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Evaluation of Emissions Benefits of Federal Reformulated Gasoline versus Conventional Gasoline

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EVALUATION OF EMISSIONS BENEFITS OF FEDERAL REFORMULATED GASOLINE VERSUS CONVENTIONAL GASOLINE

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Evaluation of Emissions Benefits of Federal Reformulated Gasoline versus Conventional Gasoline

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List of Abbreviations

1,3-BD – 1,3-butadiene
AQIRP – Auto/Oil Air Quality Improvement Research Program
AQMD – Air Quality Management District
CAAA – Clean Air Act Amendments
CARB – California Air Resources Board
CaRFG – California reformulated gasoline
CARFG2 – California reformulated gasoline phase 2
CBG – California Cleaner Burning Gasoline
CG – conventional gasoline
CO – carbon monoxide
CO_2 – carbon dioxide
CRC – Coordinating Research Council
E10 – gasoline with 10% ethanol content
E15 – gasoline with 15% ethanol content
E200 – 200 °F distillation fraction of the target fuel in terms of volume percent
E300 – 300 °F distillation fraction of the target fuel in terms of volume percent
ETBE – ethyl tert-butyl ether
EPA – United States Environmental Protection Agency
evap – evaporative
FEAT – Fuel Efficiency Automobile Test
GREET – Argonne National Laboratory Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation Model
HAPEM – Hazardous Air Pollution Exposure Model
HC - hydrocarbons
I/M – inspection and maintenance
IM240 – inspection and maintenance 240 seconds, dynamometer drive cycle
LCA – Life cycle assessment
LDT – light-duty truck
MIR – maximum incremental reactivity
MOBILE – First generation EPA mobile source emissions model
MOVES – Current generation EPA motor vehicle emissions simulator
MSAT – Federal Mobile Source Air Toxics regulation
MSAT2 - Federal Mobile Source Air Toxics regulation phase 2
MTBE – Methyl tertiary butyl ether
NAAQS – National Ambient Air Quality Standard
NO – nitric oxide
NO_2 – nitrogen dioxide
NO_x – oxides of nitrogen ($NO + NO_2$)
OBD – onboard diagnostic system
POM – polycyclic organic matter
ppb – parts per billion

ppm – parts per million
psi – pounds per square inch
RFG – Federal reformulated gasoline
RFG2 – Federal reformulated gasoline phase 2 regulation
RFS – Renewable Fuel Standard
RIA – Regulatory Impact Analysis
RVP – Reid vapor pressure
SO_2 – sulfur dioxide
T_{50} – temperature °F at which 50% of volume distilled
T_{90} - temperature °F at which 90% of volume distilled
TAME – tert-amyl methyl ether
TOG – total organic gases
VIN – Vehicle Identification Number
VOC – volatile organic compounds

Executive Summary

The Federal reformulated gasoline program (RFG) grew out of the 1990 Clean Air Act Amendments as a response to high ozone levels in a number of major urban areas. These areas now include portions of 17 states and the District of Columbia, and represent approximately 30% of the total U.S. gasoline volume. Initially, formulation changes were limited to the addition of oxygen, reductions in benzene and fuel RVP levels. These reformulations were aimed to meet a minimum emissions reduction for volatile organic compounds (VOC), air toxics and oxides of nitrogen (NO_x) when compared to a 1990 baseline gasoline in a "1990's" technology fleet. The U.S. EPA developed two computational models, the Simple Model in 1995 and the Complex Model in 1998, which refiners have used to demonstrate compliance with the regulation.

This study was undertaken to examine the derivation of the RFG Program, which is now nearly 20 years old, and to assess its effectiveness in the context of today's vehicles and fuels. A literature review was conducted to summarize the underlying basis for the RFG Program, including the 1990 technology vehicle fleet makeup, the baseline fuel composition, and effects of fuel compositional changes upon fleet-wide emissions. Derivation of the compliance models used within the RFG Program was examined, and the sensitivity of model outputs to changes in fuel property inputs was investigated.

Since the introduction of the RFG Program, gasoline compositions within the U.S. have changed in many ways – particularly with respect to oxygenated components, sulfur levels, benzene and total aromatic levels, and vapor pressure. In this study, annual average gasoline compositional data from 1997 to 2015 (summer and winter) were used to predict emissions changes in the RFG baseline vehicle fleet based on application of the Complex Model. In addition, real-world vehicle emission measurement data collected in previous experimental studies were examined to compare time series results in RFG and non-RFG regions of the country. This was done, in part, to determine whether the relatively small emissions reduction benefits of RFG could be detected within the much larger emissions reductions that occur due to fleet turnover effects.

The Simple Model only included terms for RVP and oxygen content while the Complex Model which replaced it added terms for sulfur content, aromatics content, olefin content, and distillation properties (E200 and E300). Different equations were used for VOC control Regions 1 (southern states) and 2 (northern states). In addition, distinctions were made between vehicles categorized as "normal emitters" and "high emitters." The fleet-wide emissions reduction requirements for both Phase I and Phase II RFG are shown below in Table E1. The requirements for ozone precursor reductions (VOC and NO_x) pertain only to the ozone season (June through September), whereas the toxics reduction requirements apply year-round.

In practice, fuel blenders have satisfied the VOC and NO_x emissions reduction requirements of RFG by modifying, principally, three fuel parameters: RVP, aromatic content, and sulfur content. VOC emission reduction targets were met primarily by reducing RVP and aromatic content while NO_x reduction targets were met by reducing fuel sulfur levels. The toxics reduction requirement has been met primarily by controlling fuel aromatics and benzene levels.

Table E1. Emissions Reduction Requirements of Federal Reformulated Gasoline.

RFG	Compliance Model	Minimum Emissions Reductions (using average fuel standards) Compared to 1990 Baseline Gasoline			
		VOC Region 1	VOC Region 2	Toxics	NO_x
Phase I					
1995	Simple	-	-	16.5%	No increase
1998	Complex	36.6%	17.1%	16.5%	1.5%
Phase II					
2000	Complex	29.0%	27.4%	21.5%	6.8%

Since the Federal RFG program was primarily aimed at ozone control it is surprising that the program has never been assessed by conducting 3-dimensional, photochemical air quality modeling. The EPA used the MOBILE model to assess the total in-use emissions reduction benefits resulting from implementation of Phase 1 and Phase 2 of the Federal RFG program, and the Agency found that the performance standards were being met (United States Environmental Protection Agency, 1993). Several groups have also demonstrated the emissions benefits of benzene reductions in fuel (Winebrake et al., 2001 and Harley et al., 2006). Erdal et al. (1997) used maximum incremental reactivity factors to estimate that the reformulations reduced the reactivity of VOC emissions by 11 – 15%, which contributed to reductions in peak ozone (1.1 – 1.5ppb in New York in 2005 and 3.5 – 4.0 ppb in Los Angeles in 2010). However, the only study to use ambient ozone measurements failed to show any significant benefit of Federal RFG to reduce ozone levels (Auffhammer and Kellogg, 2011).

The Federal RFG emissions reduction requirements were predicted using a "1990's" technology fleet which is a mythical fleet that does not contain just 1990 vehicles, but also some 1986 to 1989 model year vehicles that possess "1990's" technology. Table E2 provides some background on the magnitude of the observed on-road fleet emission changes that have occurred since 1990 for CO and HC emissions for fleets sampled in the Chicago (an RFG area) and Denver (a non-RFG area) areas. Mean and median fuel specific emissions values are shown for data collected in 1990 and 1992 at a Central Ave. & I-290 site near downtown Chicago and compares them with measurements collected at the current E-23/E-106 Algonquin Rd. & I-290 site in 2004 and 2016 for percent change. Similarly we compare data sets collected in Denver in 1991 (W. 6th Ave. and I-70) and 1992 (Speer Blvd. and I-25) against data from the current E-23/E-106 Denver sampling site in 2003 and 2015.

In general the median emissions have dropped faster than the mean emissions, indicating the increasing skewness of the emissions distribution. Mean fuel specific CO emissions in the Chicago area dropped by a factor of 6 between 1990 and 2004 and a factor of 11 by 2016 with mean fuel specific HC emissions reductions being roughly double those factors. In Denver, the reductions for both of these emissions species were smaller (mean CO decreases of a factor of 2 between 1991 and 2003 and more than a factor of 7 by 2015). Yet by 2015 the CO and HC emissions reductions in Denver were approaching 90% with fleet mean emissions close to those observed in Chicago. These reductions are significantly larger than those predicted from the fuel changes alone (see Table E1).

Table E2. Fuel Specific Emission Reductions for Early 1990 Fleets in Chicago and Denver.

City	Year	Location	Measurements (Mean MY)	Mean / Median gCO/kg of fuel %Reduction (Start Yr.)	Mean / Median gHC/kg of fuel %Reduction (Start Yr.)
Chicago	1990	Central Ave & I-290	13,639 (1985.3)	125 / 47.2	49.3 / 34.6
Chicago	1992	Central Ave & I-290	8,733 (1986)	121 / 32.3	33 / 25.8
Chicago	2004	Algonquin Rd & I-290	21,838 (1999.2)	21.5 / 5.3 83/89% (1990) 82/84% (1992)	2.8 / 2.1 94/94% (1990) 92/92% (1992)
Chicago	2016	Algonquin Rd & I-290	30,062 (2009.6)	10.9 / 3.1 91/93% (1990) 91/90% (1992)	1.8 / 0.9 96/97% (1990) 95/97% (1992)
Denver	1991	W. 6th Ave & I-70	13,391 (1985.9)	89 / 26.5	62.8 / 47.9
Denver	1992	Speer Blvd & I-25	49,201 (1985.7)	95.5 / 15.8	23.6 / 14.7
Denver	2003	6th Ave & I-25	21,323 (1996.4)	44 / 10.5 51/60% (1991) 54/34% (1992)	4.2 / 1.7 93/96% (1991) 82/88% (1992)
Denver	2015	6th Ave & I-25	23,318 (2005.5)	12.6 / 4.1 86/85% (1991) 87/74% (1992)	3.4 / 1.8 95/96% (1991) 86/88% (1992)

This emphasizes that many improvements were occurring during this time frame.

Since 2000 significant changes in fuel oxygen content, sulfur content and aromatic content have occurred in both RFG and conventional gasoline (CG). Calculating year over year fuel specific on-road emission reductions for Chicago, IL (2004 – 2016, RFG) and Tulsa, OK (2003 – 2015, CG) we observe that for the age adjusted gasoline fleet, the CO and NO emissions have decreased in the two cities at similar rates (52% vs 49% for CO and 66% vs 68% for NO). HC emission reductions are the one exception as total HC emissions have not dropped as fast in Tulsa as they have in Chicago (15% vs 34%) over this time period. For HC emissions there are significant differences between the Tulsa passenger and truck fleet with the passenger fleet showing increased HC emissions (-35%) during this period while the Tulsa truck fleet showed HC emission reductions (51%) similar to those seen in the Chicago trucks (62%). Keeping in mind that this is not a one to one comparison, yet the observed in-use emissions reductions are significantly larger than the model predicted benefits for the fuels alone indicating that additional factors are involved in the reductions.

Since the beginning of the Federal RFG program, fuel properties have significantly changed for both CG and RFG resulting in fuels today that are similar in most properties, the one exception is RVP where CG is allowed a 1lb psi waiver for the addition of 10% ethanol. Beginning with the phase-in of Tier 3 fuels in 2017 we expect that the differences between the two fuels will decrease again and on-

road vehicle emissions will continue to remain very low and it is unlikely that differences in fuel properties between Federal RFG and CG any longer plays a significant role in these low emissions.

1. Background

The passage of the 1990 Clean Air Act Amendments (CAAA) set in motion a number of new requirements aimed at reducing mobile source emission in the US.[1] These included reductions to US vehicle emission certification standards, new vehicle emissions equipment durability standards, which would later result in the light-duty onboard diagnostic (OBD) system, reformulated fuels and changes to inspection and maintenance (I/M) programs. Because fuels are a necessary part of a vehicle's operation, they were a major focus of the Auto/Oil Air Quality Improvement Research Program (AQIRP) in the early 1990's.[2] This effort produced one of the largest databases of potential fuel effects on light-duty vehicle emissions. AQIRP also spotlighted the large differences between low- and high-emitting vehicles and demonstrated that the latter made evaluating fleet fuel effects very difficult.[3]

The definition and use of Federal reformulated gasoline (RFG) were first stipulated by the CAAA of 1990. Full implementation of Phase I RFG regulations began in 1995; Phase II RFG was implemented in 2000. The primary purposes of the RFG regulations were to address high concentrations of the photochemical pollutant, ozone, as well as toxic air pollutants in major metropolitan areas. The locations originally subject to RFG requirements were the nine metropolitan areas then classified as "Extreme" or "Severe" non-attainment with respect to the National Ambient Air Quality Standard (NAAQS) for ozone. These include the metropolitan areas of Baltimore, Chicago, Hartford, Houston, Los Angeles, Milwaukee, New York City, Philadelphia, and San Diego. In addition, several ozone areas classified as "Marginal," "Moderate," or "Serious" agreed to "opt-in" to the RFG program as a way to help attain their air quality goals.

A map of the current Phase II RFG areas (including opt-in areas) is shown in Figure 1.[4] These areas include portions of 17 states and the District of Columbia, and represent approximately 30% of the total U.S. gasoline volume. However, the California RFG areas are exempt from the Federal requirements. California adopted its own standards for reformulated gasoline for the entire state in 1996 – called Cleaner Burning Gasoline (CBG) or CaRFG – and these already met the EPA Phase II RFG requirements. (A more detailed map showing U.S. gasoline requirements as of 2015 is included as Appendix A.)

Figure 1. Federal Phase II RFG areas, including opt-in areas.
(http://nepis.epa.gov/Exe/ZyPDF.cgi/00000FG5.PDF?Dockey=00000FG5.PDF)

Federal Phase I RFG required a year-round average oxygen content of at least 2.1 wt. %, and established a maximum benzene level of 1.0 vol.%. In addition, summertime vapor pressure was

restricted to ≤ 7.1 psi in VOC Region 1 areas (southern states) and ≤ 8.0 psi in VOC Region 2 areas (northern states). Fuels were required to meet the VOC control requirements at retail outlets from June 1 through September 15 of each year.

1.1 Simple and Complex Models

Attainment of the required reductions in ozone precursor emissions was first defined by use of the so-called "Simple Model," which relates VOC emissions of the vehicle fleet to the fuel properties of RVP and oxygen content.[5] VOCs were calculated separately for exhaust, evaporative, refueling and running loss emissions, and different equations applied to VOC Control Regions 1 and 2. In addition, Phase I RFG required a reduction in toxics emissions – defined to include benzene, formaldehyde, acetaldehyde, 1,3-butadiene (1,3-BD), and polycyclic organic matter (POM). The Simple Model was also used to determine compliance with Phase I RFG toxics reduction requirements, but the model did not include any terms that correlated changes in NO_x as a function of fuel properties.

In 1998, the EPA "Complex Model" replaced the Simple Model for determining compliance with the Phase I RFG emissions reduction requirements.[6, 7] Besides RVP and oxygen content, the Complex Model added terms for sulfur content, aromatics content, olefin content, and distillation properties (E200 and E300). Different equations were used for VOC control Regions 1 and 2. In addition, distinctions were made between vehicles categorized as "normal emitters" and "high emitters." The Complex Model equations were modified slightly two years later, when they were defined for use to assess compliance with the Phase II RFG emissions reduction requirements. The fleet-wide emissions reduction requirements for both Phase I and Phase II RFG are shown below in Table 1. The requirements for ozone precursor reductions (VOC and NO_x) pertain only to the ozone season (June through September), whereas the toxics reduction requirements apply year-round.

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2000	Complex	29.0%	27.4%	21.5%	6.8%

The emissions reduction requirements for RFG were established relative to 1990-technology vehicles using 1990 fuels. The fuel effects reflected in the Simple and Complex models were based upon results from experimental studies meant to represent a fleet of 1990-technology vehicles. [As described in EPA's Final Regulatory Impact Analysis (RIA) for RFG, emissions results were obtained from several vehicle test programs, including the Auto/Oil AQIRP, with "1990 technology" vehicles actually including 1986-1990 model years.][8]

Baseline emissions from the 1990-technology fleet were defined by EPA in the RFG Regulations.[9] Separate summer and winter emissions values were included for exhaust and non-exhaust pollutants in both VOC Control Regions 1 and 2. Different baselines were used for derivation of the Simple and the Complex Model. For the Simple Model, EPA's vehicle emissions model, MOBILE4.1 was used to apply the fuel effects over the entire fleet of 1990-technology vehicles. It was also assumed that Stage II vapor recovery systems were in use, having an emissions removal efficiency of 86%. In addition, Basic I/M programs were assumed to be in effect, with a vehicle failure rate of 20%.

For the Complex Model, MOBILE5a was used to determine fleet-wide emissions. It was also assumed that Enhanced I/M programs were in use, with a vehicle failure rate of 1%. Although it was known that vehicle on-board refueling controls would be introduced in 1996, emissions reduction impacts of this technology were not included, as the Complex Model is concerned only with 1990-technology vehicles, which would not be affected by these controls. The RIA describes several other modeling changes between derivation of the Simple and Complex Models, although the changes in the MOBILE version and in the I/M program parameters used to estimate the baseline emissions appear to be the most consequential.

1.2 Other fuel changes since 1990

Since the RFG regulations went into effect, there have been several other fuel regulatory changes. A brief chronology of the major changes for conventional summer gasolines is shown in Table 2, where the first line of data indicates properties of the 1990 baseline gasoline, as specified in EPA's RFG regulations. This is the baseline against which candidate RFG fuels are judged when determining their compliance with the emissions reduction requirements.

Table 2. Average Summer Conventional Gasoline Properties and Requirements.
(taken from U.S. Environmental Protection Agency[8])

Gasoline Standards/ Regulations	Year	Oxygen, wt. % (min.)	Sulfur, ppm (avg.)	RVP, psi[a,b] (max.)	E200, vol. %	E300, vol.%	Aromatics vol. % (max.)	Olefins, vol. % (max.)	Benzene, vol. % (avg.)
RFG Baseline	1990	0.0	339	8.7	41.0	83.0	32.0	9.2	1.53
RVP control	1992			7.8, 9.0					
Phase I RFG	1995	2.1		7.1, 8.0					0.95
Phase II RFG[c]	2000	2.1[d]		-					0.95
Tier 2	2004[e]		30	7.8, 9.0					
MSAT2	2011		30	7.8, 9.0					0.62
Current Conv.[f]	2016	3.5	30	7.8, 9.0					0.62
Tier 3[f]	2017	3.5	10	7.8, 9.0					0.62

Notes: (a) Lower value for VOC Region 1; higher value for VOC Region 2
(b) 1 psi increase allowed for fuels containing 9-10 vol.% ethanol. With this increase, 9.0 psi CG is allowed to have a vapor pressure of 10.0 psi
(c) Subsequent Tier 2 standards for sulfur and MSAT standards for benzene also apply to RFG
(d) Oxygen requirement was removed in 2006
(e) Tier 2 standards phased in 2004-2007
(f) Assumes E10 gasoline, which equates to 3.5 wt.% oxygen

As noted in Table 2, RVP controls for conventional gasoline (CG) were first implemented in 1992, establishing summertime maxima of 7.8 psi and 9.0 psi in Regions 1 and 2, respectively. These RVP limits apply to all CG since 1992. Phase I RFG had slightly lower RVP limits of 7.1 and 8.0 psi, while Phase II RFG has no special RVP limits – hence the conventional limits of 7.8 and 9.0 psi apply. A 1.0 psi waiver is allowed for CG that contains 9-10 vol.% ethanol (E10); thus the 7.8 and 9.0 psi limits for CG become 8.8 and 10.0 psi for E10 CG. This 1.0 psi waiver is not permitted for RFG.

Implementation of Tier 2 gasoline standards in 2004 reduced the annual average sulfur content to 30 ppm; a further reduction to an annual average of 10 ppm occurred in 2017, under the Tier 3 gasoline standards.[10, 11] These lower limits also apply to RFG, thus greatly reducing RFG's ability to reduce emissions by means of further lowering sulfur content. Because of this, the NO_x emissions reduction requirements originally stipulated for RFG were eliminated in 2007, following phase-in of Tier 2 gasoline standards, which lowered fuel sulfur levels to 30ppm.

Phase I RFG required a minimum oxygen content of 2.1 wt.%, as compared to the 1990 baseline level of 0.0 wt.%. The Phase II RFG oxygen content requirement was originally 2.1 wt. % as well, but this requirement was removed in 2006. Currently, RFG has no oxygen content requirement. However, to satisfy the renewable volume obligations under the Federal Renewable Fuel Standard (RFS) rules, nearly all gasoline (both CG and RFG) contains 10 vol.% E10. This level translates to an oxygen content of approximately 3.5 wt.%.[12]

Finally, implementation of the Mobile Source Air Toxics (MSAT) rule in 2011 established an annual average benzene limit of 0.62 vol.% for all gasoline (CG and RFG).[13] Benzene content is an important driver of total vehicle toxics emissions. Because of this, the toxics emissions reduction requirements originally stipulated for RFG were eliminated in 2011, following implementation of the MSAT2 rule. Considering all the fuel changes shown in Table 2, it is clear that the differences between RFG and CG today are much less than the differences when RFG was first implemented. In particular, differences in oxygen content, sulfur content, and benzene level have become very small. This suggests that the emissions reduction benefits of RFG compared to conventional fuel have also diminished with time.

This study was undertaken to examine the derivation of the RFG Program, which is now nearly 20 years old, and to assess its effectiveness in the context of today's vehicles and fuels. A literature review was conducted to summarize the underlying basis for the RFG Program, including the 1990 technology vehicle fleet makeup, the baseline fuel composition, and effects of fuel compositional changes upon fleet-wide emissions. Derivation of the compliance models used within the RFG Program was examined, and the sensitivity of model outputs to changes in fuel property inputs was investigated.

Since the introduction of the RFG Program, gasoline compositions within the U.S. have changed in many ways – particularly with respect to oxygenated components, sulfur levels, benzene and total aromatic levels, and vapor pressure. In this study, annual average gasoline compositional data from 1997 to 2015 (summer and winter) were used to predict emissions changes in the RFG baseline

vehicle fleet based on application of the Complex Model. In addition, real-world vehicle emission measurement data collected in previous experimental studies were examined to compare time series results in RFG and non-RFG regions of the country. This was done, in part, to determine whether the relatively small emissions reduction benefits of RFG could be detected within the much larger emissions reductions that occur due to fleet turnover effects.

2. Literature Review of RFG Effectiveness

Typically, the effectiveness of an ozone control regulation is assessed by conducting 3-dimensional, photochemical air quality modeling. To do this, a well-characterized meteorological domain is chosen, along with an established chemical mechanism. Gridded emissions inputs are used to represent a baseline case and one or more test cases. A recent example of this type of assessment was conducted by EPA, who evaluated the air quality impacts (including ozone) of increased ethanol usage under the RFG2 regulations.[14] To our knowledge, this type of sophisticated air quality modeling has not been done to assess the ozone reduction effectiveness of RFG regulations. However, in the RIA for the RFG Program, EPA did develop estimates of projected total in-use emissions reduction benefits resulting from implementation of Phase 1 and Phase 2 of the program.[8]

To assess the potential emission inventory benefits associated with RFG Phase 1, EPA used the MOBILE vehicle emissions model to estimate fleet-wide baseline emissions in calendar year 1998 (three years after introduction of the new fuel). The Complex Model was used to estimate the effects of fuel compositional changes between the 1990 baseline gasoline and an RFG Phase 1 fuel that met the averaging requirements under the Simple Model. VOC emissions reductions were estimated under both Basic and Enhanced I/M conditions, as both of these programs were in existence during the time frame appropriate for RFG Phase 1 gasoline. No substantial NO_x reductions were expected from Phase 1 fuels, and toxics reductions were not quantified. The VOC emissions reductions were converted to units of tons/year, assuming that RFG would be used in the 9 mandated areas plus other areas that had opted-in to the program by mid-1993.

To assess the effectiveness of RFG Phase 2, EPA used the MOBILE model to determine fleet-wide baseline emissions in calendar year 2003 (3 years after introduction of the new fuel). At this time, all areas were assumed to have Enhanced I/M programs in effect. The Complex Model was used to estimate the emissions differences between Phase 1 and Phase 2 RFG fuels. The total expected emissions reduction benefits for both the Phase 1 and Phase 2 programs, expressed as tons/year, are shown in Table 3. In addition, this table shows the expected reductions in annual cancer incidences resulting from lower toxics emissions.

We are unaware of any air quality modeling studies that used the overall emissions reductions shown in Table 3 (properly allocated spatially and temporally) to assess the ozone or air toxics benefits of the RFG Program. Nevertheless, there are several published papers/reports that provide other types of information useful in assessing the effectiveness of RFG in reducing both ozone and selected air toxics. A brief summary of this literature is provided below.

Table 3. Emissions Reductions Predicted for RFG Program[8].

Pollutant Metric	RFG Phase 1[a]		RFG Phase 2[b]	
	VOC Region 1 (South)[c]	VOC Region 2 (North)[c]	VOC Region 1 (South)	VOC Region 2 (North)
VOC, 10^3 tons/year	118/77	187/119	10.0	32.0
NOx, 10^3 tons/year	-	-	8.6	11.8
Toxics, 10^3 tons/year	-	-	0.37	0.63
Annual reduced cancer incidences[d]	24/16		4	

Notes: (a) Phase 1 benefits in 1998, relative to 1990 baseline gasoline
(b) Phase 2 benefits in 2003, relative to RFG Phase 1 gasoline
(c) First number assumes Basic I/M; second number assumes Enhanced I/M
(d) Reduced cancer incidences not broken out by VOC control area

In 1997, Spitzer published a paper in which he used the Hazardous Air Pollution Exposure Model (HAPEM) to estimate emissions reduction benefits of MTBE-containing RFG as compared to 1990 baseline CG in a 1995 vehicle fleet.[15] All five toxics defined in the RFG Program were included (benzene, formaldehyde, acetaldehyde, 1,3-BD, and POM). Results showed that use of RFG reduced seasonal-average ambient air concentrations of total toxics by 25% and 28% in summer and winter, respectively. Approximately 85% of this benefit was attributed to reductions of benzene.

Also in 1997, Erdal et al. published a study investigating the projected health benefits of MTBE-containing RFG.[16] The MOBILE5a vehicle emissions model was used to develop fleet-wide emissions estimates using 1990 CG. The MOBILE and Complex models were then used to define changes from baseline emissions when using RFG (based on 1995 fuel data). For both the base case and the RFG case, ozone-forming potential of the VOC emissions was estimated, using maximum incremental reactivity (MIR) factors for each VOC constituent. Results showed that reactivity-adjusted total organic gases (TOG) were reduced 11-15% by use of RFG, compared to use of CG. Using these reactivity-adjusted TOG emissions as an indicator of RFG's impact on peak ozone, the authors estimated that RFG would reduce peak ozone by 1.1-1.5 ppb in New York (in 2005), and by 3.5-4.0 ppb in Los Angeles (in 2010). These very small reductions were said to be in good agreement with the Auto/Oil AQIRP modeling studies.

In 2001, researchers at Argonne National Laboratory published a life cycle assessment (LCA) study in which they used the GREET Model (Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation) to investigate toxic emissions from CG, RFG, and alternative fuels.[17] At that time, the GREET Model did not include treatment of specific toxic compounds, but it was modified for this study to evaluate benzene, formaldehyde, acetaldehyde, and 1,3-BD. Total life cycle emissions of these species were determined for a 1996 baseline fleet operating on CG. This baseline was then compared against the same fleet operating on various blends of Federal RFG and CaRFG, in addition to several alternative fuel vehicle fleets. A summary of the results, shown in Table 4, indicates substantial reductions in total toxics from all types of RFG, with most of the benefit deriving from

Table 4. Percent Reduction in Life Cycle Emissions Compared to Conventional Gasoline (taken from Winebrake et al. [17])

Type of RFG	VOC	Benzene	Formald.	Acetald.	1,3-BD	Total Toxics
RFG with MTBE	15.6	35.4	-15.6	1.3	2.6	22.4
RFG with Ethanol	9.0	34.2	-2.7	-89.9	-1.2	18.6
CaRFG w/o oxygenate	15.6	40.9	-13.8	-1.1	16.4	27.2
CaRFG with Ethanol	11.8	40.2	-6.7	-47.5	11.3	25.1

benzene reductions. These calculated toxics benefits were tempered by aldehyde emissions, which increased significantly with all of the RFG formulations. Formaldehyde emissions increased the most when using MTBE-containing RFG; acetaldehyde emissions increased the most when using ethanol-containing RFG.

Some understanding about the effectiveness of RFG can also be inferred from investigations involving Phase 2 of CaRFG (CaRFG2), which was introduced early in 1996. Similar to Federal RFG, CaRFG2 required addition of oxygenates, lower RVP, and reduced levels of sulfur, benzene, and total aromatics. In addition, CaRFG2 mandated reductions in distillation temperatures (T_{50} and T_{90}) and reduction of total olefin content.[18] Fuel blenders could either produce gasolines that comply with a fixed CaRFG2 compositional formula, or use a "Predictive Model" to blend fuels that provide equivalent or greater emissions reductions. This Predictive Model is somewhat similar to EPA's Complex Model in that it estimates total vehicle emissions (evaporative and exhaust) as a function of gasoline property changes.

To assess the in-use emissions reduction performance of CaRFG2, a group of researchers from U.C. Berkeley and the Bay Area Air Quality Management District (AQMD) conducted a series of roadway tunnel measurements in the Caldecott Tunnel of Northern California from 1994 to 1997.[19, 20] Over this entire period, on-road vehicle emissions were reduced 31±5% for CO, 43±8% for VOC, and 18±4% for NO_x. These large reductions resulted from both fuel changes and fleet turnover. While difficult to cleanly separate these two effects, it was clear that CaRFG2 had a larger effect on VOC reductions than on NO_x reductions. The effect of CaRFG2 on benzene reductions was clearer, and estimated to be 30-40%. No direct assessments of ozone benefits were made, although the researchers noted that reactivity of the tunnel emissions (based on application of MIR factors) was reduced by 8% or less.

Some years later, the same U.C. Berkeley and Bay Area AQMD groups published a more in-depth analysis of CaRFG2 and fleet turnover effects on benzene emissions over a wider time window of 1991-2005.[21] Annual average ambient benzene concentrations over this time period were reduced from about 5 $\mu g/m^3$ to 1 $\mu g/m^3$, with an abrupt change from 3.6 to 2.1 $\mu g/m^3$ between 1995 and 1996. This sharp drop in ambient benzene was attributed to introduction of CaRFG2, which occurred at the

same time. The Caldecott Tunnel measurements showed a 54% reduction in vehicular benzene emissions between 1995 and 1996, of which only 4% (absolute) was attributed to fleet turnover.

A group from the Desert Research Institute (DRI) reported on a similar roadway tunnel study conducted in Southern California.[22] Sampling was done in the Sepulveda Tunnel both before (1995) and after (1996) introduction of CaRFG2. Perhaps due to greater variability in driving patterns within the Sepulveda Tunnel, these results were not as definitive as those from the Caldecott Tunnel described above. Measured reductions in the Sepulveda Tunnel were 17%, 8%, and 18% for CO, NMHC, and NO_x, respectively. However, only the CO and NO_x reductions were determined to be statistically significant. Although total toxics were not measured, a 27% reduction in benzene emissions was observed. No significant change was noted in the ozone-forming potential of the NMHC emissions, as determined using MIR factors.

In 2001, Larsen (CARB) published an assessment of the impact of CaRFG2 on ozone in three regions of California: Los Angeles, San Francisco, and Sacramento.[23] A detailed statistical modeling approach was used, based on daily ozone measurements and meteorological conditions, to compare ambient ozone concentrations before (1993-1995) and after (1996) introduction of CaRFG2. Through a variety of adjustments, meteorology was "normalized" for the two time periods. Because many other emissions changes occurred during the time period of interest, only a fraction of the observed ozone benefits was attributed to the fuel change. It was concluded that introduction of CaRFG2 had significant ozone reduction benefits of 8-13% in Los Angeles and 3-15% in Sacramento, while no consistent benefit was seen in San Francisco.

A somewhat similar type of statistical approach to assess the ozone reduction effectiveness of RFG was published in 2011 by Auffhammer and Kellogg.[24] These researchers conducted long-term trend analyses of ozone concentrations measured at hundreds of air quality monitors throughout the U.S. between 1989 and 2003. Different statistical methods were used to control for weather, and to assess ozone differences in geographic regions subject to Federal RFG, Federal RVP-control gasoline (CG), and CaRFG. It was concluded that no significant ozone reductions occurred upon introduction of either RVP-control gasoline or Federal RFG, but that use of CaRFG did result in ozone decreases. The effectiveness of CaRFG was attributed to the targeted control of olefins and aromatics, which are more potent ozone precursors than most gasoline constituents that are removed to achieve RVP reductions.

To summarize, although a primary purpose of the RFG Program was to reduce ambient ozone concentrations in specified Extreme and Severe nonattainment areas, there is very little evidence that this goal was achieved. As required by the regulations, significant reductions in ozone precursor emissions (VOC and NO_x) very likely resulted from introduction of RFG, but the translation of this to ambient ozone reductions is unclear. Due to the evolution of CG requirements since 1990 (discussed in the next section), the emissions reduction benefits of RFG compared to CG have eroded over time. Therefore, whatever ozone reduction benefit was originally provided by RFG has diminished. A second major purpose of the RFG program was to reduce concentrations of air toxics. There is much stronger evidence that this goal was achieved, particularly due to reduced benzene

emissions. However, again due to changes in CG properties, this benefit has clearly diminished over time, and may no longer be significant.

3. U. S. Fuel Properties since 1997

The US EPA routinely assembles and tracks volume-weighted fuel composition and properties for RFG and CG in 49 states (excluding California). The data used in these compilations are provided by fuel suppliers (refiners, gasoline blenders, and importers) who report such information for every batch of fuel released to the marketplace. Thus, these average fuel properties reported by EPA are not based on marketplace sampling and analysis. Furthermore, these data do not provide information about the geographic distribution of the fuels.

At the time this project began, EPA had posted only properties of volume-weighted summer and winter gasolines for the years 1997 to 2005. Very recently, this database was expanded to cover the period of 1997 to 2015. These gasoline properties (for both RFG and CG) are available on an EPA website at: https://www.epa.gov/fuels-registration-reporting-and-compliance-help/gasoline-properties-over-time. Summaries of these data for the entire period of 1997-2015 are provided in Appendix B. (Note that after 2005, gasoline properties were adjusted by EPA to account for downstream blending of ethanol and better represent the gasoline properties at retail. It is these "ethanol corrected" data that were used in this study.)

Using this information, we prepared a series of eleven trend line graphs for the volume-weighted annual average (summer and winter) fuel properties included in this EPA database that are used in the Complex Model (Figures 2-12). Where relevant, we have also included on these graphs the value of the 1990 Clean Air Act baseline for each property (both summer and winter). These baseline values are used in the Complex Model to assess emissions reductions from use of RFG (and other fuels).

Figures 2-5 graph the trends for average weight percent oxygen and the main oxygenate blend stocks providing the oxygen (MTBE, ethanol, and TAME). Note that a baseline value of zero is used for all oxygenates; thus, separate baseline points are not shown on any of these graphs. Also, no graph is included for ETBE or t-butanol, as near-zero values are reported for these oxygenates during 1997-2005, and no values are reported after 2005. As can be seen in Figure 2, average oxygen content increased for both RFG and CG during this period, with very little difference between summer and winter fuels. From 1997 to 2005, RFG had about 2-3 times the oxygen content of CG. This disparity increased even further in 2006-2008. After this time, however, the oxygen content of CG increased rapidly, while that of RFG remained flat, thereby reducing the difference in oxygen content between RFG and CG. By 2015 (the most recent year with complete data), the difference in oxygen content between RFG and CG was very small – less than 0.3% absolute.

Figures 3-5 illustrate that the oxygenate of choice switched from the methyl ethers, MTBE and TAME, to ethanol during this period. The concentration trends of MTBE and TAME closely parallel

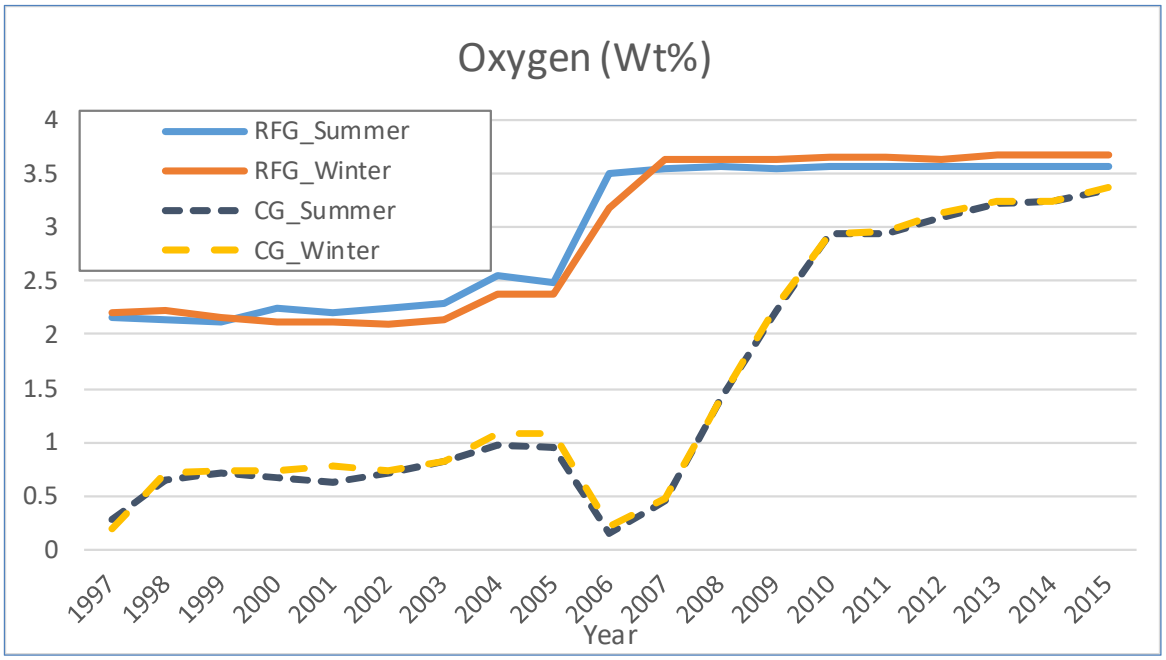

Figure 2. Average weight percent oxygen in RFG and CG during summer and winter from 1997 to 2015.

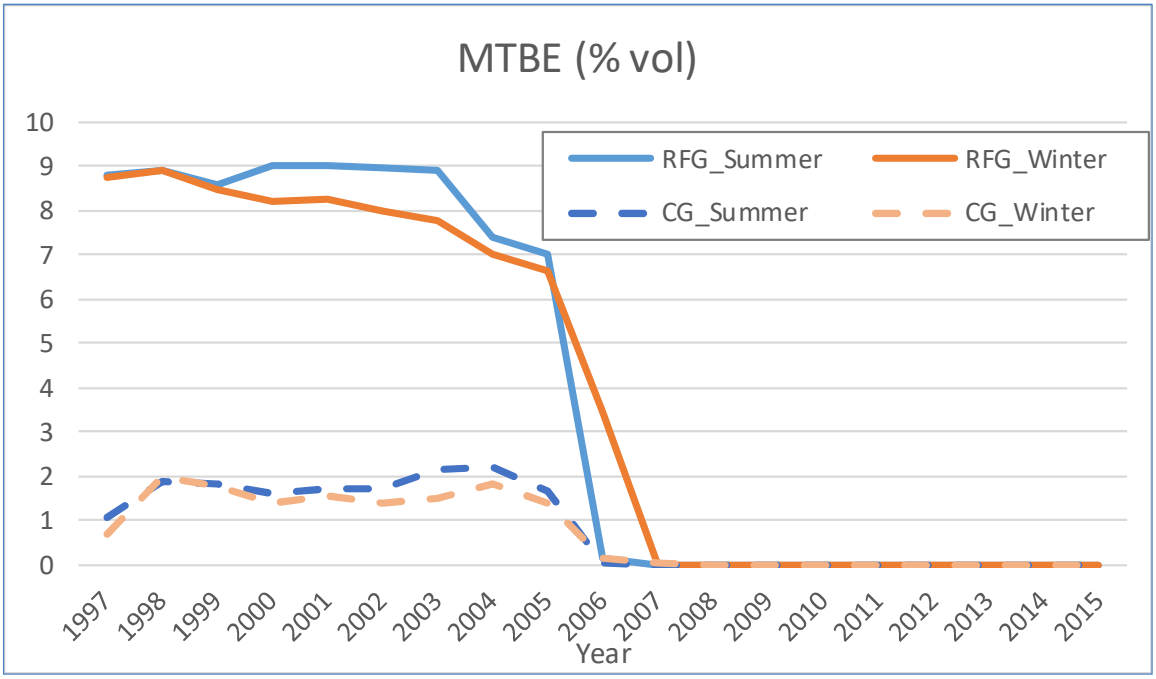

Figure 3. Average Volume percent MTBE in RFG and CG during summer and winter from 1997 to 2015.

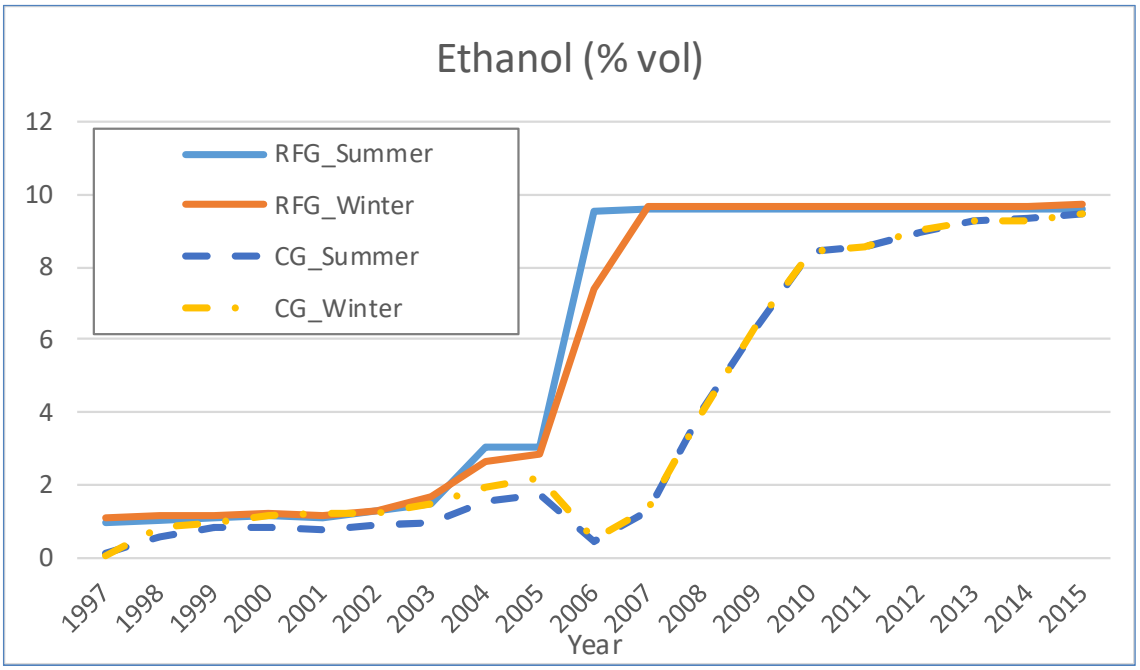

Figure 4. Average volume percent ethanol in RFG and CG during summer and winter from 1997 to 2015.

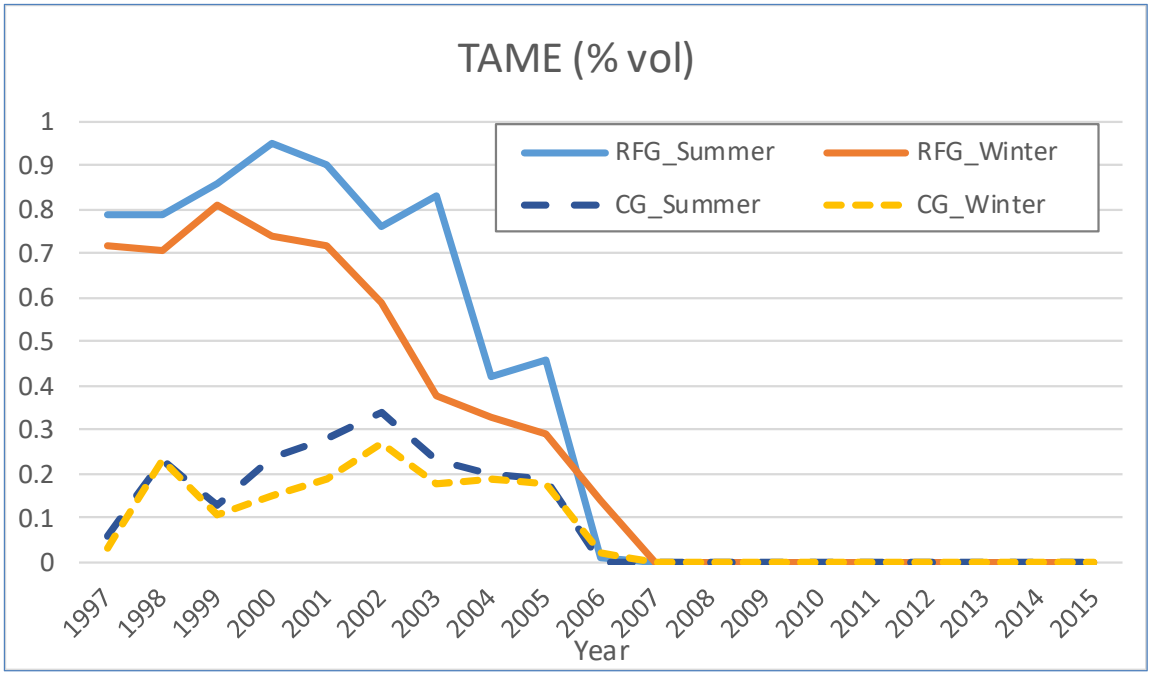

Figure 5. Average volume percent TAME in RFG and CG during summer and winter from 1997 to 2015.

each other, as these oxygenates typically were co-produced by reaction of C_{4-5} olefin streams with methanol. The approximate ratio of MTBE/TAME is 10/1. The phase-out of MTBE during 2004-2007 coincided with increased use of ethanol. Even greater ethanol usage occurred from 2008 to 2015, largely to comply with the Federal RFS requirements, which has resulted in nearly all gasoline today being E10.

Figures 6-12 show time trends for annual averages of the other fuel properties used within the Complex Model: sulfur levels, Reid vapor pressure (RVP), E200 and E300, olefin content, total aromatics content, and benzene level. Average summer and winter data are presented for both RFG and CG. These trend line graphs provide a clear picture of how average gasoline properties have changed over a 19-year period. For the most part, expected responses are seen to regulatory changes implemented during this period. For example, Figure 6 shows a sharp reduction in gasoline sulfur level in 2004, particularly evident in the CG trend lines, which coincides with introduction of Tier 2 gasoline regulations that established a regulated average sulfur content of 30 ppm. In contrast, the average gasoline sulfur level in 1990 (the baseline year for determining RFG compliance) was 339 ppm, as indicated by the data point in Figure 6. This figure also shows that since 2006, there has been very little difference in sulfur levels between RFG and CG. From 2010 onward, the average sulfur levels of both fuels (in summer and winter) have stabilized slightly below 30 ppm, in compliance with the Tier 2 gasoline requirements.

The benzene trend lines shown in Figure 12 also indicate changes to comply with evolving fuel standards. The 1990 baseline benzene levels for summer and winter gasolines were 1.53 vol.% and 1.64 vol.%, respectively. By 1997, the first year shown in these trend line graphs, the benzene level in CG was already considerably lower, at about 1.1 vol.%. It remained quite constant at this level until 2011, when introduction of the MSAT2 rules occurred. These rules limited annual average benzene levels to 0.62 vol.%, which is very near the actual levels observed since 2012. Figure 12 also shows that RFG has had lower benzene levels than CG over the entire 19-year period. While the differences were quite significant from 1997 to 2010, they became much smaller following introduction of the MSAT2 rules in 2011.

The remaining fuel properties displayed in Figures 7-11 show relatively small changes from 1997 to 2015. As shown in Figure 7, the 1990 baseline RVP value for summer gasolines was 8.7 psi. Over the entire 19-year period shown in this figure, the average RVP of summer CG has not varied from this baseline value by more than 0.5 psi. However, it is clear that during the 2nd half of the period, the RVP levels of summer CG have increased noticeably. This is attributed to the overall increased use of ethanol, and the 1 psi RVP waiver that is granted to E10 CG fuels, but not to RFG. It should also be pointed out the RVP levels shown in Figure 7 represent total fuel pool averages from both VOC Region 1 and VOC Region 2. The summer RVP levels for CG in Regions 1 and 2 are 7.8 and 9.0 psi respectively. With a 1.0 psi waiver for E10 CG, these RVP levels are permitted to rise to 8.8 and 10.0 psi, respectively.

It is also noteworthy that the RIA document for the RFG Program included considerable discussion about the topic of a 1 psi RVP waiver for RFG that contains ethanol (RIA pp 7-12). EPA argued that the Congressional intent of RFG was to reduce ozone in metropolitan areas in a fuel neutral way, and

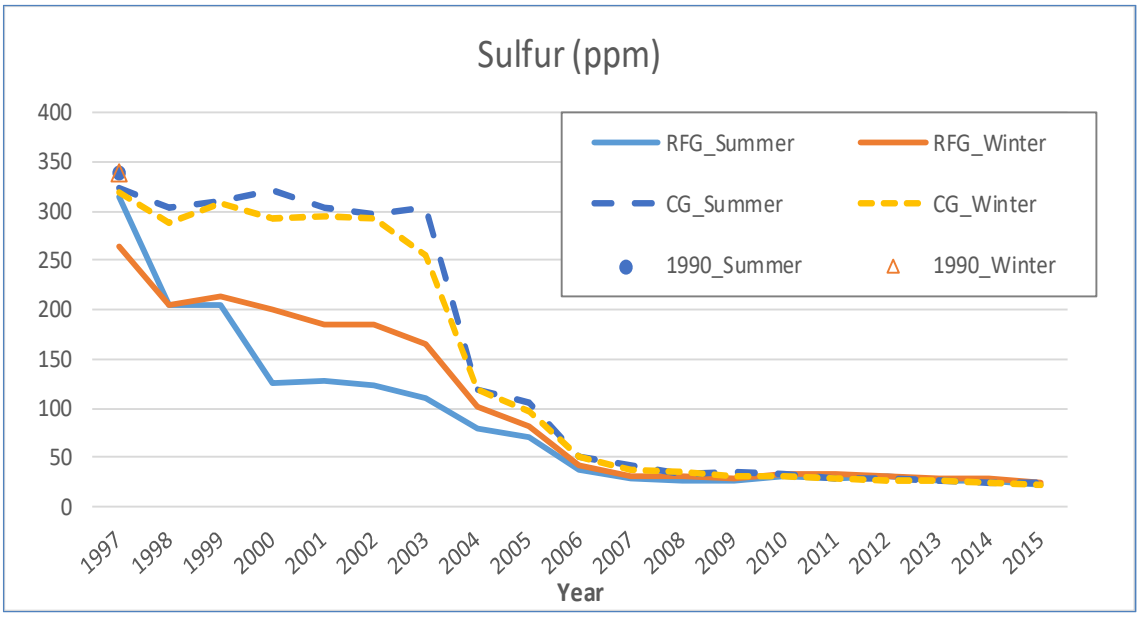

Figure 6. Average sulfur levels (ppm) in RFG and CG during summer and winter from 1997 to 2015. The base values for summer (●) and winter (Δ) fuels indicate the comparative values used in the Complex Model.

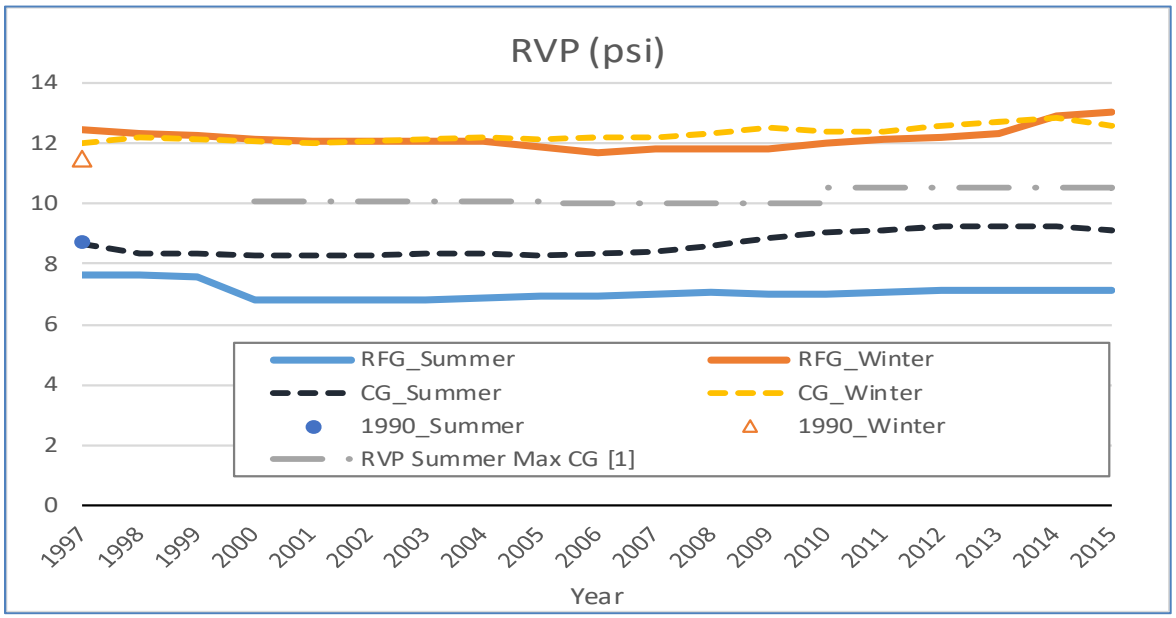

Figure 7. Average reid vapor pressure (RVP, psi) for RFG and CG during summer and winter fuels from 1997 to 2015. The base values for summer (●) and winter (Δ) fuels indicate the comparative values used in the Complex Model. [1] *Maximum summer RVP CG data Used with Permission from the Alliance of Automobile Manufacturers. The Alliance of Automobile Manufacturers North American Fuel Survey© data reflect single sample "snapshots" of market fuel properties from retail stations sampled in various cities. The number of stations varies from city to city, and cities and stations can vary from survey to survey. The cities and stations sampled are not selected to meet statistical criteria, or on the basis of market share. Surveys are taken in January (Winter) and July (Summer) of each calendar year. Reports are available through* www.autoalliance.org .

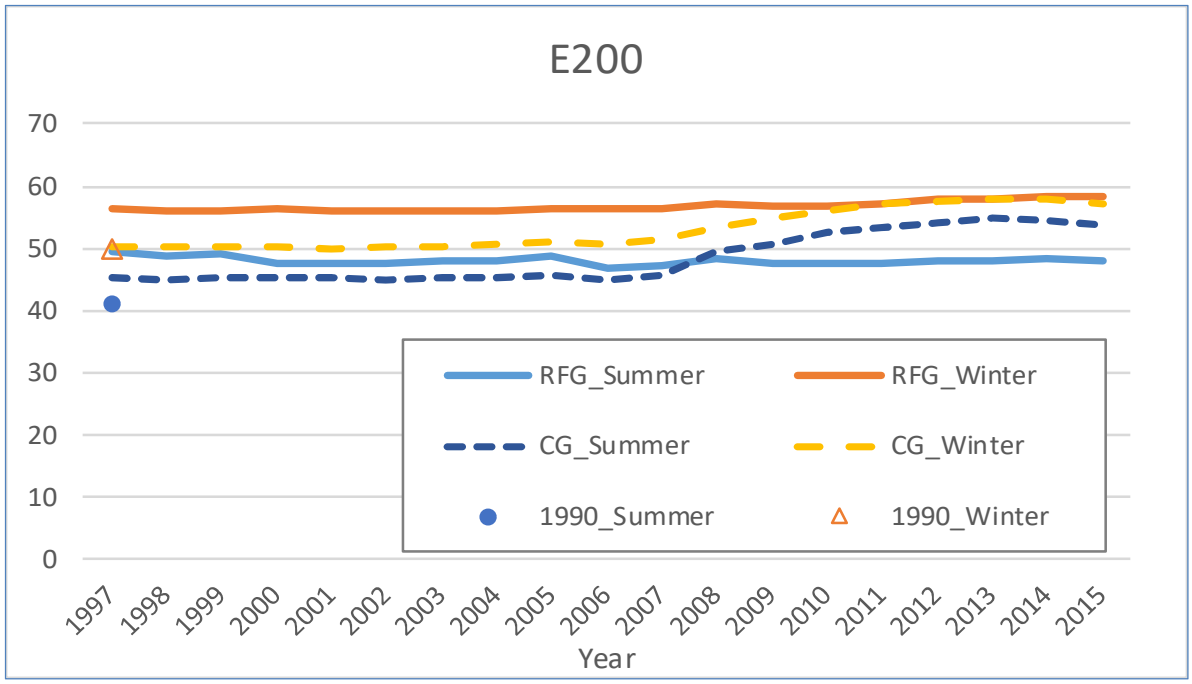

Figure 8. Average E200 values (% distilled at 200 °F) for RFG and CG during summer and winter from 1997 to 2015. The base values for summer (●) and winter (Δ) fuels indicate the comparative values used in the Complex Model.

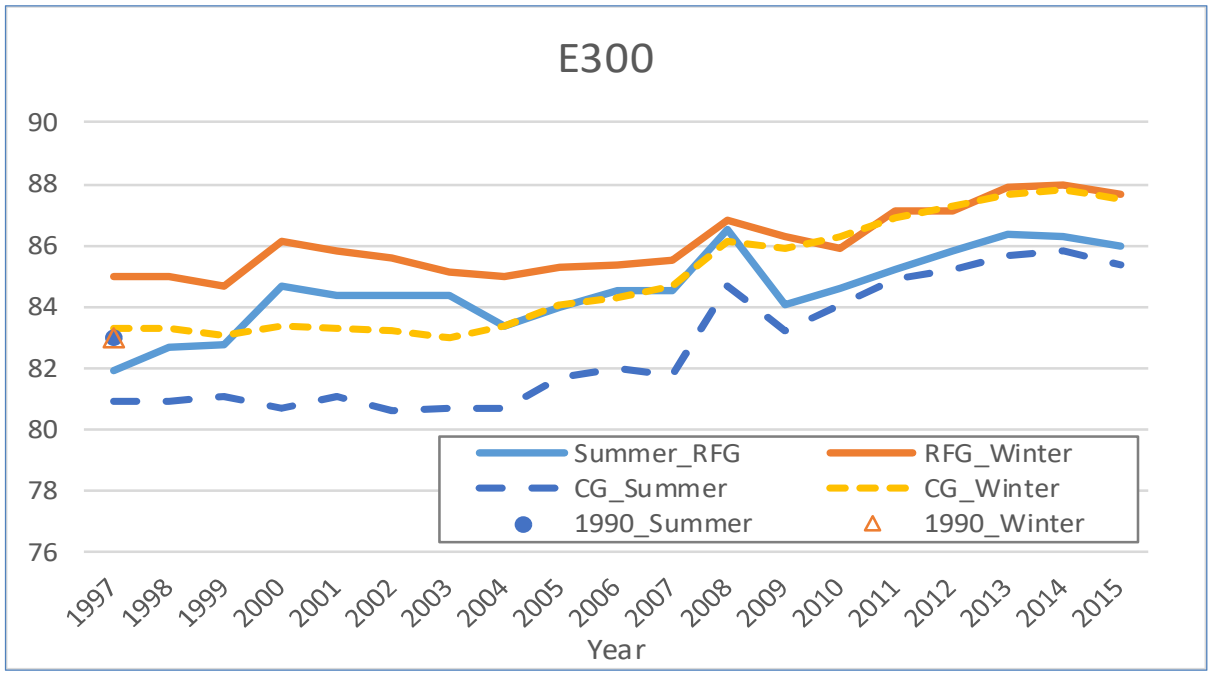

Figure 9. Average E300 (% distilled at 300 °F) for RFG and CG during summer and winter from 1997 to 2015. The base values for summer (●) and winter (Δ) fuels indicate the comparative values used in the Complex Model.

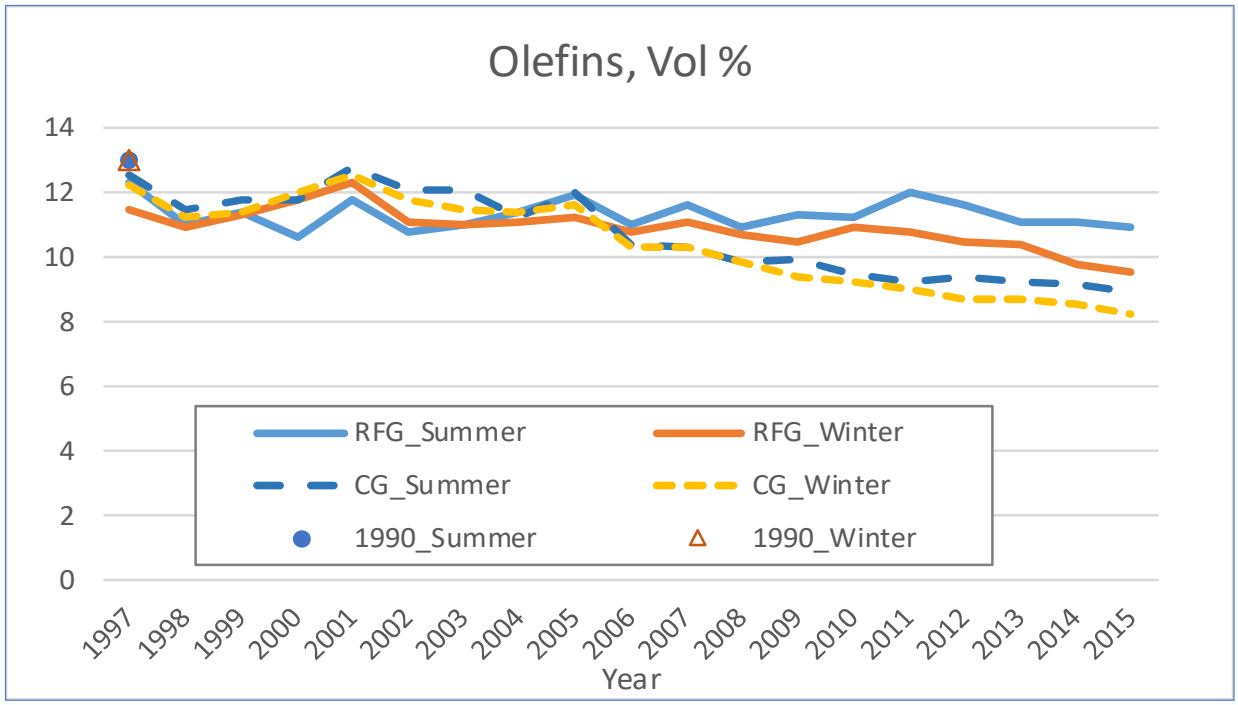

Figure 10. Average volume percent olefins in RFG and CG during summer and winter from 1997 to 2015. The base values for summer (●) and winter (Δ) fuels indicate the comparative values used in the Complex Model.

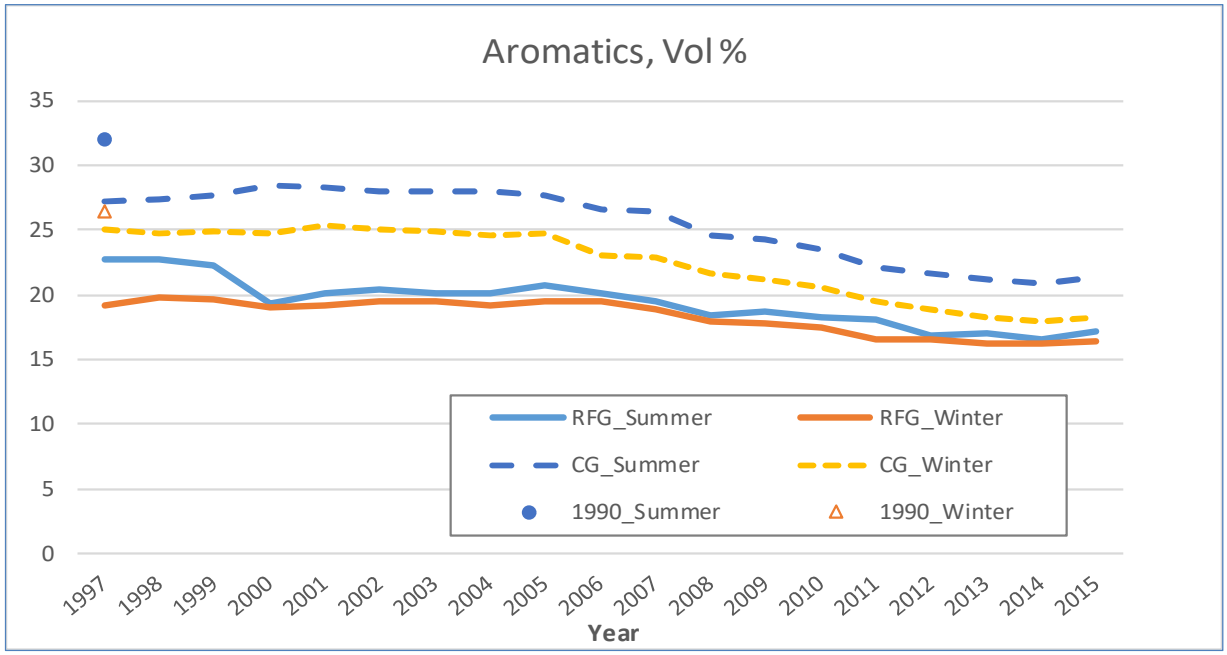

Figure 11. Average volume percent total aromatics in RFG and CG during summer and winter from 1997 to 2015. The base values for summer (●) and winter (Δ) fuels indicate the comparative values used in the Complex Model.

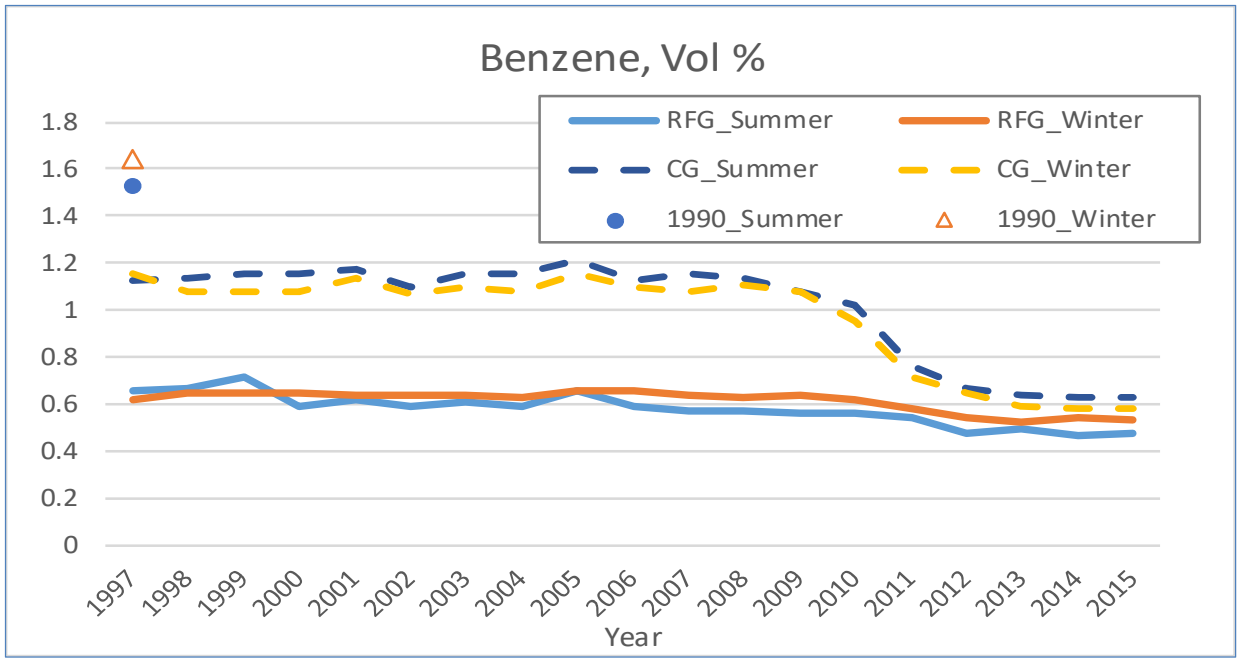

Figure 12. Average volume percent benzene in RFG and CG during summer and winter from 1997 to 2015. The base values for summer (●) and winter (Δ) fuels indicate the comparative values used in the Complex Model.

that the required emissions performance standards should be met, regardless of the oxygenate being used. It was stated that "With a 1.0 psi waiver, EPA expects there would be a significant shift to ethanol blends and a resulting significant increase in VOC emissions over what would occur without a waiver. Many areas would achieve significantly smaller reductions in VOC emissions … and in some areas with a large market share for ethanol blends, the RFG program would actually increase summertime VOC emissions …"

Although Figure 7 shows that the average RVP of summer RFG has been consistently lower than that of CG (typically by 1-2 psi), it should be pointed out that these data represent nationwide (49-state) averages, without regard to geographic location. Thus, these RVP differences do not necessarily indicate the actual marketplace difference between RFG and non-RFG areas within the same geographic region [such as between Chicago (RFG) and Detroit (non-RFG)]. Fuel survey data illustrated in the figure indicate that maximum RVP levels have been measured as high as 10.0 (9.0 psi standard + 1.0 psi ethanol waiver). At the same time, an RFG in the same VOC Region would likely have an RVP level near 7.1 psi, in order to comply with the required VOC reduction requirements. Thus, the actual RVP difference between CG and RFG would be nearly 3 psi.

The stepwise drop in RVP of summer RFG between 1999 and 2000 shown in Figure 7 coincides with the transition from Phase I to Phase II of the RFG program. As shown in Table 1, this transition also involved a change in emissions reduction targets, particularly a more aggressive VOC reduction target in northern states (VOC Region 2). Thus, achieving the RFG Phase II targets required a slight further reduction of RVP levels.

Figures 8 and 9 illustrate the trend lines for E200 and E300, respectively. These metrics of fuel volatility, which refer to the percentage of a gasoline sample that is distilled at 200 °F and 300 °F, are related to the more commonly used metrics of T_{50} and T_{90}. In their derivation of the Complex Model, EPA determined that better performance was achieved when expressing gasoline volatility in terms of 'E' values rather than 'T' values. In the RIA document for RFG (page 62), the following conversion equations were used to calculate E200 and E300 values from T_{50} and T_{90} values:

$$E200\ (\%) = 147.91 - 0.49 \times T_{50}\ (°F)$$

$$E300\ (\%) = 155.47 - 0.22 \times T_{90}\ (°F)$$

As seen in Figure 8, the E200 values for RFG (both summer and winter) have remained quite flat over the 19-year period, while the values for CG have increased significantly, by about 8 percentage points. From 1997 to 2007, the E200 values of summer CG were lower than those of RFG, but after a crossover in 2008, CG has consistently had higher E200 values. This upturn in CG's E200 values is attributed to the increasing amounts of ethanol being used, along with the attendant 'T_{50} depression' that this causes. In contrast, E300 values have increased significantly in both RFG and CG over the 19-year period shown in Figure 9, although the increase has been slightly greater for CG than for RFG. After 2010, differences in E300 between RFG and CG have been very small.

The 1990 baseline average olefin content of both summer and winter gasoline was 13.0 vol.% As shown in Figure 10, olefin contents have gradually declined since that time, with a slightly greater rate of decline in CG compared to RFG. In 2015, the average olefin contents of summer CG and RFG were 8.9 vol.% and 10.9 vol.%, respectively.

Similarly, average aromatics content has gradually declined from 1997 to 2015. As shown in Figure 11, the 1990 baseline total aromatics level was considerably higher in summer gasoline compared to winter gasoline – 32.0 vol.% vs. 26.4 vol.%. In CG, this difference between summer and winter fuels persisted throughout the entire 19-year period, although the magnitude of the difference was only about ½ as large as in the 1990 baseline fuels. For RFG, however, the difference between summer and winter aromatics levels disappeared almost completely after Phase II of the RFG program began in 2000. It is also apparent that the decline in aromatics content has been steeper in CG than in RFG. This is attributed to increased ethanol usage in CG, which lessens the need for higher octane rated blending streams. Due to this more rapid decline in CG aromatics, the difference between CG and RFG is now smaller than in previous years.

To summarize the above information about average fuel property trends, we make the following points:

- For several fuel properties of interest, the differences between CG and RFG have narrowed over time. This is most clearly seen with sulfur content, oxygen content, total aromatics, and benzene. This trend towards convergence is expected to continue with the introduction of Tier 3 gasoline beginning in 2017.

- Throughout the 19-year period of record, several fuel properties that strongly influence vehicle emissions (as discussed later) have changed (in both CG and RFG) in ways that reduce emissions. These properties include sulfur content, olefin content, total aromatics, and benzene.
- The mix of oxygenates in gasoline has changed drastically throughout the history of the RFG program. While initially the methyl ethers, MTBE and TAME, were the dominant oxygenate species, they have been completely replaced by ethanol since 2007.
- Since the mid 2000's, significant increases in ethanol usage have occurred in both CG and RFG. Consequently, ethanol content (and total oxygen content) of CG and RFG have converged.
- The impacts of a 1 psi RVP waiver for ethanol-containing CG can be seen in these fuel property trends, and is most evident in the higher summertime RVP levels of CG compared to RFG.

4. RFG Program Compliance Models

To achieve the emissions reduction requirements of RFG shown in Table 1, it was necessary to develop predictive tools that could be used by fuel suppliers to relate fuel properties to emissions outcomes. The derivation of EPA's so-called "Simple Model" and "Complex Model," which have both been used within the RFG Program, are explained in detail in the RFG RIA document.[8] The Simple Model, which was only in effect for the first few years of the RFG Program (1995-1998), related two fuel properties (RVP and oxygen content) to VOC emissions. The Complex Model, which has been in effect since 1998, added several other fuel properties (sulfur, total aromatics, benzene, olefins, E200, and E300). This model is used to predict emissions of VOC, toxics, and NO_x. As stated in the RIA (page 101), "The purpose of the Complex Model … is to be able to predict emissions based on fuel properties which are readily measureable and easily controllable."

4.1 Derivation of Complex Model

The term "Complex Model" actually refers to a set of mathematical models developed to predict the vehicle emissions impacts of changing various fuel properties. As explained in the RIA, different models were developed for "normal" and for "high emitting" 1990-technology vehicles – during both summer and winter seasons. Weighting of the fleet by normal and high emitting vehicles was different for different emissions categories. Separate models were developed for the three emission categories of VOC, NO_x, and toxics – with toxics including benzene, formaldehyde, acetaldehyde, 1,3-BD, and POM. Total VOC emissions include exhaust and non-exhaust components, with non-exhaust consisting of evaporative, refueling, and running loss emissions. Benzene emissions include both evaporative (in summer only) and exhaust components, whereas the other toxics (and NO_x) are only included in exhaust emissions.

EPA's MOBILE5a model was used to determine baseline exhaust emissions from a fleet of 1990-technology vehicles when operating on 1990 average gasoline (both summer and winter). To focus on in-use emissions from this fleet, MOBILE was run for the year 2015, but with all post-1990 vehicle programs turned off. Because the MOBILE model does not provide emissions estimates for toxic compounds, data from specific experimental programs (including the Auto/Oil AQIRP) were used to determine baseline toxics emissions. Due to very limited data, POM emissions were simply calculated as a constant fraction of total exhaust VOC.

Through a series of multiple linear regression analyses, equations were developed to relate the 1990-technology fleet exhaust emissions (expressed as g/mile) to fuel properties. Because vehicle effects are much larger than fuel effects when determining emissions, "dummy variables" were assigned to the vehicle effects, allowing a greater focus on fuel effects. (In the RIA document, EPA explained that vehicle effects accounted for about 90% of the variation in exhaust emissions from the fleet, whereas fuel effects explained 5-6% of the variation, and 4-5% of variation remained unexplained.) As described in the RIA, the "raw Complex Model" developed by this process then underwent a series of refinement and simplification steps. The fuel terms in the final exhaust Complex Model are shown below in Table 5. Shading is used to identify the few cases where the model coefficients for normal emitting and high emitting vehicles have opposite signs.

Table 5. Fuel Property Coefficients used in Final Exhaust Complex Model.*

Fuel Terms	Exhaust VOC		NOx		Exhaust Benzene	
	Normal Emitters	High Emitters	Normal Emitters	High Emitters	Normal Emitters	High Emitters
Oxygen	-0.003641	-0.003626	0.0018571	-0.00913	0.0	-0.096047
Sulfur	0.0005219	-0.000054	0.0006921	0.000252	0.0006197	0.000337
RVP	0.0289749	0.0432950	0.0090744	-0.013970	-	-
E200	-0.014470	-0.013504	0.0009310	0.0009310	-0.003376	0.0
E300	-0.068624	-0.062327	0.0008460	-0.004010	0.0	0.011251
Olefins	-0.002858	-0.002858	-0.002774	-0.002760	-	-
Aromatics	0.0323712	0.0282042	0.0083632	0.007097	0.026550	0.011882
Benzene	-	-	-	-	0.222390	0.222318
$(E200)^2$	0.0001072	0.0001060	-	-	-	-
$(E300)^2$	0.0004087	0.0004080	-	-	-	-
Arom*E300	-0.0003481	-0.000287	-	-	-	-
$(Sulfur)^2$	-	-	-6.63×10^{-7}	0.0	-	-
$(Olefins)^2$	-	-	0.0003665	0.0003665	-	-
$(Aromatics)^2$	-	-	-0.000119	-7.995×10^{-5}	-	-

* Notes: Shaded cells indicate coefficients having opposite signs for normal and high emitting vehicles
Coefficients for exhaust POM are identical to those of exhaust VOC.
Different coefficients (not shown) for other toxics (formaldehyde, acetaldehyde, and 1,3-BD)

The non-exhaust portion of the Complex Model was developed using a different process than that used for exhaust emissions. The non-exhaust model predicts emissions of benzene and VOCs in warmer "Class B" and cooler "Class C" areas. (Class B is also referred to as VOC Control Region 1, and Class C is VOC Control Region 2.) The VOC non-exhaust model was derived from the MOBILE model, while the benzene model was derived from a thermodynamic vapor equilibrium model. MOBILE4.1 was used to develop the non-exhaust Complex Model for Phase 1 of the RFG program; MOBILE5a was used for Phase 2 of the RFG Program (year 2000 and later). Other changes in the Complex Model in going from Phase 1 to Phase 2 of the RFG Program included switching from Basic to Enhanced I/M programs, and addition of light-duty trucks (LDT) in Phase 2.

The only fuel property influencing non-exhaust VOC emissions is RVP. Thus, the Complex Model includes a series of 6 regression equations (3 for Area Class B and 3 for Area Class C) that express evaporative, refueling, and running loss emissions (in units of g/mile) as a function of RVP. Non-exhaust benzene emissions are influenced not only by RVP, but also by fuel benzene content and MTBE content. (As documented in the RIA, addition of MTBE to gasoline lowers the mass percent of benzene in the vapor phase, while addition of ethanol has no such effect.)

Because the Complex Model was derived using vehicle technologies and baseline fuel compositions that are "frozen in time," EPA originally proposed to update the model every five years to incorporate more recent data on emissions effects of fuel reformulation (RIA, p 259). However, in response to comments that such frequent updates would be too disruptive, it was stated that "EPA plans to update the model through a formal rulemaking process that will be undertaken when EPA determines that sufficient new information is available to warrant such action."[8] To date, no such rulemaking process has been undertaken.

4.2 Use of the Complex Model

The purpose of the Complex Model is to assess compliance with the emissions reduction requirements of the RFG regulations. Thus, the emissions performance of a candidate fuel is evaluated by inserting its fuel property values into the Complex Model, and calculating the predicted emissions rates that would result. EPA defines the performance of a candidate fuel as "the percent change in the vehicle emissions that would occur if the baseline gasoline were to be replaced with the given fuel in the fuel tank of a typical 1990 vehicle" (RIA, p 168). Because the Complex Model was developed based on limited numbers of vehicles and test fuels, EPA also conducted considerable work (documented in the RIA) to establish valid ranges for the fuel properties utilized in the model.

From a user's perspective, the Complex Model is a spreadsheet that requires manual input of a few parameters. A screen shot of the Complex Model input page is shown in Figure 13, where color-shaded boxes have been added to highlight certain sections of the page. The only inputs that the user can modify are highlighted in the yellow and red boxes near the top left corner of Figure 13. The yellow box is used to specify the Area Class (B or C), the Season (summer or winter) and the RFG Program Phase (1 or 2). (Since the year 2000, only Phase 2 has applied.)

FINAL COMPLEX MODEL FOR VOC, NOx AND TOXICS

	Baseline fuel	Target Fuel
MTBE (wt% oxygen)	0	0
ETBE (wt% oxygen)	0	0
Ethanol (wt% oxygen)	0	3.574372195
TAME (wt% oxygen)	0	0
SULFUR (ppm)	339	22.5
RVP (psi)	8.7	7.11
E200 (%)	41	47.8
E300 (%)	83	86
AROMATICS (vol%)	32	17.1
OLEFINS (vol%)	9.2	10.9
BENZENE (vol%)	1.53	0.48

Area Class = B
Phase = 2
Season = Summer

WARNING

See Warnings and Caveats below, starting in cell A:A35

	mg/mi	mg/mi	Percent change
Exhaust VOC	907.00	719.96	-20.62
Nonexhaust VOC	559.31	321.73	-42.48
Total VOC	**1466.31**	**1041.68**	**-28.96**
Exhaust benzene	53.5400	23.2023	-56.66
Nonexhaust benzene	6.2413	1.3207	-78.84
Acetaldehyde	4.4400	10.1448	128.49
Formaldehyde	9.7000	10.1649	4.79
Butadiene	9.3800	8.4766	-9.63
POM	3.0430	2.4155	-20.62
Total exhaust toxics	80.1030	54.4041	-32.08
Total toxics	**86.3443**	**55.7248**	**-35.46**
NOx	**1340.00**	**1139.52**	**-14.96**

Warnings and Caveats:

If the current scenario and/or target fuel parameter values require warnings or caveats, such warnings or caveats will appear below :

The exhaust VOC curve has been extrapolated
The exhaust NOx curve has been extrapolated

Emitter class weightings:

	Phase I		Phase II	
	Normals	Highs	Normals	Highs
VOC+Toxics	0.52	0.48	0.444	0.556
NOx	0.82	0.18	0.738	0.262

Current settings:

	Normals	Highs
VOC+Toxics	0.444	0.556
NOx	0.738	0.262

Total oxygen content :

	Baseline	Target
OXYGEN	0	3.5743722

Baseline fuel:	CAAB	Winter
OXYGEN (wt%)	0	0
SULFUR (ppm)	339	338
RVP (psi)	8.7	8.7
E200 (%)	41	50
E300 (%)	83	83
AROMATICS (vol%)	32	26.4
OLEFINS (vol%)	9.2	11.9
BENZENE (vol%)	1.53	1.64

Flat-line extension of target fuel parameters beyond the valid range :

E300	86
Aromatics	17.1

Baseline emissions (mg/mi): Current ID value = 112

Class	B	B	C	C	B	B	C	C
Phase	1	2	1	2	1	2	1	2
Season	Summer	Summer	Summer	Summer	Winter	Winter	Winter	Winter
ID value	111	112	121	122	211	212	221	222
Exhaust VOC	446.00	907.00	446.00	907.00	660.00	1341.00	660.00	1341.00
Evap VOC	860.48	559.31	769.10	492.07	0.00	0.00	0.00	0.00
Total VOC	1306.48	1466.31	1215.10	1399.07	660.00	1341.00	660.00	1341.00
Exhaust benzene	26.1000	53.5400	26.1000	53.5400	37.5700	77.6200	37.5700	77.6200
Evap benzene	9.6591	6.2413	8.6328	5.5047	0.0000	0.0000	0.0000	0.0000
Total benzene	35.7591	59.7813	34.7328	59.0447	37.5700	77.6200	37.5700	77.6200
Acetaldehyde	2.1900	4.4400	2.1900	4.4400	3.5700	7.2500	3.5700	7.2500
Formaldehyde	4.8500	9.7000	4.8500	9.7000	7.7300	15.3400	7.7300	15.3400
Butadiene	4.3100	9.3800	4.3100	9.3800	7.2700	15.8400	7.2700	15.8400
POM	1.4963	3.0430	1.4963	3.0430	2.2143	4.4991	2.2143	4.4991
Exhaust toxics	38.9463	80.1030	38.9463	80.1030	58.3543	120.5491	58.3543	120.5491
Total toxics	48.6054	86.3443	47.5791	85.6077	58.3543	120.5491	58.3543	120.5491
NOx	660.0000	1340.0000	660.0000	1340.0000	750.0000	1540.0000	750.0000	1540.0000

Figure 13. Screenshot of RFG Complex Model.

The user's selection of Area Class and Season dictate the baseline fuel properties that are shown in the grey box in the upper left section of Figure 13. The user also inputs the 11 fuel properties of the Target fuel, which are highlighted in the red box. As is typical of all gasolines produced in the past 10-years, the example Target fuel shown here contained no ether-based oxygenates (MTBE, ETBE, and TAME), so only 8 fuel properties are input into the Complex Model spreadsheet.

Baseline emission rates for the 1990-technology vehicle fleet are calculated in the Complex Model using the baseline fuel properties appropriate for the selected Area Class, Season, and RFG Program Phase. The baseline emission rates of VOC (exhaust and evap.), NO_x, benzene (exhaust and evap.) other exhaust toxics (formaldehyde, acetaldehyde, 1,3-BD, and POM) are highlighted in the purple box of Figure 13, immediately below the grey box showing the baseline fuel properties. This page from the Complex Model also includes fixed cells showing the baseline emission rates for all 8 possible scenarios: 2 Classes, 2 Seasons, and 2 RFG Phases. These 8 sets of baseline emissions are shown in the pink box in the bottom right quadrant of Figure 13. In addition, fixed cells in an un-highlighted region at the top of the page show the emissions weighting used for VOC, toxics, and NO_x emissions.

Interestingly, the baseline emission rates changed dramatically between the RFG Phase 1 and Phase 2 periods. For a given Area Class, during both summer and winter, changing from Phase 1 to Phase 2 approximately doubled the emission rates of exhaust VOC, NO_x and total toxics. However, summer evaporative VOC emissions declined significantly in changing from Phase 1 to Phase 2. Winter evaporative emissions (including evaporative benzene) were defined to be zero in both Phase 1 and Phase 2. The two main factors explaining these differences between Phase 1 and Phase 2 are: (1) a change from MOBILE4.1 to MOBILE5a resulted in significantly higher estimates for all exhaust species, and (2) a change from Basic I/M to Enhanced I/M significantly reduced evaporative emissions.

Based on user-inputted target fuel properties, the Complex Model calculates a new set of emission factors. In the example shown in Figure 13, these emission rates are highlighted in the blue box located beneath the red box of Target fuel properties. Emission rate differences between the Target fuel and the Baseline fuel are shown in the orange-colored box. The three highlighted values in this box are the percent emissions reductions of total VOC, total toxics, and NO_x that the Complex Model predicts would result from use of the Target fuel. It is these three values that are compared with the reduction requirements stipulated in the regulations to determine whether the Target fuel satisfies the RFG requirements. In this example, the calculated reductions of VOC, NO_x, and toxics all meet or exceed the requirements for a summer RFG in Area Class B (as shown in Table 1).

4.3 Sensitivity analysis of Complex Model

In practice, fuel blenders satisfy the VOC and NO_x emissions reduction requirements of RFG by modifying, principally, three fuel parameters: RVP, oxygen content, and sulfur content. The toxics reduction requirement is met primarily by controlling fuel aromatics and benzene levels. The directional exhaust emission effects of changing each fuel property can be seen by the Complex Model coefficients shown in Table 5. These coefficients indicate that VOC exhaust emissions for

normal emitters are reduced by reducing RVP and sulfur and increasing oxygen; in high emitters, reducing sulfur has a small detrimental effect. The only fuel property affecting non-exhaust VOC emissions (both normal and high emitters) is RVP. The predicted impacts of fuel properties on NO_x emissions are more complicated, with RVP reduction being beneficial in normal emitters, but not in high emitters. Increased oxygen content is predicted to increase NO_x in normal emitters, but decrease NO_x in high emitters, while sulfur reduction reduces NO_x in all vehicles.

From the above discussion, there is a good sense of which fuel properties most strongly drive the emissions outcomes predicted by the Complex Model. However, no systematic investigation of model sensitivity is included in the RFG RIA document. Therefore, we undertook the task of investigating the sensitivity of the Complex Model outputs (for VOC, NO_x, and toxics) with respect to each of 9 model input parameters. To do this, each fuel input parameter was varied incrementally over a range of values while keeping all other fuel inputs at the levels specified for summer baseline gasoline. These baseline levels, which are shown in Table 6, are taken from the Complex Model spreadsheet, as shown in the green box of Figure 13. Table 6 also shows the fuel property limits of the Complex Model, and the range of values that we examined to explore model sensitivity.

Table 6. Baseline fuel properties (Area Class C), valid range limits of the Complex Model, and ranges of input values used to determine model sensitivity.

Gasoline Parameter	CAA Summer Baseline Properties	Complex Model Limits		Range Evaluated for Sensitivity
		Lower Limit	Upper Limit	
Ethanol (wt. % oxygen)	0	0	3.7	0 - 5.5
MTBE (wt. % oxygen)	0	0	3.7	0 - 2.7
Sulfur (ppm)	339	0	500	10 - 100
RVP [summer] (psi)	8.7	6.4	10	7 - 9
E200 (%)	41	30	70	41 - 60
E200 (%)	83	70	95	80 - 88
Aromatics (vol. %)	32	10	50	15 - 35
Benzene (vol. %)	1.53	0	2	0.4 - 1.6
Olefins (vol. %)	9.2	0	25	6-19

The ranges of fuel properties we examined do not correspond exactly with the Complex Model limits, as we were interested in examining ranges that are more consistent with those found in actual marketplace fuels. For example, while the Complex Model upper limit for ethanol is 3.7 % oxygen, we extended this to a value of 5.5%, which corresponds to E15. Also, while the valid range for sulfur is 0 to 500 ppm, we limited our examination to a much narrower range of 10-100 ppm, to better reflect actual marketplace fuels. Similarly, we examined narrower ranges of E200, E300, aromatics, and olefins to more closely represent typical marketplace fuels.

To normalize the sensitivity results for comparison of slopes, each fuel input property in the baseline fuel was assigned a value of zero. (By definition, the Complex Model results for VOC, NO_x and toxics when using baseline fuel properties are zero, since the results are expressed as percent difference from baseline.) The minimum and maximum valid limits to the Complex Model inputs for each property were assigned values of -1 and +1, respectively. In this way, the range of all fuel property inputs evaluated were between -1 and +1, except for ethanol, which as mentioned above was extended from 3.7% to 5.5%. A negative input parameter represents a fuel property with a lower value than the baseline; a positive input parameter represents a fuel property with a higher value than the baseline.

The results of sensitivity analyses for NO_x, toxics, and VOC emissions are portrayed in Figures 14, 15, and 16, respectively. Each figure has a similar format, showing percentage changes in predicted emissions (y-axis) as the values for one fuel parameter at a time are varied over the range of interest (x-axis). For each parameter, 12 separate increments were used to span the range of interest, resulting in derivation of the individual data points shown in these figures. "Best fit" lines are included for each set of results, along with mathematical formulas for some of the lines. The center point, where the lines intersect, represent baseline gasoline, at which point both parameter changes and percent changes in emissions are zero. In addition, individual diamond- and triangle-shaped points are included to indicate the position on each line that corresponds to the 2015 average fuel property for RFG and CG, respectively.

Figures 14-16 provide a detailed visual explanation of the Complex Model sensitivities to changes in fuel properties. Focusing first on NO_x emissions, Figure 14 shows that sulfur content and aromatics content are the only two fuel parameters that can be modified to substantially reduce NO_x. Actual sulfur contents of both RFG and CG have already been reduced to very low levels, as illustrated by the overlapping data points near the minimum parameter value on the sulfur curve. Aromatics content in 2015 gasolines were slightly lower in RFG (17.1%) than in CG (21.3%), as shown by the data points on the aromatics curve. The fuel property that could most significantly increase NO_x emissions is olefins content. However, as the actual 2015 olefin contents of RFG (10.9%) and CG (8.9%) are both quite close to the baseline value of 9.2%, there is very little change in NO_x from baseline levels. E200 is the only other fuel property that significantly affects NO_x. A slight difference in E200 is noted between RFG (47.8% distilled) and CG (53.6% distilled), although the effect of this difference upon NO_x emissions is very small.

Figure 15 shows that predicted toxics emissions are influenced by many different fuel properties, with the strongest effects due to total aromatics content and benzene content. As indicated by the marked data points on these curves, the lower aromatics content and benzene content of 2015 RFG vs. CG lead to lower predicted toxic emissions from RFG compared to CG. The next most significant fuel effect is sulfur content, but as discussed above, there is no significant difference in the value of this parameter between RFG and CG. A significant difference does exist in the RVP levels of these 2015 gasolines, with CG having a higher level than RFG (9.13 psi vs. 7.11 psi). In fact, the CG RVP level in 2015 is higher than the baseline level for 1990 gasoline. This increased RVP, which is largely due to the 1 psi waiver granted to E10 CG, contributes to a slight increase in predicted toxics

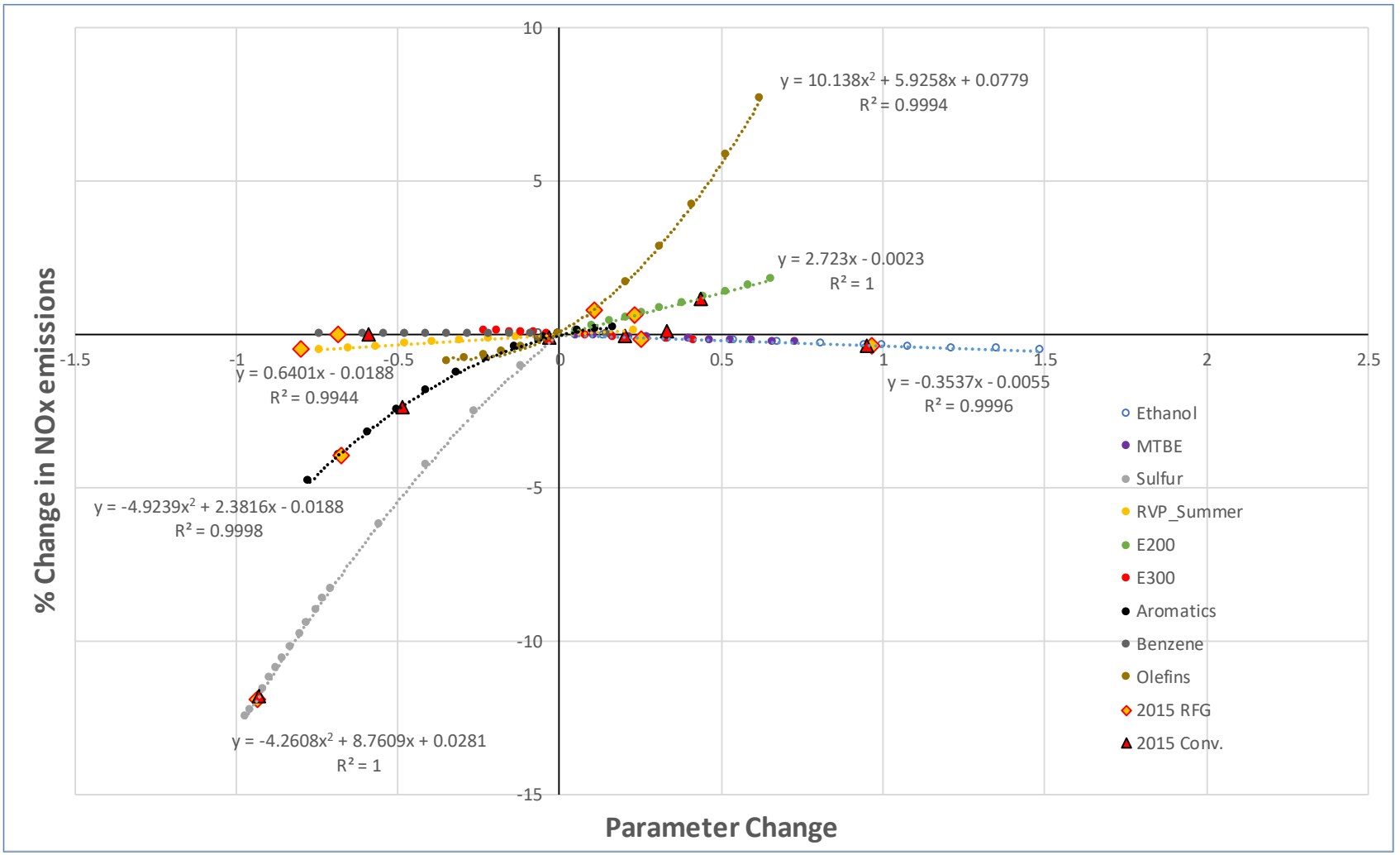

Figure 14. Percentage change in NO_x emissions for incremental changes in each input parameter, normalized by the valid range limits of the model.

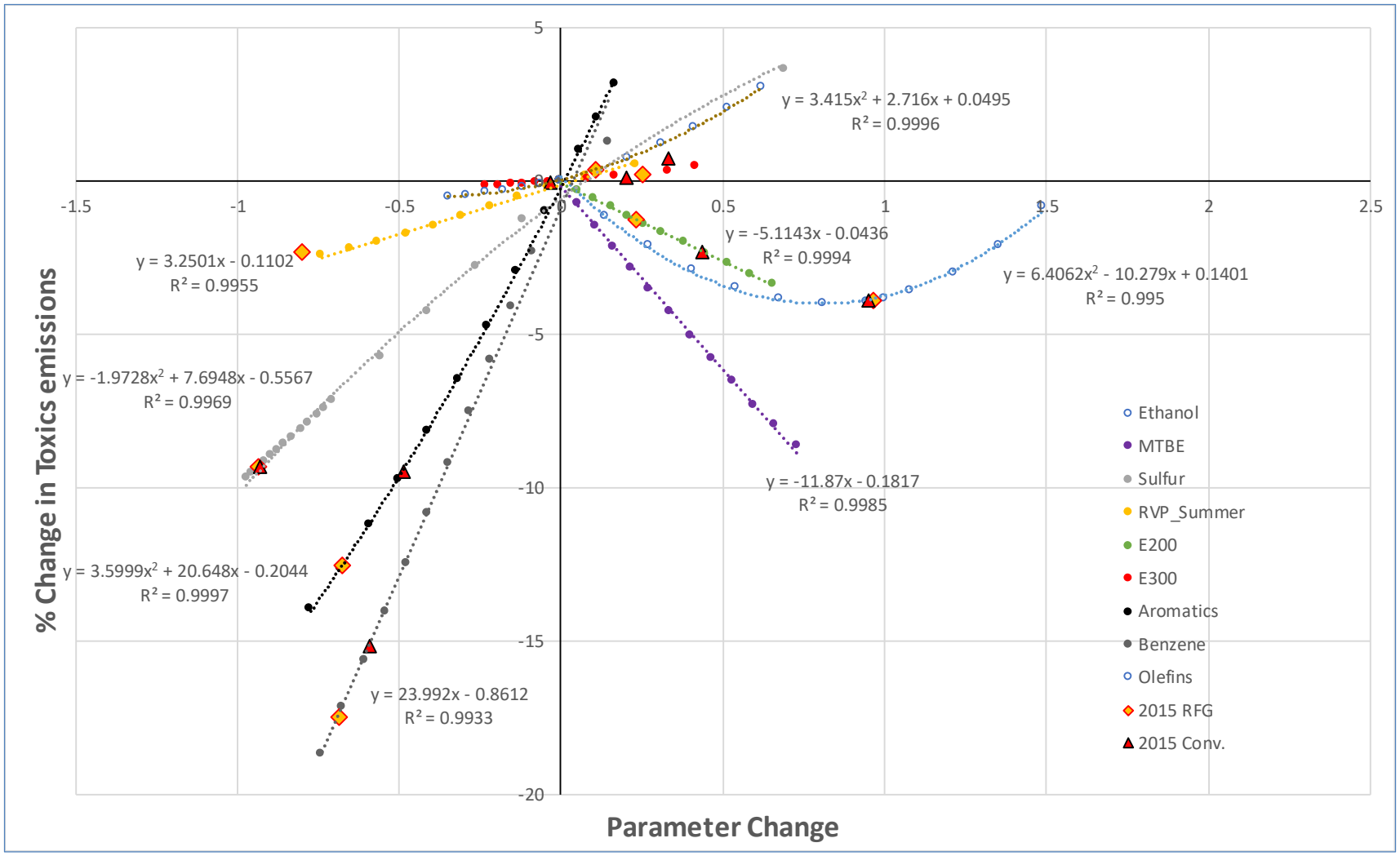

Figure 15. Percentage change in Toxics emissions for incremental changes to each input parameter, normalized by the range limits of the model.

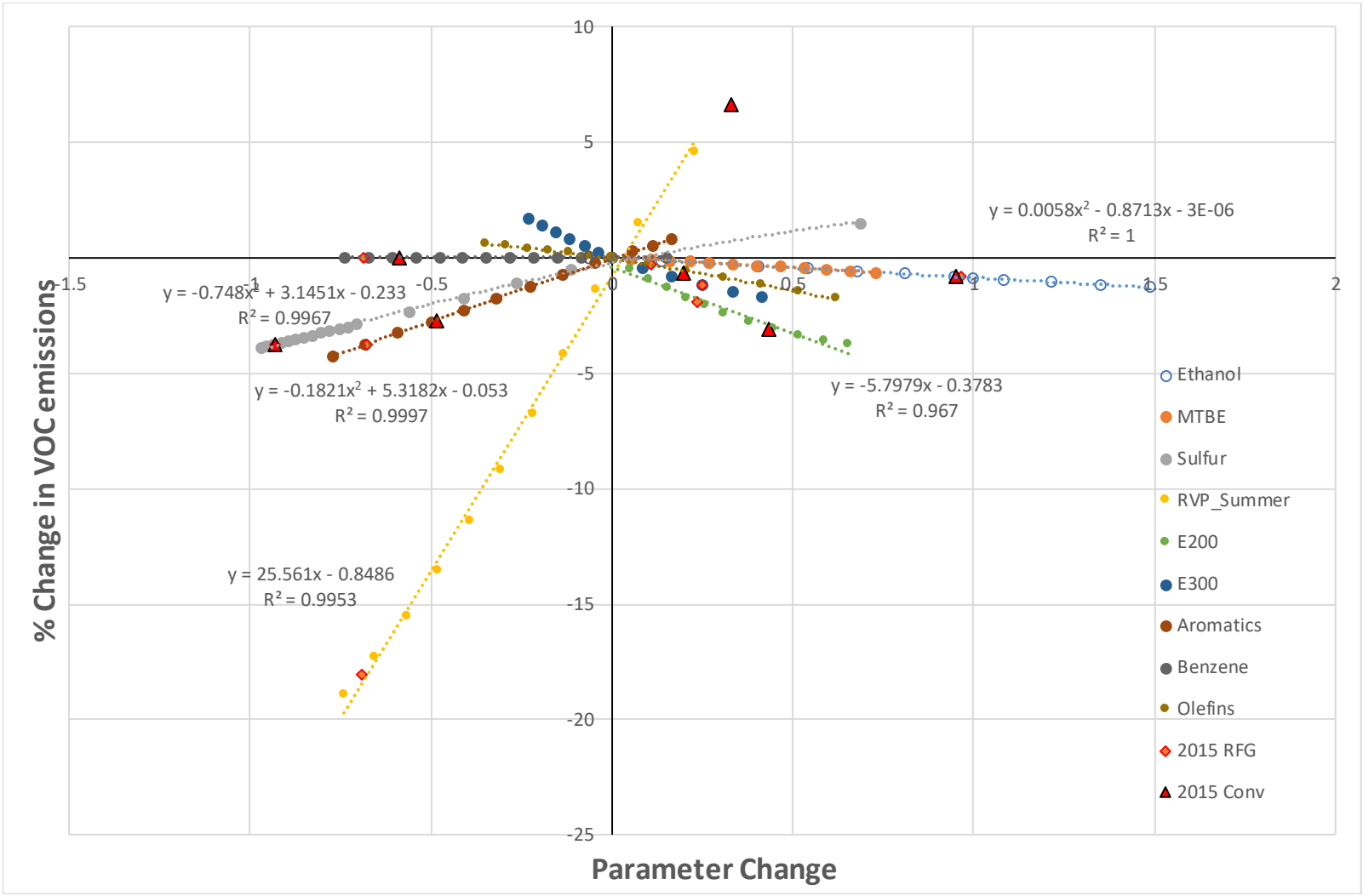

Figure 16. Percentage change in VOC emissions for incremental changes to each input parameter, normalized by the range limits of the model.

emissions for CG.

Increasing MTBE also has a strong effect in reducing toxics emissions, but since this oxygenate is no longer used in U.S. gasoline, the effect is now irrelevant. The effects of ethanol upon toxics emissions appear to be complex. At relatively low blend levels (up to about 3% oxygen), increasing ethanol decreases toxics, though not to the same extent that MTBE does (at comparable oxygen levels). At ethanol levels above 3% oxygen, predicted toxics emissions begin to increase – although it should be pointed out that the upper limit for the Complex Model is only 3.7%. Thus, this sensitivity analysis is examining higher ethanol levels than the Complex Model was meant to represent. Additional vehicle testing using recent models may be necessary to update model databases.

Figure 16 shows that predicted VOC emissions are most strongly influenced by RVP levels. The average 2015 summer RVP levels of RFG and CG lie at the extreme opposite ends of the RVP curve shown in the figure, suggesting that the high RVP of CG leads to significantly higher VOC emissions compared to RFG. VOC emissions are also influenced to a lesser degree by aromatics content, sulfur content, E200, and E300. However, the differences between RFG and CG for any of these properties are too small to significantly affect predicted VOC emissions.

In summary, this sensitivity analysis of the Complex Model has highlighted which fuel properties most strongly influence the predicted emissions of NO_x, toxics, and VOCs. These results are shown in tabular form in Table 7, where the sensitivity of each model-predicted pollutant towards different fuel properties are categorized as high, moderate, or low. These categories are based upon the magnitude of the predicted emissions differences across the range of fuel properties examined. An emissions difference of more than 10% is defined as high sensitivity, a difference of 5-10% indicates moderate sensitivity, and a difference of 2-5% indicates low sensitivity. These results provide support for the elimination of RFG's NO_x reduction requirement following introduction of Tier 2 gasoline (30 ppm sulfur), and for elimination of RFG's toxics reduction requirement following introduction of MSAT2 rules (0.62 vol.% benzene).

Table 7. Sensitivity of Complex Model to Changes in Summer Gasoline Properties.

	NO_x Emissions	Toxics Emissions	VOC Emissions
Properties with high sensitivity (>10%)	Sulfur	Aromatics Benzene	RVP
Properties with moderate sensitivity (5-10%)	Aromatics Olefins	Sulfur MTBE	Aromatics
Properties with low sensitivity (2-5%)	E200	RVP Ethanol E200	Sulfur E200 E300

5. Fuel Effects Simulations

To further examine predicted emissions differences between RFG and CG, and how these differences have changed over time, we used the Complex Model to simulate emissions results for each year from 1995 to 2015. Average annual summer and winter gasoline properties as reported by EPA and documented in Appendix B Tables B-1 and B-2 were used to represent CG and RFG, respectively. Because the Complex Model requires oxygenate levels to be input as wt.% oxygen, the volume % values reported for these oxygenates were converted into wt.%, using typical density values for gasoline and the individual oxygenates. The values for sulfur (ppm), RVP (psi), E200 and E300 (% distilled), aromatics (vol. %), olefins (vol. %), and benzene (vol. %) were input directly as reported for each year.

The Complex Model allows selection of area class B or C (VOC Control Region 1 or 2, respectively), RFG Program Phase 1 (1995-1999) or Phase 2 (2000 and later), and fuel season (summer or winter). Fuel property data for each summer blend of CG and RFG fuel were input into the model for each area class. The fuels before 2000 were entered under Phase 1 selection, while the fuels for 2000 and later were entered with a Phase 2 selection.

The emissions reduction results predicted by the Complex Model for NO_x, Toxics, and VOCs are illustrated in Figures 17, 18, and 19, respectively. Each figure shows the target reduction amount within the Phase I and Phase II RFG programs (horizontal lines), along with the Complex Model results for both CG and RFG fuels in Area Classes B and C. In general, the simulations show no significant differences in results between Class B and Class C Regions for NO_x or toxics emissions reduction estimates (Figures 17 and 18, respectively) with only slight VOC differences between the two regions (Figure 19). These results for each pollutant category are further explained below.

5.1 NO_x emissions reductions

As shown in Figure 17, the RFG Program has clearly resulted in calculated NO_x reductions that exceed the regulatory target of 6.8% over the entire time period of 2000-2015. However, gasoline property changes over the same time period have also resulted in substantial NO_x reductions from CG. From 2004 onward, average CG also met the 6.8% NO_x reduction target established for Phase II RFG. The sharp NO_x decline between 2003 and 2004 for the CG cases results from the dramatic reduction in gasoline sulfur level that began to phase in at that time. As discussed above, NO_x emission effects predicted by the Complex Model are most strongly influenced by fuel sulfur level. Since 2006, sulfur levels have been nearly the same for conventional and RFG fuels. The predicted ongoing differences in NO_x reductions between CG and RFG fuels beyond 2006 are due primarily to the slightly lower aromatics content of RFG.

5.2 Toxics emissions reductions

Toxics emissions from RFG fuels show a consistent 35% reduction (see Figure 18), which is well beyond the 21.5% reduction requirement of the program. The conventional gasolines show a more complex trend over the time period of 1997 to 2015, with several discernable step changes during this period. As discussed above, toxics emissions reductions estimated by the Complex Model are

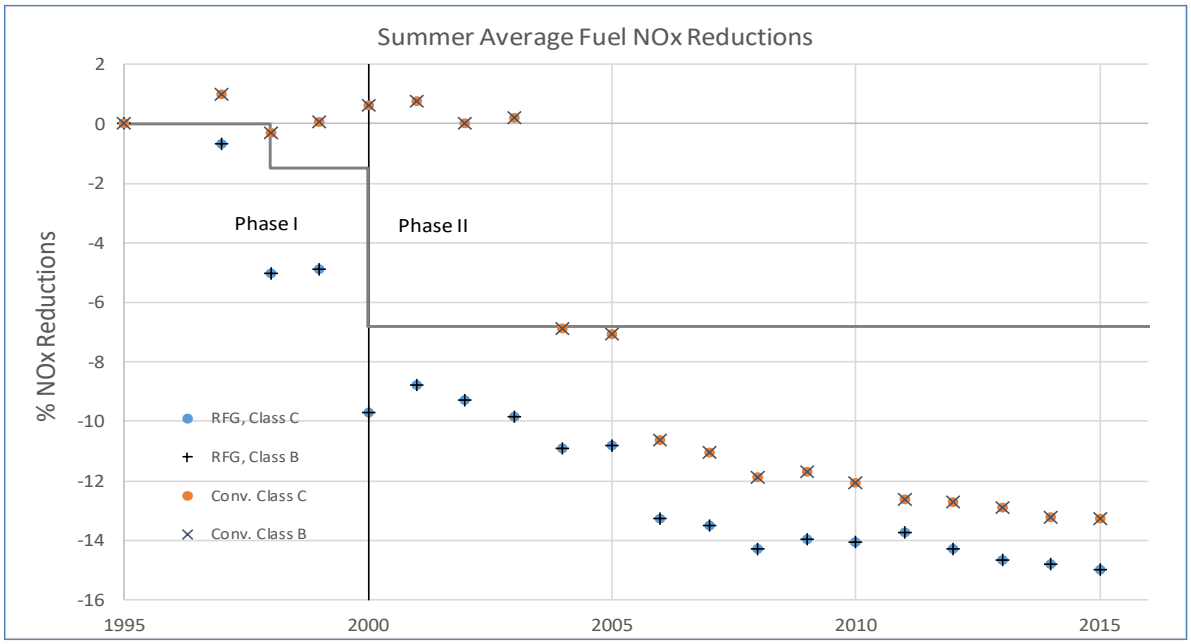

Figure 17. Complex Model predicted NO_x reductions for summer CG and RFG from 1995 to 2015. Dark horizontal lines represent emissions reduction requirements under the RFG program.

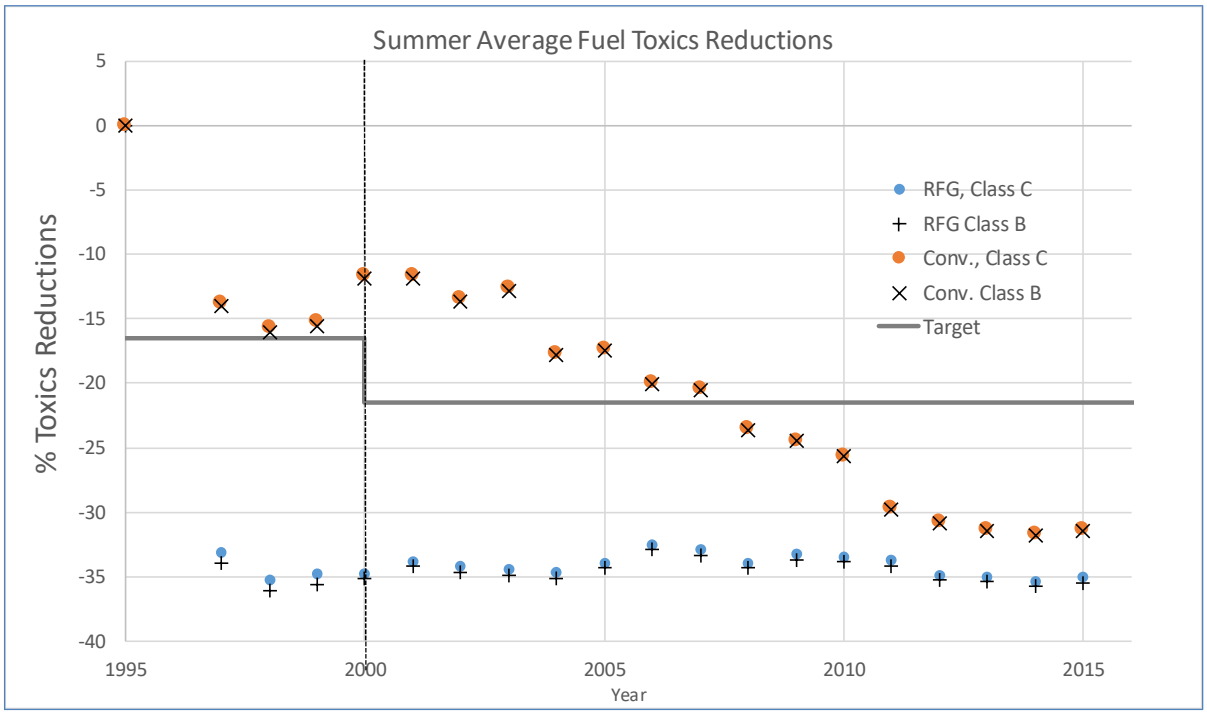

Figure 18. Complex Model predicted toxics reductions for summer CG and RFG fuels from 1995 to 2015. Dark horizontal lines represent emissions reduction requirements under the RFG program.

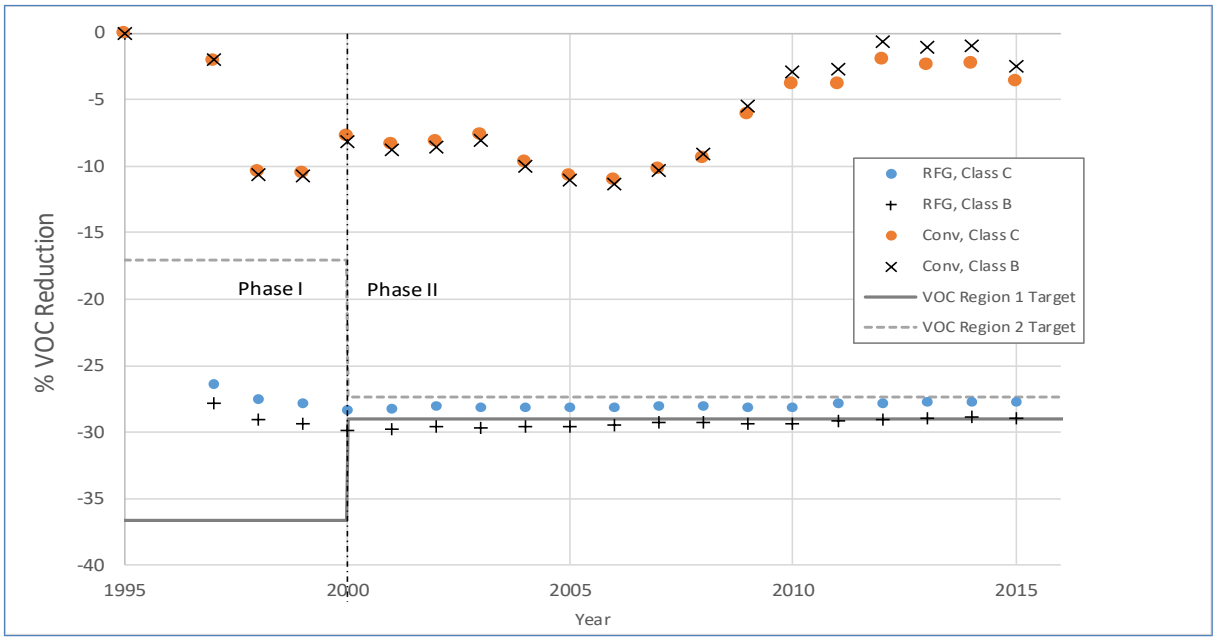

Figure 19. Complex Model predicted VOC reductions for summer CG and RFG fuels from 1995 to 2015. Dark solid horizontal line represents emissions reduction requirements in VOC Region 1; dashed horizontal line represents requirements in VOC Region 2.

strongly influenced by several fuel properties – especially benzene level, total aromatics, sulfur content and MTBE level. The combined effects of changes in all these properties are responsible for the trends seen in Figure 18. The sharp decline in CG sulfur content between 2003 and 2004 (and continued decline to 2006) is largely responsible for the step change in toxics reduction at that time. Similarly, the decline in fuel benzene levels between 2010 and 2011 (as required by the MSAT2 rule limiting average benzene to 0.62 vol.%) is responsible for the sharp change in toxics seen at that time. The small remaining predicted difference in toxics reductions between RFG and CG from 2011 onward is due to slight differences in benzene and total aromatics that persist between these fuel types.

5.3 VOC emissions reductions

The VOC emissions reduction trends predicted by the Complex Model are shown in Figure 19. The RFG Phase II requirements call for a 27.7% reduction compared to the 1990 baseline in Class C, and a 29.0% reduction in Class B. As seen in Figure 19, both of these requirements are being met. Much smaller VOC reductions are predicted for CG. The large differences in predicted emissions reductions between RFG and CG are due primarily to RVP effects. In the Complex Model, VOC emissions are most strongly (and nearly exclusively) influenced by RVP levels (refer to sensitivity analysis in Figure 16). When reduced RVP regulations were established in 1992, CG was limited to summertime RVP levels of 7.8 psi in Region 1 (Class B) and 9.0 psi in Region 2 (Class C). However, as seen in the gasoline property trends discussed previously, actual averaged RVP levels in summertime CG rose by about 1 psi between 2007 and 2012, coinciding with increased use of ethanol (see Figure 7). This increase (above the standard RVP limits) is allowable due to the 1 psi

waiver granted to CG containing 9-10 vol. % ethanol. During this period of 2007-2012, average ethanol content in CG rose from 1% to 9%. The model predicted impacts of this increase are clearly seen in the projected VOC emissions results of Figure 19.

To summarize, Figures 17 - 19 indicate that the RFG emissions reduction targets for summer fuels are being met for all pollutants. However, over the life of the RFG program, significant fuel property changes have also occurred with CG. Consequently, differences between RFG and CG have diminished significantly over the years. As a result, model predicted emissions reduction differences between RFG and CG have also diminished. This can be seen clearly for NO_x (Figure 17) and toxics (Figure 18) emissions reductions, where CG now provides nearly the same predicted benefits as RFG. The situation with VOC reductions is quite different. While RFG fuel formulations are achieving the required emissions reduction benefits, conventional gasolines are predicted to provide a much smaller benefit. This is a consequence of higher RVP levels in CG, which is enabled, in part, by the 1 psi RVP waiver granted to ethanol-containing gasoline. A comparison of CG and RFG emissions reductions calculated using the Complex Model is provided below in Table 8. Using average summer gasoline properties for 2015 suggests that CG provides about 90% of the emissions reduction benefits of RFG for NO_x and toxics, but only 13% of the benefit for VOC.

Table 8. Fleet-wide Model Predicted Emissions Reductions for Summer, 2015.

Pollutant	RFG Target	Complex Model Predictions		Relative Benefit, Conv./RFG
		RFG	Conventional	
NO_x	6.8%	15.0%	13.3%	0.89
Toxics	21.5%	35.0%	31.5%	0.90
VOC (Region 1, Class B)	29.0%	29.0%	2.5%	0.09
VOC (Region 2, Class C)	27.4%	27.7%	3.6%	0.13

A similar set of Complex Model simulations were conducted to compare the RFG and CG emissions reductions predicted for winter gasolines. Since the RFG Program is largely concerned with summer fuels, these winter fuel results are of less importance. The Complex Model predicted NO_x, toxics, and VOC emissions reductions from the winter fuels are shown in Appendix C Figures C-1, C-2, and C-3, respectively. Because there are no differences between Area Classes B and C during winter, only a single set of results is shown for RFG and CG in each figure.

The wintertime NO_x results (Figure C-1) are very similar to the summer fuel results shown in Figure 17, with RFG and CG converging at a value of approximately 14% emissions reduction compared to baseline. The winter toxics trend results shown in Figure C-2 resemble the summer fuel trends shown in Figure 18, but with smaller predicted emissions reduction benefits. For example, the toxic emissions reduction benefit predicted for summer RFG in 2015 is 35%, while the winter RFG benefit is only 28%. One factor contributing to this difference is that the Complex Model assumes zero evaporative benzene emissions in the winter, whereas evaporative benzene is a significant contributor to summertime toxics.

The wintertime VOC results are shown in Figure C-3. These results are problematic and should be viewed as unreliable because of limits that the Complex Model imposes on fuel RVP. The Complex Model assigns an RVP level of 8.7 psi to both summer and winter baseline fuels and imposes allowable RVP input limits of 6.4 – 10 psi for RFG and 6.4 – 11 psi for conventional gasoline. However, most national average wintertime fuels have RVP levels of 12 – 13, as reported in the data sets provided by EPA (Appendix B). Inputting these higher RVP values into the Complex Model, results in error-tagged emissions reduction estimates. It should also be remembered that the VOC reduction requirements of the RFG Program do not apply during winter months, so these problems with Complex Model estimates of VOC from winter fuels are not consequential.

6. Use of the MOVES2014 Model

In an effort to more realistically estimate the long-term on-road vehicle emissions trends in the U.S., a number of simulations were run using the current EPA vehicle emissions model, MOVES2014 (Note: MOVES has replaced EPA's earlier MOBILE Model).[25] Four simulations covering the period of 1990 to 2017 are identified in Table 9. All these simulations utilized national default values for the LD gasoline fleet and fuel information. Run 6 simulated a winter period, while the other three runs simulated summer periods. [Note: National default fuel is meant to represent the mix of marketplace fuels being used in the locations and times being modeled. Due to the geographic variability contained within national default fuel, its composition is not uniform, and thus cannot be compared directly with the average fuel properties shown in Appendix B that were used in the Complex Model assessments described above.]

Runs 5, 7, and 8 were all based on the same fleet and time period, but differed in their time aggregation step (annual or hourly) and in the emissions processes that were included (only Run 7 included evaporative emissions). Use of an hourly time step – which is necessary to estimate evaporative emissions – greatly increases the computer time required to conduct a simulation. On a typical personal computer used in this project, it took approximately 28 hours to complete a run using an hourly time step, and less than 30-min. to complete a run with an annual time step.

Emissions output results from the MOVES Model are provided in units of mg/mi. As described above, the principal results from the Complex Model are provided in units of percent change from a 1990 baseline, although mg/mi results can also be obtained. For comparison with Complex Model results, the MOVES2014 Run No. 7 is most appropriate, as this included evaporative emissions in addition to running and start emissions.

In Figures 20-22, the MOVES-predicted emissions rates are shown over the period of 1990-2017 for NO_x, VOC, and toxics, respectively. As expected, these results (grey-colored points) show significant reductions for each pollutant, over the entire time period, with most of this reduction due to fleet turnover.

Emissions rates calculated using the Complex Model (for both CG and RFG) are also shown in Figures 20 - 22. To determine these results, the annual average fuel properties for CG and RFG for

Table 9. Definition of Parameters Used in two Runs of MOVES2014.

MOVES Parameters	Run 5 National Default	Run 6 National Default	Run 7 National Default	Run 8 National Default
Scale	On Road, National Inventory	On Road, National Inventory	On Road, National Inventory	On Road, National Inventory
Geographic Bounds	Nation	Nation	Nation	Nation
Time Span				
Time Aggregation	Annual	Annual	Hourly	Hourly
Years	1990-2017	1990-2017	1990-2017	1990-2017
Months	April – Aug. (Summer)	Nov. – Feb. (Winter)	April- Aug. (Summer)	April- Aug. (Summer)
Vehicles	Gasoline: LD Truck, Passenger Car, Passenger Truck	Gasoline: LD Truck, Passenger Car, Passenger Truck	Gasoline: LD Truck, Passenger Car, Passenger Truck	Gasoline: LD Truck, Passenger Car, Passenger Truck
Road Type	All*	All*	All*	All*
Pollutants and Processes				
Total HC	Running, Start	Running, Start	Running, Start, Evap.	Running, Start
NMHC	Running, Start	Running, Start	Running, Start, Evap.	Running, Start
VOC	Running, Start	Running, Start	Running, Start	Running, Start
NO_x	Running, Start	Running, Start	Running, Start	Running, Start
Benzene	Running, Start	Running, Start	Running, Start, Evap.	Running, Start
Butadiene	Running, Start	Running, Start	Running, Start	Running, Start
Formaldehyde	Running, Start	Running, Start	Running, Start	Running, Start
Acetaldehyde	Running, Start	Running, Start	Running, Start	Running, Start

* The simulation runs were completed with all road types, but road type 1 was excluded from the computation of average mg/mi due to no VMT reported on this road type.

each year from 1997 to 2015 (as shown in Appendix B) were input into the Complex Model, and the mg/mi emissions outputs for NO_x, VOC, and toxics were obtained. (This is the same approach as was used to derive the emissions reduction results shown in Figures 17-19.) The Complex Model-predicted emissions trends all show a discontinuity at year 2000, due to transitioning from Phase 1 to Phase 2 of the RFG program, and changes in the Complex Model that this entailed.

Unlike the MOVES results, which show a continuous reduction in emissions rates from 2000 to 2015, the Complex Model-predicted emissions rates are relatively flat over this time period. This is explained by the fact that the Complex Model is based on an assumed, fixed fleet consisting of only 1990 technology vehicles, which does not undergo fleet turnover in the way the actual fleet does, as modeled in MOVES. To provide a better comparison with the Complex Model results, a MOVES simulation was also run in which the fleet was limited to 1990 vehicles. The results (not shown here) indicated much flatter trends from 2000 to 2017, with the emission rates being closer to those shown

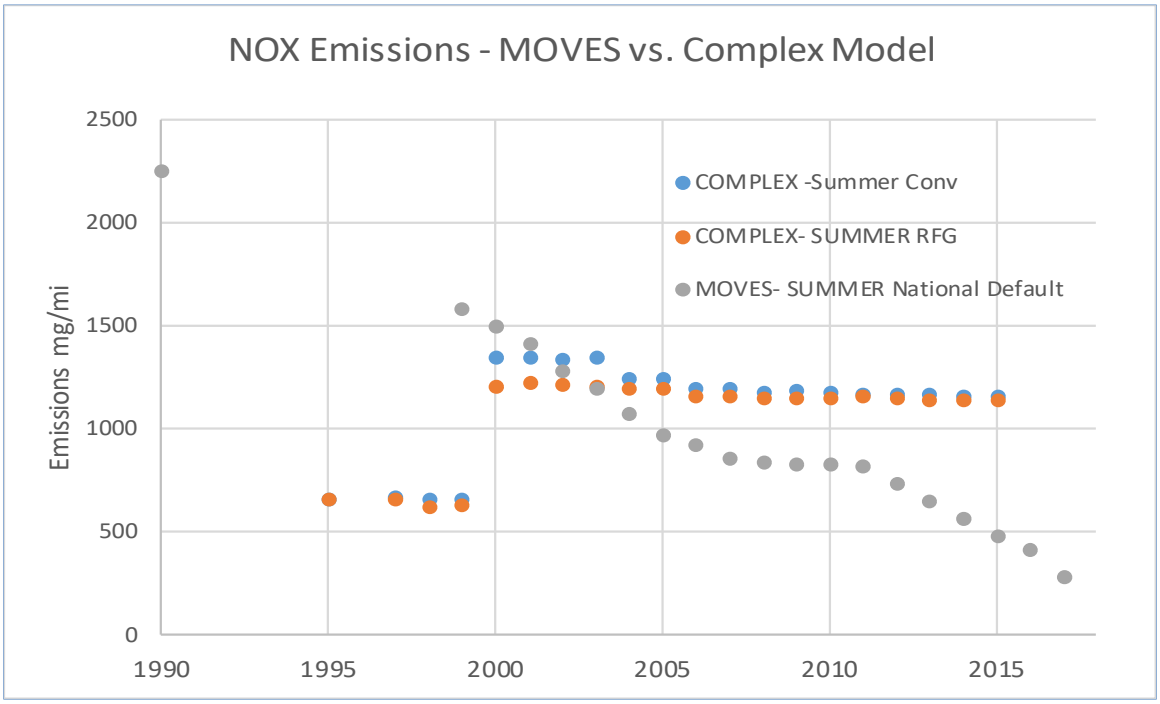

Figure 20. NO_x emissions from summer fuels as determined by the Complex Model and by MOVES2014 (National Default Run No. 7; hourly time aggregation).

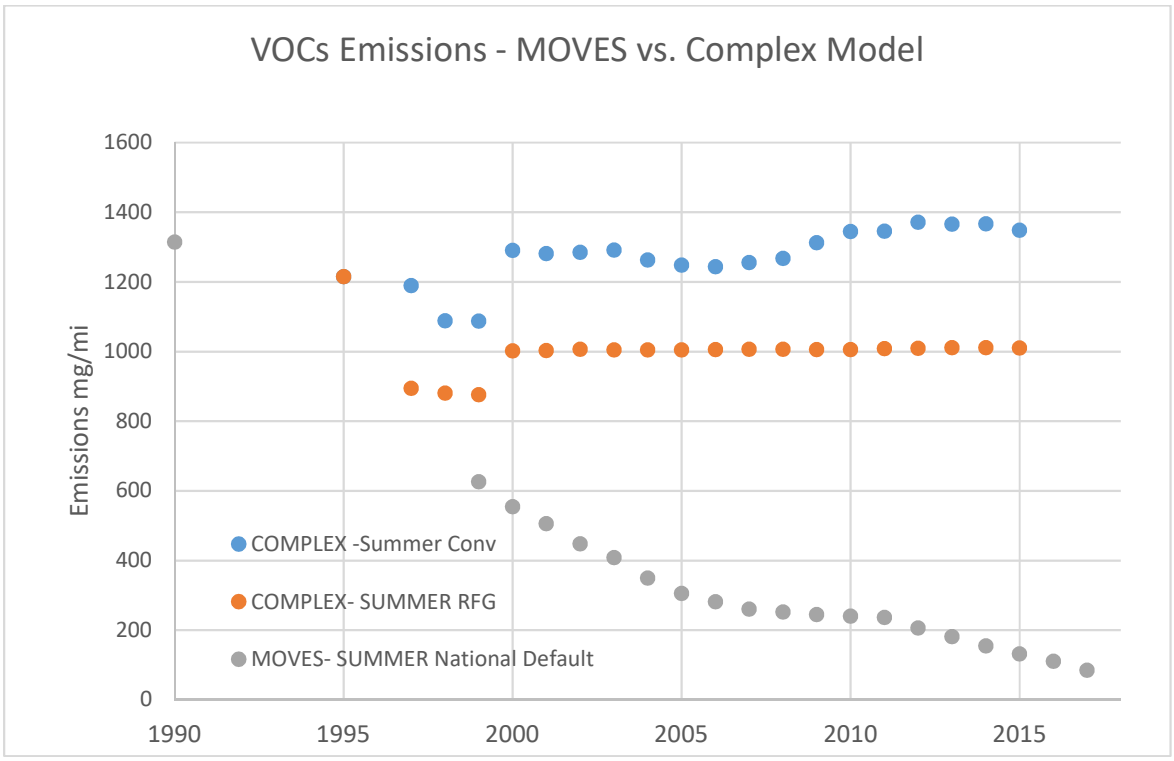

Figure 21. VOC emissions from summer fuels as determined by the Complex Model and by MOVES2014 (National Default Run No. 7; hourly time aggregation).

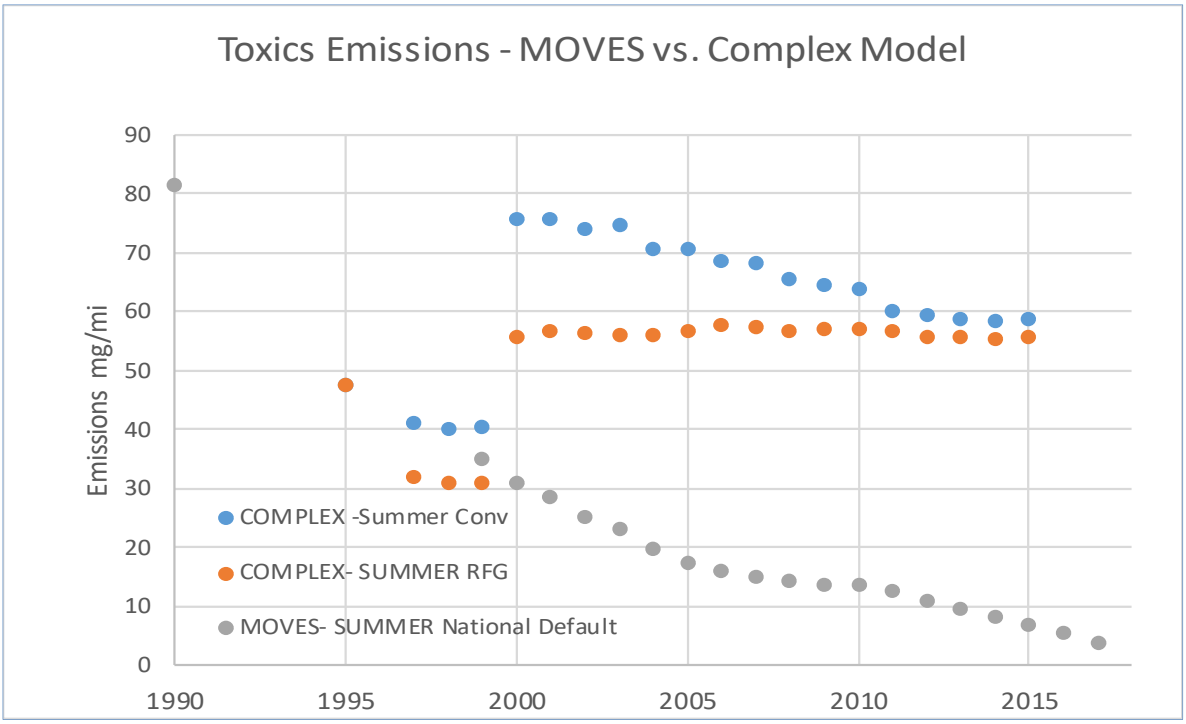

Figure 22. Toxics emissions from summer fuels as determined by the Complex Model and by MOVES2014 (National Default Run No. 7; hourly time aggregation).

in Figures 20 – 22 that were obtained from the Complex Model than to those obtained from the National Default MOVES Run No. 7.

It would be of interest to conduct additional MOVES runs to examine the long-term impacts of fuel changes upon model-predicted fleet-wide emissions. For example, modifying the fuel inputs in MOVES to reflect the 19-year fuel compositional trends shown in Appendix B would perhaps provide a more realistic assessment of the emissions benefits of RFG compared to CG. However, such efforts are beyond the scope of this project.

7. On-Road Light-duty Emission Trends

The Federal RFG program was one of several new regulations promulgated by the EPA under the authority of the 1990 CAAA that targeted on-road vehicle emissions.[1] Looking back in time to evaluate RFG benefits requires the very difficult task of trying to assign credits to reductions that likely occurred as a consequence of many changes. One unique feature of the RFG regulations was the requirement to measure all emission benefits against a "1990's" baseline fleet operating on a baseline gasoline with properties representing calendar year 1990 values. This is a mythical fleet that does not contain just 1990 vehicles, but also some 1986 to 1989 model year vehicles that possess "1990's" technology. All of the Complex Model sensitivity simulations (Figures 14 – 16) and fleet emission reduction predictions (Figures 17 – 19) are calculated against this 1990's baseline fleet. For

example the 15% reduction in NO_x emissions for 2015 that was calculated using the Complex Model and shown previously in Table 8 represents the estimated NO_x benefit for a "1990's" fleet using the RFG fuel compared to a baseline fuel with 1990 property values.

Since the rules have been promulgated, not only have conventional fuels changed but the on-road fleet has changed tremendously. The University of Denver first began collecting fuel specific on-road carbon monoxide (CO) vehicle emission measurements in 1988, and closely followed with hydrocarbons (HC) measurements in the Chicago area in 1990.[26, 27] To provide some background on the magnitude of the observed on-road fleet emission changes since 1990 we calculated mean and median fuel specific CO and HC emissions for fleets sampled in the Chicago and Denver areas. Table 10 shows the mean and median fuel specific emissions for data collected in 1990 and 1992 at a Central Ave. & I-290 site near downtown Chicago and compares them with measurements collected at the current Algonquin Rd. & I-290 site in 2004 and 2016 for percent change. Similarly we compare the same statistics for data collected in Denver in 1991 (W. 6th Ave. and I-70) and 1992 (Speer Blvd. and I-25) against data from the current Denver sampling site in 2003 and 2015. Keep in mind that the early 90's Chicago and Denver on-road fleet do not technically qualify as an official baseline fleet as outlined in the RFG regulations, however, they do serve to highlight the large reductions in on-road CO and HC emissions that have occurred. They also provide a bench mark for comparing and contrasting the emission reductions predicted for a "1990s" technology fleet as represented by the Complex Model to have occurred solely due to changes in fuel properties.

In general the median emissions have tended to drop faster than the mean emissions, which is an indicator of the increasing skewness in the emissions distribution. Mean fuel specific CO emissions in the Chicago area dropped by a factor of 6 between 1990 and 2004 and a factor of 11 by 2016, with mean fuel specific HC emissions reductions being roughly double those factors. In Denver, the reductions in both emission species were much smaller (mean CO decreases of a factor of 2 between 1991 and 2003 and more than a factor of 7 by 2015) than in Chicago through 2003 perhaps owing to an older Denver fleet. Yet by 2015 the reductions of both CO and HC emissions in Denver were approaching 90% with fleet mean emissions closer to those observed in Chicago. These reductions are significantly larger than those predicted from fuel changes alone. This emphasizes that likely many vehicular improvements were also occurring during this time frame potentially along with other unknown factors.

Beginning in the late 1990's, with funding from the Coordinating Research Council (CRC) as part of the E-23 program, four monitoring sites were selected to have reoccurring measurements using consistent data collection times, equipment and measurement methods. The equipment consisted of the Fuel Efficiency Automobile Test (FEAT) capable of collecting fuel specific tailpipe measurements of CO, HC, nitric oxide (NO), speed and acceleration and a photograph of the vehicles license plate.[28] FEAT measures all species as a ratio to carbon dioxide (CO_2) and then using carbon balance converts the individual species measured ratios (CO/CO_2, HC/CO_2 and NO/CO_2) to a fuel specific value such as gCO/kg of fuel.[29] Because FEAT measures a ratio, vehicles with zero emissions (ratios of 0) will have some normal distribution of measurements that will be both positive and negative. The width of this distribution will depend on the noise level of the instrument and any

Table 10. Fuel Specific Emission Reductions for Early 1990 Fleets in Chicago and Denver.

City	Year	Location	Measurements (Mean MY)	Mean / Median gCO/kg of fuel %Reduction (Start Yr.)	Mean / Median gHC/kg of fuel %Reduction (Start Yr.)
Chicago	1990	Central Ave & I-290	13,639 (1985.3)	125 / 47.2	49.3 / 34.6
Chicago	1992	Central Ave & I-290	8,733 (1986)	121 / 32.3	33 / 25.8
Chicago	2004	Algonquin Rd & I-290	21,838 (1999.2)	21.5 / 5.3 83/89% (1990) 82/84% (1992)	2.8 / 2.1 94/94% (1990) 92/92% (1992)
Chicago	2016	Algonquin Rd & I-290	30,062 (2009.6)	10.9 / 3.1 91/93% (1990) 91/90% (1992)	1.8 / 0.9 96/97% (1990) 95/97% (1992)
Denver	1991	W. 6th Ave & I-70	13,391 (1985.9)	89 / 26.5	62.8 / 47.9
Denver	1992	Speer Blvd & I-25	49,201 (1985.7)	95.5 / 15.8	23.6 / 14.7
Denver	2003	6th Ave & I-25	21,323 (1996.4)	44 / 10.5 51/60% (1991) 54/34% (1992)	4.2 / 1.7 93/96% (1991) 82/88% (1992)
Denver	2015	6th Ave & I-25	23,318 (2005.5)	12.6 / 4.1 86/85% (1991) 87/74% (1992)	3.4 / 1.8 95/96% (1991) 86/88% (1992)

additional environmental factors. A negative value does not mean that the vehicle is cleaning the air but that it is a zero measurement in a distribution paired with a similar magnitude positive measurement that is also a zero. A theoretical fleet with zero emissions would end up with a measurement distribution centered at a mean of zero with a similar number of negative and positive measurements. Because of this fact we do not eliminate negative readings from the measurement databases as this would bias the data high. The data which underlie many of the following analyses include negative values which are from the lower percentiles of that fleet's emissions distribution.

The sites monitored for E-23 were in 1) the northwest suburbs of Chicago IL. (Algonquin Rd. to EB SH53/I-290) with measurements starting in 1997, 2) Denver CO (NB I-25 to WB 6th Ave.) starting in 1999, 3) West Los Angeles (SB La Brea Ave. to EB I-10) starting in 1999 and 4) Phoenix AZ (WB Sky Harbor Blvd. to SB SH143) starting in 1998. In addition, measurements were also made in Omaha NE (2002 and 2004) and Tulsa OK (2003 and 2005). These last two sites were selected because they were relatively large metropolitan areas that were not subject to any state run I/M programs. Initially five days of measurements were collected at each site on a yearly basis (this frequency was later reduced to an every other year schedule) with the aim of collecting emission measurements and vehicle information to provide a database of approximately 20,000 records over a ten year period (1997 – 2006). The resulting data, reports and publications are publically available at http://feat.biochem.du.edu.[30]

The CRC's follow up E-106 program sponsored two additional measurement collection campaigns in Chicago (2014 and 2016) and Tulsa (2013 and 2015). In addition, the California Air Resources Board sponsored measurements in 2013 and 2015 at the west LA site and DU sponsored measurements at the Denver site in 2014 and 2016. All measurements were collected using the FEAT system with improved capabilities to measure the additional species of ammonia, nitrogen dioxide and sulfur dioxide (SO_2). However, with the significant reductions in fuel sulfur levels and like reductions in the tailpipe SO_2 levels to below FEAT's detection capabilities we have stopped calibrating the measurements from that channel. The Phoenix site was dropped because the measurement site ceased to exist when the roadway was reconstructed.

These sites were originally chosen in an attempt to cover the variety of vehicle fleets, fuels, emission certification standards and I/M program types found in the US. For example, the Los Angeles site typically has the oldest vehicle fleet, a low fleet percentage of diesel vehicles, California certified vehicle emission standards, a hybrid decentralized/centralized acceleration simulation mode I/M program and California reformulated fuel. The Chicago site generally has the newest vehicle fleet (salted winter roadways is thought to be the primary reason for this) a lower fleet percentage of pickup trucks, an OBD only I/M program and Federal RFG. Denver has one of the higher fleet percentages of trucks and diesel vehicles, is at high altitude, a centralized IM240 I/M program and the measurements are collected in the winter and was one of the first areas to use oxygenated fuels. Tulsa has many fleet similarities to Denver but since it is currently not a non-attainment designated metro area, it uses conventional fuels and does not have a light-duty I/M program.

Light-duty vehicle emissions for CO, HC and NO have been on a significant downward trend for the last two decades (see Table 10 for CO and HC). Figure 23 shows the mean fuel specific emission measurements for CO, HC and NO that have been collected in Chicago IL, Denver CO and Tulsa OK as part of the CRC's E-23 and E-106 measurement program since 1997. Each site and measurement years HC emissions have been normalized to the lowest emitting sub-fleets (specific makes and or model years) mode or mean emissions for comparison (See Appendix D).[31] In general reductions in fleet fuel specific mean emission levels have followed similar trends at each of these three sites despite differences in fleet composition (gas / diesel, passenger / truck), driving mode, fuels (RFG vs CG), I/M programs (Chicago biannual OBD, Denver biannual IM240, Tulsa none) and socio-economics. Table 11 shows the percent overall reductions (data shown in Figure 23) and the year over year changes in the mean and median emissions of CO, HC and NO within the total time span covered by the series of measurements performed at each of the three sites. The comparison covers a different time period for each city which impacts the magnitude of the overall reductions with Chicago having the longest measurement record and Tulsa the shortest. As shown in Figure 23 and Table 11 all three species have experienced significant reductions over the sampling period. Year over year reductions for the mean fuel specific CO emissions ranged from 10% in Denver to 8.5% in Tulsa. Year over year mean HC emissions declined 6.2% in Chicago and 1.9% in Tulsa while light-duty NO mean emissions were reduced 9.1% in Denver and 8.6% in both Chicago and Tulsa. Year over year reductions of fuel specific median emissions have not dropped at the same rates in all of the cities. Chicago has seen the median emissions drop faster than the means while Denver and Tulsa have seen CO and HC medians decline at a slower rate. However, reductions in fuel specific median

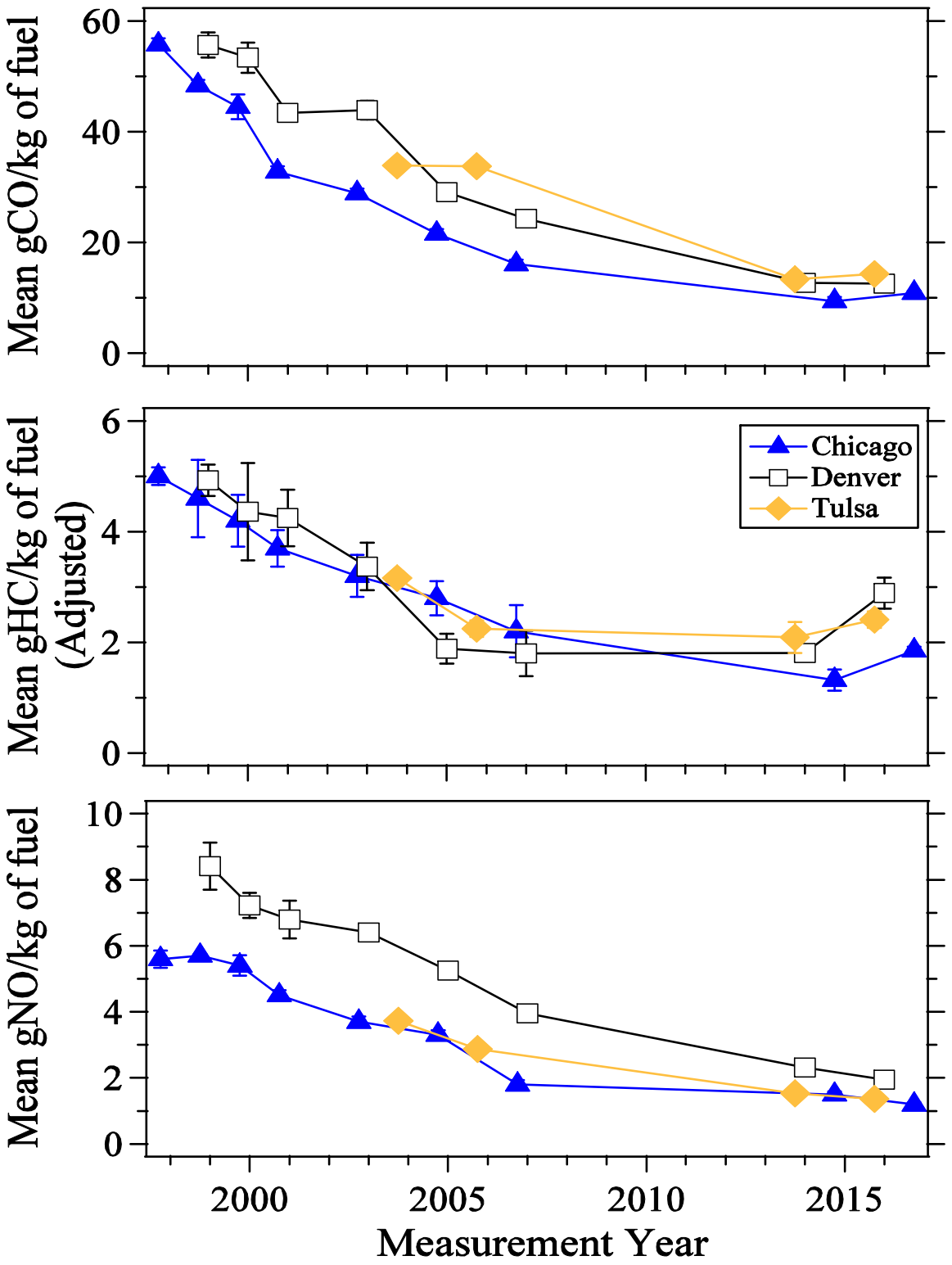

Figure 23. Chicago IL (▲), Denver CO (□) and Tulsa OK (◆) mean fuel specific historical emission trends for CO (top), HC (middle) and NO (bottom) by measurement year. Uncertainties plotted are standard errors of the mean determined from the daily means.

Table 11. Percent Overall and Year over Year Emission Reductions.

Location (Fuel)	Initial Year (Final Year)	Percent Overall and Year over Year Mean and Median Emission Reductions		
		CO (Overall Mean) Mean / Median	HC (Overall Mean) Mean / Median	NO (Overall Mean) Mean / Median
Chicago (RFG)	1997 (2016)	(80.5%) 9.1% / 11.5%	(65.1%) 6.2% / 7.4%	(78.4%) 8.6% / 20.7%
Denver (CG)	1999 (2015)	(77.5%) 10% / 9.5%	(42%) 4.8% / 4%	(63.2%) 9.1% / 19.6%
Tulsa (CG)	2003 (2015)	(57.9%) 8.5% / 6.8%	(25%) 1.9% / 5.4%	(62.2%) 8.6% / 25.3%

NO emissions have outpaced reductions in the means for all three sites as Tier 2 vehicles have entered the fleet. The absolute differences in the emission means for all three sites have converged as the levels have decreased and for CO and HC emissions there are signs that the fleet mean decreases may be leveling off at each of these sites.

A number of factors have contributed to these large reductions in tailpipe emissions. We have already discussed the number of significant changes to the fuel properties that have occurred since 2000. In addition to fuel, the fleet composition (passenger versus truck) has changed. For example, in Chicago the share of our measurements that were from vehicles identified by the POLK VIN decoder as passenger cars dropped from 71% of the total in 1997 to 55% of the total by 2014. Also, the emission certification standards were lowered over this time period. In 2000, the fleets were dominated by Tier I certified vehicles (~1997 – 2003) and today they are dominated by Tier 2 certified vehicles (2009 & newer). One of the more important consequences of this change was to require the same gram per mile emissions standards for passenger vehicles and trucks eliminating differences allowed in Tier I vehicles. The "Great Recession" of 2008 – 2009 significantly increased the age of the fleet (~2 model years in Denver and 1 to 1.5 model year age increases for Tulsa and Chicago respectively) which has worked to slow the historical emissions reduction.[32] Since fleet age is one of the best established factors in predicting fleet mean emissions, accounting for age differences between communities is important.

Change in vehicle technology is also an important determinant of trends in fleet average emissions, even when those technology changes are not accompanied by a reduction in tailpipe emission standards. Since 1990 there have been two major reductions in vehicle emission standards beginning with Tier I vehicles that were introduced starting in 1994. Vehicles meeting Tier 2 standards began to be phased-in in 2004. However, one of the more noticeable changes resulting in lower fleet emissions was the introduction in 1996 of vehicles equipped with Onboard Diagnostic II technology. These vehicles were required to meet an increased durability requirement and were the first to be equipped with a computer readable diagnostic report of all emission sensors. In most of our data sets there is a

significant reduction in fuel specific emissions beginning with the 1996 models, still visible even after 20 years. Figure 24 shows fuel specific CO, HC and NO emissions from the four measurement campaigns conducted in Tulsa, OK. The 1996 models all have lower fleet average emissions in each measurement year than their 1995 counterparts and the differences generally increase with time. Fuel specific CO emissions for 1996 models are 23% lower in 2003, which increases to 40% lower in 2015. Fuel specific HC emissions for 1996 models are 27% lower in 2003 that increases to 57% lower in 2015. Fuel specific NO emissions for 1996 models are 37% lower in 2003 and the difference increases to 49% in 2015.

We also explored several additional fleet factors to gauge their potential importance and impacts in our fuel specific fleet emissions data sets through decoding vehicle identification numbers (VIN). VIN decoding provided fuel type, vehicle type (Truck or Passenger as defined by the POLK VIN decoder) and engine size in liters. Data from Chicago and Tulsa were used to assemble graphs of emissions for gasoline only vehicles versus model year for the different vehicle types and different engine sizes. Figure 25 details fuel specific emissions for CO (top panels), HC (middle panels) and NO (bottom panels) emissions for Chicago trucks and passenger vehicles and for two engine size groupings (< 3l, >=3l and < 5l) labeled as 2l and 4l. As expected, emissions versus model year generally show increases with increasing age and because of the multiple selection criteria, which has reduced the number of vehicle measurements in each model year, the noise on individual groups has increased. Despite the increase in noise it is clear that for fuel specific HC emissions there is a significant decrease in emission levels for trucks with both engine size groups when compared to passenger vehicles. The HC emission normalization process was performed on the fleet producing an adjustment value that is larger than would have been produced if using only trucks. This is the reason that the lower emitting truck groups have a number of negative means. The CO and NO emissions show little difference between cars and trucks or engine size groupings. The differences in HC emissions appear to be specific to vehicle type (passenger or truck) and disappear if we only select for engine size.

Figure 26 show similar graphs for the 2015 Tulsa data set. There is more noise, likely due to the smaller size of the 2015 Tulsa database, but again CO and NO emissions show few emission differences. However, the HC emissions are again almost always lower for trucks when compared with the cars. For the 2l grouped engines, 15 out of the 17 model years shown have lower truck emissions. A similar trend is shown for the 4l group with the trucks having lower mean gHC/kg of fuel emissions in 14 out of the 17 model years shown. We have no immediate explanation for why only the HC emissions seem to be affected. CO and NO do not show any significant difference. However, the differences are large enough that it warrants at least incorporating a check for vehicle type and fractions when comparing emissions trends.

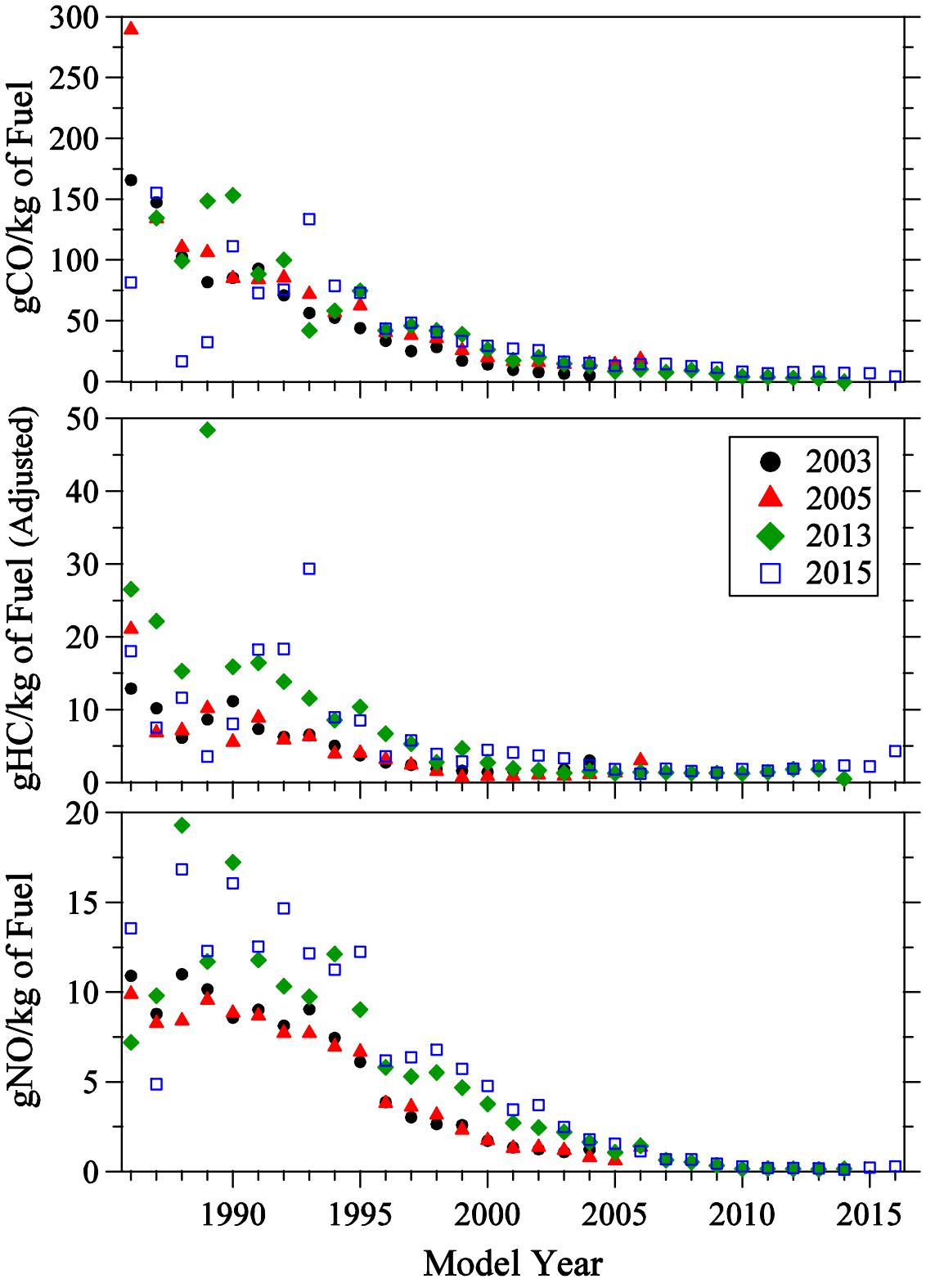

Figure 24. Fuel specific CO (top), HC (middle) and NO (bottom) emissions by model year for the four years of measurements in Tulsa, OK.

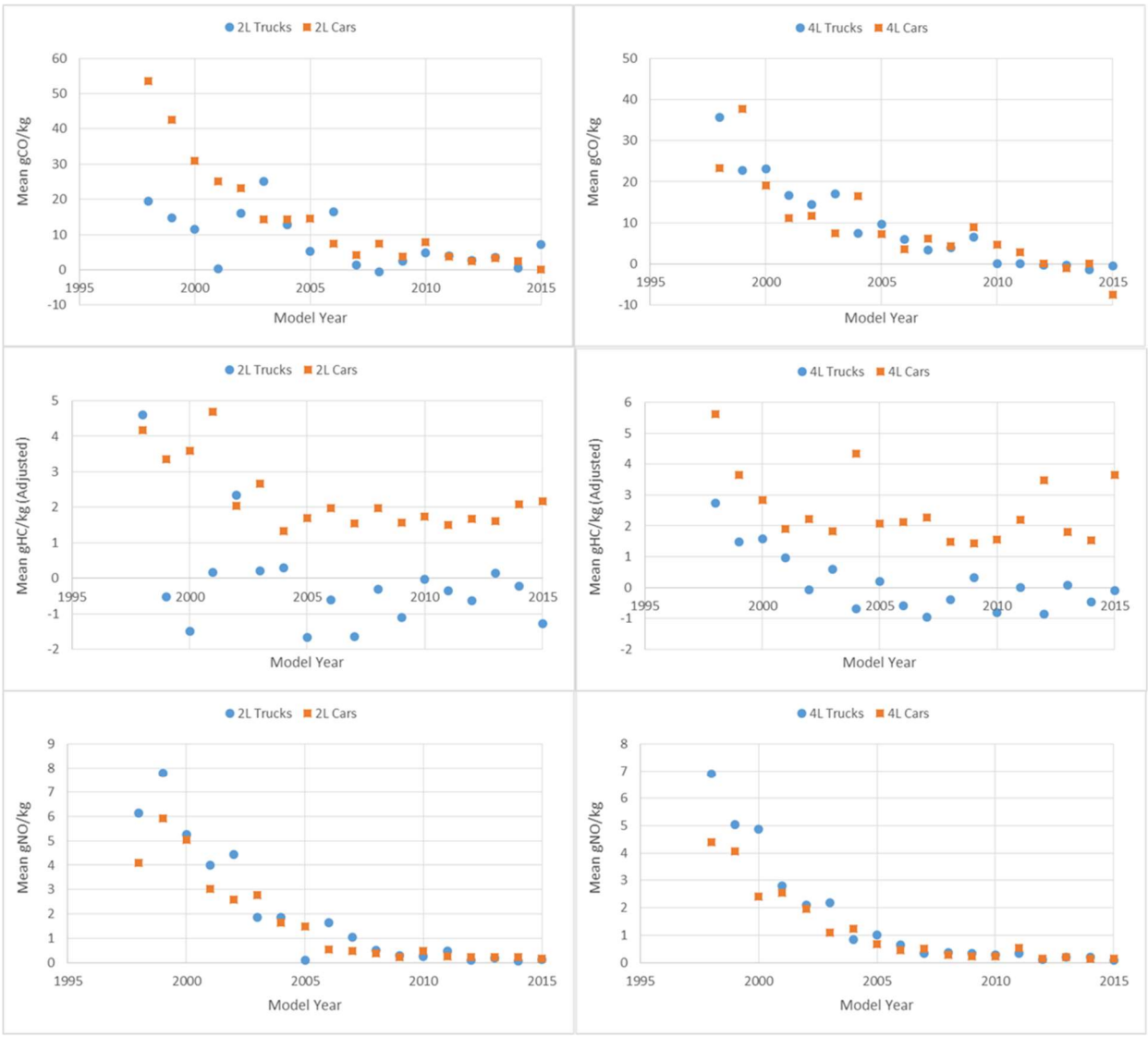

Figure 25. Data from the 2014 measurements in Chicago of fuel specific emissions for CO (top), HC (middle) and NO (bottom) versus model year for Trucks (●) and Cars (■). The left panels are for vehicles with engines smaller than 3l (labeled as 2L) and the right panels are for engine larger than 2.9l and smaller than 5l (labeled as 4L).

8. Fuel Effects Analysis

8.1 Oxygen increases

The use of the Complex Model to predict emissions changes resulting from the annual trends in national average fuel properties (shown earlier in Figures 2 – 12 and described in Section 5) highlights three major changes in fuel formulation. They are: 1) increases in fuel oxygen content, 2) sulfur reductions, and 3) changes in RVP and the reductions of benzene and aromatics in fuels. Each

Figure 26. Data from the 2015 measurements in Tulsa of fuel specific emissions for CO (top), HC (middle) and NO (bottom) versus model year for Trucks (●) and Cars (■). The left panels are for vehicles with engines smaller than 3l (labeled as 2L) and the right panels are for engines larger than 2.9l and smaller than 5l (labeled as 4L).

of these changes was instituted to provide benefits for different vehicle emission species which are illustrated in the Complex Model sensitivity simulations (Figures 14 – 16).

RFG, as has been previously mentioned, is generally considered a part of the ozone abatement strategy for several areas within the US. However, in association with the national renewable fuels mandates the oxygen levels in both RFG and CG experienced significant changes in the last decade. As shown in Figure 2 the weight percent oxygen in both RFG and CG has increased during winter and summer since 2005. Conventional fuels saw the largest increases with more than a tripling of the wt. % of oxygen from around 1% to more than 3%, however, RFG also saw increases from 2.5% to 3.5% between 2005 and 2007. Adding oxygen to motor fuels has been previously shown to have a net benefit in reducing tailpipe CO emissions in light-duty vehicle fleets during the late eighties and

early nineties.[33-35] These studies in general showed CO emissions reductions on the order of 20% in both tailpipe and ambient emission levels, however, these older fleets contained a significant fraction of older technology vehicles with carbureted engines.

We compared mean emission levels and emission trends between our Chicago, IL, Denver, CO and Tulsa, OK data sets. We have included Denver in the analysis because of data availability, however, it should be pointed out that our Denver measurements were collected during the winter season and Denver has traditionally increased fuel oxygen during the winter season since the late 80's. Therefore, it is the likely that the wt. % of oxygen in Denver did not experience as large a change as expected in Tulsa. We have data sets from Tulsa collected in 2003, 2005, 2013 and 2015 while data was collected in Chicago in 1997 – 2000, 2002, 2004, 2006, 2014 and 2016. We chose to perform the comparison between the 2003 and 2015 Tulsa data sets and the 2004 and 2016 Chicago data sets and initially we limited the comparison to gasoline vehicles only. Table 12 compares the mean g/kg of fuel emissions for CO, HC and NO. Because the data are collected a year apart, the ages of the same model year vehicles are one year older in Chicago. To adjust for this, we have performed a simple age correction whereby we created a Tulsa fleet that has the same age as the 2004 Chicago fleet. This involves calculating the fraction of 0, 1, 2, etc. year old vehicles in the Chicago fleet and then applying that age distribution to the 2003 Tulsa fleet emissions by age to calculate an age adjusted mean.

Table 12. Tulsa and Chicago Mean Emission Comparison for the Gasoline Fleet.

Species	Tulsa 2003 g/kg of Fuel	Tulsa Age Adjusted to Chicago	Chicago 2004 g/kg of Fuel	Age Adjusted %Difference
CO	34.4 ± 0.6	29.2 ± 0.6	21.7 ± 0.8	34.3%
HC	3.2 ± 0.1	2.8 ± 0.1	2.8 ± 0.3	1.7%
NO	3.44 ± 0.03	3.09 ± 0.03	3.2 ± 0.1	-2.1%
Species	Tulsa 2015 g/kg of Fuel	Tulsa Age Adjusted to Chicago	Chicago 2016 g/kg of Fuel	Age Adjusted %Difference
CO	14.8 ± 0.7	14.1 ± 0.7	11.0 ± 0.4	27.5%
HC	2.4 ± 0.2	2.4 ± 0.2	1.9 ± 0.1	30.8%
NO	1.14 ± 0.04	1.06 ± 0.04	1.01 ± 0.06	4.9%
Species	Tulsa Year over Year %Difference	Tulsa Age Adjusted Year over Year %Difference	Chicago Year over Year %Difference	Difference
CO	57%	51.7%	49.1%	2.6
HC	22.9%	14.7%	33.7%	-19
NO	66.9%	65.6%	67.9%	2.3

There are inherent differences in the gasoline fleet mean emissions between the two cities. The 2003 Tulsa means are larger for all species than those measured in Chicago in 2004. However, when the data are age corrected the differences for HC and NO go away but only about half of the difference in

the CO means can be explained by age differences. This same observation cannot be made when comparing the 2015 Tulsa and 2016 Chicago measurements where HC emissions decreased in Chicago more than they did in Tulsa and the differences were not altered by the age correction. For changes in fuel oxygen content we might expect CO (and to a lesser extent HC) mean emissions to decrease as oxygen content rises and NO emissions to perhaps be negatively impacted. If we look at the year over year percent differences in Table 12 for these two cities we observe that for the gasoline fleet the CO and NO emissions have decreased in the two cities at similar rates (51.7 vs 49.1 for CO and 65.6 vs 67.9 for NO) while HC emission reductions have not dropped as fast in Tulsa as they have in Chicago (14.7 vs 33.7).

Tables 13 and 14 show analyses similar to those in Table 12, except that we have separately analyzed the Chicago and Tulsa gasoline passenger and truck fleets. For example, the age adjusted HC emissions comparison show that for both cities gasoline passenger vehicles have consistently higher emissions than trucks and it's the combination of those two segments that in turn drive the fleet emission comparisons shown in Table 12. The Tulsa fleet generally has a higher percentage of trucks (Tulsa 2003 53.5% and Tulsa 2015 has 60.2% of the fleet) while Chicago has more passenger vehicles (Chicago 2004 61.9% and Chicago 2016 has 52.1% of the fleet). However, even when we split the gasoline fleet out into passenger vehicles and trucks, the year over year changes in CO and NO emissions are again similar between the two cities. The largest discrepancy is for NO and the age adjusted Tulsa passenger fleet which lags the Chicago passenger fleet by about 8% year over year for NO emission reductions. However, for CO emissions which should be the species best tied to fuel oxygen content changes there is no statistically significant difference in the CO emission reductions.

There is a similar picture in Denver. Table 15 compares the Denver 2005 and 2013 data sets with the Chicago 2004 and 2014 data sets. We have limited the comparison in Denver to the 2013 data (as opposed to the 2015 data) because the ramp was rebuilt between 2013 and 2015 and we desired to eliminate this additional variable. In addition, the Denver data is collected during the winter and the Chicago data is collected in late summer. The Denver site prior to 2015 was an uphill interchange ramp (4.6° incline) that limited decelerations which is likely a factor in the HC emission means being lower before and after age corrections when compared to the Chicago fleet. The message again for CO and NO are similar, that over this comparison time period both species show similar year over year emissions reductions in both cities, again indicating factors other than simply fuel changes are behind these trends.

Mean emissions are significantly influenced by the high emitter portion of the fleet. This is the population segment shown in prior studies to be the most sensitive to changes in fuel oxygen levels. However, as previously pointed out all of those studies were conducted in the late eighties and early nineties when the fleet included a large number of carbureted vehicles. The early 2000 data sets that were used as the emissions baseline values are fleets composed largely of Tier I vehicles which will be dominated by computer controlled port fuel injected engines. These engines were designed to actively manage the engine's air fuel ratio and will work against the simple addition of oxygen to the fuel by simply adding more fuel to maintain a stoichiometric air to fuel ratio. Additionally, the national introduction of Tier 2 vehicles beginning in 2004 to the fleet further lowered on-road

Table 13. Tulsa and Chicago Mean Emission Comparison for the Gasoline Passenger Fleet.

Species	Tulsa 2003 g/kg of Fuel	Tulsa Age Adjusted to Chicago	Chicago 2004 g/kg of Fuel	Age Adjusted %Difference
CO	37 ± 0.7	30 ± 0.6	23.1 ± 0.9	29.3%
HC	3.6 ± 0.1	3.1 ± 0.1	3.4 ± 0.4	-8.5%
NO	3.40 ± 0.03	2.87 ± 0.03	3.3 ± 0.2	-12%
Species	Tulsa 2015 g/kg of Fuel	Tulsa Age Adjusted to Chicago	Chicago 2016 g/kg of Fuel	Age Adjusted %Difference
CO	16.3 ± 0.8	15.3 ± 0.7	11.7 ± 0.4	30.8%
HC	4.2 ± 0.3	4.2 ± 0.3	2.9 ± 0.1	45.5%
NO	1.16 ± 0.04	1.09 ± 0.04	0.99 ± 0.06	10.4%
Species	Tulsa Year over Year %Difference	Tulsa Age Adjusted Year over Year %Difference	Chicago Year over Year %Difference	Difference
CO	55.8%	48.8%	49.4%	-0.6
HC	-17.7%	-34.8%	15.2%	-50
NO	65.8%	61.9%	69.7%	-7.8

Table 14. Tulsa and Chicago Mean Emission Comparison for the Gasoline Truck Fleet.

Species	Tulsa 2003 g/kg of Fuel	Tulsa Age Adjusted to Chicago	Chicago 2004 g/kg of Fuel	Age Adjusted %Difference
CO	32.2 ± 0.6	26.5 ± 0.5	19.4 ± 0.7	36.7%
HC	2.8 ± 0.1	2.5 ± 0.1	1.8 ± 0.2	39.3%
NO	3.47 ± 0.03	3.07 ± 0.03	3.0 ± 0.1	3.2%
Species	Tulsa 2015 g/kg of Fuel	Tulsa Age Adjusted to Chicago	Chicago 2016 g/kg of Fuel	Age Adjusted %Difference
CO	13.8 ± 0.7	13.0 ± 0.6	10.3 ± 0.4	25.8%
HC	1.3 ± 0.1	1.2 ± 0.1	0.67 ± 0.02	83.1%
NO	1.12 ± 0.04	1.00 ± 0.03	1.04 ± 0.06	-3.0%
Species	Tulsa Year over Year %Difference	Tulsa Age Adjusted Year over Year %Difference	Chicago Year over Year %Difference	Difference
CO	57.1%	51.2%	46.9%	4.3
HC	55.2%	50.5%	62.3%	-11.8
NO	67.6%	67.3%	65.2%	2.1

Table 15. Denver and Chicago Mean Emission Comparison for the Gasoline Fleet.

Species	Denver 2005 g/kg of Fuel	Denver Age Adjusted to Chicago	Chicago 2004 g/kg of Fuel	Age Adjusted %Difference
CO	29.7 ± 1.0	22.2 ± 0.4	21.7 ± 0.8	2.2
HC	1.9 ± 0.3	1.2 ± 0.1	2.8 ± 0.3	-56.8
NO	4.81 ± 0.11	3.87 ± 0.04	3.2 ± 0.1	22.6
Species	Denver 2013 g/kg of Fuel	Denver Age Adjusted to Chicago	Chicago 2014 g/kg of Fuel	Age Adjusted %Difference
CO	12.7 ± 0.9	9.11 ± 0.2	9.6 ± 0.8	-4.6%
HC	1.8 ± 0.1	1.6 ± 0.1	1.3 ± 0.2	22.3%
NO	2.31 ± 0.15	1.64 ± 0.02	1.31 ± 0.08	24.6%
Species	Denver Year over Year %Difference	Denver Age Adjusted Year over Year %Difference	Chicago Year over Year %Difference	Difference
CO	57.0%	59.0%	56.0%	3.0
HC	5.6%	-32.2%	53.3%	-85.5
NO	52.0%	57.5%	58.2%	-0.7

emissions in both locations.

8.2 Sulfur reductions

The second significant fuel change over the last decade and a half has been the reduction in fuel sulfur levels and its predicted effects on reducing NO_x emissions. Previous research has shown the benefits to on-road NO_x emissions as a result of decreasing fuel sulfur, especially during hot stabilized operation.[36, 37] Figure 17 shows the Complex Model predicted reductions in NO_x emissions for RFG and CG. Sulfur reductions between 2003 and 2004, which coincided with the introduction of Tier 2 fuels, result in a predicted 7% reduction in NO_x emissions for CG with only a 1% NO_x reduction for RFG fuels during the same time period. Additional reductions occurred between 2005 and 2006 with the model predicting an additional 4% reduction in NO_x emissions for CG and ~2% for RFG as a result. Our previous discussion of fuel oxygen changes showed that mean NO emission reduction in Chicago, Denver and Tulsa have been similar over this same time period and much larger than predicted just for fuel changes, highlighting the fact that average NO emissions have been reduced at similar rates with both fuels.

It is preferable to use mean emissions when evaluating benefits associated with changes in fuel parameters due to the ability to account for fleet age differences when doing the comparisons. However, we also explored for potential differences among the lower emitting portions of the fleet using emission percentiles. We used the E-23/E-106 data collected in Chicago in 2004 and 2006 and in Tulsa in 2003 and 2005 as our surrogates for a RFG and CG fuel comparison, and we compared the fuel specific on-road NO emission reductions for the first three emission quartiles. Figures 27 and 28 shows gNO/kg of fuel emissions for gasoline light-duty passenger vehicles and gasoline trucks in

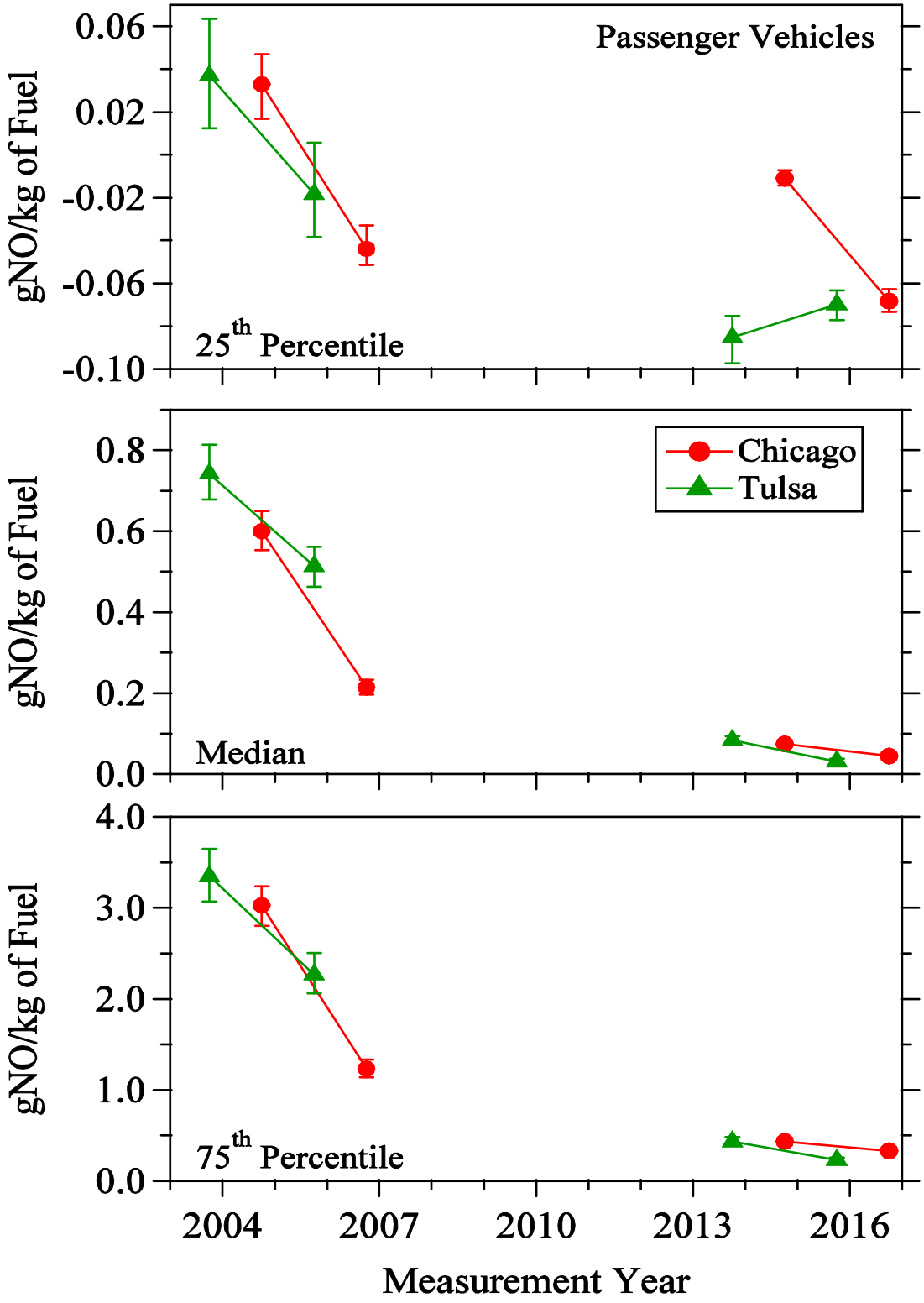

Figure 27. Chicago (●) and Tulsa (▲) fuel specific NO emissions comparison by percentiles for gasoline passenger vehicles by measurement year. Uncertainties are 95% confidence intervals.

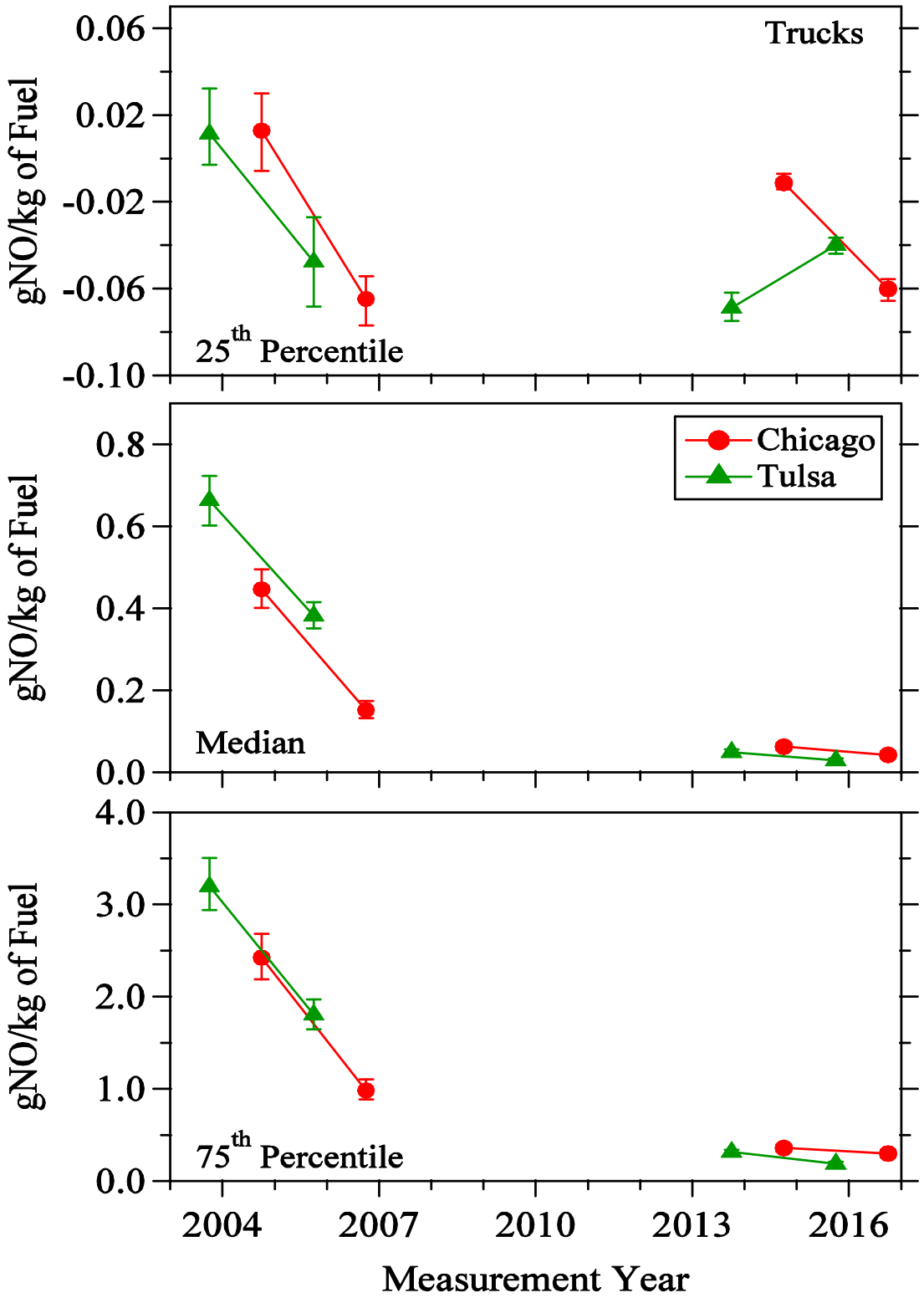

Figure 28. Chicago (●) and Tulsa (▲) fuel specific NO emissions comparison by percentiles for gasoline trucks by measurement year. Uncertainties are 95% confidence intervals.

the Chicago (circles) and Tulsa (triangles) areas for the 25th (top graphs), Median (50th, middle graphs) and 75th percentiles (bottom graphs) between 2003 and 2016. The uncertainties plotted are 95% confidence intervals calculated using resampling techniques (see Appendix E for actual values).

In general, the uncertainties in the percentiles increase as the emissions percentile decreases. Both the Chicago and Tulsa passenger and truck fleet show significant decreases in gNO/kg of fuel emissions at all three percentiles between 2003 and 2007. Passenger vehicle fuel specific NO emissions show slightly lower rates of decrease for the median and the 75th percentile while emission rate decreases for the trucks are very similar for all three percentiles graphed despite the age differences. Figure 6 showed the timeline for the sulfur reductions in CG and RFG and highlight the fact that fuel sulfur levels were reduced by approximately 60% (from 300ppm to ~120ppm) between 2003 and 2004 for the CG while RFG sulfur levels were reduced approximately 40% (from 170ppm to ~100ppm). The Complex Model predicted NO_x emission benefits of 2 to 3% for changes in the sulfur levels of RFG to 11% for sulfur reductions in CG (see Figure 17). The percent emissions reductions in fuel specific NO emissions shown in Figures 27 and 28 for Tulsa range from a 30% reduction for the passenger vehicles to a 42% reduction for the trucks. While Chicago emission reductions between years 2004 and 2007 for both types of vehicles have fuel specific NO emission reductions in excess of 59%. Both cities show large multiplies of reduction in NO emissions that are in excess of the Complex Model predicted emission reductions for the mythical "1990's" fleet, again indicating that while fuels are certainly contributing to the reductions observed, there are additional factors that appear to contribute substantially more.

8.3 Reductions in Gasoline Aromatics and Changes in RVP

The last fuel formulation changes we will discuss are the reductions in the aromatic constituents in gasoline fuels and the changes in allowed RVP. Figures 11 and 12 chronicle the changes in total aromatics and benzene levels that have occurred since the late nineties. Total aromatics have traditionally been higher in CG than in RFG but reductions beginning around 2005 in CG have narrowed the gap, though there is still about a 4 to 5% by volume higher aromatic content in CG (see Figure 11). Contributing to the reductions in total aromatics benzene levels were reduced significantly after the MSAT2 rule in 2011 where levels became similar across all gasoline fuels. As previously discussed, benzene reductions in the fuel have been shown by others to lower vehicle benzene emissions in both CG and RFG.[19-21] The Complex Model has a small sensitivity (~4% reduced VOC emissions, see Figure 16) to reductions in aromatics and a similar benefit to reductions in benzene levels as well.

Also shown in Figure 16 is a much larger benefit (up to ~20%) and conversely dis-benefit to decreases and increases in fuel RVP. Of all the fuel properties investigated, summer RVP is the one parameter where the differences between CG and RFG have increased as a result of the 1lb waiver allowed in CG for the use of ethanol. Figure 7 shows that between 2007 and 2009 RVP increased in CG while it remained constant in the summertime RFG fuels. This increase eliminated most of the VOC emission reductions predicted by the Complex Model for CG (see Figure 19) and created one of the largest predicted differences between CG and RFG (~25%) for the 1990 reference fleet.

FEAT is only capable of measuring total tailpipe hydrocarbon emissions and is unable to distinguish reductions in particular compounds or changes in evaporative or running loss emissions. Age adjusted mean gHC/kg of fuel tailpipe emissions have decreased more than twice as fast for the Chicago gasoline fleet as the Tulsa fleet between 2003 and 2016 (see Table 12). The lower rate of decrease for the Tulsa fleet is the result of the Tulsa passenger fleet experiencing small increases in mean HC emissions between 2003 and 2015 (see Table 13) while the Tulsa gasoline truck fleet had age adjusted reductions that were more in line with the Chicago gasoline trucks (50.5% versus 62.3% reductions, see Table 14).

Figures 29 and 30 are the emissions percentile trend plots for fuel specific HC emissions for the gasoline passenger and truck fleets in Chicago and Tulsa. Because the mean emission comparison spans a larger time period, the observed overall reductions do not tell the entire story. Unlike the previous graphs for fuel specific NO emissions there are few consistent trends with the HC emissions data. Both locations show large decreases during certain time periods to be followed by large increases in others. The gasoline passenger fleets (see Figure 29) generally show consistent decreases (the exception is the 75th percentile Tulsa data though the increase is likely not statistically significant) in the earlier data sets followed by increases at all percentiles for both locations for the data collected since 2013. The Chicago gasoline truck fleet follows the same pattern observed with the Chicago gasoline passenger fleet with fuel specific HC emission decreases between 2004 and 2006 followed by increases between 2014 and 2016. Tulsa gasoline trucks have more increases than decreases in HC emissions between 2003 and 2005 followed by consistent emission reductions after 2005.

The inconsistencies in the on-road fuel specific HC trend data again point to additional factors. One observation is that the high emitters in each city's fleet show opposite trends. In Tulsa the gHC/kg of fuel for the 99th percentile has increased during each successive measurement set for the gasoline passenger vehicles (37, 39, 48 and 54 gHC/kg of fuel for 2003, 2005, 2013 and 2015 data sets). 99th percentiles for gasoline trucks in Tulsa have changed little over time (35, 39, 41 and 40 gHC/kg of fuel). Both of the Chicago gasoline fleets have generally decreased (38, 42, 30 and 28 gHC/kg of fuel for the passenger fleet and 37, 33, 27 and 23 for the truck fleet). These are significant differences between the two fleets that fuel effects are likely not a contributing factor.

9. Conclusions

The Federal reformulated gasoline program grew out of the 1990 Clean Air Act Amendments as a response to high ozone levels in a number of major urban areas. Initially, changes in the property characteristics of RFG were limited to those related to the addition of oxygen and reductions in benzene and fuel RVP levels. As emission certification standards were progressively lowered, fuel properties that were once driven largely by Federal RFG requirements, began to occur in all fuels to support modern emission control devices in all vehicles. As a result:

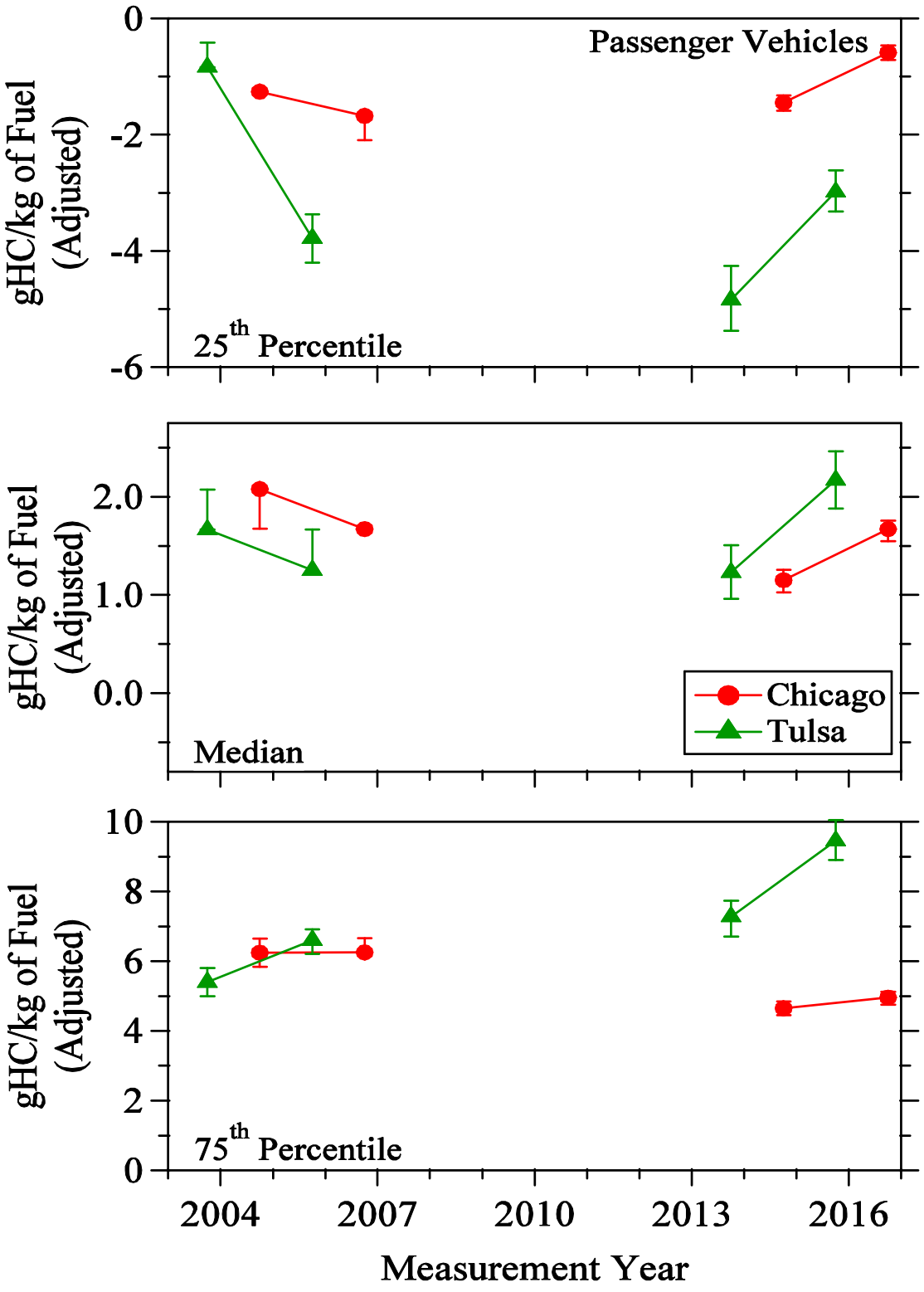

Figure 29. Chicago (●) and Tulsa (▲) fuel specific HC emissions comparison by percentiles for gasoline passenger vehicles by measurement year. Uncertainties are 95% confidence intervals.

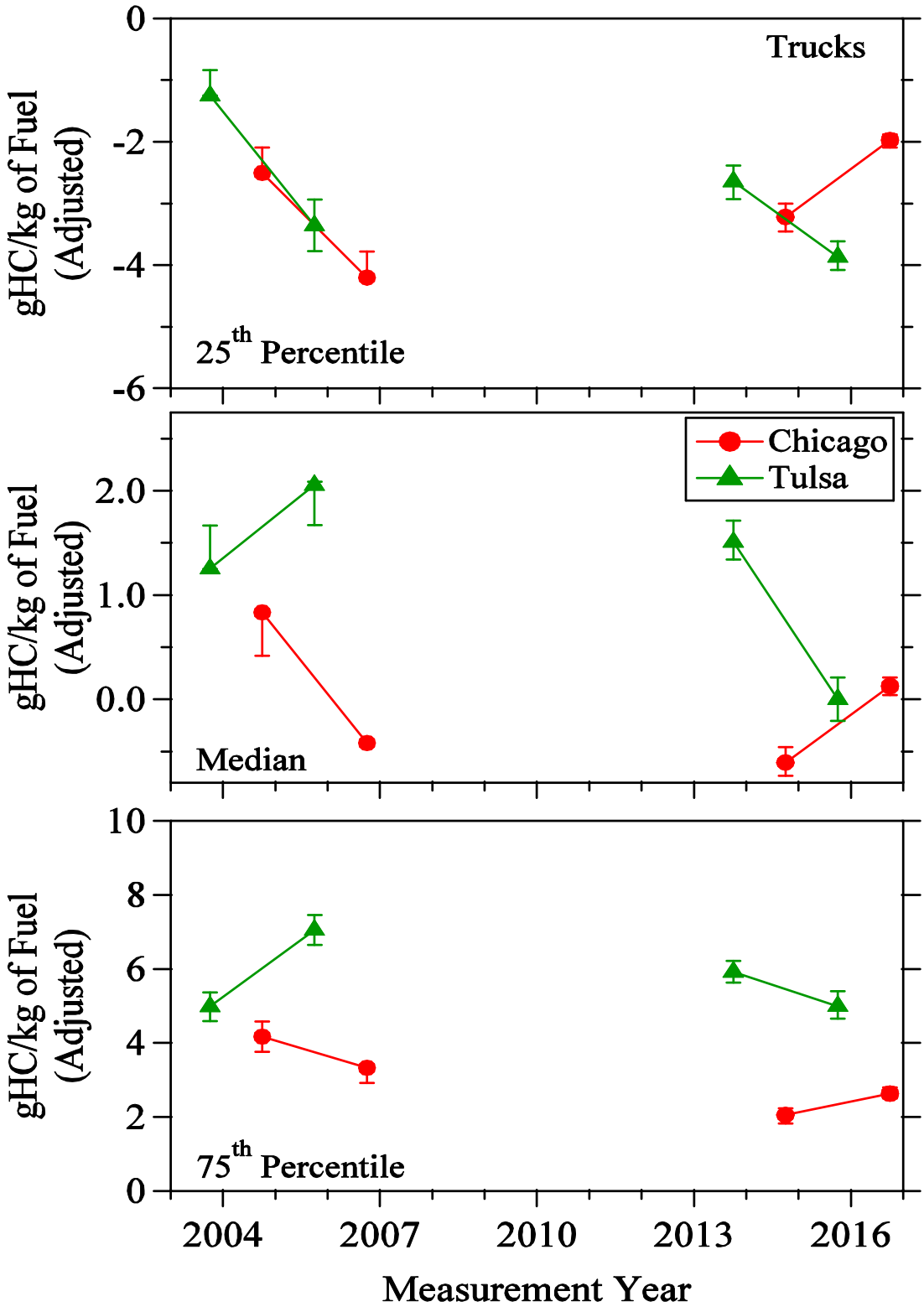

Figure 30. Chicago (●) and Tulsa (▲) fuel specific HC emissions comparison by percentiles for gasoline trucks by measurement year. Uncertainties are 95% confidence intervals.

- The differences between CG and RFG have narrowed over time. This is especially true for sulfur content, oxygen content, total aromatics, and benzene. This trend towards convergence is expected to continue with the introduction of Tier 3 gasoline beginning in 2017.
- Throughout the 19-year period of record, these same fuel properties that strongly influence vehicle emissions have changed in both CG and RFG in ways that reduce emissions.
- Gasoline oxygenates have changed drastically throughout the history of the RFG program. While initially the methyl ethers, MTBE and TAME, were the dominant oxygenate species, they have now been completely replaced by ethanol.
- Since the mid 2000's, significant increases in ethanol usage have occurred in both CG and RFG. Consequently, ethanol content (and total oxygen content) of CG and RFG have converged while RVP has diverged as a result of the 1lb. psi RVP waiver for ethanol-containing CG.

Since RFG was primarily aimed at ozone control it is surprising that the effectiveness of the program has never been assessed by conducting 3-dimensional, photochemical air quality modeling. Only indirect assessments of ozone reduction effectiveness have been conducted, with the results being mixed. For example, Erdal et al. used maximum incremental reactivity factors to estimate that the reformulations reduced the reactivity of VOC emissions by 11 – 15%, which contributed to reductions in peak ozone (1.1 – 1.5ppb in New York in 2005 and 3.5 – 4.0ppb in Los Angeles in 2010).[16] However, a study by Auffhammer and Kellogg using ambient ozone measurements failed to show any significant benefit of Federal RFG to reduce ozone levels.[24]

Since 1990 on-road fleet vehicle emissions have experienced dramatic reductions for all species with on-road fuel specific measurements showing reductions of more than 90% in Chicago and more than 86% in Denver for CO and HC. Since 2000, significant changes in fuel oxygen content, sulfur content and reductions in aromatic content have occurred in both RFG and CG. Calculating year over year fuel specific on-road emission reductions for Chicago, IL (2004 – 2016, RFG) and Tulsa, OK (2003 – 2015, CG) we have observed that for the age adjusted gasoline fleet the CO and NO emissions have decreased in the two cities at similar rates (52% vs 49% for CO and 66% vs 68% for NO). HC emission reductions are the one exception as total HC emissions have not dropped as fast in Tulsa as they have in Chicago (15% vs 34%) over this time period. For HC emissions there are significant differences between the Tulsa passenger and truck fleet with the passenger fleet showing increased HC emissions (-35%) during this period while the Tulsa truck fleet showed HC emission reductions (51%) similar to those seen in the Chicago trucks (62%). Again the observed reductions are significantly larger than the model predicted benefits for the fuels alone in the mythical "1990's" vehicle fleet, indicating that additional factors are involved in the reductions.

Since the beginning of the Federal RFG program, fuel properties have significantly changed for both the CG and RFG resulting in fuels today that are similar in most properties, the one exception is RVP where CG is allowed a 1lb psi waiver for the addition of 10% ethanol. Beginning with the phase-in of Tier 3 fuels in 2017 we expect that the differences between the two fuels will decrease again and on-

road vehicle emissions will continue to remain very low and it is unlikely that differences in fuel properties between Federal RFG and CG any longer plays a significant role in these low emissions.

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APPENDIX A: U.S. Gasoline Requirements

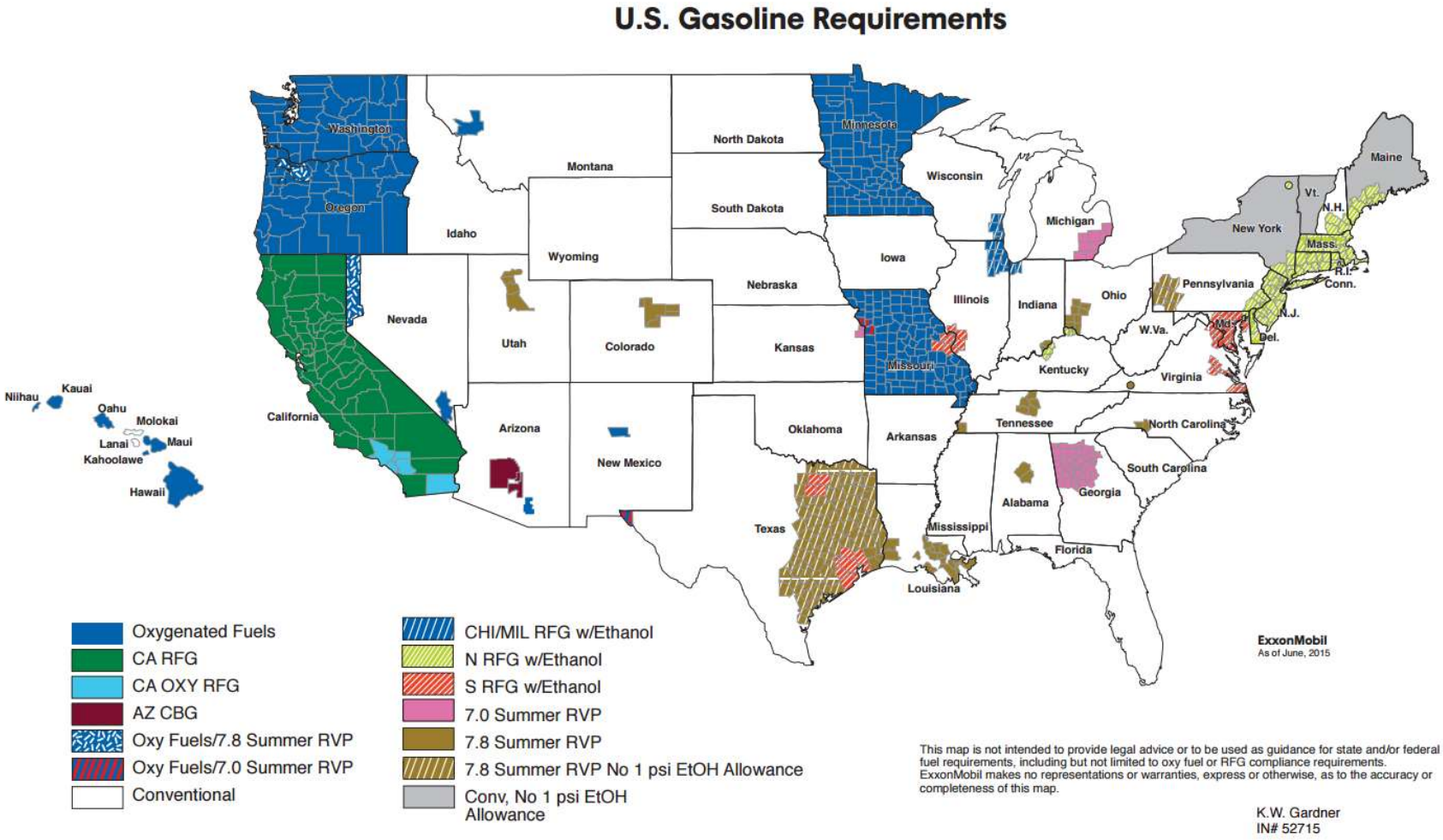

Figure A-1: Source: http://www.nacsonline.com/YourBusiness/FuelsCenter/Documents/2016/US-Gasoline-Requirements-Map.pdf

APPENDIX B: Average Gasoline Properties: 1997 - 2015

Table B-1. Average Conventional Gasoline Properties

Data taken from EPA website: https://www.epa.gov/sites/production/files/2017-02/documents/conventional-gasoline.pdf

SUMMER FUELS

	1990*	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Volume (billion gal)	-	38.69	39.07	39.02	38.26	39.00	40.79	43.36	43.04	40.90	44.95	43.99	39.14	39.80	39.41	40.94	42.01	41.26	41.89	43.01
Oxygen (Wt%)	0.00	0.27	0.65	0.72	0.66	0.63	0.71	0.81	0.97	0.95	0.16	0.46	1.41	2.23	2.93	2.95	3.10	3.23	3.25	3.34
API Gravity	57.4	58.2	58.1	58.2	57.7	57.5	57.7	57.3	58.1	58.4	58.2	58.2	59.2	58.6	58.9	59.2	59.5	59.6	59.8	62.7
Methanol (%Vol)	-	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.00	-	-	-	-	-	-	-	-	-	-
MTBE (%Vol)	-	1.08	1.91	1.81	1.62	1.73	1.73	2.18	2.19	1.66	0.03	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Ethanol (%Vol)	-	0.10	0.59	0.84	0.84	0.74	0.93	0.98	1.52	1.75	0.45	1.32	4.05	6.35	8.41	8.55	8.96	9.27	9.31	9.47
ETBE (%Vol)	-	0.00	0.00	0.00	0.01	0.01	0.00	0.04	0.05	0.02	-	-	-	-	-	-	-	-	-	-
TAME (%Vol)	-	0.06	0.23	0.13	0.24	0.28	0.34	0.23	0.20	0.19	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
t-Butanol (%Vol)	-	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	-	-	-	-	-	-	-	-	-	-
Sulfur (ppm)	339	324	304	309	320	304	296	303	118	106	50.2	41.8	33.0	35.6	32.6	29.6	29.1	27.4	24.0	23.9
Aromatics (%Vol)	32.0	27.2	27.4	27.6	28.5	28.3	28.0	27.9	28.0	27.7	26.6	26.4	24.5	24.2	23.5	22.1	21.6	21.2	20.8	21.3
Olefins (%Vol)	13.0	12.5	11.5	11.8	11.8	12.8	12.1	12.1	11.2	12.0	10.4	10.3	9.86	9.95	9.49	9.27	9.38	9.26	9.16	8.91
Benzene (%Vol)	1.53	1.13	1.14	1.15	1.15	1.17	1.10	1.15	1.15	1.21	1.13	1.15	1.14	1.08	1.02	0.76	0.67	0.64	0.63	0.63
RVP (psi)	8.70	8.67	8.32	8.32	8.27	8.27	8.27	8.31	8.31	8.30	8.31	8.40	8.63	8.86	9.06	9.10	9.23	9.22	9.23	9.13
T50 (^{o}F)	218.0	211.9	212.3	211.6	211.9	212.5	213.8	213	212.7	211.1	-	-	-	-	-	-	-	-	-	-
T90 (^{o}F)	330.0	337.4	336.3	334.3	335.6	333.5	335	335.7	334.7	330.7	-	-	-	-	-	-	-	-	-	-
E200 (% distilled)	-	45.2	44.8	45.2	45.2	45.2	45.0	45.2	45.2	45.7	44.9	45.7	49.5	50.5	52.4	53.5	54.0	54.7	54.6	53.6
E300 (% distilled)	-	80.9	80.9	81.1	80.7	81.1	80.6	80.7	80.7	81.7	82.0	81.8	84.7	83.2	84.1	84.9	85.2	85.7	85.8	85.4

WINTER FUELS

	1990*	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Volume (billion gal)	-	41.27	46.21	47.52	48.30	49.08	49.72	47.99	47.70	47.83	47.57	47.48	43.25	43.93	44.83	49.30	47.25	48.56	49.84	50.19
Oxygen (Wt%)	0.00	0.19	0.72	0.74	0.74	0.77	0.73	0.83	1.07	1.08	0.212	0.47	1.4	2.266	2.95	2.97	3.13	3.24	3.24	3.38
API Gravity	57.4	61.3	61.5	61.4	61.4	60.8	61	60.7	61.8	61.9	62	62.1	62.3	61.9	61.8	62	62.4	62.6	62.7	65.3
Methanol (%Vol)	-	0.00	0.01	0.00	0.00	0.01	0.01	0.01	0.00	0.00	-	-	-	-	-	-	-	-	-	-
MTBE (%Vol)	-	0.69	1.97	1.78	1.39	1.54	1.38	1.5	1.86	1.41	0.17	0.03	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Ethanol (%Vol)	-	0.03	0.81	0.99	1.19	1.24	1.20	1.48	1.94	2.19	0.49	1.33	4.02	6.44	8.44	8.58	8.99	9.24	9.25	9.46
ETBE (%Vol)	-	0.00	0.00	0.00	0.01	0.01	0.00	0.01	0.02	0.04	-	-	-	-	-	-	-	-	-	-
TAME (%Vol)	-	0.03	0.23	0.11	0.15	0.19	0.27	0.18	0.19	0.18	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
t-Butanol (%Vol)	-	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	-	-	-	-	-	-	-	-	-	-
Sulfur (ppm)	338	319	287	307	293	295	292	256	120	97	50.6	38.7	35.1	31.9	31.6	28.3	27.5	25.8	24.0	22.6
Aromatics (%Vol)	26.4	25.0	24.7	24.9	24.8	25.4	25.0	24.9	24.6	24.7	23.0	22.8	21.7	21.2	20.6	19.5	18.9	18.3	17.9	18.3
Olefins (%Vol)	13.0	12.2	11.2	11.4	12.0	12.5	11.8	11.5	11.4	11.6	10.3	10.3	9.82	9.42	9.24	9.00	8.66	8.69	8.54	8.23
Benzene (%Vol)	1.64	1.15	1.08	1.08	1.08	1.14	1.07	1.1	1.08	1.15	1.1	1.08	1.11	1.08	0.95	0.71	0.65	0.59	0.58	0.58
RVP (psi)	11.50	12.0	12.2	12.1	12.1	12.0	12.0	12.2	12.2	12.1	12.2	12.2	12.3	12.5	12.4	12.4	12.6	12.7	12.8	12.6
T50 (^{o}F)	200.0	198	199.6	199.7	199	202.1	201.4	200.1	199.8	199.9	-	-	-	-	-	-	-	-	-	-
T90 (^{o}F)	333.0	328.7	327.7	328.2	325.5	327.2	327.2	328.7	326.5	324.1	-	-	-	-	-	-	-	-	-	-
E200 (% distilled)	-	50.4	50.2	50.1	50.4	49.9	50.2	50.4	50.8	50.9	50.6	51.3	53.4	54.9	56.1	57.0	57.6	58.0	57.8	57.2
E300 (% distilled)	-	83.3	83.3	83.1	83.4	83.3	83.2	83.0	83.4	84.1	84.3	84.7	86.1	85.9	86.3	86.9	87.3	87.7	87.8	87.5

* Clean Air Act Baseline gasoline properties

Table B-2. Average Federal Reformulated Gasoline Properties

Data taken from EPA website: https://www.epa.gov/sites/production/files/2017-02/documents/reformulated-gasoline.pdf

SUMMER FUELS

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Volume (billion gal)	12.49	12.75	13.07	13.07	13.24	13.85	13.59	14.22	13.57	14.83	13.95	13.82	14.01	14.44	13.59	13.72	13.19	13.88	14.37
Oxygen (Wt%)	2.15	2.13	2.11	2.24	2.21	2.25	2.30	2.55	2.49	3.51	3.54	3.57	3.55	3.56	3.56	3.57	3.57	3.57	3.57
API Gravity	58.0	57.9	58.1	58.9	58.5	58.5	58.6	58.2	58.4	57.1	58.2	58.9	58.3	58.5	58.6	59.2	59.4	59.6	60.9
Methanol (%Vol)	0.02	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	-	-	-	-	-	-	-	-	-	-
MTBE (%Vol)	8.81	8.91	8.60	9.04	9.02	8.95	8.91	7.42	7.02	0.16	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Ethanol (%Vol)	0.95	1.02	1.07	1.14	1.10	1.30	1.50	3.04	3.03	9.51	9.58	9.59	9.59	9.62	9.61	9.60	9.59	9.58	9.61
ETBE (%Vol)	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	-	-	-	-	-	-	-	-	-	-
TAME (%Vol)	0.79	0.79	0.86	0.95	0.90	0.76	0.83	0.42	0.46	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
t-Butanol (%Vol)	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	-	-	-	-	-	-	-	-	-	-
Sulfur (ppm)	314	204	205	126	127	124	110	80	71	37.3	28.5	26.8	27.6	30.2	29.5	31.0	27.3	27.4	22.5
Aromatics (%Vol)	22.7	22.7	22.2	19.3	20.1	20.4	20.1	20.1	20.7	20.1	19.5	18.4	18.7	18.3	18.1	16.9	17.0	16.5	17.1
Olefins (%Vol)	12.3	11.0	11.4	10.6	11.8	10.8	11.0	11.4	11.9	11.0	11.6	10.9	11.3	11.2	12.0	11.6	11.1	11.1	10.9
Benzene (%Vol)	0.66	0.67	0.71	0.59	0.62	0.59	0.61	0.59	0.66	0.59	0.57	0.57	0.56	0.56	0.54	0.48	0.49	0.47	0.48
RVP (psi)	7.63	7.61	7.60	6.78	6.79	6.80	6.83	6.87	6.91	6.94	7.01	7.05	7.01	7.02	7.08	7.11	7.12	7.14	7.11
T50 (°F)	201.9	203.1	201.8	204.7	204.9	204.6	203.7	204.5	201.9	-	-	-	-	-	-	-	-	-	-
T90 (°F)	334.6	326.4	331.4	326.6	326.4	327.4	328.3	333.2	329.5	-	-	-	-	-	-	-	-	-	-
E200 (% distilled)	49.5	48.9	49.2	47.6	47.5	47.5	47.9	47.9	48.7	46.7	47.4	48.2	47.5	47.5	47.7	48.1	48.1	48.5	47.8
E300 (% distilled)	81.9	82.7	82.8	84.7	84.4	84.4	84.4	83.4	84.0	84.5	84.5	86.5	84.1	84.6	85.2	85.8	86.4	86.3	86.0

WINTER FUELS

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Volume (billion gal)	14.77	14.92	15.17	15.95	15.84	16.44	16.68	17.21	17.36	21.03	17.61	18.24	18.18	18.17	17.38	16.78	16.74	17.46	17.95
Oxygen (Wt%)	2.20	2.22	2.16	2.12	2.11	2.09	2.14	2.38	2.37	3.17	3.63	3.63	3.63	3.65	3.66	3.64	3.67	3.67	3.68
API Gravity	62.5	62.0	62.0	62.4	62.2	62.2	62.1	62.0	61.9	60.7	61.3	61.9	61.7	61.7	62.4	62.6	63.0	63.3	63.7
Methanol (%Vol)	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	-	-	-	-	-	-	-	-	-	-
MTBE (%Vol)	8.74	8.94	8.47	8.21	8.27	8.01	7.76	7.03	6.63	3.47	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Ethanol (%Vol)	1.10	1.16	1.18	1.22	1.18	1.31	1.68	2.68	2.86	7.36	9.67	9.65	9.65	9.68	9.67	9.63	9.66	9.68	9.70
ETBE (%Vol)	0.00	0.00	0.00	0.00	0.02	0.01	0.00	0.00	0.03	-	-	-	-	-	-	-	-	-	-
TAME (%Vol)	0.72	0.71	0.81	0.74	0.72	0.59	0.38	0.33	0.29	0.14	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
t-Butanol (%Vol)	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	-	-	-	-	-	-	-	-	-	-
Sulfur (ppm)	264	205	214	200	185	184	164	101	81.0	41.4	32.3	31.9	30.1	32.5	32.7	31.4	28.9	28.6	24.0
Aromatics (%Vol)	19.2	19.8	19.6	19.0	19.2	19.4	19.4	19.1	19.5	19.5	18.9	17.9	17.7	17.4	16.6	16.6	16.3	16.3	16.4
Olefins (%Vol)	11.5	10.9	11.3	11.8	12.3	11.1	11.0	11.1	11.2	10.8	11.1	10.7	10.5	10.9	10.8	10.5	10.4	9.8	9.6
Benzene (%Vol)	0.62	0.65	0.65	0.65	0.64	0.64	0.64	0.63	0.66	0.66	0.64	0.63	0.64	0.62	0.58	0.54	0.52	0.54	0.53
RVP (psi)	12.4	12.3	12.3	12.1	12.0	12.1	12.1	12.2	11.9	11.7	11.8	11.8	11.8	12.0	12.1	12.2	12.3	12.9	13.0
T50 (°F)	183.4	181.6	183.6	182.9	184.2	183.4	183	181.5	180.7	-	-	-	-	-	-	-	-	-	-
T90 (°F)	320.7	319.9	325.2	317.2	317.3	321.3	324.9	325.0	323.5	-	-	-	-	-	-	-	-	-	-
E200 (% distilled)	56.5	56.1	56.0	56.3	55.9	56.0	56.0	56.2	56.3	56.4	56.4	57.1	56.6	56.6	57.3	57.8	58.0	58.4	58.3
E300 (% distilled)	85.0	85.0	84.7	86.1	85.8	85.6	85.1	85.0	85.3	85.4	85.5	86.8	86.3	85.9	87.1	87.1	87.9	88.0	87.7

APPENDIX C: Complex Model Emission Reduction Predictions for Winter Fuels

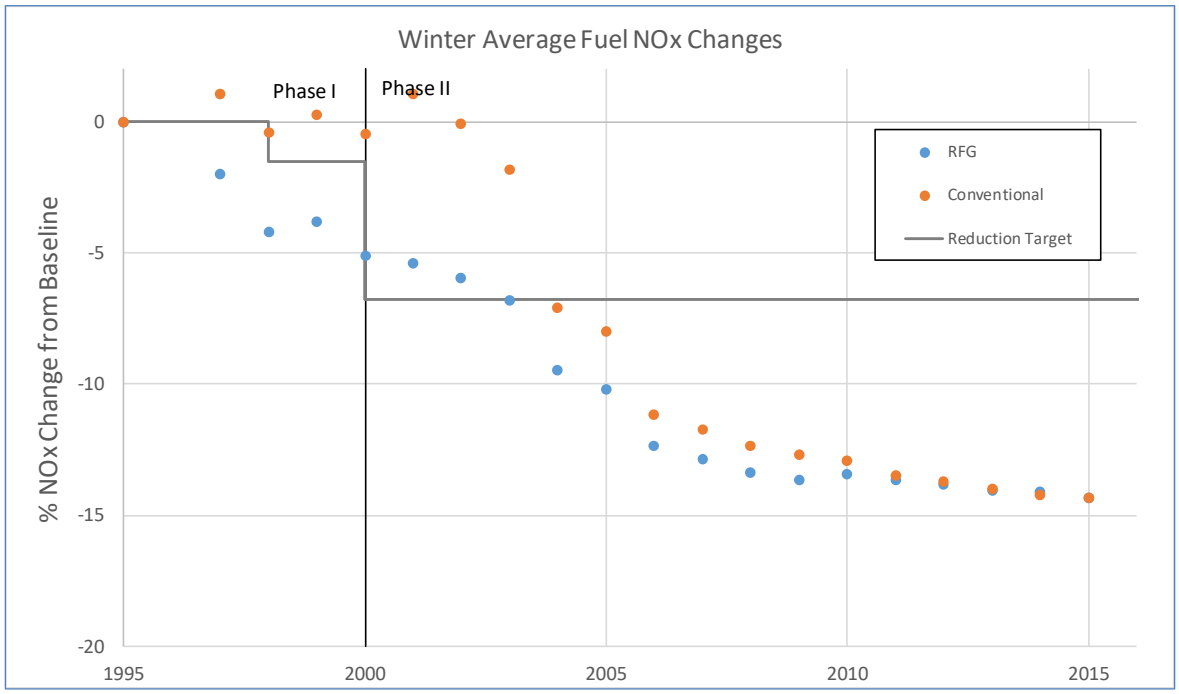

Figure C-1. Complex Model predicted NO_x reductions for winter CG and RFG fuels from 1995 to 2015. Dark horizontal lines represent emissions reduction requirements under the RFG program.

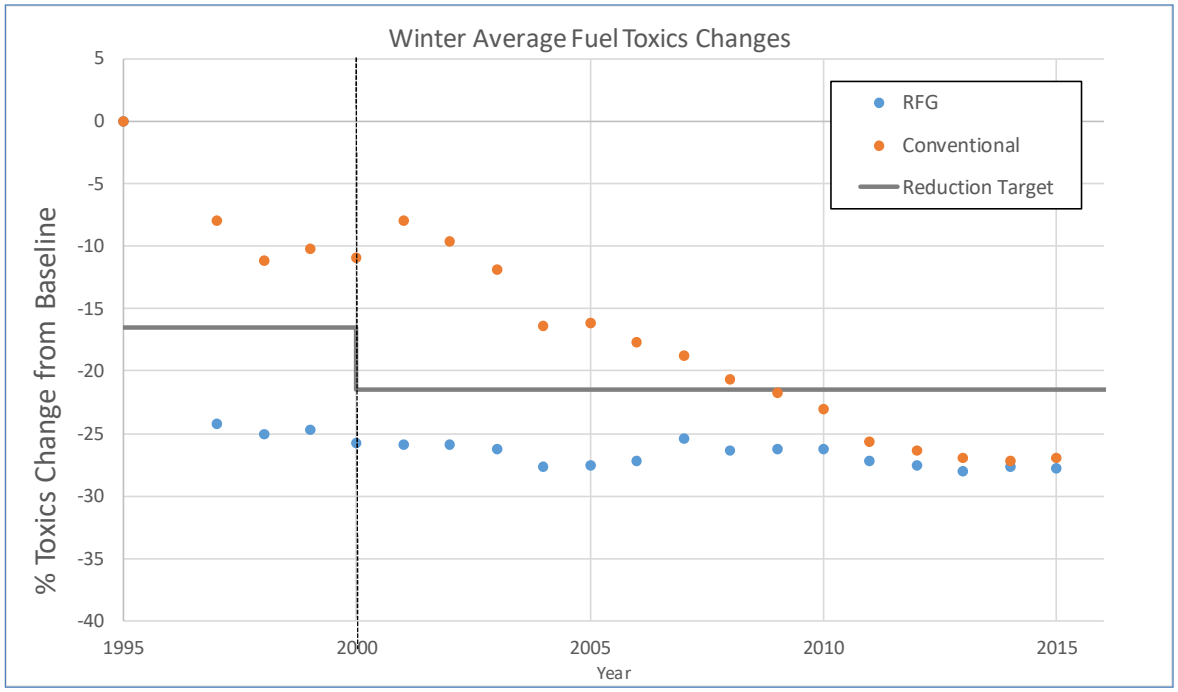

Figure C-2. Complex Model predicted toxics reductions for winter CG and RFG fuels from 1995 to 2015. Dark horizontal lines represent emissions reduction requirements under the RFG program.

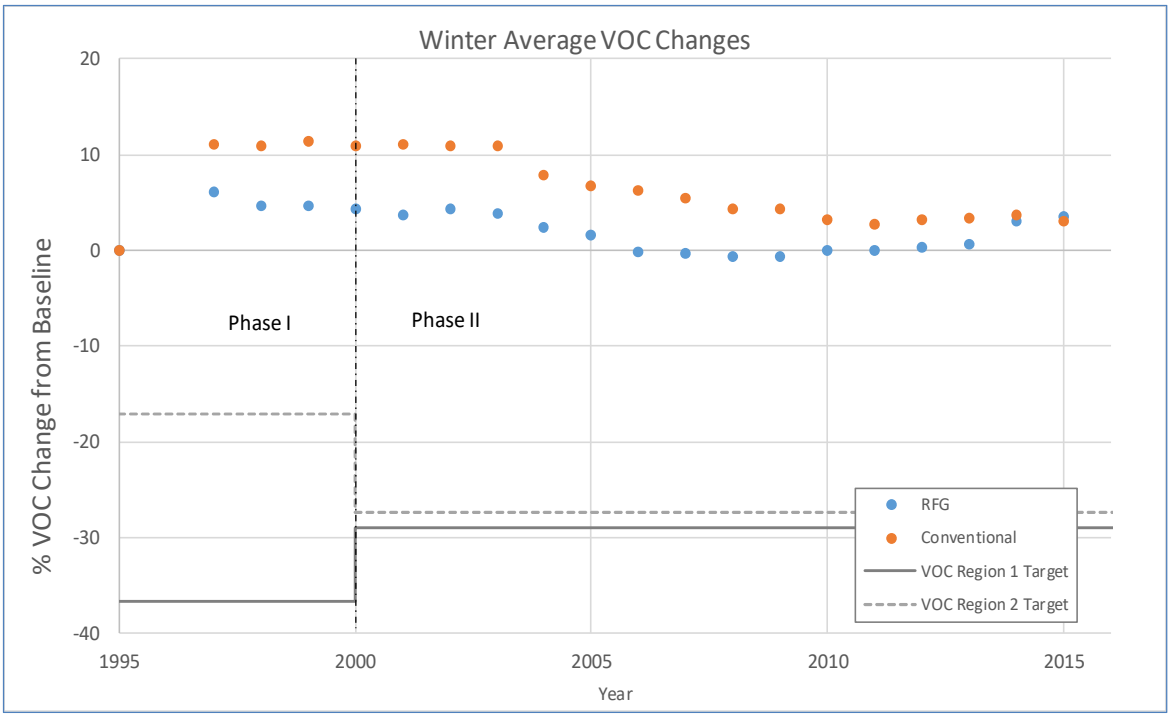

Figure C-3. Complex Model predicted VOC reductions for winter CG and RFG fuels from 1995 to 2015. Dark solid lines represent emissions reduction requirements in VOC Control Region 1; dashed horizontal lines represent requirements in VOC Control Region 2.

APPENDIX D: Methodology to Normalize Mean gHC/kg of fuel Emissions

The hydrocarbon channel on FEAT has the lowest signal to noise ratio of all the measurement channels in large part because the absorption signals are the smallest (millivolt levels). FEAT uses one detector for the target gas absorption and a second detector for the background IR intensity (reference). These channels are ratioed to each other to correct for changes in background IR intensities that are not the result of gas absorption. The detector responses are not perfectly twinned and for the low signal HC channel these intensity corrections can result in small artifacts, which can be a positive or negative offset of the emissions distribution, being introduced into the measurement. In addition the region of the infrared spectrum that we use for HC absorption measurements is overlapped by an absorption band for liquid water. Normally this is not an issue as fully warmed up vehicles emit little if any liquid water at the tailpipe. However, there are times when low temperatures and high dew points cause water vapor to condense at the tailpipe and create an additional absorption artifact in the measurements that are not related to HC emissions. In these cases the normalization value calculated will be larger because it includes an additional adjustment for the liquid water emissions.

The offset is calculated by computing the mode and means of the newest model year vehicles, and assuming that these vehicles emit negligible levels of hydrocarbons, using the lowest of either of these values as the offset. We then add (for negative offsets) or subtract this value from all of the hydrocarbon measurements adjusting the zero point of the emissions distribution. Since it is assumed that the newest vehicles are the lowest emitting this approximation will slightly over correct because the true offset will be a value somewhat less than the average of the cleanest model year and make.

The Chicago 2014 measurement included a correction for both of the previously discussed issues as the first three days of measurements were with normal temperatures and low humidity while the last three days experienced the exact opposite. FEAT ratios are first reported as percent emissions and the normalization calculations are performed using these percent values. Below are the data tables used for estimating the HC normalization value for the 2014 Chicago measurements.

For the Monday through Wednesday time slot Honda's vehicles had the lowest average HC emissions with a mean %HC of 0.0013. In Table S2 the mode calculation has two values that are very close to each other 0.001 and 0.0015. We chose to average those two values and the HC normalization value for the first time period used was 0.00125% which is approximately 0.5 gHC/kg of fuel.

For the Thursday through Saturday time period Honda vehicles again had the lowest HC emission. The average of 2009 – 2014 Honda vehicles is 0.003% which is the same as the mode shown in Table S2. This is approximately 1.25 gHC/kg of fuel.

2014 Chicago Mode Calculations
For model year 2009 and newer vehicles

Table D1. HC Normalization Mode Calculation.

Monday – Wednesday		Thursday - Saturday	
%HC	Counts	%HC	Counts
-0.0015	129	-0.0015	73
-0.001	147	-0.001	59
-0.0005	138	-0.0005	75
0	125	0	67
0.0005	126	0.0005	79
0.001	152	0.001	69
0.0015	155	0.0015	75
0.002	143	0.002	85
0.0025	104	0.0025	51
0.003	131	0.003	94
0.0035	129	0.0035	68
0.004	120	0.004	77
0.0045	115	0.0045	80
0.005	124	0.005	88

This method will successfully normalize the fleet HC means but may over or under correct smaller sub-fleets.

APPENDIX E: On-Road Database Statistics and Confidence Intervals

Table E-1. Chicago 2004 Fuel Specific Emissions

	Fleet			Gasoline Passenger			Gasoline Trucks		
Species	CO	HC	NO	CO	HC	NO	CO	HC	NO
Measurements	21838	21779	21834	13418	13382	13416	8113	8093	8111
Mean	21.5	2.79	3.34	23.0	3.41	3.26	19.4	1.76	2.98
95% C.I.				0	-1.26	0.02	0	-2.52	-0.01
25th Percentile	0	-1.68	0.03	0	-1.26	0.03	0	-2.51	0.01
95% C.I.				1.32	-1.25	0.05	0	-2.10	0.03
95% C.I.				5.31	1.67	0.55	3.98	0.42	0.40
Median	5.3	1.26	0.56	5.32	2.08	0.60	3.99	0.83	0.45
95% C.I.				5.36	2.09	0.65	4.00	0.84	0.50
95% C.I.				18.62	5.84	2.80	13.20	3.77	2.19
75th Percentile	17.3	5.42	2.99	19.93	6.24	3.02	13.36	4.17	2.42
95% C.I.				21.25	6.65	3.24	14.66	4.58	2.68
99th Percentile	282.5	37.69	35.50	270.6	38.29	35.05	294.8	36.82	35.37
Mean MY	1999.2			1998.8			1999.7		

Table E-2. Chicago 2006 Fuel Specific Emissions

	Fleet			Gasoline Passenger			Gasoline Trucks		
Species	CO	HC	NO	CO	HC	NO	CO	HC	NO
Measurements	22200	22158	22191	13667	13645	13662	8233	8213	8229
Mean	16.1	2.20	1.77	17.6	3.47	1.66	13.9	0.11	1.55
95% C.I.				-1.33	-2.10	-0.05	-1.34	-4.21	-0.08
25th Percentile	-1.33	-2.90	-0.05	-1.33	-1.68	-0.04	-1.34	-4.20	-0.06
95% C.I.				-1.32	-1.68	-0.03	-1.33	-3.78	-0.05
95% C.I.				2.66	1.67	0.20	1.34	-0.42	0.13
Median	2.66	0.84	0.20	2.67	1.67	0.21	2.63	-0.42	0.15
95% C.I.				3.93	1.68	0.23	2.65	-0.42	0.17
95% C.I.				13.21	6.22	1.14	9.18	2.92	0.89
75th Percentile	11.95	5.40	1.24	13.49	6.25	1.23	9.30	3.33	0.98
95% C.I.				14.61	6.66	1.33	10.58	3.34	1.10
99th Percentile	236.2	38.89	23.09	238.5	41.6	22.80	233.2	33.13	22.05
Mean MY	2001			2000.7			2001.5		

Table E-3. Chicago 2014 Fuel Specific Emissions

	Fleet			Gasoline Passenger			Gasoline Trucks		
Species	CO	HC	NO	CO	HC	NO	CO	HC	NO
Measurements	20395	20282	20394	11179	11114	11178	8862	8816	8862
Mean	9.40	1.32	1.49	10.74	2.39	1.37	7.66	-0.08	1.26
95% C.I.				-5.17	-1.59	-0.01	-6.96	-3.45	-0.01
25th Percentile	-5.6	-2.29	-0.01	-4.8	-1.45	-0.01	-6.47	-3.22	-0.01
95% C.I.				-4.40	-1.32	-0.01	-5.99	-3.00	-0.01
95% C.I.				1.99	1.02	0.07	0.27	-0.73	0.06
Median	2.93	0.36	0.07	2.26	1.15	0.07	0.67	-0.61	0.06
95% C.I.				2.65	1.26	0.08	1.06	-0.46	0.07
95% C.I.				12.36	4.44	0.40	9.43	1.82	0.32
75th Percentile	11.84	3.52	0.44	13.15	4.65	0.44	10.26	2.05	0.36
95% C.I.				13.95	4.85	0.48	11.12	2.23	0.40
99th Percentile	180.9	29.55	8.96	191.7	30.24	25.48	166.9	26.66	26.27
Mean MY	2007.5			2007.3			2007.7		

Table E-4. Chicago 2016 Fuel Specific Emissions

	Fleet			Gasoline Passenger			Gasoline Trucks		
Species	CO	HC	NO	CO	HC	NO	CO	HC	NO
Measurements	30062	30046	30060	15014	15010	15013	13779	13768	13779
Mean	10.9	1.85	1.19	11.74	2.94	1.00	10.33	0.67	1.05
95% C.I.				-0.83	-0.71	-0.073	-1.33	-2.10	-0.066
25th Percentile	-0.93	-1.30	-0.061	-0.67	-0.59	-0.068	-1.20	-1.97	-0.06
95% C.I.				-0.40	-0.46	-0.063	-0.93	-1.88	-0.056
95% C.I.				3.45	1.55	0.037	2.53	0.04	0.036
Median	3.08	0.91	0.047	3.60	1.67	0.044	2.78	0.13	0.042
95% C.I.				3.85	1.76	0.050	2.93	0.21	0.047
95% C.I.				10.66	4.75	0.31	9.14	2.51	0.28
75th Percentile	10.34	3.86	0.34	11.24	4.95	0.33	9.65	2.63	0.30
95% C.I.				11.82	5.12	0.36	10.12	2.80	0.32
99th Percentile	156.8	26.2	24.45	159.6	27.9	21.6	154.4	22.6	24.0
Mean MY	2009.6			2009.2			2009.7		

Table E-5. Tulsa 2003 Fuel Specific Emissions

	Fleet			Gasoline Passenger			Gasoline Trucks		
Species	CO	HC	NO	CO	HC	NO	CO	HC	NO
Measurements	20318	20300	20313	9211	9208	9208	10615	10601	10613
Mean	33.95	3.22	3.73	37.10	3.66	3.40	32.23	2.85	3.47
95% C.I.				1.33	-0.83	0.01	1.33	-1.25	-0.003
25th Percentile	1.34	-0.84	0.04	2.63	-0.83	0.04	1.33	-1.25	0.01
95% C.I.				2.65	-0.42	0.06	2.60	-0.84	0.03
95% C.I.				7.92	1.67	0.68	6.61	1.25	0.60
Median	7.83	1.66	0.76	7.96	1.67	0.74	6.63	1.25	0.66
95% C.I.				9.23	2.07	0.81	6.65	1.66	0.72
95% C.I.				26.75	5.00	3.07	19.85	4.58	2.94
75th Percentile	24.49	5.37	3.73	29.04	5.40	3.35	21.14	4.98	3.20
95% C.I.				31.61	5.81	3.65	22.59	5.36	3.50
99th Percentile	526.9	35.87	36.57	543.7	37.24	35.88	505.6	34.80	37.21
Mean MY	1997.6			1996.8			1998.2		

Table E-6. Tulsa 2005 Fuel Specific Emissions

	Fleet			Gasoline Passenger			Gasoline Trucks		
Species	CO	HC	NO	CO	HC	NO	CO	HC	NO
Measurements	18890	18787	18889	8381	8329	8381	10027	9978	10026
Mean	33.52	2.25	2.86	36.42	1.84	2.69	31.90	2.51	2.43
95% C.I.				4.01	-4.20	-0.04	5.31	-3.77	-0.07
25th Percentile	5.33	-3.38	-0.02	5.31	-3.79	-0.02	5.33	-3.36	-0.05
95% C.I.				5.35	-3.37	0.01	5.38	-2.94	-0.03
95% C.I.				14.62	1.23	0.46	14.59	1.67	0.35
Median	14.79	1.67	0.47	15.85	1.25	0.51	14.68	2.06	0.38
95% C.I.				15.96	1.67	0.56	15.87	2.09	0.41
95% C.I.				32.96	6.21	2.06	29.02	6.65	1.65
75th Percentile	26.77	6.91	2.31	34.37	6.61	2.27	30.22	7.05	1.80
95% C.I.				36.20	6.92	2.50	31.45	7.45	1.97
99th Percentile	447.3	39.03	31.07	511.5	38.98	30.96	400.1	39.11	30.54
Mean MY	1999.3			1998.5			2000.0		

Table E-7. Tulsa 2013 Fuel Specific Emissions

	Fleet			Gasoline Passenger			Gasoline Trucks		
Species	CO	HC	NO	CO	HC	NO	CO	HC	NO
Measurements	21115	20745	21115	8326	8112	8326	12190	12044	12190
Mean	13.36	2.09	1.53	14.25	1.94	1.34	13.23	2.16	1.19
95% C.I.				-5.10	-5.38	-0.10	-3.06	-2.93	-0.07
25th Percentile	-3.33	-3.44	-0.07	-4.53	-4.84	-0.09	-2.80	-2.65	-0.07
95% C.I.				-3.86	-4.26	-0.08	2.42	-2.39	-0.06
95% C.I.				3.73	0.96	0.07	3.05	1.34	0.04
Median	3.70	1.46	0.07	4.26	1.23	0.08	3.39	1.51	0.05
95% C.I.				4.72	1.51	0.09	3.74	1.71	0.06
95% C.I.				15.59	6.71	0.40	13.32	5.63	0.29
75th Percentile	15.12	6.38	0.41	16.70	7.28	0.43	14.20	5.91	0.32
95% C.I.				17.82	7.73	0.48	15.17	6.22	0.34
99th Percentile	218.3	45.43	29.12	259.0	48.43	28.41	210.4	40.85	26.75
Mean MY	2006.3			2006.0			2006.6		

Table E-8. Tulsa 2015 Fuel Specific Emissions

	Fleet			Gasoline Passenger			Gasoline Trucks		
Species	CO	HC	NO	CO	HC	NO	CO	HC	NO
Measurements	19601	19475	19599	7569	7513	7569	11437	11378	11435
Mean	14.31	2.41	1.36	16.05	4.22	1.16	13.63	1.25	1.13
95% C.I.				-1.61	-3.32	-0.08	-0.27	-4.08	-0.04
25th Percentile	-0.40	-3.57	-0.05	-1.06	-2.98	-0.07	0	-3.87	-0.04
95% C.I.				-0.53	-2.62	-0.06	0.39	-3.61	-0.04
95% C.I.				6.62	1.88	0.02	5.31	-0.21	0.02
Median	6.09	0.71	0.03	7.14	2.17	0.03	5.70	0	0.03
95% C.I.				7.56	2.46	0.04	5.98	0.21	0.03
95% C.I.				18.36	8.91	0.21	14.58	4.66	0.17
75th Percentile	16.91	6.65	0.23	19.26	9.45	0.23	15.34	4.99	0.19
95% C.I.				20.37	10.05	0.26	16.27	5.40	0.21
99th Percentile	184.4	48.12	29.08	207.4	54.5	27.96	170.5	39.71	28.54
Mean MY	2008.2			2007.9			2008.3		

Table E-9. Denver 2003 Fuel Specific Emissions

	Fleet			Gasoline Passenger			Gasoline Trucks		
Species	CO	HC	NO	CO	HC	NO	CO	HC	NO
Measurements	21323	21283	21277	10041	10025	10030	10632	10609	10598
Mean	44.02	3.38	6.41	51.83	4.52	6.14	38.03	2.42	5.71
95% C.I.				2.65	0.42	0.35	1.33	-1.25	0.18
25th Percentile	2.65	-0.42	0.31	2.66	0.42	0.39	2.65	-1.25	0.21
95% C.I.				3.97	0.42	0.43	2.65	0.84	0.23
95% C.I.				10.61	2.08	1.65	7.97	0.83	1.08
Median	10.55	1.66	1.60	11.90	2.08	1.76	9.25	0.83	1.17
95% C.I.				11.94	2.08	1.88	9.28	0.83	1.27
95% C.I.				38.18	4.57	6.22	26.48	3.33	5.32
75th Percentile	33.41	4.15	7.24	40.88	4.96	6.69	29.00	3.63	5.76
95% C.I.				44.05	5.01	7.21	30.47	3.74	6.27
99th Percentile	571.4	42.47	51.99	651.2	46.90	51.61	504.7	39.46	52.99
Mean MY	1996.4			1995.5			1997.2		

Table E-10. Denver 2005 Fuel Specific Emissions

	Fleet			Gasoline Passenger			Gasoline Trucks		
Species	CO	HC	NO	CO	HC	NO	CO	HC	NO
Measurements	20030	19915	19996	9352	9298	9343	10050	9997	10025
Mean	29.38	1.89	5.26	36.21	2.87	5.01	23.73	1.05	4.51
95% C.I.				1.33	-0.42	0.18	0	-1.26	0.11
25th Percentile	1.33	-0.84	0.18	1.33	-0.42	0.22	0	-1.26	0.13
95% C.I.				2.63	0	0.24	1.33	-0.84	0.15
95% C.I.				7.98	1.25	1.11	5.34	0.42	0.76
Median	6.69	0.84	1.08	8.07	1.25	1.21	6.64	0.42	0.83
95% C.I.				9.30	1.25	1.31	6.56	0.42	0.89
95% C.I.				26.50	3.32	4.76	17.29	2.09	3.67
75th Percentile	22.56	2.91	5.27	27.87	3.34	5.11	18.60	2.09	4.01
95% C.I.				30.43	3.36	5.50	19.92	2.5	4.37
99th Percentile	421.0	29.46	47.26	492.5	33.95	46.75	366.1	23.58	47.21
Mean MY	1998.1			1997.2			1998.9		

Table E-11. Denver 2013 Fuel Specific Emissions

	Fleet			Gasoline Passenger			Gasoline Trucks		
Species	CO	HC	NO	CO	HC	NO	CO	HC	NO
Measurements	19242	19224	19214	7884	7880	7870	10722	10708	10711
Mean	12.57	1.80	2.74	15.84	2.67	2.43	10.47	1.18	2.22
95% C.I.				-2.40	-0.29	0.05	-3.19	-1.13	0.03
25th Percentile	-2.66	-0.67	0.05	-2.25	-0.17	0.06	-3.02	-1.01	0.03
95% C.I.				-1.86	-0.04	0.07	-2.78	-0.88	0.04
95% C.I.				2.39	1.67	0.26	1.14	0.88	0.18
Median	1.98	1.30	0.25	2.78	1.80	0.28	1.33	0.96	0.19
95% C.I.				3.06	1.92	0.30	1.60	1.05	0.21
95% C.I.				11.63	4.03	1.17	8.00	2.88	0.84
75th Percentile	10.24	3.55	1.32	12.50	4.26	1.31	8.68	3.00	0.94
95% C.I.				13.58	4.44	1.47	9.30	3.13	1.05
99th Percentile	225.5	22.14	37.83	260.5	24.25	34.24	191.7	18.49	37.09
Mean MY	2005.2			2004.6			2005.5		

Table E-12. Denver 2015 Fuel Specific Emissions

	Fleet			Gasoline Passenger			Gasoline Trucks		
Species	CO	HC	NO	CO	HC	NO	CO	HC	NO
Measurements	23298	21130	23292	7749	6850	7749	14673	13487	14668
Mean	12.59	2.89	1.95	15.47	5.12	1.77	11.18	1.72	1.39
95% C.I.				-5.99	-3.53	-0.05	-4.79	-4.20	-0.04
25th Percentile	-4.40	-5.45	-0.03	-5.08	-3.27	-0.04	-4.32	-3.88	-0.04
95% C.I.				-4.25	-2.99	-0.03	-3.93	-3.57	-0.03
95% C.I.				4.49	2.76	0.13	3.19	1.09	0.09
Median	4.12	1.76	0.12	5.07	2.98	0.14	3.55	1.26	0.10
95% C.I.				5.72	3.17	0.16	3.97	1.46	0.1
95% C.I.				20.40	10.41	0.62	14.50	6.20	0.40
75th Percentile	17.49	7.92	0.61	21.73	10.90	0.68	11.89	6.53	0.44
95% C.I.				23.13	11.31	0.77	16.04	6.78	0.48
99th Percentile	213.9	46.84	34.13	226.6	55.69	30.69	195.3	41.00	30.55
Mean MY	2007.2			2006.4			2007.6		