

Attachment

*Additional information concerning the California request for a waiver
from the federal oxygen requirement for reformulated gasoline*

(February 7, 2000)

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I. COMPARING THE CALIFORNIA AIR RESOURCES BOARD'S PHASE 3 REFORMULATED GASOLINE PREDICTIVE MODEL TO THE U.S. EPA COMPLEX MODEL

There are a number of differences between the Air Resource Board's (ARB) Predictive Model and the U.S. EPA's Complex Model. These differences exist primarily because: first, the two models were developed subject to different legal restrictions; and second, the ARB's Predictive Model was developed subsequent to the U.S. EPA's Complex Model. These two factors allowed the ARB access to a more robust database and more sophisticated mathematical modeling techniques. This second factor is responsible for the major differences between the two models, including the treatment of high-emitters.

The ARB Predictive Model was developed under the authority of the California Health and Safety Code Section 43018. This section directed the ARB staff to adopt standards and regulations which will result in the most cost-effective combination of control measure on all classes of motor vehicles and motor vehicle fuels, including but not limited to specifications for vehicular fuel composition. As a result, the ARB Predictive Model was developed to be as representative as possible of the California motor vehicle fleet and to preserve the emission benefits of California reformulated gasoline, while affording refiners greater flexibility by allowing them to establish, within limits, alternative fuel specifications.

The U.S. EPA Complex Model was developed in response to federal Clean Air Act section 211(k), which defined a set of performance specifications to be achieved using specified baseline vehicles and specified baseline gasoline properties. As a result, the Complex Model was designed to represent the emissions effects of federal reformulated gasoline in 1990 model year vehicles relative to emissions from those same vehicles from 1990 industry average gasoline.

Summarized below are discussions of the factors that brought about the differences between the two models.

A. Database Differences

The development of the U.S. EPA Complex Model was accomplished by 1993. The California Phase 2 Reformulated Gasoline (CaRFG2) Predictive Model was developed in 1994 and was updated in 1999 to be the CaRFG3 Predictive Model. Between the time that the Complex Model was developed and the CaRFG2 Predictive Model was completed, a significant amount of additional data became available. Table 1 presents information regarding the datasets used in the development of the Complex Model and the CaRFG Predictive Models.

Table 1. Summary of CaRFG Predictive Model and Complex Model Databases

	ARB CaRFG2 Predictive Model	ARB CaRFG3 Predictive Model	U.S. EPA Complex Model
Data Points	6900	9000	5300
Number of Vehicles	960 (Normal Emitter) 140 (High-emitter) 1100 (Total)	1110 (Normal Emitter) 170 (High-emitter) 1280 (Total)	480 (Normal Emitter) 32 (High-emitter) 512 (Total)
Number of Fuels	250	290	200
Vehicle Types	California Certified, 1981 –1992 Model Years	California Certified, 1981 –2005 Model Years	1990 Model-Year Technology
Number of Studies	20	35	15

B. Statistical Tools

There are also significant differences relating to the statistical basis for the two models. The ARB model was developed after the U.S. EPA developed the Complex Model. Between these two events, the SAS Institute Inc., a statistical software company, developed a procedure for estimating the regression coefficient for a mixed-effects model. Prior to this, the only practical procedure for estimating regression coefficients for models as large and complicated as the Predictive Model or the Complex Model was a standard linear regression procedure. The SAS Institute’s mixed-effects procedure (Proc Mixed) was not available during the development of the Complex Model.

The significant difference between these two procedures is how the vehicles are treated as part of the statistical calculations. In a standard linear regression application, such as that used for the Complex Model, vehicles are treated as if they are the entire population of interest. In a mixed-effects linear regression application, such as that used for the Predictive Model, vehicles are treated as if they are only a sample of vehicles from the on-road population of vehicles. A mixed-effects regression procedure properly accounts for the variation associated with a set of vehicles being only a sample. The availability of more advanced statistical software tools is a major reason why the Predictive Model performs somewhat differently from the Complex Model. Today, the SAS

Institute's Proc Mixed procedure is the standard for the analysis of complicated models based on large and sophisticated sampling designs. In fact, updates to this tool that were made available since 1994 account for a significant amount of the changes that occurred in the CaRFG3 model just recently developed. Finally, as discussed below, the availability of this procedure is why the ARB and the U.S. EPA used a different procedure to handle high-emitters.

C. High-emitters

The differences in databases and statistical tools lead to high-emitters being handled differently during the development of the two models. The procedure used during the development of the Complex Model is given in the U.S. EPA's December 20, 1993, Draft - Final Regulatory Impact Analysis for Reformulated Gasoline. This document describes how the Complex Model was developed and how high-emitters were handled.

The 32 high-emitters in the U.S. EPA Complex Model database were first modeled by themselves. This provided the model developers with a list of terms that could be added to the overall model as high-emitter offset terms. For the overall model, given the statistical tools available at the time, the use of high-emitter offset terms was considered to be appropriate and necessary for the proper modeling of the high-emitters in the Complex Model database.

The CaRFG2 Predictive Model database contained significantly more high-emitting vehicles than the Complex Model database (140 compared to 32). With the availability of the SAS Institute's Proc Mixed procedure, the ARB staff was able to model the random effects associated with a large database of vehicle/emission data. The ARB staff, in consultation with Dr. David Rocke of the University of California, Davis, examined the modeling of high-emitters terms simultaneously with normal-emitters. Emission effects associated with changing fuel parameters on high-emitters were modeled as offset terms. While this was similar in approach to the procedure used to model the high-emitter offset terms in the Complex Model, the result of this analysis with the more robust database and more sophisticated modeling approach was that the high-emitter offset terms were found not to be statistically significant. This implies that differential terms representing different responses for high-emitters versus normal-emitters were unnecessary in the statistical treatment used by the ARB, and that high-emitter effects were adequately captured in the modeling of the combined fleet of high and normal emitters.

To further determine if this approach was valid, the ARB staff reviewed the Auto/Oil Air Quality Improvement Research Programs Technical Bulletin No. 11, "A Study of Fuel Effects on Emissions from High Emitting Vehicles." This study concluded that, "Direct comparison of fuel pairs showed that most fuel effects on mass emissions of hydrocarbons, carbon monoxide, and nitrogen oxides were not distinguishably different in the normal and high-emitters tested." In light of the substantially larger number and percentage of high-emitters in the Predictive

Model database compared to the Complex Model database, the Auto/Oil Air Quality Improvement Research Program Technical Bulletin No. 11, and the more sophisticated statistical tools that became available, it was agreed by ARB staff, consultants, and stakeholders from the automotive and refining industries that all vehicles in the Predictive Model database should be modeled together.

D. Random Balance

In the development of the Complex Model, the Random Balance procedure was used to help reduce the number of terms in the model. This was to address possible fungibility problems generated by the way in which the 10 individual technology sub-classes in the Complex Model were to be combined. The Random Balance procedure is a mathematical algorithm used to determine the relative contribution of each term in the model to the overall fit of the model within a specified region of the parameter space. The parameter space is the range of possible values a set of properties can have, while still having the candidate alternative formulation considered a viable candidate. The details of this procedure are provided in the U.S. EPA's December 20, 1993, Draft - Final Regulatory Impact Analysis for Reformulated Gasoline.

The developers of the Predictive Model also used the Random Balance procedure. However, in California the region of possible candidate fuels is much more narrowly defined because the cap limits set by ARB are much more restrictive than those allowed by U.S. EPA. The parameter space or the cap limits for both the Complex Model and the CaRFG3 Predictive Model are presented in Table 2. This table illustrates that there is a major difference in the nature of the fuel properties handled by the two models, since the region of viable candidate formulations is significantly smaller for the Predictive Model than for the Complex Model.

Table 2. Comparison of upper limits for fuel property values between the CaRFG3 regulations and the U.S. EPA RFG regulations.

Fuel Property	CaRFG2 Cap Limits	CaRFG3 Cap Limits	EPA RFG Upper Limits for Complex Model Use*
Oxygen (wt.%)	3.5	3.7	4.0
Sulfur (ppmw)	80	30**	500
RVP (psi)	7.0	7.2	10.0
T50 (degrees F)	220	220	241***
T90 (degrees F)	330	330	389***
Aromatics (vol. %)	30	35	50
Olefins (vol. %)	10	10	25
Benzene (vol. %)	1.2	1.1	2.0

* As specified in 40 CFR section 80.45(f).

** Goes from 80 ppm to 60 ppm for two years and then to 30 ppm.

*** Based on U.S. EPA's correlation between E200 and T50 and E300 and T90.

Within the region of viable candidate formulations for both models, the Random Balance procedure was used to remove terms that may not provide any significant influence within that range. For California, there were several terms that were statistically significant over the entire range of data, but did not provide any significant influence on the predictive power of the Predictive Model within the cap limits specified by the CaRFG2 rules. This allowed the Predictive Model with its very low cap limits to be “fine tuned” for CaRFG fuels in a manner that was not possible for the Complex Model. (This is why the CaRFG Predictive Model should not be used to assess fuels that do not meet all the cap limits.) Details of this procedure can be found in Appendix J of the October 22, 1999, ARB staff report, Proposed California Phase 3 Reformulated Gasoline Regulations.

E. NOx/Oxygen Response in the CaRFG3 Predictive Model

During the development of the CaRFG3 Predictive Model several stakeholders commented upon the change in how NOx responded to changes in oxygen content compared to the CaRFG2 Predictive Model. The NOx response to changes in oxygen content is steeper in the CaRFG3 Predictive Model than it had been in the CaRFG2 Predictive Model. Stakeholders inquired as to whether the increased steepness of the slope could be related to the addition of new data, or to a change in statistical treatment. The ARB staff determined (see ARB analysis in Attachment A) that the change in response was not due to the addition of new data, but was due to the removal of the RVP-by-oxygen interaction term. During the development of the CaRFG3 Predictive Model, the RVP-by-oxygen interaction term was found to no longer meet the 5 percent significance criteria for remaining in the model. Because the RVP-by-oxygen term no longer met the statistical significance for entry into the model¹, it was removed.

The ARB staff has verified the appropriateness of removing the RVP-by-oxygen term. First, the CaRFG2 Predictive Model was re-evaluated using the new SAS version of the Proc Mixed procedure. It was found that had the new version been available in developing the CaRFG2 Predictive Model the RVP-by-oxygen term would have been found to be not statistically significant, even with the more limited dataset available at that time. Second, the CaRFG2 Predictive Model without the RVP-by-oxygen term responds very similarly to the CaRFG3 Predictive Model. Finally, the new SAS Proc Mixed procedure is superior to the version used in 1994 and it would have been used in 1994 had it been available. The details of this effort were independently reviewed by Dr. David Rocke of the University of California, Davis, and are provided in the attached memo (see Attachment B).

¹ The significance level of the RVP-by-oxygen interaction term was estimated to be 0.59. A term must have a significance level of 0.05 or less to be included in the model.

II. IDENTIFYING THE NOX BENEFITS REPRESENTATIVE OF NONOXYGENATED AND OXYGENATED-WITH-ETHANOL GASOLINES PRODUCED TO MEET THE CaRFG3 STANDARDS

The California Air Resources Board (ARB) staff has evaluated the factors that are likely to affect the sorts of gasoline formulations that refiners will produce for California's federal RFG areas in compliance with the California Phase 3 reformulated gasoline (CaRFG3) regulations. Two scenarios have been identified for summertime gasoline made without MTBE. The first is gasoline containing oxygen from ethanol, made to comply with the current requirements of the federal RFG year-round oxygen mandate. The second is a nonoxygenated gasoline, which refiners would have the option to make if the U.S. Environmental Protection Agency (U.S. EPA) waives the federal RFG oxygen mandate pursuant to federal Clean Air Act section 211(k)(2)(B), as requested by Governor Davis. Under both scenarios, the gasoline would meet all of the federal RFG requirements other than the oxygen mandate.

The evaluation shows that nonoxygenated CaRFG3 will be produced by refiners in a way that will result in additional reductions in NOx compared to CaRFG3 that would be produced with ethanol. This is consistent with the simulation analysis results presented previously in the December 24, 1999, letter and with the expanded simulation analysis results presented in Part V.

A. California Refineries

Refineries in California use more post-distillation processing than is typical in the rest of the U.S. In part, this is due to the heavy crudes that most California refineries run and to the lack of a heating-oil market. These factors create a greater need for cracking distillates into gasoline than is the case in other areas. Also, some of the extra post-distillation processing is due to California's regulations on the properties of gasoline and diesel fuel for vehicular emission control. Limits on the aromatic, olefinic, and sulfur contents of fuels lead directly to more use of processes that involve hydrogen treating. Also, they lead indirectly to processes such as alkylation and isomerization that mitigate the octane lost when the aromatic content of gasoline is controlled. (While some of these factors apply to refineries that meet federal fuel regulations, the scope and stringency of California's regulations are greater and the need for more post-distillation processing is greater.)

Table 1, based on data from the Oil & Gas Journal (12/20/99), shows the ratio of several process feed capacities or outputs to crude capacity, for both the California refining industry and the U.S. industry less California. The asterisks mark processes that are involved in meeting the fuel regulations in California. In each such case, the process is more prevalent in California. In some cases, such as hydrocracking and isomerization, the higher ratios reflect more frequent presence in California refineries as well as greater feed capacities. The near-

universal presence of these processes in California refineries provides greater flexibility in controlling fuel properties.

Table 1. Downstream Process/Crude Ratios

	California	US (ex-Calif)
Vacuum distillation	.56	.43
Coking	.24	.11
Catalytic cracking	.33	.34
Naphtha reforming	.20	.22
Hydrocracking *	.21	.07
Hydrotreating *	.20	.10
Hydrotreating *	.64	.53
Alkylation *	.08	.06
BTX	0	.03
Isomerization *	.06	.04
Ether production	.01	.01
Hydrogen (1000 cf/bbl) *	.54	.15
Sulfur (tons/1000 bbl) *	1.88	1.39
Asphalt production	.03	.03

* involved in meeting California's fuel regulations

Refineries in California must manage butanes differently than refineries generally do in the rest of the U.S. The state's limit on summertime RVP is more severe than any federal limit outside of RFG areas. Compliance requires the elimination (by distillation) of all butane from summer gasoline. This creates a need to mitigate the loss of octane otherwise provided by butanes, and -- given the lack of a market in California -- either exporting butanes or storing them for winter gasoline blending. Also, when the RVP limit declines for evaporative model purposes in 2003 and when ethanol is used, this need will additionally extend also to the pentane content of gasoline.

The refineries in California that produce CaRFG are mid-sized compared to the range of size of gasoline-producing refineries in the U.S. With the exception of one small, independently owned refinery in Bakersfield, all gasoline-producing refineries in California are between 61,000 and 260,000 BPD in crude capacity. In contrast, Gulf Coast refineries that produce gasoline range from 50,000 to 500,000 BPD, with most exceeding 200,000 BPD. On the other hand, in the far western U.S. other than California and Washington, most of the other refineries that produce gasoline are 60,000 BPD or less crude capacity.

The capital invested per barrel of capacity is probably greater in California than is typical elsewhere. In the mid-1990's, refineries in California spent about \$4 billion to comply with the CaRFG2 regulations. Somewhat earlier, there was also considerable expenditure for the state's regulation of the aromatic content of diesel. While many other refineries in the U.S. also spent to meet federal fuel regulations, the changes to those refineries were more modest and tended to be in the larger (e.g., Gulf Coast) plants.

B. How the CaRFG3 Predictive Model Works

Virtually all California gasoline marketed today is produced using the CaRFG2 Predictive Model, because of the flexibility the Model provides refiners. It is widely anticipated that refiners producing gasoline meeting the CaRFG3 requirements will similarly use the CaRFG3 Predictive Model in virtually all cases.

Both the existing CaRFG2 regulations and the pending CaRFG3 regulations impose standards for eight gasoline properties: summertime Reid vapor pressure (RVP), T50, T90, and sulfur, aromatic, olefin, benzene and oxygen contents. The standards are set forth in Table 2.

Refiners and importers are responsible for assuring that each batch of gasoline meets either the flat or averaging limits for all properties when the batch is supplied from the production or import facility. Unlike the flat and averaging limits which apply only at the production or import facility, the cap limits apply throughout the gasoline distribution system.

The Predictive Model compliance option allows a refiner to identify alternative flat and averaging limits that apply to a batch of gasoline being supplied from the refinery. The CaRFG3 Predictive Model consists of a number of submodels which make predictions of the impact that changes in each of the gasoline properties being regulated will have on emissions from California's fleet of gasoline vehicles. Submodels for each of three vehicle emissions control technology "Tech" classes predict the impact of specification changes on exhaust emissions of total hydrocarbons (THC), oxides of nitrogen (NOx) and potency weighted toxics (called "PWT" and consisting of benzene, 1,3-butadiene, formaldehyde, and acetaldehyde). There are also optional models for assessing the impact of changes in RVP on evaporative emissions of THC and benzene. A candidate set of "Predictive Model specifications" will be treated as meeting the applicable standards if (i) each of the specifications is within the applicable cap limits, and (ii) for each pollutant – NOx, THC and PWT – the predicted increase in emissions is no more than 0.04%.

Table 2

Property	Flat Limits		Averaging Limits		Cap Limits	
	CaRFG Phase 2	CaRFG Phase 3	CaRFG Phase 2	CaRFG Phase 3	CaRFG Phase 2	CaRFG Phase 3
Reid Vapor Pressure (pounds per square inch; warmer months only)	7.00	7.00 or 6.90 w/ evap PM	Not Available	Not Available	7.00	6.40 – 7.20
Sulfur Content (parts per million by weight)	40	20	30	15	80	30 *
Benzene Content (percent by volume)	1.0	0.8	0.8	0.7	1.2	1.1
Aromatics Content (percent by volume)	25.0	25.0	22.0	22.0	30.0	35.0
Olefins Content (percent by volume)	6.0	6.0	4.0	4.0	10.0	10.0
T50 (degrees Fahrenheit)	210	213	200	203	220	220
T90 (degrees Fahrenheit)	300	305	290 (max. 310)	295	330	330
Oxygen Content (percent by weight)	1.8 - 2.2	1.8 - 2.2	Not Available	Not Available	1.8** - 3.5	1.8** - 3.7
					0 - 3.5	0 – 3.7

* From 12/31/02 to 12/31/04 the sulfur cap limit is 60.

** Applies in the winter in CO nonattainment areas.

In most cases, having to meet the CaRFG3 limit for a particular property results in some increase in production costs; it may also limit production volume. A refiner's goal, will be to produce the most economically advantageous Predictive Model alternative formulation which passes for each of the three pollutants parameters (before accounting for any necessary compliance safety margin). However, in meeting the emissions criteria for the most constraining pollutant, a refiner usually faces a situation where its least-cost alternative formulations achieve a better than required emissions performance for one or two of the regulated pollutants.

C. Factors That Affect a Refiner's Selection of CaRFG3 Predictive Model Formulations

In deciding upon its optimal CaRFG3 formulations using the CaRFG3 Predictive Model, each refiner will be influenced by a number of factors having complex interrelationships. These include the Model's emissions responses to changes in various fuel properties and the characteristics and costs of various gasoline components, as well as the way the refinery is designed and operated.

The CaRFG3 Model's Emissions Responses. Attachment C shows plots of the changes in exhaust emissions of THC and NO_x resulting from changes in oxygen, sulfur, olefins, aromatics, T50, and T90.² The attachment also shows the changes in exhaust PWT from changes in each of those properties and benzene. In each plot, the flat limit is shown as resulting in no change in emissions. Attachment C also includes plots of changes in evaporative emissions of THC (reactivity-weighted) and benzene resulting from changes in RVP.

Considering oxygen content *alone* (i.e., as if no other properties change), a nonoxygenated gasoline would have 3.2% higher exhaust THC emissions than gasoline at the 2.0 wt.% flat limit for oxygen. This increase must be offset by THC emissions reductions from changes in other properties. The nonoxygenated gasoline would have a 1.6% increase in PWT, which will also have to be offset. The nonoxygenated gasoline would have (before adjusting other properties) about 2% lower NO_x emissions than the 2.0 wt.% oxygen blend.

Setting aside economic and production considerations for the moment, a refiner could, by using the Predictive Model, provide the needed hydrocarbon reductions (from the example above) by decreases below the flat limits for sulfur, aromatics, T50, T90 or RVP (using the evaporative model), or by increases in olefin content above the flat limit. PWT reductions could be achieved by decreasing benzene, aromatics, olefins, T90, T50, RVP, or sulfur. Again, considering just the Predictive Model, a refiner could use the lower NO_x emissions of the nonoxygenated blend to produce fuels with either higher sulfur, increases in olefins, or increases in aromatics (changes in T50, T90, benzene or RVP would not significantly change NO_x emissions). However, as is discussed later, it is very unlikely, due to other considerations, that refiners would find it beneficial to take full advantage of this NO_x flexibility.

² Since benzene content has not been shown to affect emissions of THC or NO_x, there are no submodels for these effects; there of course is a submodel on the effects of benzene content on PWT. In the case of RVP, only the evaporative emissions impacts are modeled, and then only if the refiner chooses to use the evaporative emissions model rather than have a flat RVP limit of 7.00 psi.

Characteristics of fuel components. For a refiner that has been producing gasoline with 2.0 wt.% oxygen from 11 percent by volume (vol.%) MTBE (the most typical oxygenate in California), eliminating the MTBE reduces volume by 11 vol.% and severely reduces the octane number. It also increases T50 by about 10 degrees F.

Adding ethanol to gasoline to achieve 2.0 wt.% oxygen will initially recover about 5.7% of the volume lost from removing the 11% volume MTBE, leading to restoration of about half of the lost dilution from MTBE. But the ethanol will also increase the RVP of the gasoline by about 1 psi. To reduce the RVP of the summertime base gasoline sufficiently to offset the RVP effect from adding ethanol, refiners will remove the high volatility components (such as pentane), resulting in a loss of volume of about 5%. Thus, before other changes are made, the net volume loss of replacing MTBE with ethanol or providing no oxygen will be about the same – a volume loss of about 10-11%.³

Removing MTBE, which has an octane value of 110, results in a significant loss of octane. The lost octane could be made up by adding ethanol, alkylate (a refinery product consisting of branched C₇ - C₉ paraffins), or reformate (an aromatic-rich product), or a combination of these. The blending octane value for alkylate is 91 to 99, which may be sufficient to meet the additional octane needs for regular-grade (87) and mid-grade (89). Alkylate provides other beneficial blending characteristics, as it introduces no sulfur, aromatics or olefins. It increases T50 to some extent. Because of the CaRFG3 limit on aromatics, the addition of reformate will be small. Aromatics are also a benzene precursor in the Predictive Model. In the future, alkylates use will increase to supply both volume and octane.⁴

D. The expected emissions impact of CaRFG3 nonoxygenated and oxygenated-with-ethanol blends

ARB Evaluation. In the October 22, 1999, ARB staff report on the proposed CaRFG3 regulations, ARB staff evaluated what fuels might be produced by refiners to meet the CaRFG3 regulations. Overall, staff concluded that aromatics and olefins would not change significantly because increases in either result in significant increases in toxic emissions. Sulfur will probably be reduced for both non-oxygenated RFG and RFG with ethanol. Sulfur is the only parameter that when reduced, reduces emissions of all pollutants.

³ The California Energy Commission's June 1999 Findings on a Timetable for the Phaseout of MTBE From California's Fuel Supply (Appendix D to the CaRFG3 Staff Report, and referred to as CEC MTBE Findings) estimates that substituting 5.7 vol.% ethanol for 11 vol.% MTBE will result in a decline in production capability of about 10%, taking into account the need to remove pentanes.

⁴ CEC MTBE Findings, page 7, December, 1999.

In the case of refiners that produce nonoxygenated CaRFG3, refiners will probably reduce RVP, T50 and T90 in addition to sulfur to achieve needed hydrocarbon emission reductions when oxygen is eliminated. Reducing these properties will not increase NOx emissions and have a relatively minimal impact on toxic emissions. In most cases, staff believe that refiners will seek to minimize any total hydrocarbon overcompliance in the model, because such a strategy will generally enable them to maximize production. Volume and octane will then be made up from an increased use of alkylates. For producing CaRFG3 with ethanol, refiners will probably reduce olefins, RVP, and T50 in addition to sulfur. Alkylates will be increased to make up volume.

As discussed earlier, the cap limits for CaRFG3 are so stringent that refiners have limited flexibility. This and the above analysis led to the CaRFG3 blends described in Chapter V of the October 22, 1999, staff report. As presented in the staff report, the nonoxygenated CaRFG3 blends will lower NOx emissions compared to CaRFG3 blends with ethanol. This is primarily due to the removal of oxygen and its impact on NOx emissions.

Also, based on its knowledge of the California refinery system and on extensive conversations with each of the individual refiners, ARB staff concluded that, in general, it is impractical for refiners in their actual production of fuels to produce nonoxygenated gasolines to utilize a substantial amount of the NOx overcompliance margin associated with a zero oxygen level. In order to do this, a refiner would need to increase one or more of the three gasoline properties -- sulfur content, olefin content, or aromatic content -- that principally increase NOx emissions. Staff's assessment is that increasing sulfur is not viable, because such an increase would adversely affect THC and PWT performance, and these parameters are far more critical to production than is NOx. Similarly, there is little incentive to increase olefin content because this generally adversely affects PWT performance, involves increases to sulfur content, and adds little to production volume. Finally, increases in aromatic content are sharply limited by the need to maintain PWT, and in particular benzene. With the lower benzene content standard in CaRFG3, reducing benzene to further allow more aromatics is much more difficult.

MathPro Evaluation. The CEC contracted with MathPro, Inc.⁵ to model the composition and production cost of gasolines meeting the CaRFG3 regulations. MathPro possesses the best available overall model of the California refiner system, and is used by many parties to estimate how the state's refinery systems will likely respond to changes in either fuel regulations or component costs.

⁵ Evaluating the Cost and Supply of Alternatives to MTBE in California's Reformulated Gasoline, MathPro, Inc., prepared for the California Energy Commission, 1998-1999.

The modeled gasolines included ethanol-blended and nonoxygenated gasolines. The model output includes emission predictions (from the Predictive Model) for HC, NO_x, and PWT emissions. MathPro's report, dated December 7, 1999, was included in ARB's supplemental submittal to EPA on December 24.

MathPro's results indicate that: 1) given flexibility, substantial amounts of nonoxygenated gasoline would likely be produced, and 2) on average, NO_x emissions from the predicted nonoxygenated CaRFG3 gasoline would be substantially less than NO_x emissions from the ethanol-blended gasoline. The range of additional NO_x reductions (nonoxygenated vs. ethanol-blended at 2% oxygen) is 1.5% to 1.8%. The NO_x reduction apparently results from measures to overcome: (1) the removal of oxygen, (2) the loss of HC control provided by the oxygen, and (3) the increase in benzene emissions (i.e., PWT) stemming from increasing the reformat content by 25% to recover the octane otherwise provided by ethanol.

The measures to control HC and benzene emissions from the nonoxygenated gasoline are decreased T50, decreased T90, and reduced sulfur content. While increasing the olefin content would also mitigate the HC problem, it is not practically available. The olefins exist mainly in the dominant source of sulfur -- FCC gasoline -- so that increasing their content in the non-oxygenated gasoline would entail a counter-productive increase in sulfur. Also, a further increase in PWT from added olefins (increasing butadiene) or from added sulfur would not be tolerable.

Decreasing the RVP from the ethanol cases to the non-oxygenated cases was not a practical way to mitigate the extra HC emissions because the RVP in the ethanol cases was already down to 6.6 psi. If the MathPro model had found it more economical to make the ethanol-blended gasoline with a higher RVP, reducing that RVP in the non-oxygenated gasoline could have offset the HC effect of an increase in the sulfur content. However, the problem with the PWT emissions would have remained, limiting both the sulfur content and the olefin content of the non-oxygenated gasoline.

III. DISCUSSION OF CARBON MONOXIDE, HYDROCARBONS, AND OXIDES OF NITROGEN ISSUES

During the development of the CaRFG3 regulations, issues were raised concerning whether emissions of carbon monoxide (CO), hydrocarbons, and oxides of nitrogen (NO_x), should be treated on an equal basis in evaluating the performance of CaRFG3 blends. Similarly, concerns were expressed that, since CaRFG3 blends with oxygen contents above 2% are provided a hydrocarbon credit for CO reductions, nonoxygenated CaRFG3 blends should also be debited for not reducing CO.

These issues were thoroughly evaluated. CO, hydrocarbons, and NO_x do behave differently in the atmosphere and cannot be treated the same. A debit for nonoxygenated CaRFG3 blends related to CO emissions is also not needed to maintain equivalency of ozone-forming potential. While these blends do not reduce CO to the same extent as CaRFG3 blends with 2% oxygen, the nonoxygenated CaRFG3 blends result in less evaporative emissions, compensating for the higher CO emissions effects on ozone. These issues are discussed below in more detail.

A. Should CO, Hydrocarbons, and NO_x be treated the same?

Hydrocarbons, NO_x, and CO do not have equivalent roles in air pollution. Emission reductions of the three pollutant types are not interchangeable.

With respect to ozone formation, hydrocarbons and CO are similar in that they participate in reactions that restore atmospheric NO to NO₂, whose photolysis directly leads to ozone. The relative importance of hydrocarbons and CO in this regard is approximated by their relative values of MIR (maximum incremental reactivity), which is a scale of effectiveness in producing ozone. The typical mix of hydrocarbons in vehicular emissions has a much greater MIR than does CO; accordingly, much greater reductions of CO are needed to produce the same effect on ozone of a given reduction in exhaust (or evaporative) hydrocarbon emissions.

NO_x species do not have MIR values. MIR values cannot be assigned to NO_x species because they participate in ozone formation in a way fundamentally different from the participation by hydrocarbons and CO. Therefore, the relative importance of hydrocarbons/CO and NO_x cannot be approximated simply, and equivalence of reductions also cannot be determined simply.

Hydrocarbons, CO and NO_x also differ in their roles in the formation of particulate matter (PM). PM in California contains very substantial amounts of nitrates, which derive directly from NO_x. The nitrate fraction is larger for PM of small diameter (e.g., PM_{2.5}) than for larger PM. For example, on exceptionally bad days the nitrate portion of PM_{2.5} is sufficient to exceed the federal standard

for PM_{2.5}. Hydrocarbons in gasoline vehicle emissions, having relatively low molecular weights, are less important in PM formation. CO has no direct role in PM.

NO_x comprise a family of highly reactive gaseous compounds that contribute to air pollution in both urban and rural environments. NO_x emissions are produced during the combustion of fuels at high temperatures. The primary sources of atmospheric NO_x include stationary sources (such as power plants and industrial boilers), highway sources (such as light-duty and heavy-duty vehicles) and off-road sources (such as construction and agricultural equipment). Ambient levels of NO_x can be directly harmful to human health and the environment. NO_x also contributes to the production of secondary chemical products that in turn cause additional health and welfare effects. Prominent among these is ozone and secondary particle formation.

The conversion of NO_x into fine particulate matter (such as ammonium nitrate) is of significant human health and environmental concern. In general, PM is divided into primary and secondary sources. Primary sources include dust, dirt, soot, smoke, and liquid droplets directly emitted into the air by sources such as factories, power plants, cars, trucks, wood stoves/fireplaces, construction activity, forest fires, agricultural activities such as tillage, and natural windblown dust. Particles formed secondarily in the atmosphere by condensation or the transformation of emitted gases such as SO₂, NO_x, and VOCs are also considered particulate matter.

Secondary nitrate particles account for a substantial fraction of the airborne particulate in some areas of the country, especially in the West.⁶ Measurement of ambient PM in some western U.S. urban areas that are having difficulty meeting the current NAAQS for PM₁₀ have indicated that secondary PM is a very important component of the problem. In the Los Angeles Basin, secondary PM comprises about 25 percent of the measured PM₁₀.⁷

Because the atmospheric chemistry of secondary PM formation has common attributes to that of ozone, secondary PM tends to be a regional rather than a strictly local phenomenon. For this reason, the U.S. EPA and the State of California believe that regional-scale NO_x control, including the control of mobile NO_x sources, are necessary to reducing secondary PM.⁸

Without reductions in nitrogen oxides emissions from mobile sources, it will not be possible to demonstrate attainment of the ambient PM₁₀ standard in most urban areas of California. Thus, the greater NO_x emissions associated with

⁶ Federal Register: 40 CFR, Parts 9 and 86, Control of Emissions of Air Pollution from Highway Heavy-Duty Engines, Volume 61, Number 125, Notice of Proposed Rules, U.S. EPA, June 27, 1996.

⁷ Summary of Locale-Scale Source Characterization Studies, EPA-230-S-95-002, July, 1994, (Air Docket A-96-40).

⁸ Federal Register: 40 CFR, Parts 9 and 86, Control of Emissions of Air Pollution from Highway Heavy-Duty Engines, Volume 61, Number 125, Notice of Proposed Rules, U.S. EPA, October 21, 1997.

maintaining the federal RFG oxygen mandate will prevent or interfere with attainment of the National Ambient Air Quality Standard for PM10 regardless of the impact of the mandate on CO and HC emissions.

B. CO debit issue and non-oxygenated fuels

The CaRFG3 regulations approved by the ARB Board on December 9, 1999, requires the phase-out of MTBE from the California gasoline supply by December 31, 2002. Ethanol, which until this time has been used in a small percentage of CaRFG, will become the only viable oxygenate for California refiners, and its use is likely to increase dramatically. Removing oxygen from California gasoline will have several specific effects on emissions. First, removing oxygen, while keeping other properties constant, will increase exhaust CO and hydrocarbon emissions. Second, removing oxygen will decrease exhaust emissions of NOx. Third, removing ethanol will reduce permeation emissions.

Removing oxygen from gasoline tends to increase emissions of CO for much of the on-road fleet. While the most modern emissions control technologies (Tier 1 and later) are relatively insensitive to changes in fuel oxygen content, most older emission control technologies realize some benefits associated with oxygen. While decreasing the oxygen content of gasoline will tend to increase CO emissions, there are other factors which will mitigate the effect on ozone-forming potential.

1. Expected CO Emissions from Representative Nonoxygenated and 2.0 Wt. % Gasoline Produced to Meet the CaRFG3 Standards.

Reducing gasoline oxygen content from 2.0 wt.% to 0 wt.%, without making other changes needed to comply with the CaRFG3 regulations, would result in an estimated increase of 4.6 percent (228 tpd⁹) in CO and about a 3% increase in exhaust HC. However, for such a fuel to be lawful under the CaRFG3 program, the increase in exhaust HC must be eliminated by changes to other properties. The most likely approach will be to reduce sulfur content T50. Using the CaRFG3 Predictive Model, reducing the sulfur content from 20 ppm to 10ppm and reducing T50 from 211 °F to 205 °F will offset the increase in exhaust HC from reducing the oxygen content from 2.0% to 0%. Reducing these two properties will also reduce CO emissions. These effects are expected to mitigate about 95 TPD of the increase in CO emissions associated with removing oxygen from California gasoline. Thus, the net result of removing oxygen (2.0% to 0%), reducing sulfur content, and lowering T50 is an increase of CO emissions of about 133 tpd (228 tpd - 95 tpd). Details are provided in Appendix G of the CaRFG3 Staff Report.

⁹ This estimate is based on the Mobile Emission Inventory Model EMFAC7G. The EMFAC7G CO inventory is about 4,995 tpd. Adjusting this to the EMFAC 2000 CO inventory (12,386 tpd) would yield a net CO increase due the removal of oxygen (including a reduction in the sulfur content and lowering of T50) of about 332 tpd.

2. Changes in Hydrocarbon Emissions Due to Permeation Losses from Gasoline 2.0 wt. % Oxygen from Ethanol

The soft fuel components of automotive fuel systems tend to be significantly more permeable to ethanol than to the other hydrocarbons in gasoline. Based on available fuel permeation data from two Society of Automotive Engineering Technical Papers, 920163 and 970307, evaporative emissions associated with the permeation of ethanol were estimated to be 16 tpd greater in 2005 from '65-'05 model-year vehicles for non-oxygenated gasoline compared to gasoline with 10 volume % EtOH (assuming all fuel contained ethanol). This estimate is based on resting loss emissions only, and the assumption that all resting loss emissions are due to permeation losses. Resting loss emissions are defined as the evaporative emissions occurring when the ambient temperature declines or remains constant. This covers a period of about 16 hours a day. Since permeation losses occur throughout the entire day, permeation losses were 1.5 times ($1.5 \times 16 = 24$) that of resting losses in the inventory. Therefore, the evaporative emissions due to permeation losses is about 24 tpd. Permeation effects also likely play some role in running loss emissions, but these cannot be estimated at this time, and are therefore excluded from this analysis. The 24-tpd increase in evaporative emissions is based on gasoline with 10% ethanol. Gasoline/ethanol blends with 2.0 % oxygen contain 5.5% EtOH. If we assume that the relationship between permeation losses and fuel ethanol content is linear, then the difference in evaporative emissions when comparing non-oxygenated gasoline to gasoline/ethanol blends with 2.0% oxygen is about 13 tpd.

The difference in permeation losses between the two fuels is assumed to be made up of only ethanol. The specific reactivity for ethanol is 1.88 and the specific reactivity for CO is 0.07. Thus, a 13-tpd difference in evaporative emissions due to reductions in permeation losses is equivalent to about 350-tpd in CO emissions.

3. Net Impacts on Ozone-Forming Potential

Based on the above analysis, ARB staff has concluded that the increase in ozone-forming potential from the increase in CO emissions associated with removing oxygen from gasoline is fully offset by CO emission reductions from changes in fuel properties and by lower permeation emissions from the nonoxygenated fuel. In addition, as part of the Resolution 99-39 (see Attachment G) approving the CaRFG3 regulations, the Board has directed the ARB staff to further investigate potential increases in hydrocarbon emissions from materials permeability associated with the use of ethanol. Further analysis is to include laboratory testing. Staff is required to provide the Board with an update in October 2000 and a report on the permeability testing results by December 2001.

IV. ARB'S EFFORTS TO ADDRESS THE AIR QUALITY EFFECTS OF COMMINGLING

During the CaRFG3 rulemaking process, concerns were expressed that the CaRFG3 regulations did not deal appropriately with the issue of "commingling" (related to the potential mixing of ethanol and non-ethanol gasolines in California under the CaRFG3 regulations). The ARB staff believes the recommended 0.1 reduction in Reid vapor pressure (RVP) in the CaRFG3 regulations should be sufficient to offset the emissions impact due to ethanol "commingling effects". However, the ARB is committed, both by its own resolution and by state law, to continuing to study this issue further. If new information demonstrates the need for more stringent RVP levels the staff will return to the ARB Board with appropriate recommendations to mitigate this effect.

A. Background

When two fuels are mixed together in a vehicle fuel tank where one is a complying CaRFG3 with ethanol and the other is a complying CaRFG3 fuel with no oxygen, the resulting blend will normally have a higher vapor pressure than either of the two preblend fuels. This is called the "commingling effect."

The CaRFG3 regulations approved by the ARB Board on December 9, 1999, require the phaseout of MTBE from the California gasoline supply by December 31, 2002. Ethanol, which until this time has been used in a small percentage of CaRFG, will become the only viable oxygenate for California refiners, and its use is likely to increase dramatically. If a waiver from the federal oxygen requirement is granted, significant amounts of nonoxygenated gasoline are also expected in portions of the state now subject to the federal RFG program.

Because of this there will be a much greater potential for mixing of ethanol and non-ethanol blends in vehicle tanks, and there is a concern about the potential air quality impacts that could occur. A waiver from the federal RFG oxygenate mandate could increase the likelihood of commingling of ethanol and non-ethanol fuels in areas where the oxygenate mandate is currently in effect.

B. How Commingling Was Addressed in CaRFG3

In the rulemaking for CaRFG3, ARB staff estimated that the ethanol "commingling effect" would most likely result in an estimated 0.1 pound per square inch (psi) or less increase in the actual RVP of gasoline in vehicle tanks in areas like southern California (See Attachments D and E for the ARB and SAI analyses on commingling effects). To compensate for any loss in air quality benefits associated with this effect, the CaRFG3

regulations reduce the flat limit for RVP from 7.0 psi to 6.9 psi for gasoline produced using the revised CaRFG3 Predictive Model's procedure for evaporative emissions. It is expected that most summertime gasoline will be subject to this limit. Details are provided in the attached copy of the December 9, 1999, hearing transcripts (see Attachment F).

As part of the discussion (see Attachment F) and approval of the CaRFG3 regulations, the ARB Board recognized that it was possible that commingling could, under certain circumstances, result in a greater emissions increase than estimated. Accordingly, the Board directed the ARB Executive Officer in Resolution 99-39 (see Attachment G): "...further evaluate the expected real-world emissions impact in 2003 and beyond from the commingling of CaRFG3 containing ethanol with CaRFG3 not containing ethanol ... and to report his findings to the Board with any appropriate recommendations by December 2001."

Through Resolution 99-39, ARB staff is directed by the Board to investigate the emissions effects of ethanol commingling. The ARB staff will investigate the expected prevalence of CaRFG3 containing ethanol and CaRFG3 not containing ethanol by supplier, grade, and geographic area. ARB will also collect information needed to determine other pertinent factors such as refueling patterns and customer brand and grade loyalty. The ARB staff will also have samples collected of actual in-use fuels to further investigate the frequency and impact of commingling.

C. State Law Requirements

California law provides further assurance that any unanticipated increase in hydrocarbon emissions from commingling following an oxygen waiver will be addressed. Senate Bill 989 (see Attachment H) (Stats. 1999, ch. 812 - Senator Sher) added new section 43013.1 to the California Health and Safety Code, effective January 1, 2000. Attachment I is a copy of pages from a 2000 Pocket Part to West's Annotated California Codes, showing the text of this new section. It provides in part,

(b) The [Air Resources Board] shall ensure that regulations for California Phase 3 Reformulated Gasoline (CaRFG3) adopted pursuant to Executive Order D-5-99 meet all of the following conditions:

- (1) Maintain or improve upon emissions and air quality benefits achieved by California Phase 2 Reformulated Gasoline in California as of January 1, 1999, including emission reductions for all pollutants, including precursors, identified in the State Implementation Plan for ozone, and emission reductions in potency-weighted air toxics compounds.

The ARB staff estimates that representative gasoline produced to meet the approved CaRFG3 standards will result in a decrease in just 0.1% more HC than the HC decrease from representative 1998 gasoline produced to meet the CaRFG2 standards. If the HC increases associated with commingling are equivalent to an RVP increase of significantly more than 0.1 psi, the lower RVP standard will not offset the commingling effects. In that case, SB 989 will require the ARB to take the steps necessary to assure there will be no real-world increase in HC emissions taking commingling into account.

D. Summary

As the CaRFG3 regulations are implemented and refiners determine their refinery modifications and designs, the ARB staff will be able to better assess how much and where ethanol will be used in California to comply with the CaRFG3 standards. Staff will estimate the effects of commingling based on blending levels of ethanol, gasoline buyer patterns, market share, and refueling patterns. With this information, staff will be able to better assess the potential marketplace use of ethanol and the potential emissions impacts of ethanol commingling. If this assessment suggests that the current treatment of RVP in the CaRFG3 regulations is inadequate to prevent emissions increases due to commingling, staff will develop proposals to strengthen the CaRFG3 regulations. Both the Board resolution and state law provide assurance that the ARB will make the needed regulatory changes, if they are determined to be necessary to prevent emission increases.

IV. SIMULATION ANALYSIS OF FUTURE GASOLINES PRODUCED TO COMPLY WITH THE CARFG3 SPECIFICATIONS

To verify the consistency of the NO_x reduction associated with reducing oxygen content in gasoline from 2 percent by weight to zero percent the ARB staff created a computer simulation that calculates the NO_x reduction across many possible alternative formulations that qualify as legal fuels under the Predictive Model. The results were described in the ARB's December 24, 1999 letter to U.S. EPA Assistant Administrator Robert Perciasepe. Since the initial December 24, 1999 submittal, the size of the computer simulation has been greatly increased. The number of fuel formulations evaluated increased from about one million to about 13.5 million, of which about 6.7 million would comply under the Predictive Model. The set of possible alternative formulations is described in Table 3.

Table 3. Boundaries and resolution of computer simulation.

	Lower Bound	Upper Bound	Increment
Oxygen	0	2	2
Aromatics	15	35	5
Olefins	0	10	1
Sulfur	0	30	1
T50	175	220	2.5
T90	285	330	2.5
Benzene	.1	1.1	0.1

The procedure for the computer simulation was as follows:

- Generate a large database of different alternative formulations based on the parameters given in Table 3. 13.5 million fuels were generated.
- Each set of fuel properties is evaluated with the CaRFG3 Predictive Model, and is kept if the formulation passed the test to be a permissible alternative formulation.
- A percent change in NO_x is then calculated for each alternative formulation.
- The average change in NO_x is calculated for each level of oxygen.
- The difference is then estimated by subtracting the zero percent oxygen average NO_x value from the 2 percent oxygen average NO_x value.

Table 4 present the results of the computer simulation. The average NO_x reduction for a passing zero percent oxygen fuel is -4.2 percent, calculated from about 3.2 million passing fuels. The average reduction for a passing 2 percent oxygen fuel is -2.5 percent, calculated from about 3.5 million passing fuels. The difference between the set of fuels passing the CaRFG3 Predictive Model with

zero percent oxygen and the set of fuels passing the CaRFG3 Predictive Model with 2 percent oxygen is -1.7 percent.

Table 4. Summary of computer simulation.

	Number of Fuels	Average NOx Reduction
0 Percent Oxygen	3.2 Million	-4.2%
2 Percent Oxygen	3.5 Million	-2.5%
		Difference = -1.7%

Table 5 presents a more detailed summary of the results of the computer simulation. It is read by comparing the percent of values greater than some number. For zero oxygen, half of the fuels that passed had NOx reductions greater than -4.2 percent. At 2 percent oxygen half of the fuels that passed had NOx reductions greater than -2.4 percent. About 50 percent of the 2 percent oxygen fuels achieve less than a 2.4 percent reduction in NOx, while only about 25 percent of the zero oxygen fuels achieve a 2.5 percent or less reduction in NOx. This information is presented in graphical form in Figure 1. The computer program that generated the dataset and calculated the reductions in NOx for complying formulations of CaRFG3 fuel is presented in Figure 2.

Table 5. Percent of NOx values at two oxygen levels.

Percent of Values	0 Percent Oxygen	2 Percent Oxygen
100%	0.04%	0.04%
90%	-0.7%	-0.2%
75%	-2.5%	-1.3%
50%	-4.2%	-2.4%
25%	-5.8%	-3.7%
10%	-7.2%	-4.9%
0%	-10.1%	-7.4%

Figure 1. Cumulative percent change in NOx.

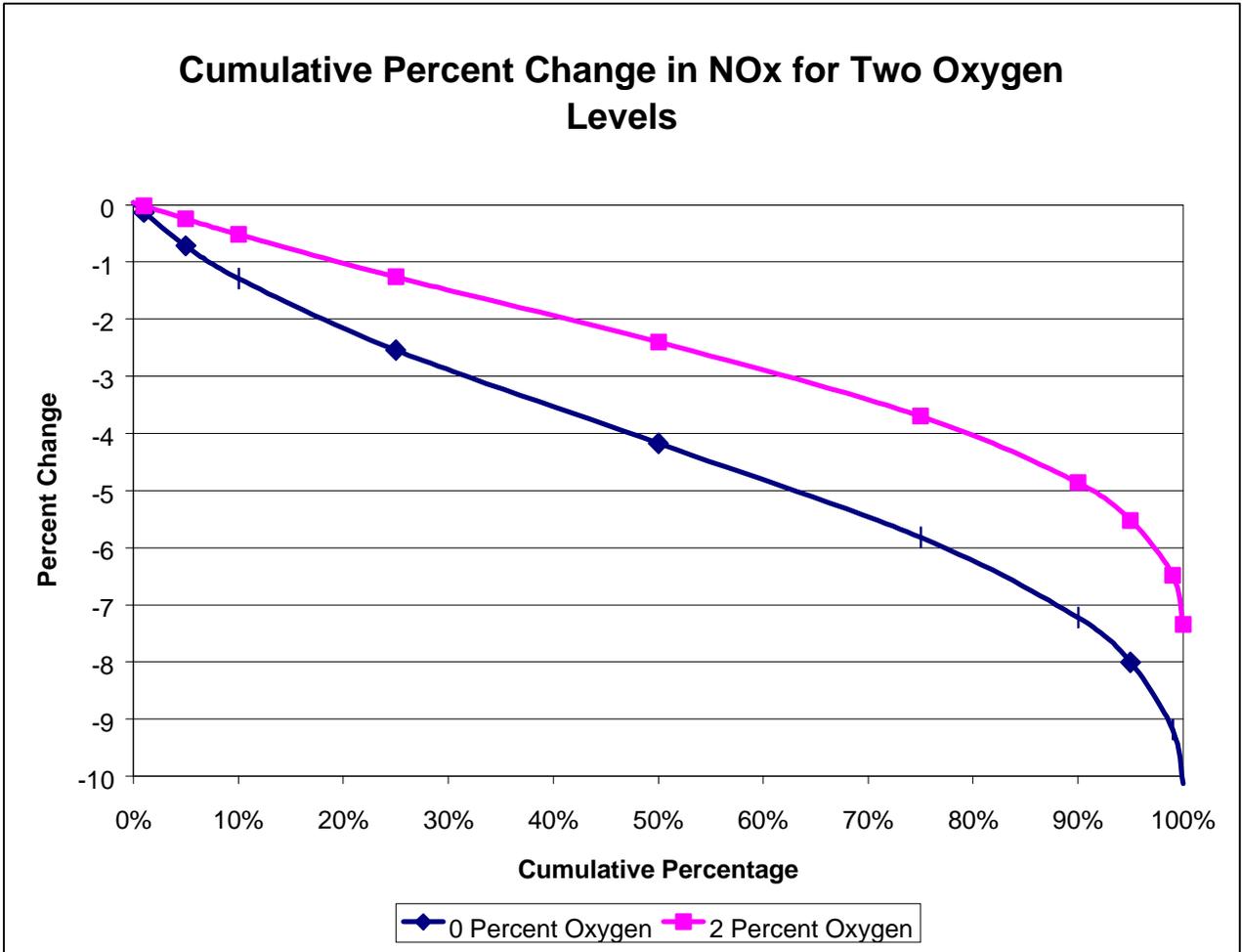


Figure 2. **Computer Program for Simulation.**

```
data dataset ;
  do oxy = 0 to 2 by 2;
  do benz = .1 to 1.1 by 0.1;
  do t90 = 285 to 330 by 2.5;
  do ar = 15 to 35 by 5;
  do ol = 0 to 10 by 1;
  do su = 0 to 30 by 1;
  do t50 = 220 to 175 by -2.5 ;

  end;
  end;
  end;
  end;
  end;
  end;
  end;
  end;
run;

data dataset;
  set dataset;
  nox=%NOx;
run;

data dataset;
  set dataset;
  if %THC < 0.04 and %NOx < 0.04 and %toxics < 0.04 then pass = 'YES';
  else pass = 'NO';
run;

proc sort data=dataset out=dataset; by oxy nox; run;

proc univariate data=dataset ;
  where pass='YES';
  by oxy;
  var nox ;
run;
```

VI. SENSITIVITY ANALYSIS TO EVALUATE THE EFFECT OF NOT INCLUDING OFF-ROAD EMISSIONS IN THE CARFG3 PREDICTIVE MODEL

During the development of the CaRFG3 regulations and the CaRFG3 Predictive Model, concerns were raised about the benefits of oxygenated compounds in gasoline and the representativeness and applicability of the Predictive Model to all gasoline usage and emissions within California. The concerns were based on the theory that oxygenated compounds in gasoline produce much greater carbon monoxide (CO) and reactive organic compound (ROG) exhaust emission reductions in uncontrolled engines, such as off-road engines, than in controlled engines, such as on-road engines. Due to limitations in test data that define how various fuel properties affect emissions from off-road engines, the Predictive Model was built solely on on-road vehicle emission data.

In order to investigate the concerns raised about the benefits of oxygenated gasoline for off-road emissions, ARB staff performed an analysis on the complete gasoline emission inventory using the CaRFG3 Predictive Model with simplifying assumptions about how nonoxygenated and oxygenated CaRFG3 gasolines would affect on and off-road emissions. These results were compared to the same analysis with the 1998 average Phase 2 gasoline.

The analysis shows that: 1) there is an increase in oxides of nitrogen emissions from use of CaRFG3 with ethanol, compared to nonoxygenated CaRFG3; and 2) the decreases in CO and exhaust ROG, associated with CaRFG3 containing ethanol, are probably offset by increased evaporative ROG emissions, when corrected for ozone-forming potential.

Off-road vehicles emit a disproportionate share of gasoline emissions primarily because they have remained uncontrolled until recent action by the ARB and U.S. EPA. Tighter emissions standards on these engines should lead to the use of more sophisticated emissions control technology such as advanced fuel control systems, post combustion controls, and evaporative controls. As the number of newer off-road vehicles increase, the effect of fuel property changes on their emissions will be more like on-road automobile emissions and would need the same fuel, CaRFG3.

A. Off-Road Emissions

Off-road vehicles are expected in 2005 to consume about 4.5 percent of the gasoline consumed by all on- and off-road motor vehicles and engines. Four-stroke engines are expected to consume about 79 percent of the total off-road gasoline, and 2-stroke engines will consume the remaining 21 percent. Within the 4-stroke, off-road engine category, pleasure craft are expected to consume about 55 percent of the gasoline; and other categories such as industrial, lawn and garden, and light-duty commercial equipment, are expected to consume

about 11 percent, 11 percent, and 14 percent of the gasoline, respectively. Within the 2-stroke, off-road engine category, pleasure craft are expected to consume about 81 percent of the gasoline, and lawn and garden equipment are expected to consume about 18 percent of the gasoline.

In evaluating emissions from off-road sources, staff found that there are very little data available on the effect of changing fuel parameters on exhaust emissions, and none with California fuels. Pleasure craft account for about 75 percent of the ROG and 66 percent of the NO_x from this category. However, there has been no program to test fuel effects in these engines in any systematic way. Further, there appear to be no usable evaporative emissions data for off-road engines. The data that are available were summarized in Appendix M of the October 22, 1999, ARB staff report, *Proposed California Phase 3 Reformulated Gasoline Regulations*. From this review, ARB staff determined that there were insufficient data to allow development of a predictive model for fuel effects on emissions from off-road engines, especially marine engines and two-stroke engines. The limited available data suggested that the decrease in exhaust CO and ROG emissions associated with oxygen in fuel would be accompanied by an increase in evaporative ROG and exhaust NO_x emissions when ethanol is used as an oxygenate.

To estimate a baseline emission inventory for off-road engines, ARB staff used the existing exhaust emission estimates for the year 2005. The evaporative emissions for off-road sources were not available from this model, and had to be estimated separately. Evaporative emissions for 4-stroke, off-road engines were estimated by applying the ratio of evaporative to exhaust ROG emissions found in the on-road inventory for light-duty trucks without catalytic control. Evaporative emissions for 2-stroke, off-road engines were estimated by applying the ratio of evaporative to exhaust ROG emissions for on-road motorcycles. The off-road evaporative emission estimates are likely to be underestimated due to the lower evaporation rates from metal fuel tanks and fuel injection systems, which are of greater prevalence in the on-road motorcycle fleet than in the off-road, 2-stroke fleet. The emission estimates are shown in Table 1.

Although off-road vehicles consume less than five percent of the gasoline consumed in California, they represent a significant part of emissions from gasoline vehicles and engines. Under the current EMFAC7G on-road inventory, off-road vehicles produce about 40 percent of ROG emissions, about 30 percent of CO emissions and about 11 percent of emissions of NO_x. Two-stroke engines, principally those used on watercraft, account for about 60 percent of the ROG from off-road sources. Conversely, four-stroke engines, again from watercraft, account for more than 90 percent of NO_x from the off-road category. Table 1 shows the statewide impact of off-road gasoline vehicle emissions compared to emissions associated with all gasoline engines and vehicles. Additional details are in Table 4.

**Table 1
Statewide Emissions Associated with Gasoline Engines - 2005 (TPD)**

	On-Road*		Off-Road		Gasoline Total
	tpd	Percent	tpd	Percent	tpd
NOx	820	89%	99	11%	919
CO	5831	69%	2671	31%	8502
ROG					
Exhaust	381	--	301	--	681
Evaporative	222	--	72	--	294
Container	0	--	92	--	92
Dist. S&T	65	--	3	--	68
Total ROG	668	59%	468	41%	1136

* EMFACT7G is in the process of being updated. Based on the preliminary data for the updated model estimates of emissions from on-road sources are expected to approximately double, and is the percent contribution of off-road ROG emissions to the total will decrease substantially.

B. Sensitivity Analysis

To respond to concerns about possible different fuel effects of CaRFG3 on emissions from off-road engines, a sensitivity analysis was conducted by staff.

Because there are insufficient off-road engine data to model the effect of fuel properties on emissions, the only way to do a sensitivity analysis on the effects of excluding off-road vehicles from the Predictive Model was to use a simpler surrogate model to reflect how off-road emissions might affect the results. The best technique available to staff to estimate exhaust emission effects from off-road vehicles was the Tech 3 model, which is a component of the Predictive Model. The Tech 3 model was developed from a data set of older on-road vehicles (pre-1981), and the technology used in those vehicles is somewhat representative of current off-road vehicles that are four-stroke engines. The Tech 3 model may represent the exhaust emission effects from larger four-stroke off-road vehicles reasonably well, but this cannot be proven with existing data. Further, the Tech 3 model's usefulness is likely to be very limited in predicting the effects on emissions from changes in fuel properties in smaller engines and in two-stroke engines. This is a significant drawback, because these sources represent a large majority of the off-road ROG emissions.

Recognizing these limitations, ARB staff proceeded to use this sensitivity analysis to evaluate the difference of the predictions made with the Predictive Model (on-road gasoline vehicle emissions) to those of a composite model that includes both on-road and off-road emission effects. In this analysis, the emissions from three expected future fuels were compared to the average gasoline produced in 1998 (with MTBE). Two of the fuels contain ethanol at 2.0 wt. % oxygen and 3.5 wt. % oxygen and one fuel was nonoxygenated. Sulfur

was held constant in using the Tech 3 model for estimating changes in off-road engine exhaust emissions.

The changes in emissions were compared for NOx, ROG, and CO. The effects of the fuel differences on materials permeation and on evaporative emissions were also included. Determining the effects of ethanol-oxygenated gasoline on permeation emissions from on-road and off-road fuel systems and portable containers is the subject of an ongoing ARB investigation. To estimate changes in evaporative emissions from off-road engines, the evaporative portion of the on-road predictive model was used along with the U.S. EPA off-road evaporative model. Separate tech-group models have not been developed for evaporative emissions. The ROG and CO emissions were adjusted for reactivity to compare their ozone-forming potential.

C. Results of Sensitivity Analysis

Table 2 summarizes the results of the analysis of the statewide effects. Additional details are in Table 5. The statewide analysis shows that modelling the combined effects of fuel oxygen: (1) changes both on-road and off-road emissions, and (2) produces relative results that are similar to the modelling of oxygen-effects in the on-road-only fleet. For example, both on and off-road models show essentially the same change for NOx. With respect to reactivity weighted CO and hydrocarbons, the difference between combined results and the on-road are relatively small when oxygen goes from zero to 2 weight percent. Based on this, ARB staff believes that any errors from not including the off-road emissions are relatively small and unlikely to change the predicted effects based on on-road emissions.

**Table 2
Percent Change in Statewide Emissions Projected in 2005
for CaRFG3 Fuels Compared to the 1998 Average Gasoline**

Future CaRFG3 Fuels	NOx Emission			Reactivity Weighted Emissions ¹		
	On-Road	Off-Road	Total	On-Road	Off-Road	Total
Non-Oxygenated	-4.8	-3.3	-4.7	-4.8	-1.6	-3.4
Ethanol, 2 wt %	-1.2	-0.4	-1.1	-4.4	-2.4	-3.6
Oxygen						
Ethanol, 3.5 wt%	-0.2	+0.7	-0.1	-4.5	-3.7	-4.2
Oxygen						

1. Includes exhaust and evaporative ROG, exhaust CO, and permeation emissions from engines, vehicle and equipment fuel systems, and portable containers.

To further evaluate this issue in an urban ozone area, a similar analysis was performed for the South Coast Air Quality Management District (SCAQMD). The SCAQMD has the worst air quality in the state and about 40 percent of the state's gasoline is consumed there. As shown in Tables 3 and 6, the analysis yielded the same relative results as the statewide analysis.

Table 3
Percent Change in South Coast Emissions Projected for 2005
for CaRFG3 Fuels Compared to the 1998 Average Gasoline

Future CaRFG3 Fuels	NOx Emission			Reactivity Weighted Emissions ¹		
	On-Road	Off-Road	Total	On-Road	Off-Road	Total
Non-Oxygenated	-4.8	-3.3	-4.6	-4.9	-1.6	-3.6
Ethanol, 2 wt %	-1.2	-0.4	-1.1	-4.3	-2.2	-3.5
Oxygen						
Ethanol, 3.5 wt%	-0.2	+0.7	-0.1	-4.1	-3.5	-3.9
Oxygen						

1. Includes exhaust and evaporative ROG, exhaust CO, and permeation emissions from engines, vehicle and equipment fuel systems, and portable containers.

D. Conclusion

Because of the lack of test data, simplifying modelling was necessary. These analyses should be interpreted with caution, at least in terms of the precise quantification of results. That being said, the evaluation of existing data for fuel effects on off-road engines does not substantiate that there are CO and ROG benefits for CaRFG with ethanol in the off-road fleet that need to be modelled as part of the CaRFG3 Predictive Model. The analysis does show that there is an increase in NOx emissions from use of CaRFG3 with ethanol, compared to nonoxygenated CaRFG3. Also, the analysis indicates that decreases in CO and exhaust ROG, associated with CaRFG3 containing ethanol, are accompanied by increased evaporative ROG emissions, when corrected for ozone-forming potential.

**Table 4
On-road and Off-road Engine Data
Statewide 2005**

	Engine Population	Fuel Consump gallons	Emissions (tons/day)							
			PM	Exhaust NOx CO		ROG	Evap. ROG	Containr ROG	Dist. S&T ROG	Sum ROG
ONROAD ENGINES TOTAL	27650939	37554830	5.40	820.22	5830.65	380.56	222.26	0.00	64.71	667.53
<i>Percent of Onroad + Offroad</i>	<i>79.69</i>	<i>95.59</i>	<i>19.78</i>	<i>89.26</i>	<i>68.58</i>	<i>55.86</i>	<i>75.50</i>	<i>0.00</i>	<i>95.59</i>	<i>58.77</i>
OFFROAD ENG (2-stroke < 25 hp)	2381657	88814	1.04	0.90	111.67	42.65	2.13	23.09	0.15	68.03
Construction	3701	865	0.02	0.02	1.04	0.03	0.00	0.22	0.00	0.25
Industrial	93	88	0.00	0.00	0.10	0.00	0.00	0.02	0.00	0.03
Lawn and Garden	2153439	63293	0.16	0.61	71.78	23.33	1.17	16.45	0.11	41.06
Light-duty Commercial	24034	4579	0.06	0.07	6.33	0.74	0.04	1.19	0.01	1.97
Logging	10079	8821	0.20	0.04	13.03	6.08	0.30	2.29	0.02	8.69
Pleasure Craft	190311	11168	0.60	0.17	19.38	12.48	0.62	2.90	0.02	16.03
OFFROAD ENGN (4-stroke < 25 hp)	3640736	266744	1.49	6.18	573.67	21.75	10.87	69.34	0.46	102.42
Agricultural	159537	23593	0.07	0.60	56.78	1.92	0.96	6.13	0.04	9.05
Airport Ground Support	28	11	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
Construction	79581	25628	0.53	0.66	52.38	1.78	0.89	6.66	0.04	9.37
Industrial	1579	1010	0.00	0.03	1.90	0.04	0.02	0.26	0.00	0.32
Lawn and Garden	3097046	117964	0.13	2.42	241.63	9.33	4.66	30.67	0.20	44.86
Light-duty Commercial	277579	79076	0.48	1.89	184.29	7.83	3.91	20.56	0.14	32.43
Logging	15813	9788	0.27	0.28	18.52	0.46	0.23	2.54	0.02	3.24
Transport Refrigeration	5343	9610	0.01	0.31	18.04	0.39	0.20	2.50	0.02	3.11
Pleasure Craft	4230	66	0.00	0.00	0.11	0.01	0.00	0.02	0.00	0.03
OFFROAD ENGN (< 25 hp) TOTAL	6022393	355558	2.53	7.09	685.34	64.40	13.01	92.43	0.61	170.45
<i>Percent of Onroad + Offroad</i>	<i>17.36</i>	<i>0.91</i>	<i>9.27</i>	<i>0.77</i>	<i>8.06</i>	<i>9.45</i>	<i>4.42</i>	<i>100.00</i>	<i>0.91</i>	<i>15.01</i>
OFFROAD ENGN (2-stroke ≥ 25 hp)	412237	287254	17.43	14.71	239.67	131.11	6.56	0.00	0.49	138.16
Lawn and Garden	497	2167	0.00	0.04	2.84	0.07	0.00	0.00	0.00	0.08
Light-duty Commercial	51	76	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.01
Pleasure Craft	411689	285011	17.43	14.67	236.73	131.03	6.55	0.00	0.49	138.07
OFFROAD ENGN (4-stroke ≥ 25 hp)	610515	1088779	1.94	76.85	1746.25	105.16	52.58	0.00	1.88	159.62
Agricultural	12537	12831	0.06	1.37	10.15	0.42	0.21	0.00	0.02	0.65
Airport Ground Support	2694	23985	0.01	2.51	10.60	0.51	0.25	0.00	0.04	0.81
Construction	10748	20399	0.32	1.25	28.88	0.88	0.44	0.00	0.04	1.36
Industrial	20364	147995	0.04	14.81	114.15	5.35	2.68	0.00	0.25	8.28
Lawn and Garden	63540	30515	0.17	1.10	65.21	1.75	0.88	0.00	0.05	2.68
Light-duty Commercial	138084	104582	0.77	5.77	194.70	6.52	3.26	0.00	0.18	9.97
Pleasure Craft	362548	748472	0.58	50.04	1322.56	89.72	44.86	0.00	1.29	135.87
OFFROAD ENGN (≥ 25hp) TOTAL	1022752	1376033	19.37	91.56	1985.93	236.27	59.14	0.00	2.37	297.77
<i>Percent of Onroad + Offroad</i>	<i>2.95</i>	<i>3.50</i>	<i>70.95</i>	<i>9.96</i>	<i>23.36</i>	<i>34.68</i>	<i>20.09</i>	<i>0.00</i>	<i>3.50</i>	<i>26.22</i>
OFFROAD ENGINES TOTAL	7045145	1731591	21.90	98.65	2671.27	300.67	72.14	92.43	2.98	468.22
<i>Percent of Onroad + Offroad</i>	<i>20.31</i>	<i>4.41</i>	<i>80.22</i>	<i>10.74</i>	<i>31.42</i>	<i>44.14</i>	<i>24.50</i>	<i>100.00</i>	<i>4.41</i>	<i>41.23</i>
ONROAD+OFFROAD ENGN TOTAL	34696084	39286421	27.30	918.87	8501.92	681.23	294.40	92.43	67.69	1135.75

NOTES:

1. Offroad evap. ROG assumed to be 5% of exhaust ROG for 2-stroke engines and 50% of exhaust ROG for 4-stroke engines.
2. Container ROG emissions distributed proportionally to fuel consumption over offroad engines < 25hp.

Table 5

STATEWIDE

CALIFORNIA PHASE 3 RFG EMISSION COMPARISON TABLES FOR 2005--
TONS PER DAY

EMFAC7G MY '71-'05	Onroad Exhaust NOx (tpd)	Offroad Exhaust NOx (tpd)	Onroad Exhaust ROG (tpd)	Offroad Exhaust ROG (tpd)	Specific Reactivity (ton/ton)	Onroad Evap. ROG (tpd)	Offroad Evap. ROG (tpd)	Container Evap. ROG (tpd)	Specific Reactivity (ton/ton)	Onroad Perm. Adj. (tpd)	Offroad Perm. Adj. (tpd)	Container Perm. Adj. (tpd)	Specific Reactivity (ton/ton)	Onroad Exhaust CO (tpd)	Offroad Exhaust CO (tpd)	Specific Reactivity (ton/ton)	Total Exhaust NOx (tpd)	Onroad Reactivity (tpd)	Offroad Reactivity (tpd)	Total Reactivity (tpd)
MTBE, 2 wt% oxy.	820	99	381	301	3.7	222	72	92	2.5	0	0	0	0.00	5831	2671	0.07	919	2351	1694	4044
Nonoxygenated	780	96	387	318	3.4	208	67	92	2.3	-3.2	-1.0	-3.0	0.78	6098	2981	0.07	876	2238	1667	3905
EtOH, 2 wt% oxy.	810	99	381	307	3.5	215	70	92	2.3	7.4	2.4	7.0	2.75	5831	2671	0.07	909	2246	1653	3899
EtOH, 3.5 wt% oxy.	819	100	371	302	3.5	238	77	92	2.3	16.2	5.2	15.4	2.17	5312	2102	0.07	918	2245	1631	3875

STATEWIDE

CALIFORNIA PHASE 3 RFG EMISSION COMPARISON TABLES FOR 2005--
PERCENT DIFFERENCE FROM PHASE 2 RFG

EMFAC7G MY '71-'05	Onroad Exhaust NOx (%)	Offroad Exhaust NOx (%)	Onroad Exhaust ROG (%)	Offroad Exhaust ROG (%)	Specific Reactivity (ton/ton)	Onroad Evap. ROG (%)	Offroad Evap. ROG (%)	Container Evap. ROG (%)	Specific Reactivity (ton/ton)	Onroad Perm. Adj. (tpd)	Offroad Perm. Adj. (tpd)	Container Perm. Adj. (tpd)	Specific Reactivity (ton/ton)	Onroad Exhaust CO (%)	Offroad Exhaust CO (%)	Specific Reactivity (ton/ton)	Total Exhaust NOx (%)	Onroad Reactivity (% dif)	Offroad Reactivity (%dif)	Total Reactivity (%dif)
MTBE, 2 wt% oxy.	0.00	0.00	0.00	0.00	3.7	0.00	0.00	0.00	2.5	0	0	0	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00
Nonoxygenated	-4.84	-3.26	1.64	5.50	3.4	-6.51	-6.51	0.00	2.3	-3.2	-1.0	-3.0	0.78	4.58	11.60	0.07	-4.67	-4.80	-1.55	-3.44
EtOH, 2 wt% oxy.	-1.21	-0.39	-0.09	2.06	3.5	-3.33	-3.33	0.00	2.3	7.4	2.4	7.0	2.75	0.00	0.00	0.07	-1.12	-4.44	-2.40	-3.59
EtOH, 3.5 wt% oxy.	-0.18	0.74	-2.72	0.23	3.5	7.12	7.12	0.00	2.3	16.2	5.2	15.4	2.17	-8.90	-21.30	0.07	-0.08	-4.52	-3.72	-4.19

Table 6

SOUTH COAST
 CALIFORNIA PHASE 3 RFG EMISSION COMPARISON TABLES FOR 2005--
 TONS PER DAY

EMFAC7G	Onroad Exhaust	Offroad Exhaust	Onroad Exhaust	Offroad Exhaust	Specific Reactivity	Onroad Evap.	Offroad Evap.	Container Evap.	Specific Reactivity	Onroad Perm. Adj.	Offroad Perm. Adj.	Container Perm. Adj.	Specific Reactivity	Onroad Exhaust	Offroad Exhaust	Specific Reactivity	Total Exhaust	Onroad Reactivity	Offroad Reactivity	Total Reactivity
MY '71-'05	NOx (tpd)	NOx (tpd)	ROG (tpd)	ROG (tpd)	(ton/ton)	ROG (tpd)	ROG (tpd)	ROG (tpd)	(ton/ton)	(tpd)	(tpd)	(tpd)	(ton/ton)	CO (tpd)	CO (tpd)	(ton/ton)	NOx (tpd)	(tpd)	(tpd)	(tpd)
MTBE, 2 wt% oxy.	275	42	128	86	3.7	76	22	30	2.5	0	0	0	0.00	1920	839	0.07	317	789	503	1292
Nonoxygenated	262	40	130	91	3.4	71	21	30	2.3	-1.3	-0.4	-1.0	0.78	2008	936	0.07	302	750	495	1246
EIOH, 2 wt% oxy.	272	42	128	88	3.5	73	21	30	2.3	3.1	0.9	2.3	2.75	1920	839	0.07	313	755	492	1247
EIOH, 3.5 wt% oxy.	275	42	124	87	3.5	81	24	30	2.3	6.7	2.0	5.0	2.17	1749	660	0.07	317	756	486	1242

SOUTH COAST
 CALIFORNIA PHASE 3 RFG EMISSION COMPARISON TABLES FOR 2005--
 PERCENT DIFFERENCE FROM PHASE 2 RFG

EMFAC7G	Onroad Exhaust	Offroad Exhaust	Onroad Exhaust	Offroad Exhaust	Specific Reactivity	Onroad Evap.	Offroad Evap.	Container Evap.	Specific Reactivity	Onroad Perm. Adj.	Offroad Perm. Adj.	Container Perm. Adj.	Specific Reactivity	Onroad Exhaust	Offroad Exhaust	Specific Reactivity	Total Exhaust	Onroad Reactivity	Offroad Reactivity	Total Reactivity
MY '71-'05	NOx (%)	NOx (%)	ROG (%)	ROG (%)	(ton/ton)	ROG (%)	ROG (%)	ROG (%)	(ton/ton)	(tpd)	(tpd)	(tpd)	(ton/ton)	CO (%)	CO (%)	(ton/ton)	NOx (%)	(% dif)	(%dif)	(%dif)
MTBE, 2 wt% oxy.	0.00	0.00	0.00	0.00	3.7	0.00	0.00	0.00	2.5	0	0	0	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00
Nonoxygenated	-4.84	-3.26	1.64	5.50	3.4	-6.51	-6.51	0.00	2.3	-1.3	-0.4	-1.0	0.78	4.58	11.60	0.07	-4.63	-4.88	-1.59	-3.60
EIOH, 2 wt% oxy.	-1.21	-0.39	-0.09	2.06	3.5	-3.33	-3.33	0.00	2.3	3.1	0.9	2.3	2.75	0.00	0.00	0.07	-1.10	-4.27	-2.22	-3.47
EIOH, 3.5 wt% oxy.	-0.18	0.74	-2.72	0.23	3.5	7.12	7.12	0.00	2.3	6.7	2.0	5.0	2.17	-8.90	-21.30	0.07	-0.06	-4.13	-3.45	-3.86