by the vehicle fleet in question. We will use MOBILE6.2 here to project the impact of decreased MTBE use and increased ethanol use on non-exhaust benzene emissions.

Benzene is also emitted via permeation. Just as MOBILE6.2 does not include the effect of ethanol on VOC emissions via permeation, it does not include the effect of ethanol on benzene emissions via permeation. Thus, we will add this effect outside of the MOBILE6.2 model in the same way as was just described for VOC emissions via permeation.

Both the CRC E-65 study and the E-65 Phase 3 follow-on study referenced above measured the benzene content of permeation emissions during some of the tests performed. Table 3.1-21 presents the available data by fuel type for both studies.

Table 3.1-21. Benzene Permeation Emissions: CRC E-65 Studies

E-65 Phase	No. of Vehicles	E0	E6 (Average Aromatics)	E6 (High Aromatics)	E10	MTBE Blend
Fuel Benzene Content (vol%)						
Phase 1	---	0.73	0.72	---	---	0.53
Phase 3	---	0.41	0.55	0.43	0.51	---
Benzene Emissions (% of total permeation emissions)						
Phase 1	10	2.5-2.6%	2.2%	---	---	2.2%
Phase 3	4-5	1.4%	1.4%	1.4%	1.7%	---
Benzene Emissions Adjusted to 0.88 vol% Fuel Benzene (% of total permeation emissions)						
Phase 1	10	3.0-3.1%	2.7%	---	---	3.6%
Phase 3	4-5	3.0%	2.2%	2.8%	2.9%	---

As can be seen from Table 3.1-21, the benzene content of permeation emissions is slightly higher for the Phase 1 study than Phase 3. This is consistent with the higher benzene contents of the fuels tested in Phase 1. The Phase 1 fuels have particularly low benzene contents compared to levels typical across the U.S. Therefore, assuming a linear relationship between benzene fuel content and benzene permeation emissions, we adjusted the benzene permeation emissions to those for a fuel benzene content of 0.87 vol%, which is the average of the benzene fuel content of summertime gasoline produced nationwide in the base, RFS and EIA cases from the recent refinery modeling described in Chapter 2. We focused on summer benzene content since permeation emissions are a strong function of temperature. These figures are shown in the bottom third of Table 3.1-21. As can be seen, the benzene content of permeation emissions is much more consistent across the two Phases of E-65 after being adjusted to consistent fuel benzene content than before this adjustment.

There appears to be no definite trend in the benzene content of permeation emissions with increasing ethanol fuel content. Both CRC studies found that the addition of ethanol does not simply increase permeation emissions via increased emissions of ethanol, but also through increased emissions of other fuel components. Thus, we will assume for this analysis that the benzene fraction of permeation emissions is independent of ethanol fuel content (i.e., benzene emissions increase at the same rate as total permeation emissions). This is also consistent with our conclusion in Chapter 2 that ethanol blending does not affect benzene fuel content. Given this, we determined the average benzene fraction of permeation emissions by averaging the benzene fraction across all the fuels and vehicles tested, excluding the MTBE blend. This average was 3%. This figure will be used here to estimate the benzene portion of the increase in permeation emissions resulting from ethanol blending.

Given this, we determined the average benzene fraction of permeation emissions by averaging the benzene fraction across vehicles. Thus, the average benzene fraction of

permeation emissions is the average of the figures in the rightmost column of Table 3.1-21, or 2%.

3.1.1.4 PM Emissions

The amount of data evaluating the impact of ethanol and MTBE blending on direct emissions of PM from gasoline-fueled vehicles is extremely limited. Three fairly limited studies have evaluated the impact of ethanol blending on PM emissions from gasoline vehicles. These studies are summarized below.

The Colorado Department of Public Health and Environment tested 24 vehicles on two winter grade commercial fuels at 35°F in Denver (i.e., at high altitude).^{JJJ} Both fuels were obtained from a local refinery. One fuel was non-oxygenated and represented fuel sold outside of the Denver area. The other contained 10 vol% ethanol and represented fuel sold in the Denver area, which has an oxygenated fuel mandate. As would be expected, the fuels differed in other qualities besides ethanol content. The ethanol blend had a 2 vol% lower aromatic content, which is somewhat less than expected. However, it also had a 53 F lower T50 level, which is a much greater difference than is typical. The two fuels used during this testing appear to have been used in random order (i.e., sometimes the non-oxygenated fuel was tested first, other times the E10 fuel was tested first).

Half of the 24 vehicles were certified to Tier 0 emission standards, while the other half were certified to Tier 1 standards. Each group of 12 vehicles included 8 cars and 4 light trucks.

The study found that PM emissions for the 24 vehicles over the FTP decreased from about 9 mg/mi to about 6 mg/mi with the ethanol blend, for a reduction of 36%. In addition, the vehicles with the highest base PM emission rates showed by far the largest reductions, both in absolute terms and in terms of percentage. PM emissions from Tier 1 vehicles decreased from roughly 5.5 mg/mi to 4 mg/mi with the ethanol blend, for a reduction of 27%. Essentially all of the emission reduction occurred during Bag 1 of the test (i.e., related to the cold start).

PM emissions were also measured over a warmed up California Unified Cycle (i.e., no cold start). PM emissions for the 24 vehicles over this cycle for the two fuels were not statistically different. The ethanol blend increased PM emissions from the Tier 0 vehicles slightly and decreased those from the Tier 1 vehicles slightly.

Finally, PM emissions were also measured over an EPA REPO5 Cycle, again with no cold start. PM emissions over this cycle were 4-5 times those over the California Unified Cycle, indicating the impact of high speed, aggressive driving on PM emissions. However, despite this general increase in PM emissions, for the 24 vehicles PM emissions over the REPO5 cycle were again very similar for the two fuels. This time, however, the ethanol blend decreased PM emissions from the Tier 0 vehicles slightly and increased those from the Tier 1 vehicles slightly.

Overall, this testing indicates that the effect of ethanol (together with lower aromatics and T50 levels) may reduce PM emissions due to cold starting at 35 F under high altitude conditions.

However, PM emissions during warmed up driving are very low and an effect of fuel quality was indiscernible.

The State of Alaska, in conjunction with General Motors Corp. and EPA, measured PM emissions from ten vehicles ranging in model year from 1977 to 1994 using two fuels.^{KKK} The non-oxygenated fuel was a commercial wintertime fuel from the Fairbanks areas. The ethanol blend in this study was created from the non-oxygenated fuel via splash blending. Testing was performed in Alaska using a portable dynamometer. Three of the vehicles were also tested at EPA's laboratory in Research Triangle Park, N.C, ranging in model year from 1987 to 1994. The testing in Alaska was performed at -20°F, 0°F, and 20°F. The EPA testing was performed at these same temperatures plus 75 F. Both sets of testing began with the non-oxygenated fuel, followed by testing with the E10 fuel. This could introduce a bias into the results, but the degree of this is unknown.

The cold conditions led to difficulties in measuring PM emissions in Alaska. Therefore, few acceptable measurements of PM were made and the results were not presented in the paper. The fact that the EPA testing was conducted in a laboratory made vehicle conditioning and operation and particulate collection more feasible. The PM emissions from the three vehicles tested by EPA on the two fuels are presented in the paper.

Only one measurement of PM emissions was made for each combination of vehicle, fuel and temperature. Thus, no direct measurement of test to test variability is available. We calculated the percentage difference in PM emissions between the E10 and E0 fuel for each of the eleven combinations tested. PM emissions with the ethanol blend ranged from 81% lower to 84% higher than those with the E0 fuel. Thus, there appears to be considerable variability in the test results. Taken together, the average of the percentage changes for each condition showed the ethanol blend reducing PM emissions by 21%. However, this decrease was not statistically significant at the 90% confidence level. The ethanol blend more consistently decreased PM emissions at -20 F and 0F, but not at 20 F or 75 F. The paper states that PM emissions at the higher two temperatures were very low and the differences tended to be within measurement accuracy. It is important to note, however, that the lower end of this range is 20 F. Only a small percentage of driving in the U.S. occurs below this temperature.

The third and final study was performed by EPA's laboratory in Research Triangle Park, N.C.^{LLL} This study was conducted in three phases; the last two of which are relevant here. In Phase II, PM emissions from two 1993-1995 model year vehicles were tested at -20 F, 0 F, and 20 F. In Phase III, PM emissions from an additional five 1987-2001 model year vehicles were tested at -20 F, 0 F, 20 F and 40 F. Both phases utilized two fuels, one a wintertime non-oxygenated fuel and the other a 10 vol% ethanol fuel created from the non-oxygenated fuel via splash blending. Both phases measured PM emissions over the FTP and over a series of four back-to-back IM240 tests.⁵⁰ It is not clear whether the fuels were always tested in the same order or tested randomly. Some testing was performed with various malfunctions induced on the

⁵⁰ The IM240 test is a warmed up test consisting of a portion of the FTP driving cycle. It was designed as a short transient test cycle for use in vehicle inspection and maintenance programs.

vehicles, like disconnecting the oxygen sensor. We focus on the emissions from the properly operating vehicles here.

Of the 26 combinations of vehicles and temperatures tested, valid PM measurements over the FTP were successfully obtained for both fuels in 21 of them. The average percent change in PM emissions due to ethanol blending was +1%, in other words a very slightly increase. In contrast to the results of the two test programs discussed previously, the ethanol blend did not show a benefit at -20 F, and showed only a very slight 1% reduction in PM emissions at 0 F. The data show some tendency for the ethanol blend to produce a greater PM emission reduction for the highest emitting vehicles. However, this trend is not as clear as in the Colorado study. Thus, this study indicates no clear effect of ethanol on PM emissions.

The IM240 testing showed much lower PM emission levels due to the warmed up nature of the test. There was also no clear trend in the effect of ethanol on PM emissions in this testing.

The available data indicate that ethanol blending might reduce exhaust PM emissions under very cold weather conditions (i.e., 0 F or less), particularly at high altitude. There is no indication of PM emission reductions at higher temperatures and under warmed up conditions. The data are certainly too limited to support a quantitative estimate of the effect of ethanol on PM emissions.

Fine particles can also be formed through a series of chemical reactions in the atmosphere from gasses such as sulfate (SO_4^{2-}), nitrate (NO_3^-), ammonia (NH_3), and volatile organic compounds (VOC) emitted from motor vehicles. This aerosol formed secondarily in the atmosphere through these gas to particle conversions will be discussed in greater detail in Chapter 5 of this document. Emerging science is indicating that gaseous aromatic compounds are likely among the most important VOCs which are precursors of carbonaceous PM which is formed in the atmosphere. Therefore, we discuss the effect of fuel quality on aromatic hydrocarbon emissions in the next section.

3.1.1.5 Aromatic Emissions

The Auto/Oil Air Quality Improvement Research Program tested over 100 vehicles from model years 1983 - 1989 on a fuel matrix of over 80 fuel blends to determine the exhaust emission effects of varying fuel parameters - including ethanol and aromatics.^{MMM} Phase 1 of this study tested two fleets of vehicles: twenty (20) 1989 model year vehicles, and fourteen (14) 1983-1985 model year vehicles. A matrix of 16 fuels (Matrix A) was developed in the first portion of the study with half the fuels containing 20% aromatics by volume and half with 45% aromatics by volume. This data was used to investigate the impact of changing aromatic levels in the fuel on the aromatics emitted in the exhaust as a function of total hydrocarbon emissions. Linear regression of the test data indicates that there is a linear relationship between the level of aromatics by volume in the fuel and the mass of aromatics emitted in the exhaust. Based on the results of this regression, aromatics have a tendency to be emitted less than proportionally to their percent volume in the fuel, as shown in the following equation:

$$Aromatics_{Exhaust} (wt\%) = 0.64 \times Aromatics_{Fuel} (vol\%)$$

The coefficient in the above equation was statistically significant at the 90% confidence level (0.64 ± 0.02). However, when we considered the presence of an intercept, it was not statistically significant (-0.35 ± 2.26). Therefore, we forced the regression line through zero and repeated the regression.

The Auto/Oil program also produced data which allows the effect of ethanol on aromatic hydrocarbon emissions to be assessed. As discussed in Section 2.2, ethanol blending tends to reduce the aromatic content of gasoline. Of interest here is whether ethanol has any other effect on aromatic hydrocarbon emissions beyond that associated with reducing the aromatic content of gasoline.

The Auto/Oil data contained a subset of fuels designed specifically for this analysis. A total of 4 ethanol blends were produced by splash blending ethanol into four non-oxygenated fuels. Two of the non-oxygenated fuels came from the original group of sixteen tested during Phase 1 of the research study. Base fuel A (industry average fuel) was a 9 RVP fuel with 32% aromatics. Base fuel F was also a 9 RVP gasoline with 20% aromatics. Two new non-oxygenated fuels were created from base fuels A and F. In both cases, and butane was removed to lower the RVP level by 1 psi resulting in fuels V and S, respectively. To each of these 4 non-oxygenated fuels, 10% ethanol was splash blended resulting in the final 8 fuel test matrix. A summary of the differences between the expected and actual aromatic content in the fuel and in the exhaust as a function of THC is shown in Table 3.1-22.^{NNN}

**Table 3.1-22.
Expected vs. Predicted Non-Oxy and E10 Fuel Properties and
Exhaust Aromatics Reductions for Auto/Oil AQIRP “Fuel Matrix B”**

Non-Oxy Fuel	Fuel Aromatics	E10 Fuel	Fuel Aromatics Expected^a	Measured Fuel Aromatics	% Reduction in Exhaust Aromatics Expected	% Reduction in Exhaust Aromatics Actual
A	32	X	28.8	27.2	2.05	2.39
V	33.5	W	30.15	29.0	2.14	1.54
F	20	U	18	19.1	1.28	0.93
S	21.2	T	19.08	18.1	1.36	0.63

^aBased on dilution as a result of splash blending 10% ethanol

The aromatic contents of the ethanol blends, as listed in Table 3.1-22, do not reflect the 10% reduction from the aromatic contents of their non-oxygenated base fuels which would be expected from splash blending with 10 vol% ethanol. The discrepancies between the measured and estimated fuel aromatic contents are small, on the order of 1-2 vol% aromatics. However, when the total difference is on the order of 3 vol% ethanol, these discrepancies are significant. The discrepancies are likely the result of measurement uncertainty of both base and ethanol fuels.

Using the relationship between fuel aromatic content and aromatic hydrocarbon emissions developed above, we can predict the reduction in exhaust aromatic emissions

associated with the differences in the aromatic contents of the non-oxygenated fuels and their ethanol containing counterparts. We believe that it is most accurate to use the expected aromatic contents for the ethanol blends rather than the measured levels, since it is likely that the volume of ethanol added was very close to 10 vol%.

The expected reduction in the percentage of VOC emissions represented by aromatic hydrocarbons based on the expected reduction in fuel aromatic content is shown in the second to the last column in Table 3.1-22. The measured reduction in the percentage of VOC emissions represented by aromatic hydrocarbons is shown in the last column. In three out of four cases (all but fuels A and X), the actual reduction in aromatic emissions is less than the predicted reduction based on dilution. Had we used the measured aromatic contents for the ethanol blends, the outcome would have been the same: In three out of four cases (in this case all but fuels F and U), the actual reduction in aromatic emissions is less than the predicted reduction based on dilution.

Qualitatively, this indicates that there does not appear to be any additional benefit in reducing aromatic hydrocarbon emissions associated with the use of ethanol beyond that expected from the reduction in the aromatic content of gasoline portion associated with ethanol blending.

Based on our analysis in Section 2.2, increased ethanol blending will significantly reduce gasoline aromatic content. This could cause a corresponding reduction in the aromatic fraction of exhaust VOC emissions relative to non-oxygenated conventional gasoline. In addition, ethanol also reduces total exhaust VOC emissions from older vehicles and may do so from newer vehicles, based on the CRC E-67 study. This would further reduce emissions of aromatic hydrocarbons. As will be discussed further in Chapter 5, this reduction in aromatic hydrocarbon emissions could reduce ambient levels of secondary organic PM.

3.1.1.6 Emission Effects Associated with Specific Fuel Blends

3.1.1.6.1 Conventional Gasoline Analysis

In Section 2.2 of Chapter 2, we estimated the effect of blending ethanol and MTBE on the quality of conventional gasoline (see Tables 2.2-3 and 2.2-4). Here, we present the effect of these changes in fuel quality on emissions from motor vehicles in percentage terms, relative to those of a typical non-oxygenated U.S. gasoline blend. Because of the Tier 2 sulfur standards, sulfur is held constant at 30 ppm. Also, due to the MSAT standards, we assume that benzene levels are not affected, as well. Table 3.1-23 presents the gasoline qualities of a typical 9 RVP CG, as well as MTBE and ethanol blends which reflect the effect of adding these two oxygenates to gasoline.

Table 3.1-23. CG Fuel Quality With and Without Oxygenates^a

Fuel Parameter	Typical 9 RVP CG	MTBE CG Blend	Ethanol CG Blend
RVP (psi)	8.7	8.7	9.7
T50	218	207	205
T90	332	321	329
Aromatics (vol%)	32	25.5	27.4
Olefins (vol%)	7.7	7.7	7.5
Oxygen (wt%)	0	2	3.5
Sulfur (ppm)	30	30	30
Benzene (vol%)	1.0	1.0	1.0

^aAssumes summer (July) conditions

Table 3.1-24 presents the differences in emissions of the MTBE and ethanol blends relative to that of non-oxygenated conventional gasoline.

Table 3.1-24. Effect of Oxygenates on Conventional Gasoline Emissions^a

Pollutant	Source	11 Vol% MTBE	10 Vol% Ethanol	9.7 RVP CG
Exhaust VOC	EPA Predictive Models	-9.2%	-7.4%	+1.1%
NOx		2.6%	7.7%	+1.1%
CO ^b	MOBILE6.2	-6% / -11%	-11% / -19%	+12.7%
Exhaust Benzene	EPA Predictive and Complex Models	-22.8%	-24.9%	-2.6%
Formaldehyde		+21.3%	+6.7%	-3.7%
Acetaldehyde		+0.8%	+156.8%	-2.0%
1,3-Butadiene		-3.7%	-13.2%	-2.6%
Non-Exhaust VOC	MOBILE6.2	Zero	+30%	+30%
Non-Exhaust Benzene	MOBILE6.2 & Complex Models	-9.5%	+15.8%	+15.8%

^aAssumes summer (July) conditions

^bThe first figure shown applies to normal emitters; the second applies to high emitters.

The two oxygenated blends both reduce exhaust VOC and CO emissions, but increase NOx emissions. The MTBE blend does not increase non-exhaust VOC emissions due to the fact that non-oxygenated and MTBE blends have to meet the RVP standard. Ethanol blending increases non-exhaust VOC emissions in two ways. First, ethanol blends are allowed 1.0 psi higher RVP levels in most areas with CG. Second, ethanol increases permeation emissions. The most notable effect on toxic emissions in percentage terms is the increase in acetaldehyde with the use of ethanol. Acetaldehyde emissions more than double. However, as will be seen below, base acetaldehyde emissions are low relative to the other toxics. Thus, the absolute increase in emissions is relatively low.

3.1.1.6.2 Reformulated Gasoline (RFG) Analysis

The previous section discussed the relative emission changes to expect when adding ethanol to the conventional non-oxygenated gasoline pool. A second scenario to consider is the case where RFG areas change from MTBE, a commonly used oxygenate in RFG areas, to either ethanol RFG or a non-oxygenated RFG.

Table 3.1-25 presents the gasoline qualities of three types of RFG: non-oxygenated, a typical MTBE RFG as has been marketed in the Gulf Coast and a typical ethanol RFG which has been marketed in the Midwest. The fuel specifications shown are based on specific RFGs predicted by the refinery modeling discussed in Chapter 2 for the cases and PADDs shown. These specific fuels were selected as they represented PADD-wide RFGs which contained primarily one oxygenate at the desired volumetric concentration.

Table 3.1-25. Summer RFG Fuel Quality With and Without Oxygenates^a

Fuel Parameter	Non-Oxygenated RFG	MTBE RFG	Ethanol RFG
Case	PADD 3 Reference	PADD 1 Reference	PADD 2 RFS
OXYGEN (wt%)	0.0	2.1	3.7
SULFUR (ppm)	30.0	30.0	30.0
RVP (psi)	7.0	7.0	7.0
E200 (%)	52.0	59.9	57.6
E300 (%)	87.5	88.9	81.9
T50 (F)	184	190	185
T90 (F)	335	342	335
AROMATICS (vol%)	20.1	21.0	20.0
OLEFINS (vol%)	14.6	4.3	13.6
BENZENE (vol%)	0.7	0.7	0.7

^aAssumes summer (July) conditions

Table 3.1-26 presents the emission impacts of these three types of RFG relative to the 9 RVP CG described in Table 3.1-23.

Table 3.1-26.
Effect of RFG on Per Mile Emissions from Tier 0 Vehicles
Relative to a Typical Conventional Gasoline^a

Pollutant	Source	Non-Oxy RFG	11 Volume Percent MTBE	10 Volume Percent Ethanol
Exhaust Emissions				
VOC	EPA Predictive Models	-13.4%	-15.3%	-9.7%
NOx		-2.4%	-1.7%	7.3%
CO	MOBILE6.2	-22%	-31%	-36%
Exhaust Benzene	EPA Predictive and Complex Models	-21.2%	-29.7%	-38.9%
Formaldehyde		-5.9%	19.4%	2.3%
Acetaldehyde		-0.2%	-9.5%	173.7%
1,3-Butadiene		20.9%	-29.2%	6.1%
Non-Exhaust Emissions				
VOC	MOBILE6.2 & CRC E-65	-30%	-30%	-18%
Benzene	MOBILE6.2 & Complex Models	-40%	-43%	-32%

^aAssumes summer (July) conditions

As can be seen, the oxygenated RFG blends are predicted to produce a greater reduction in CO emissions, but increase NOx emissions. Exhaust VOC emission effects are mixed. Non-exhaust VOC emissions with the exception of permeation are roughly the same due to the fact that the RVP level of the three blends is the same. However, the increased permeation emissions associated with ethanol reduces the overall effectiveness of ethanol RFG. The most notable effect on toxic emissions in percentage terms is the increase in acetaldehyde with the use of ethanol. Acetaldehyde emissions more than double. However, as will be seen below, base acetaldehyde emissions are low relative to the other toxics. Thus, the absolute increase in emissions is relatively low. The ethanol RFG also produces a greater reduction in exhaust benzene emissions and somewhat lower reduction in non-exhaust benzene emissions.

The exhaust emission effects shown for VOC and NOx emissions only apply to Tier 0 vehicles in our primary analysis. In the sensitivity analysis, these effects are extended to Tier 1 and later vehicles. The effect of RVP on non-exhaust VOC emissions is temperature dependent. The figures shown above represent the distribution of temperatures occurring across the U.S. under summer conditions (average July fuel specifications).

3.1.2 High-Level Ethanol Blends

The vast majority of ethanol blended into gasoline as a result of the RFS is expected to be used in a 10 vol% ethanol blend (E10) rather than an 85 vol% ethanol blend (E85), as discussed in Chapter 1. At the same time, some ethanol is likely to be used as E85, and its use is growing. Current estimates indicate that roughly 6 million FFVs are on the road today, with US automakers projecting an additional 3 to 5 million FFVs produced annually over the next several years. The analysis to follow relies upon the limited amount of data available on both older and

current technology (Tier 2) FFVs, the later of which will dominate the FFV fleet in future years. Based on this data of Tier 2 vehicles, we believe that with the increased use of E85 (which is inherently a low-sulfur fuel) emissions should be neutral or better than operation on E0 or E10 fuel blends for CO and NOx. NMOG emissions may be higher primarily due to emissions of unburned ethanol at cold starts, while running NMOG emissions are lower with E85 based on certification data. The sections to follow examine these issues in greater detail.

3.1.2.1 Exhaust emissions

3.1.2.1.1 Regulated Gaseous Pollutants

Relatively little data is available for investigating the effects of high level ethanol blends on exhaust emissions. Part of the 1993 Auto/Oil Air Quality Improvement Research Program (AQIRP) investigated the emissions associated with the use of E85 blends. Emissions over the Federal Test Procedure (FTP) were measured from three Tier 0 and Tier 1 certified flexible-fuel vehicles with three test fuels. A source of emission data for Tier 2 FFVs is EPA's Certification and Fuel Economy Information System (CFEIS) database, which contains certification data for five model year 2006 FFVs certified to Tier 2 standards (bins 5-8).⁰⁰⁰ However, certification data, composed of regulated emissions while operating on E85, represents very limited operating conditions. It does not include aggressive driving or cooler ambient temperature starts or operation.

The Auto/Oil Study found that E85 reduced FTP composite NOx emissions by 49% compared to conventional gasoline with 1988 industry average fuel properties. This is likely the result of improved catalyst efficiency due to the low sulfur concentration in E85 (only 5 ppm vs. 339 ppm in the industry average fuel). The 2006 CFEIS data from Tier 2 FFVs, on the other hand, shows only a 3% decrease in NOx emissions with E85 from a cold start test but a significant 45% decrease in hot running NOx emissions. CO emissions are reduced at least 33% on a cold start according to CFEIS, while the Auto/Oil study did not find statistically significant changes in CO emissions. Emissions of Non-Methane Organic Gases (NMOG) increased 10% for the Tier 2 CFEIS vehicles. The Auto/Oil data showed NMOG increased by 26%, but this change was not statistically significant (p-value of 0.28). However, CFEIS data indicated a 50% reduction in CO and HC emissions during hot operation. The measurement used to determine NMOG in both CFEIS and Auto/Oil data include the mass of oxygen in all measured organic species except methane.

While the emissions of NMOG appear to increase with E85 compared to E0 for Tier 2 certified vehicles, the majority (~55%) of E85 NMOG emissions are direct emissions of ethanol, which has a relatively low reactivity compared to other NMOG species. Thus there may still be a slight NMOG benefit based on ozone reactivity despite a potential net increase in total NMOG emissions. An important point worth noting is that the cold start emissions with E85 represent a greater % of bag weighted emissions than with E0. This manifests itself primarily in the form of unburned ethanol emissions during cold start, before the combustion chamber has reached a high enough temperature to promote complete ethanol vaporization. Thus NMOG emissions with E85 at colder temperatures could be much greater (2 to 3 times higher) than with E0 due to prolonged periods at low temperature. Because of this unique start behavior and the lower

emissions observed during hot operation, emissions from E85 may be better quantified if separated between starts and hot driving operation.

3.1.2.1.2 Air Toxics

With increasing use of E85, some air toxics may increase while others decrease relative to E0. Emissions of Benzene and 1,3-Butadiene decrease while acetaldehyde, formaldehyde, and emissions of ethanol increase. The net result is an increase in total air toxics, but this is largely driven by increase ethanol and acetaldehyde emissions. Table 3.1-27, below, shows the percent change in FTP composite g/mile emissions of several air toxics for the three FFVs tested on three fuels as part of the 1993 Auto/Oil study. The fuels tested were AQIRP gasoline with 1988 Industry average qualities (CG), a 1996 California phase 2 reformulated gasoline (RFG blended with MTBE), and an E85 blend with identical gasoline specs as RFG.^{PPP}

**Table 3.1-27.
Percent Difference in Toxic Emissions Between E0 and E85**

	% Difference Between Fuels		
	RFG vs CG	E85 vs CG	E85 vs RFG
Formaldehyde	-2	93	97
Benzene	-55	-87	-72
1,3-Butadiene	-31	-85	-79
Acetaldehyde	-18	2620	3220
Total Toxics	-42	108	255

The increase in acetaldehyde emissions is substantial, on the order of 20 to 30 times that of E0. This is substantially higher than the 15 to 20 fold increase shown with Tier 2 FFVs in the CFEIS data. Emissions of benzene, 1,3-butadiene, ethylbenzene, hexane, styrene, toluene, m-xylene, p-xylene, o-xylene, and naphthalene are all expected to decrease significantly (50-80%) with the use of E85 vs. E0 according to CFEIS, which is consistent with the Auto/Oil results presented in Table 3.1-27. Regardless of vehicle technology, the increased emissions of acetaldehyde could be a potential concern due to its strong odor, as well as its respiratory system irritating and potentially carcinogenic properties.

3.1.2.1.3 Particulate Matter

Even less data exists to draw firm conclusions on direct particulate matter emissions due to increased E85 use. Theoretically, E85 use has the potential to increase direct emissions of PM under modes of rich engine operation. This is especially important at cold start, before the catalyst has reached its operating temperature and when an E85 fueled vehicle runs substantially richer than if it were fueled with E0. In this situation, the low temperatures in the combustion chamber, compounded by the evaporative cooling effect of ethanol, makes fuel vaporization difficult and may increase exhaust emissions of raw fuel and PM at cold start. Sustained periods of high load may also have increased emissions of PM with E85 than with E0 due to richer operation with E85. Results from a 2003 SAE paper showed a negligible increase in

direct PM emissions from E85 vs. E0 fueled vehicles over the European Test Cycle (Directive 70/220/EEC and its amendments).^{QQQ} Tests conducted at 23°C and 16°C showed an increase in PM emissions with decreasing temperature for both E0 and E85, with slightly higher PM emissions at cold temperature with E85. This study only used one E85 blend and one model year 2002 FFV, however, so these results cannot be considered entirely representative of the on-road FFV vehicle fleet. Again, since the projected use of ethanol as E85 is very small compared to its use as E10, the emissions impacts associated with E85 will be also be quite small on an absolute scale.

As discussed above, emerging science is beginning to identify gaseous aromatics as an important precursor to secondary organic aerosol. Exhaust aromatic emissions should be reduced with E85 since the fuel aromatics content of E85 is much lower than that for E0 or E10 blends. This reduction in exhaust aromatics should reduce the formation of secondary organic aerosol. However, as mentioned earlier, no specifications currently exist for the 15% gasoline portion of E85. Thus, the degree to which the aromatic content of E85 will be lower than gasoline is not known with any confidence. Lack of data regarding the speciation of VOC emissions also prevents any quantitative estimate of any benefit in this area.

3.1.2.2 Non-Exhaust Emissions

We currently have very little data regarding non-exhaust emissions from E85 vehicles. Theoretically, evaporative emissions of E85 fueled vehicles have the potential to be lower than with E0 or E10. This is because ethanol blended with a given gasoline at the 85% level is likely to be less volatile than E0 or E10 (with the same gasoline fuel quality). This is not entirely certain, however, since there is no fuel specification for the hydrocarbon composition of the 15% of E85 that is gasoline. Thus, the RVP of the final E85 blend could be closer to that of E0 or E10 fuels than commonly thought to be the case. Moreover, since the volatility of ethanol blends peaks between 6 and 30 vol% ethanol, the fuel in the tank of drivers of flex-fuel vehicles who alternate between E85 and gasoline will experience a wide range of ethanol concentrations in the fuel at any given time, and therefore a wide variation in the corresponding evaporative emissions.

Similarly, we have very little data with which quantitative predictions of the impact of E85 use on non-exhaust emissions of air toxics (e.g., benzene) can be drawn. The Auto/Oil study mentioned in the previous section tested the same three Tier 0 and Tier 1 vehicles for hot-soak evaporative emissions. They found no statistically significant change in NMOG or OMHCE⁵¹ evaporative emissions, yet found a statistically significant 60% reduction in benzene emissions. Directionally, you would expect both hydrocarbon and air toxic evaporative emissions to decrease due to the dilution of the hydrocarbon portion of the fuel with ethanol. However, again, it is highly dependent on the volatility of the gasoline component of the specific E85 used and its benzene content, neither of which is regulated.

⁵¹ Organic Material Hydrocarbon Equivalent

3.2 Effect of Fuel Quality on Spark-Ignited Nonroad Equipment Emissions

We use EPA’s NONROAD emission model to estimate the effect of gasoline quality on emissions from nonroad equipment. We use the 2005 version of this model, NONROAD2005, which includes the effect of ethanol on permeation emissions from several types of equipment: all small spark-ignition equipment (including handheld and non-handheld equipment less than or equal to 25 hp), all spark-ignition recreational marine watercraft (includes all outboard, stern-drive inboard, and personal watercraft). Note that these categories do not include recreational vehicles (motorcycles, ATVs, and snowmobiles) or large spark-ignition equipment.

Only a limited number of fuel parameters affect emissions in NONROAD. Exhaust VOC, CO and NOx emissions are a function of sulfur and oxygen. Here, only the latter fuel parameter is of interest. Emissions of all three pollutants are assumed to change proportionally with fuel oxygen content. Table 3.2-1 shows the effect of moving to a 10 volume percent ethanol blend (3.5 wt% oxygen) on these emissions, either from a non-oxygenated fuel or from an 11 volume percent MTBE blend (2.0 wt% oxygen).^{RRR}

Table 3.2-1.
Effect of a 10 Volume Percent Ethanol Fuel on Nonroad Exhaust Emissions

Base Fuel	4-Stroke Engines		2-Stroke Engines	
	Non-Oxygenated	11 Volume Percent MTBE	Non-Oxygenated	11 Volume Percent MTBE
VOC	-16%	-7%	-2%	-1%
CO	-22%	-9%	-23%	-10%
NOx	+40%	+17%	+65%	+28%

As can be seen, the higher oxygen content of ethanol blends reduces exhaust VOC and CO emissions. However, it also increases NOx emissions quite substantially, especially from 4-stroke engines. However, it should be noted that NOx emissions from these engines tend to be fairly low to start with, given the fact that these engines run richer than stoichiometric. Thus, a large percentage increase of a relative low base value can be a relatively small increase in absolute terms. This will be seen below in Chapter 4, when we evaluate the impact of increased ethanol use on the local and national emission inventories.

Non-exhaust VOC emissions (other than permeation) are a function of gasoline RVP and ethanol content in NONROAD2005. Ethanol content only affects permeation emissions. Both of these emissions are temperature dependent, so the effect of ethanol and RVP is also temperature dependent. Based on the results of modeling national emissions in July, a 10 volume percent ethanol blend increases non-exhaust VOC emissions by 15 percent. This assumes a 1.0 psi increase in RVP.

Hose permeation emissions in the public version of NONROAD2005 are independent of fuel quality. In support of the development of new emission standards for small nonroad engines, EPA has been testing small nonroad engines for hose permeation emissions using fuels

with and without ethanol. Based on this testing, as well as discussions with nonroad equipment manufacturers, we developed new hose permeation emission rates for NONROAD2005 for both gasoline and E10 fuels. Roughly, these revised permeation rates indicate that emissions with E10 are 2-3 times higher than those for gasoline. This increase is similar to that found for the three oldest onroad vehicles in the CRC E-65 study, discussed in section 3.1.1.1.4 above.⁵² The NONROAD2005 hose permeation factors^{SSS} were adjusted as follows:

- 1) Permeation emissions in the public version of NONROAD2005 were 450 grams per meter-squared per day ($\text{g/m}^2/\text{day}$) for both small spark-ignition engines and for the supply hoses on portable fuel tanks in recreational marine watercraft, applicable to all fuels. For both types of equipment, the permeation emission rates were changed to 122 $\text{g/m}^2/\text{day}$ for gasoline and 222 $\text{g/m}^2/\text{day}$ for E10.
- 2) Permeation emissions in the public version of NONROAD2005 were 100 $\text{g/m}^2/\text{day}$ for supply hoses on outboard recreational marine watercraft (> 25 hp), 300 $\text{g/m}^2/\text{day}$ for supply hoses on personal watercraft (PWC), and 110 $\text{g/m}^2/\text{day}$ for fill neck hoses on both outboards and PWC. These three permeation emission rates were changed to 42 $\text{g/m}^2/\text{day}$ for gasoline and 125 $\text{g/m}^2/\text{day}$ for E10.
- 3) Permeation emissions from sterndrive/inboard recreational marine watercraft in the public version of NONROAD2005 were 100 $\text{g/m}^2/\text{day}$ for supply hoses and 110 $\text{g/m}^2/\text{day}$ for fill neck hoses. Both of these permeation emission rates were changed to 22 $\text{g/m}^2/\text{day}$ for gasoline and 40 $\text{g/m}^2/\text{day}$ for E10.
- 4) Permeation emissions in the public version of NONROAD2005 were 0 $\text{g/m}^2/\text{day}$ for vent hoses on all recreation marine watercraft. This permeation emission rate was changed to 2.5 $\text{g/m}^2/\text{day}$ for gasoline and 4.9 $\text{g/m}^2/\text{day}$ for E10.
- 5) One final adjustment was to double the vent hose length for all gasoline-fueled outboards, personal watercraft, and sterndrive/inboard watercraft.

The NONROAD emissions model does not estimate emissions of toxic air pollutants from nonroad equipment. However, the National Mobile Inventory Model (NMIM) does make such estimates. NMIM utilizes the MOBILE and NONROAD models to develop national emission estimates for motor vehicles and nonroad equipment. For the most part, NMIM provides the relevant inputs to MOBILE6.2 and NONROAD and processes the results. However, with respect to nonroad toxic emissions, NMIM takes exhaust and non-exhaust VOC emission estimates from NONROAD and applies a set of toxic fractions of VOC emissions based on fuel quality.^{TTT} NMIM contains estimates of the toxic fractions of VOC emissions for three fuels: a non-oxygenated gasoline, an MTBE blend and an ethanol blend. NMIM applies the fraction of VOC emissions represented by each of the air toxics to either the exhaust or non-

⁵² Permeation emissions from nonroad equipment are not regulated. Thus, the elastomers used in the fuel systems of nonroad equipment are likely to be more similar to those of older onroad vehicles than those of later onroad vehicles which were subject to stringent non-exhaust VOC emission standards.

exhaust VOC emissions estimated by NONROAD. The toxic fractions of VOC were derived from motor vehicle testing. Thus, they are considered approximate.

We hope to update our projections of the effect of gasoline quality on exhaust and non-exhaust emissions from nonroad equipment based on additional testing to be conducted over the next several years if funding allows. These updated projections could be used in the comprehensive assessment of the impact of the fuel-related provisions of the Energy Act which is due in 2009.

3.3 Effect of Fuel Quality on Compression-Ignited Vehicle and Equipment Emissions – Biodiesel

Biodiesel is expected to be one of two renewable fuels to be used in significant volumes through 2020. While ethanol will dominate the market, biodiesel use is likely to grow considerably reaching 300 million gallons by 2012, according to EIA estimates. It is produced domestically from vegetable oils, animal fats and recycled cooking oils, with the majority of this product coming from soybean oil. It is typically used in 2%, 5% and 20% blends with diesel fuel which have been assigned B2, B5 and B20 designations, respectively.

In 2002, EPA issued a report entitled “A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions” based on existing data from various test programs. This report included a technical analysis of biodiesel effects on regulated and unregulated pollutants from diesel powered vehicles and concluded that biodiesel fuels improved PM, HC and CO emissions of diesel engines while slightly increasing their NO_x emissions.

While the conclusions reached in the 2002 EPA report relative to biodiesel effects on VOC, CO and PM emissions have been generally accepted, the magnitude of the B20 effect on NO_x remains controversial due to conflicting results from different studies. Significant new testing is being planned with broad stakeholder participation and support in order to better estimate the impact of biodiesel on NO_x and other exhaust emissions from the in-use fleet of diesel engines. We hope to incorporate the data from such additional testing into the analyses for other studies required by the Energy Act in 2008 and 2009, and into a subsequent rule to set the RFS program standard for 2013 and later.

3.4 Emissions from Fuel Production Facilities

3.4.1 Ethanol

The primary impact of renewable fuel production and distribution regards ethanol, since it is expected to be the predominant renewable fuel used in the foreseeable future. For the NPRM, we estimated the impact of increased ethanol production, including corn farming, on emissions based on DOE’s GREET model, version 1.6. This estimate also included emissions related to distributing the ethanol and take credit for reduced emissions related to distributing displaced gasoline. Since the time of the NPRM analysis, DOE has published the next version of

GREET, version 1.7. The emission estimates related to ethanol production and distribution in GREET1.7 differ significantly from those in GREET1.6. In addition, through EPA's regional offices, we contacted a number of States to obtain the latest emission estimates for ethanol plants currently in production. These plant-specific estimates provide a useful comparison to the inherently generic emission factors used by a nationwide-average model, such as GREET.

In Section 3.4.1.1, we describe and compare the emission estimates from the GREET model, both versions 1.6 and 1.7. In Section 3.4.1.2, we describe the data obtained from the States and consolidate it into two sets of emission factors; one for wet mills and one for dry mills. Finally, in Section 3.4.1.3, we describe how we will use both the GREET and State estimates in estimating national emissions from new ethanol plants in Chapter 4.

3.4.1.1 GREET Emission Estimates

The emissions related to producing and distributing ethanol for use in gasoline blends from both GREET1.6 and 1.7 are summarized in Table 3.4-1. GREET presents emission factors in a variety of units, such as per bushel of corn harvested, gallons of ethanol produced, etc. All the emission factors shown in this table have been converted to a per gallon of ethanol produced or distributed basis using the default conversion factors contained in GREET. One of GREET's default assumptions is that 80% of ethanol plants are associated with dry corn milling, while the other 20% are associated with wet milling. Nearly all future ethanol plants are planned to be dry mill facilities. Therefore, we only show the emission factors for dry mill ethanol plants below.

**Table 3.4-1.
Well-to-Pump Emissions for Producing and Distributing Ethanol from Corn
Dry Mill Facility (grams per gallon ethanol)**

Pollutant	Corn Farming and Transportation	Ethanol Production	Co-Product Credits	Ethanol Transportation	Gasoline Transportation Credit	Total Emissions
Dry Mills - GREET1.6						
VOC	0.8	6.8	-4.1	0.5	-0.9	3.1
CO	4.3	2.9	-3.3	0.2	-0.1	4.1
NOx	11.3	4.6	-6.9	1.5	-0.4	10.1
PM10	8.1	0.4	-2.5	0.0	0.0	6.1
SOx	1.2	6.1	-0.9	0.2	-0.1	6.5
Dry Mills - GREET1.7						
VOC	1.6	2.6	-2.5	1.6	-1.5	1.8
CO	4.0	1.7	-1.7	0.2	-0.1	4.1
NOx	10.7	3.9	-4.1	1.3	-0.4	11.4
PM10	1.1	4.2	-0.5	0.0	0.0	4.9
SOx	5.0	3.7	-2.4	0.2	-0.1	6.4
Wet Mills - GREET1.6						
VOC	0.8	6.8	-1.8	0.5	-0.9	5.5
CO	4.3	3.3	-2.1	0.2	-0.1	5.7
NOx	11.3	6.2	-4.8	1.5	-0.4	13.8
PM10	8.1	0.5	-2.3	0.0	0.0	6.4
SOx	1.2	9.2	-0.6	0.2	-0.1	9.9
Wet Mills - GREET1.7						
VOC	1.6	2.6	-3.2	1.6	-1.5	1.1
CO	4.0	2.3	-2.1	0.2	-0.1	4.3
NOx	10.7	4.9	-4.6	1.3	-0.4	11.9
PM10	1.1	5.9	-0.6	0.0	0.0	6.5
SOx	5.0	4.1	-2.7	0.2	-0.1	6.5

As can be seen, the emission estimates from the two versions of GREET differ significantly. In particular, VOC emissions in GREET1.7 are about 60% as large as those estimated in GREET1.6 for dry mills and even lower for wet mills. The other differences are in the $\pm 20\%$ range, and differ in direction depending on pollutant.

The default mix of dry and wet mill ethanol plants is 80/20 in both versions of GREET. This is a reasonable estimate for current production. However, the vast majority of new plants are expected to be of the dry mill variety. Therefore, we will use the above emission factors for a 80/20 mix of dry and wet mill plants to estimate the emissions from current ethanol plants and the dry mill emission factors to estimate the emissions from future plants.

While emissions related to ethanol production and distribution will increase, areas with refineries might experience reduced emissions, not necessarily relative to current emission

levels, but relative to those which would have occurred in the future had ethanol use not risen. However, to the degree that increased ethanol use reduces imports of gasoline, as opposed to the domestic production of gasoline, these reduced refinery emissions will occur overseas and not in the U.S. Therefore, we will not take any credit for reduced refinery emissions here.

Similarly, areas with MTBE production facilities might experience reduced emissions from these plants as they cease producing MTBE. However, some of these plants are likely to be converted to produce other gasoline blendstocks, such as iso-octane or alkylate. In this case, their emissions are not likely to change substantially.

The emission factors shown in Table 3.4-1 do include a credit for reduced emissions related to a reduction in the volume of non-oxygenated gasoline being distributed. These are taken directly from the GREET emission estimates for conventional gasoline production and distribution. We assumed that ethanol use will reduce gasoline use one for one on an energy basis.

3.4.1.2 Ethanol Production Emissions Received from States

The emissions from most of the steps involved in ethanol production and distributions are very diffuse (e.g., tractors plowing corn fields). However, the emissions from ethanol production plants are point sources whose emissions are often measured and tracked by local or state governments. We contacted over a dozen States in an attempt to improve our estimate of emissions from ethanol production. The results of this process are summarized below.^A

We received emission estimates from 13 States for current ethanol plants with a combined capacity of 3 billion gallons per year. The emission data involved annual emission estimates for one or more years between 2001-2005. Overall, these plants represent roughly three-fourths of current ethanol capacity. The emission data cover a very wide range of plant capacities, ranging from 0.4 to 274 million gallons of ethanol per year.

The capacity-weighted average emissions of wet and dry mill ethanol plants are summarized in Table 3.4-2.

Table 3.4-2. Emissions From Ethanol Plants: State Data (g/gal ethanol)

	Wet Mills	Dry Mills
VOC	17.5	4.0
CO	15.0	1.9
NOx	18.3	5.5
PM10	8.8	2.2
SOx	24.6	7.0

As can be seen, the emissions from wet mills are much higher than those from dry mills. In general, the wet mill plants are older than the dry mills. They also involved a different set of processes and produce a different set of by-products.

The ethanol plant emissions from GREET1.6 and GREET1.7 are shown in Table 3.4-3 below.

Table 3.4-3. Emissions From Ethanol Plants: GREET (g/gal ethanol)

	Wet Mills		Dry Mills	
	GREET1.6	GREET1.7	GREET1.6	GREET1.7
VOC	6.8	2.6	6.8	2.6
CO	3.3	2.3	2.9	1.7
NOx	6.2	4.9	4.6	3.9
PM10	0.5	5.9	0.4	4.2
Sox	9.2	4.1	6.1	3.7

As can be seen from comparing the emission estimates in Tables 3.4-2 and 3.4-3, the State data indicate that the emission from wet mills are much higher than those estimated in either version of GREET. In contrast, the emission data obtained from the States for dry mills is generally consistent with the estimates in GREET1.6 and higher than those in GREET1.7. An exception to the latter are emissions of PM10, which the state data indicate are lower than the estimate in GREET1.7 and higher than that in GREET1.6.

The reasons for the differences in the State data and the estimates in GREET1.6 and GREET1.7 are not known. It is possible, particularly for wet mills, that the State estimates include the emissions from an entire geographically-defined facility which may include more operations than just corn milling. It is also possible that the estimates in GREET represent emissions from plants which would be designed today or in the future and are less representative of plants which were built over 20 years ago. This deserves further investigation. At this time, we will use the average of the State emission data as a second estimate of ethanol plant emissions, along with GREET1.7, in order to better indicate the range of possible emissions from these plants.

3.4.1.3 Selection of Ethanol Production and Distribution Emission Estimates

We have available three estimates of the emissions from ethanol plants and two estimates of the emissions from the other steps in the process of growing corn through ethanol distribution. The estimates contained in GREET1.7 represent an update of those in GREET1.6. Therefore, we will use the emission factors from GREET1.7 in lieu of those in GREET 1.6 in Chapter 4 where we estimate national emissions from ethanol production and distribution.

In addition, we develop a second estimate of these emissions by substituting the average emission factors based on the State data for the dry mill ethanol plant emissions contained in GREET1.7. While the State data represents emissions from current plants and our primary focus is future plants, it is not certain that the emissions of the two sets of ethanol plants will differ. Therefore, the use of the State data will provide a useful indication of the potential uncertainty in the GREET1.7 estimates. We chose not to use the state data for wet mills, as these emission factors are often a factor of 10 higher than those from GREET1.6 or GREET1.7. More understanding of the processes producing these emissions is needed before they can be all

assigned to ethanol production. Thus, we use the GREET1.7 emission factors for wet mill ethanol production, while using the state data for dry mill ethanol production.

The two sets of estimates are shown in Table 3.4-4. In both sets of estimates, the emission factors for current ethanol plants assume an 80/20 mix of dry and wet mills, while those for future ethanol plants assume 100% dry mills.

**Table 3.4-4.
Selected Emission Factors for Ethanol Production and Distribution
(g/gal ethanol)**

	GREET1.7		GREET1.7 + State Data	
	Current Plants	Future Plants	Current Plants	Future Plants
VOC	1.8	1.8	3.6	3.2
CO	4.0	4.1	4.4	4.3
NOx	11.4	11.4	10.8	13.0
PM10	4.9	4.9	6.1	2.8
Sox	6.4	6.4	7.2	9.7

3.4.2 Biodiesel

Like ethanol, we base our emission factors for biodiesel production distribution on the estimates contained in the GREET model, version 1.7. Table 3.4-6 shows the emission factors associated with soybean farming, soy oil production and esterification, and biodiesel distribution. We also include emissions related to distributing the biodiesel and take credit for reduced emissions related to distributing displaced diesel fuel.

**Table 3.4-5.
Well-to-Pump Emissions for Producing and Distributing Biodiesel from Soybeans
(grams per gallon biodiesel)**

Pollutant	Total: Soybean Farming and Transportation	Biodiesel Production	Biodiesel Transportation	Diesel Fuel Transportation Credit	Total Emissions
VOC	2.7	34.8	0.2	-0.2	37.6
CO	10.6	2.1	0.2	-0.1	12.7
NOx	19.3	5.5	0.9	-0.6	25.1
PM10	2.6	2.2	0.0	0.0	4.8
SOx	17.6	4.1	0.1	-0.1	21.8

At the same time, areas with refineries might experience reduced emissions, not necessarily relative to current emission levels, but relative to those which would have occurred in the future had biodiesel use not risen. However, to the degree that increased biodiesel use reduces imports of diesel fuel, as opposed to the domestic production of diesel fuel, these reduced refinery emissions will occur overseas and not in the U.S.

Chapter 3: Appendix
Fuel Property Tables and Summary of Predicted Emissions Changes

Table 3A-1. CRC E-67 Study Test Fuel Properties

Inspection	Units	Fuel A	Fuel B	Fuel C	Fuel D	Fuel E	Fuel F	Fuel G	Fuel H	Fuel I	Fuel J	Fuel K	Fuel L
API Gravity	°API	62.1	59.9	57.6	61.4	56.7	60.1	57.1	60.6	57.2	56.6	59.3	54.4
Relative Density	60/60°F	0.7310	0.7393	0.7482	0.7337	0.7519	0.7387	0.7502	0.7366	0.7498	0.7525	0.7416	0.7611
DVPE	psi	7.74	7.84	7.70	7.65	7.80	7.62	7.78	7.85	7.68	7.57	7.71	7.69
Oxygenates--D 4815													
MTBE	vol %	0.03	0.03	0.13	0.03	0.11	0.08	0.13	0.09	0.16	0.13	0.16	0.16
ETBE	vol %	0.02	0.02	0.01	0.01	0.01	0.08	0.04	0.01	0.01	0.01	0.02	0.01
EtOH	vol %	0.02	5.62	10.37	0.00	10.26	0.00	10.15	0.05	5.94	5.90	0.00	10.49
O2	wt %	0.02	2.10	3.84	0.01	3.78	0.03	3.76	0.04	2.22	2.19	0.03	3.83
Sulfur Content	ppm	18.8	16.7	19.0	18.2	17.2	18.1	17.5	18.6	16.8	19.1	21.9	20.6
D 86 Distillation													
IBP	°F	94.2	107.6	104.3	88.8	106.3	94.2	103.7	94.2	100.7	102.6	93.9	106.1
5% Evaporated	°F	126.3	127.2	124.6	123.2	124.3	121.6	125.3	122.7	124.0	126.0	117.9	129.4
10% Evaporated	°F	136.0	133.2	130.5	133.3	130.5	135.0	133.2	134.0	130.2	134.4	129.7	140.0
20% Evaporated	°F	148.6	140.8	138.8	147.6	139.5	154.7	143.7	151.6	139.0	146.6	148.4	152.4
30% Evaporated	°F	163.6	154.1	146.6	164.1	147.2	177.0	152.9	173.3	150.8	175.5	174.4	158.8
40% Evaporated	°F	179.8	176.1	153.7	182.3	153.8	200.2	163.4	197.0	191.0	220.5	208.5	202.1
50% Evaporated	°F	194.7	190.9	192.7	199.5	197.7	216.8	212.2	216.3	215.9	236.6	236.1	232.7
60% Evaporated	°F	209.0	203.2	223.5	216.9	226.2	227.6	226.7	230.4	235.9	251.5	255.2	248.7
70% Evaporated	°F	224.2	219.3	245.7	237.9	259.2	238.2	237.0	245.9	260.9	271.9	279.6	273.5
80% Evaporated	°F	243.4	240.9	281.5	274.3	299.7	254.7	251.7	273.7	311.3	305.2	319.1	307.7
90% Evaporated	°F	294.3	289.8	329.2	355.0	351.7	295.0	290.7	326.9	354.2	329.2	355.5	349.1
95% Evaporated	°F	327.4	325.9	343.4	367.3	364.9	324.0	327.8	343.7	366.6	338.7	368.6	367.4
EP	°F	351.2	352.0	374.0	392.0	385.4	361.2	365.4	374.4	391.8	365.8	390.3	389.6
Recovery	vol %	97.0	97.9	97.7	97.9	97.4	97.2	96.7	98.0	97.9	97.6	98.1	97.3
Residue	vol %	1.8	1.1	1.2	0.8	1.4	1.7	1.5	1.0	1.1	1.2	1.0	1.0
Loss	vol %	1.2	1.0	1.1	1.3	1.2	1.1	1.8	1.0	1.0	1.3	0.9	1.7
Driveability Index		1082.4	1075.8	1128.0	1153.3	1165.1	1148.0	1151.2	1176.8	1211.5	1254.9	1258.2	1282.3
E200	vol %	53.6	57.6	52.1	50.6	50.6	40.0	47.4	41.7	43.1	35.2	37.6	39.4
E300	vol %	90.9	91.5	84	83.6	80.0	90.9	79.5	85.2	77.8	78.4	75.2	78.0

Table 3A-2. Summary of EPA E-67 vs. EPA Predictive Model Effects of E10 and MTBE Use Relative to CG and RFG

	Base Fuel: AAM Summer avg. non-oxy fuel	E0: AAM CG RVP -1 psi delta	E0: AAM CG RVP -2 psi delta	E10: AAM Summer Avg	E10: AAM Summer avg, T50 limited to 195°F	E10: AAM Summer avg, T50 T90 O2 only for EPA model (T50=195°F)	11% MTBE: Fuel props are deltas from AAM CG	Phase 2 RFG: Non- oxy, from 1993 region 2 class C Data, low RVP	RFG Class C MTBE: 1993 region 2 data, low RVP	RFG E10: 1993 region 2 data (L),T50 & T90 delta from AAM data, low RVP	
Fuel Parameters											
	RVP (psi)	8.7	7.8	6.8	9.7	9.7	8.7	8.7	6.7	6.7	6.7
	T50 (°F)	218	218	218	186	195	195	206	214	212	194
	T90 (°F)	332	332	332	325	325	325	324	325	321	322
	Aromatics (vol %)	32	32	32	27	27	32	25.5	25.48	25.48	25.48
	Olefins (vol %)	7.7	7.7	7.7	6.1	6.1	7.7	7.7	13.1	13.1	13.1
	Oxygen (wt%)	0	0	0	3.5	3.5	3.5	2.1	0	2.1	3.5
	Sulfur (ppm)	30	30	30	30	30	30	30	30	30	30
Predicted Emissions Changes											
EPA Predictive Models (% change)											
	NOx	0.0	-1.0	-2.1	7.7	7.3	7.7	2.6	-1.7	2.4	6.3
	NMHC	0.0	-1.0	-2.0	-7.4	-7.0	-7.5	-9.2	-7.7	-11.1	-12.9
EPA E-67 Model (% change)											
	NOx	0.0	0.0	0.0	9.2	6.7	6.7	-1.9	-0.7	-2.2	8.8
	NMHC	0.0	0.0	0.0	-5.7	-6.5	-6.5	-4.7	-3.2	-1.9	-7.2

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