Fuel Trends Report: Gasoline 2006 - 2016

EPA United States Environmental Protection Agency

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Gasoline 2006 - 2016

Office of Transportation and Air Quality
U.S. Environmental Protection Agency

NOTICE

This technical report does not necessarily represent final EPA decisions or positions. It is intended to present technical analysis of issues using data that are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments.

United States
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Agency

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Definitions

Aromatics – A class of hydrocarbons in gasoline containing at least a single benzene ring.

Benzene – A specific unsaturated (see olefin definition) hydrocarbon containing six carbon atoms and six hydrogen atoms.

CBOB – (Conventional Blendstock for Oxygenate Blending) a gasoline blending material (usually sub-octane) which must be blended with an oxygenate, essentially ethanol, before it would comply with all gasoline specifications and regulations.

CG – conventional gasoline; intended to be sold in areas other than RFG areas.

E200 – The volumetric percent of a gasoline sample which has boiled off when the sample is heated to 200 degrees Fahrenheit.

E300 - The volumetric percent of a gasoline sample which has boiled off when the sample is heated to 300 degrees Fahrenheit.

Olefins – A class of hydrocarbons which are unsaturated, meaning that a pair of hydrogen atoms on adjacent carbon atoms is missing, replaced by a double bond between those two carbon atoms. Olefins are much more chemically reactive than other hydrocarbons.

ppm - Parts per million

RFG – reformulated gasoline is blended from refinery streams designed to meet reformulated gasoline regulations and be sold in specific areas required to use reformulated gasoline.

RVP – (Reid Vapor Pressure) a measure of the hydrocarbon vapor pressure in pounds per square inch above the gasoline sample when it is heated to 100 degrees Fahrenheit

Sulfur – a chemical element naturally occurring in crude oil and is present in gasoline which has an adverse effect on catalytic converters and other internal combustion engine aftertreatment devices.

Chapter 1. Executive Summary

This report provides the public with data on gasoline fuel properties and how they have been trending over time due to both EPA standards and shifts in market dynamics.[1] The results presented here are compiled from data provided to EPA by refiners, gasoline blenders and importers to verify compliance with our gasoline fuel quality standards.

This report follows a similar one from 2008, entitled "Fuel Trends Report: Gasoline 1995-2005." That report presented data on key chemical and physical properties of gasoline during those years, and highlighted how gasoline properties changed due to the Reformulated Gasoline (RFG) Program, which took effect in 1995 and 1998.[2]

This report presents data on certain chemical and physical properties of gasoline from 2006-2016, a time period which has seen both the phase in of new fuel standards and a variety of shifts in the overall fuels market.

This report finds of a number of key trends in gasoline fuel properties:

- Gasoline sulfur:
    - Tier 2 sulfur standards were gradually phased-in from 2004 to 2006 and lowered gasoline sulfur to the level of the standard, which is 30 ppm.
    - Tier 3 sulfur standards took effect January 1, 2017, and will be gradually phased in through 2020. When fully phased-in, Tier 3 standards will lower gasoline sulfur to 10 ppm.
    - The data show that many refiners exercised the option to reduce sulfur levels in 2014-2016 to generate early credits for compliance with Tier 3 standards.
    - In 2016, gasoline sulfur levels ranged from 22-24 ppm, a 93 percent reduction from 1990 levels.

- Benzene:
    - The Mobile Source Air Toxics (MSAT2) benzene standard, which was phased in from 2011 to 2014, lowered gasoline benzene levels to 0.62 volume percent.
    - Refiners began to reduce their gasoline benzene levels in 2007 to generate early credits for compliance.
    - In 2016, refiners reduced benzene levels in RFG well below the standard to about 0.5 volume percent, while CG benzene levels met the standards and ranged from 0.58-0.63 percent by volume.
    - Overall, 2016 benzene levels are 60 percent lower compared to 1990 benzene levels.

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[1] This report focuses solely on gasoline for which we have detailed fuel property information. .Diesel fuel is not covered in this report.

[2] Fuel Trends Report: Gasoline 1995 – 2005; U.S. Environmental Protection Agency; https://*nepis.**epa**.gov/Exe/ZyPURL.cgi?Dockey=P100B3YI.TXT*.

- Ethanol content:
  - The Renewable Fuel Standard (RFS) program, which requires increases in the volume of renewable fuels consumed, took effect in 2006 and continues to be implemented.
  - By 2013, nearly all U.S. gasoline contained approximately 10 percent ethanol.
- Other:
  - There were also modest changes in other fuel properties resulting from both these changes and other market shifts that occurred over this time period.

The Data

It is important to understand exactly what this data is to understand how it can best be used. The fuel property data are reported to EPA for every batch of gasoline produced at the refinery, blended at terminals or imported into to the U.S., and sold in the U.S.[3] Although these figures are calculated from data drawn from compliance reports submitted by refiners, the figures here do not represent actual compliance information used to determine whether any specific regulatory party has satisfied their statutory and regulatory requirements. The data do not include gasoline exported outside the U.S., nor does it include gasoline sold in California (but does include gasoline produced in California and sold outside the state elsewhere in the U.S.). Prior to analyzing or reporting the data, EPA staff and EPA contractors review and quality-control the data for omissions and incorrect values. As it comprises every batch of gasoline sold in the U.S. outside of California - over 50,000 batches/year - it represents the most accurate and comprehensive set of data available for gasoline properties in the United States.

Batch data properties are measured at the refinery/importer, not at the retail station. Of greatest interest to the public, however, is understanding the quality of fuel going into vehicles at retail stations in particular areas. In light of this, it’s helpful to understand a few points about the intersection between fuel distribution/transportation and fuel quality.

First, the majority of gasoline batches are aggregated in pipelines and terminals, as well as mixed in retail stations, so the fuel dispensed at retail will be combinations of multiple refinery batches.

Second, gasoline distribution is fungible, meaning that gasoline of the same grade or type is combined together in large batches and is shipped across the country, so the gasoline produced in a given part of the country is not necessarily the fuel dispensed in that part of the country, and vice versa.

[3] A refinery batch is a discreet volume of gasoline which is produced, tested (for compliance purposes) and distributed at that volume from that refinery.

Third, while gasoline properties are not expected to be affected significantly during shipment from the refinery to retail stations,[4] the blending of ethanol into gasoline occurs downstream at terminals just prior to gasoline's shipment to retail stations. This downstream blending of ethanol will affect gasoline's other properties. However, this issue does not apply for RFG because RFG refiners must account for the downstream blending of ethanol in their batch gasoline property data as reported to us. They do this by making a "hand blend" of ethanol in each batch sample to reflect the gasoline properties with the ethanol blended in. Most conventional gasoline, though, is not reported to us with ethanol blended in if ethanol is blended in downstream. In order to consistently estimate the average downstream properties of gasoline at retail, and show fuel properties for conventional gasoline and reformulated gasoline on a consistent basis, we have adjusted the refinery reported gasoline properties for this report, where appropriate, to account for the downstream blending of ethanol.

Because this refinery-gate batch data cannot be used to make conclusions about the gasoline properties in any specific retail market, we must look to other data sets where available for this purpose. One such set of data is collected annually by the Reformulated Gasoline Survey Association and reported to EPA.[5] This is a large retail survey (about 5000 samples) that collects data on a range of fuel properties from retail stations in RFG areas across the country. Although the primary purpose for collecting this data is to determine whether the oil industry is complying with the RFG and other fuel program requirements, we used this data in this report to provide some insight into regional fuel quality differences where possible. However, it is limited to only gasoline samples collected from RFG areas and thus, provides no insight into conventional gasoline fuel properties. Other sources of retail gasoline property data collected more broadly across the U.S. include the retail fuel survey by the Alliance of Automobile Manufacturers and the now discontinued retail fuel survey by Northrop Grumman/TRW. These are spot surveys sampling a smaller fraction of all the gasoline sold at retail for a couple points in time per year and are sold to cover their sampling and testing costs. At various places in the body of this report, the gasoline properties from the RFG and the Alliance retail surveys are compared to the gasoline properties from the batch data. There is another potential source of other gasoline property data which is collected by some states. Some of the states which collect this sort of data collection include California, Texas, and Arizona. These states collect such fuel property data because they want to ensure that the gasoline consumed in the state meets the fuel quality standards put in place to help address the serious air pollution issues they experience in their state. Of these states, only Texas routinely makes this gasoline property data available to the public.[6]

At a high level, this report presents data related to measured fuel properties over time, and shows how those fuel properties have changed in response to regulatory and market-based shifts. We present this data in different ways to highlight key trends. In Table 1 and Table 2 below, fuel

[4] Some mixing of fuel batches will occur between the refinery and retails stations which will help to average out fuel properties.
[5] The RFG Survey Association is a non-profit industry trade association formed on behalf of the oil industry and EPA to facilitate compliance with the Reformulated Gasoline fuel quality and emissions standards (https://rfgsa.org).
[6] 2014 Summer Fuel Field Study (Revised) – Final Report; Prepared for: Texas Commission on Environmental Quality (TCEQ) by Eastern Research Group (ERG), Inc.; August 15, 2014, Revised January 2015; ERG Report No. 0292.03.020.

property data is presented for the year 1990 (RFG baseline gasoline properties prior to the RFG program), the year 2000 (after the RFG program was implemented, but prior to Tier 2 and Tier 3 gasoline sulfur standards, MSAT2 benzene standards and RFS2), and the year 2016, which is the most recent year that the fuel property data is available. The fuel property data is presented separately for summer and winter (the end of the report contains definitions for the properties listed in these tables).

Table 1 Summary of Summertime Gasoline Properties (ethanol adjusted)

Note: see "Definitions" at beginning of report for a glossary of terms used in tables below

	1990	**2000**		**2016 RFG**		**2016 CG**	
Property	**Baseline**	**RFG Average**	**CG Average**	**Average**	**95%**	**Average**	**95%**
Sulfur (ppm)	339	126	324	23.1	48.2	22.5	51.0
Benzene (vol%)	1.53	0.59	1.15	0.51	0.86	0.63	1.27
RVP (psi)	8.7	6.78	8.27	7.1	7.47	9.08	10.0
Aromatics (vol%)	32	19.3	28.5	17.12	27.3	21.76	32.1
E200 (vol%)	41	47.6	45.2	47.9	54.8	53.0	61.4
E300 (vol%)	83	84.7	80.7	85.6	92.0	84.8	91.1
Olefins (vol%)	13.1	10.6	11.8	10.5	18.7	8.38	16.4
Ethanol (vol%)	0.6	1.14	0.84	9.61	9.97	9.28	9.8

Table 2 Summary of Wintertime Gasoline Properties (ethanol adjusted)

	1990	2000		2016 RFG		2016 CG	
Property	**Baseline**	**RFG Average**	**CG Average**	**Average**	**95%**	**Average**	**95%**
Sulfur (ppm)	339	200	293	24.4	48	23.0	55.0
Benzene (vol%)	1.64	0.65	1.08	0.51	0.84	0.58	1.13
RVP (psi)	11.5	12.1	12.1	13.1	14.9	12.6	15.0
Aromatics (vol%)	26.4	19	24.8	16.4	25.1	18.8	28.7
E200 (vol%)	50	56.3	50.4	58.1	62.5	56.2	62.8
E300 (vol%)	83	86.1	83.4	87.0	92.7	86.6	93.0
Olefins (vol%)	11.9	11.8	12	9.16	18.8	8.12	17.0
Ethanol (vol%)	0.6	1.22	1.19	9.7	10.1	9.28	9.8

Comparing the year 2000 batch data gasoline properties to the 1990 RFG baseline gasoline properties in Table 1 and Table 2, the RFG program, caused a reduction in RVP, sulfur, benzene aromatics, while causing an increase in E200, E300 and the use of oxygenates.

The Tier 2 gasoline sulfur standards phased-in primarily over the period from 2004 to 2006 with some ongoing phase-in through 2010. Due to the Tier 2 sulfur standards, average gasoline sulfur decreased from about 260 parts per million (ppm) down to about 30 ppm. The Tier 3 gasoline sulfur standards took effect January 1, 2017, but actually phases-in from 2014 to 2020 through an early credit generation program. The data shows that refiners had already been reducing gasoline sulfur levels in 2014 through 2016 to generate early credits for Tier 3. As a result, the average gasoline sulfur level is already below 30 ppm and is expected to continue to steadily decline to 10 ppm by 2020. Once fully phased in, U.S. gasoline sulfur levels will be 97 percent lower than in 1990. An associated effect of gasoline desulfurization is a reduction in olefins, which is evident in the data. Another associated effect of lower sulfur gasoline is that it allows refiners to adjust other gasoline properties under the RFG program while still maintaining overall environmental performance. Specifically, refiners have been able to take advantage of lower sulfur levels to modestly reduce the amount of RVP control they need to comply with the RFG VOC performance standard. This, along with the reduction in the number of low-RVP and RFG areas, and the 1 psi waiver, has caused summertime RVP levels to increase slightly over time.

The Mobile Source Air Toxics (MSAT2) standards phased-in from 2007 to 2014. Now fully implemented, MSAT2 has caused the average benzene levels in conventional gasoline to decrease from about 1.15 volume percent to about 0.6 volume percent. Although the MSAT2 gasoline benzene program was established to reduce CG to equal the 0.62 volume percent level of RFG, RFG refiners further reduced the benzene level in RFG from about 0.62 volume percent down to about 0.5 volume percent. In 2016 gasoline benzene levels were 60 percent lower than in 1990.

The Renewable Fuel Standard (RFS) standards began to take effect in 2006 and continues to phase-in today. The RFS2 standards resulted in the blending of much more ethanol into the gasoline pool, such that nearly all gasoline contained 10 volume percent ethanol starting in 2013. Due to the increased blending of ethanol, the weight percent of oxygen has increased substantially in gasoline. Initially, refiners splash-blended the ethanol into the conventional gasoline pool.[7] However, as the percentage of ethanol blended into gasoline grew, refiners began to match-blend ethanol into the CG pool. Today, the majority of finished E10 gasoline is match-blended.[8] Ethanol's high octane value has also allowed refiners to significantly reduce the aromatic content of the gasoline, a trend borne out in the data. Other direct effects of blending in ethanol are described below.

While the reformulated gasoline (RFG) program initially resulted in RFG having very different fuel qualities (lower RVP, sulfur, benzene, aromatics and higher E200 and E300) compared to conventional gasoline, the implementation of subsequent fuel programs (Tier 2/3 sulfur standards, MSAT benzene standards, RFS renewable fuels mandates) caused conventional gasoline to look very similar in fuel properties as RFG. The primary difference now between RFG and conventional gasoline is that during the summer, RFG is required to have lower RVP than most conventional gasoline.

Market-induced changes in fuel trends have been occurring alongside changes brought about by EPA's regulatory programs. For example, crude oil prices have changed dramatically from 2005 to present which affects how refineries refine fuel. Also, U.S. crude consumption has changed due to hydraulic fracturing in the United States which has introduced more light, sweet crude oil as well as increased heavy crudes such as the tar sands from Canada. Finally, over the last decade, diesel fuel production by U.S. refiners has increased relative to gasoline production, which affects how refiners produce and blend up their refined products. As can be seen in the API gravity and E300 values, besides the effect of blending in more ethanol, gasoline has become "lighter" over time. One possible reason for this is heavier hydrocarbons, previously cut into the gasoline pool by refineries, have been shifted into the distillate pool to meet the rising demand for these products.

[7] When ethanol is splash-blended with gasoline, the gasoline is a finished gasoline meeting all gasoline specifications, particularly octane, and the high octane value of ethanol results in E10 exceeding the octane specification, causing octane "giveaway."

[8] When ethanol is match-blended with gasoline, the gasoline material (called a blendstock for oxygenate blending or a BOB) is about 3 octane numbers lower than the octane specification and the BOB must be blended with 10 percent denatured ethanol to produce a finished gasoline that meets the octane specifications.

Chapter 2. About This Report

This report summarizes changes in U.S. gasoline properties during the years from 2006 to 2016 and covers the years following a previous gasoline trends report titles "Fuel Trends Report: Gasoline 1995 – 2005."[9] As indicated by the title, the previous gasoline trends report summarized gasoline property data from 1995 to 2005. During that 1995 to 2005 period, the Reformulated Gasoline program phased-in and the Tier 2 gasoline sulfur program had started to phase-in. The previous gasoline trends report made the following findings:

- **Gasoline Sulfur Decreases** -- Average annual sulfur content in all gasoline dropped from about 300 ppm in 1997 to about 90 ppm in 2005.

- RFG NOx Reductions Exceed Requirements **--** RFG exceeded applicable NOx performance standards during both Phase I (1998-1999) and Phase II (2000 and beyond).

- RFG Toxics Reductions Exceed Requirements **--** On average, Phase I RFG complied with Phase II standards, and toxic performance still improved with the transition to Phase II standards.

- Conventional Gasoline NOx, Toxics and VOC Emissions Decreased **--** Between 1998 and 2005, the summer NOx emissions of conventional gasoline were reduced by 5.7 percent, while summer exhaust toxics were reduced by 4.7 percent. VOC emissions decreased by over 27 percent.

- Ethanol Use in RFG Increased and MTBE Use Decreased **--** In the summer of 1996, about 11 percent of the RFG sold contained ethanol while virtually all the remainder contained MTBE. By the summer of 2005, the ethanol share increased to about 53 percent, with corresponding decreases in MTBE.

This report primarily summarizes changes in U.S. gasoline properties during the years from 2006 to 2016. During the 2006 to 2016 timeframe the following EPA fuels programs phased-in:

- The completion of the phase-in of the Tier 2 sulfur regulations,
- The implementation of the MSAT2 toxics regulations,
- Removal of the oxygenate mandate for RFG,
- The implementation of RFS and the start and ongoing implementation of the RFS2 regulations, and
- The beginning of the implementation of the Tier 3 sulfur regulations.

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[9] Fuel Trends Report: Gasoline 1995 – 2005; U.S. Environmental Protection Agency; https://*nepis.**epa**.gov/Exe/ZyPURL.cgi?Dockey=P100B3YI.TXT*.

This report discusses how the phase-in of these various regulations affected gasoline properties over this period of time. While perhaps not as obvious as the fuel regulations, this report also discusses how the marketplace may have affected gasoline properties.

While this report does generally not incorporate the data analyzed in the 1995 to 2005 gasoline trends report, it provides summaries of gasoline quality prior to 2006 to allow a comparison of the most recent gasoline properties to the gasoline properties from those years to show how much gasoline properties have changed over time. While the focus of this report is the gasoline batch data reported to EPA, this report also compares the batch data to survey data of reformulated and conventional gasoline at retail stations. This report analyzes the data in a variety of ways to help the reader better understand the gasoline properties and how they vary by refinery, gasoline types and grades.

Chapter 3. About the Data

A. Batch Data Reported to EPA

This report summarizes the volume and properties of all the refined batches of gasoline produced or imported during the years 2006 – 2016 for consumption in the United States. A refinery batch is a discreet volume of gasoline which is produced by a refinery and distributed from that refinery. For example, the refiner will blend together refinery gasoline streams from different refinery units within the refinery into a large gasoline storage tank, and when that tank is full, or when the intended volume of gasoline is collected, the refiner ships the entire tankful, or batch, of gasoline to a pipeline for moving that gasoline batch to market. Once the batch of gasoline is produced and ready to ship, the refiner tests the gasoline to determine its properties. To comply with EPA's standards each gasoline batch must meet any per-gallon standards, such as RVP, and, along with other gasoline batches, the annual-average volume-weighted standards, such as the 10 ppm gasoline sulfur standard. In addition, there are industry standards, such as ASTM standards, that also apply.

EPA requires refiners and importers of RFG and conventional gasoline to submit compliance reports which summarize the properties of the gasoline in each of the gasoline batches.[10,11] While the batch reports were initially required to track compliance with the RFG program, this data is important for tracking compliance with subsequent fuel programs as well. Although the data summarized in this report are calculated from data drawn from compliance reports submitted by refiners, the data here do not represent actual compliance information used to determine whether any specific regulatory party has satisfied their statutory and regulatory requirements. How refiners report the batch gasoline property data is also specified in the regulations. Refiners and importers of conventional gasoline are allowed to compile composite gasoline samples up to one month for purposes of batch reporting. The batch-by-batch gasoline property data reported by any individual refinery is considered confidential business information (CBI) and this information cannot be released to the public, except in an aggregated or anonymous form, which protects CBI.

The gasoline properties being evaluated in this report include sulfur, benzene, aromatics, RVP, olefins, E200 and E300.[12] These gasoline properties were chosen from the broader list of reported properties because they have been shown to affect motor vehicle emissions of hydrocarbons, oxides of nitrogen and/or air toxics. The association between these fuel properties and motor vehicle emissions was first made in the reformulated gasoline program.[13] The effect of sulfur on the catalytic converters of later year motor vehicles, and ultimately the emissions

[10] 40 C.F.R. '80.75
[11] 40 C.F.R. '80.105
[12] See the definitions for these terms at the end of the report.
[13] Regulation of Fuels and Fuels Additives: Standards for Reformulated and Conventional Gasoline – Final Rule; FR 7716 Sections III and IV; February 16, 1994.

from those vehicles, was studied and led to the Tier 2 and Tier 3 gasoline sulfur regulations.[14,15] Then a subsequent fuel property testing program named EPAct (named for the Energy Policy Act legislation which initiated the testing program) was conducted by EPA in conjunction with DOE and the Coordinated Research Council using Tier 2 vehicles.[16, 17] The EPAct study included all the original gasoline properties established under the RFG rule, except for olefins and benzene. Other than the very simple discussion which links these gasoline properties to motor vehicle emissions as part of the discussion about the RFG program below, this report does not attempt to identify or quantify the emissions impact of any of the gasoline properties, but simply report out these properties. The emissions impact of all these various motor vehicle emissions modeling efforts is summarized in documentation used for the MOVES2014 emissions model.[18]

All refiners and importers of gasoline sold in the U.S. are required to comply with the reporting requirements described above, except for refiners and importers of gasoline produced or imported for use in California. Refiners and importers of California gasoline are exempted from the federal reporting requirements, and certain other federal enforcement requirements.

With any data collection process, it is important to ensure the quality of the data. Regulatory requirements, such as independent sampling and testing of some samples and statistical quality control provisions for laboratories that conduct compliance testing, help to ensure the quality of the reporting data that refiners and importers submit to EPA. However, instances of missing, incomplete or incorrectly reported data still occur. For this report residual data errors were eliminated from the analyses in two ways. For estimation of most seasonal average property values, data were excluded on a property-specific basis. For each property, an assessment was made to determine if the data was missing from a batch record. This was not entirely straightforward, because, for some properties a value of zero is possible. For these properties, a blank or null value might indicate a true "zero" value, rather than missing data. It is also possible that zeros may have been used to represent missing data. For some properties, additional property-specific exclusion criteria were sometimes added to remove values that were clearly impossible (e.g. when a property value reported as a volume percentage substantially exceeded 100 percent).

These additional screens excluded only a small proportion of the data from most of the analyses. The additional data screens for this report removed some erroneous data items, although valid data may also have been removed. The level of screening did not have much effect on the averages, suggesting that if any over-screening might have occurred, it would have had a

[14] Control of Air Pollution from New Motor Vehicles: Tier 2 Motor Gasoline Emissions Standards and Gasoline Sulfur Control Requirements – Final Rule; FR 6698 Section IV(A)(2); February 10, 2000.
[15] Control of Air Pollution from Motor Vehicles: Tier 3 Motor Vehicle Emission and Fuel Standards – Final Rule; FR 23414 Section IV(6); April 28, 2014.
[16] EPAct/V2/E-89: Assessing the Effect of Five Gasoline Properties on Exhaust Emissions from Light-Duty Vehicles Certified to Tier 2 Standards; Final Report on Program Design and Data Collection; April 2013; EPA-420-R-13-004.
[17] Assessing the Effect of Five Gasoline Properties on Exhaust Emissions from Light-Duty Vehicles Certified to Tier 2 Standards: Analysis of Data from EPAct Phase 3 (EPAct/V2/E-89) – Final Report; April 2013; EPA-420-R-13-003.
[18] Fuel Effects on Exhaust Emissions from On-Road Vehicles in MOVES2014 – Final Rule; U.S. Environmental Protection Agency, February 2016 (EPA-420-R-16-001)

negligible impact on the summary results presented. Removal of extreme values for certain properties visibly affected the tails of property value distributions by volume for the properties, but had little effect on median values. Removal of data on a batch basis rather than a property basis for some of these analyses probably removed some erroneous data values for properties, even when the property value did not meet the outlier criteria for that property.

B. Adjustments for Ethanol Blending for this Report

Depending on whether a batch of gasoline was RFG or conventional gasoline (CG), the properties are reported to EPA differently with respect to the presence and impact of downstream blending of ethanol. RFG is reported as blended with ethanol, while CG typically is not.[19] Thus, to put all the data on the same basis for summarizing the results here, adjustments were necessary to ensure the data reflected gasoline fuel properties as sold at retail.

In the prior report covering 1995-2005, no attempt was made to account for the downstream blending of ethanol into CG, as it was still in relatively limited use (see below). However, this changed rather suddenly and significantly starting in 2006, when ethanol replaced methyl tertiary butyl ether (MTBE) as the primary oxygenate used for RFG, and the RFS program began mandating increased use of renewable fuels in all gasoline. Consequently, the gasoline property results reported here for 2006 and later were adjusted to reflect the total volume of ethanol blended in the gasoline pool to best estimate the volume and qualities of gasoline consumed at retail. Batches reported to EPA as conventional blendstock for oxygenate blending (CBOB) were adjusted assuming that ethanol was blended downstream of the refinery into CBOB at 10 volume percent of denatured ethanol. However, early on, from 2006 to 2011, most ethanol was "splash blended" into conventional gasoline instead of into CBOBs. This is because most terminals don't have extra storage tanks to store both a CBOB as well as conventional gasoline (they must be kept separate from each other), thus conventional gasoline would need to be produced until that entire market converts over to E10, and if it fits with the gasoline delivery schedule by pipelines, barges or ships, then that market could convert over to CBOBs. During this period of time when ethanol was being splash-blended into conventional gasoline, the batch data does not reveal which part of the gasoline pool is eventually blended with ethanol.

By subtracting the volume of ethanol blended into RFG and CBOBs, which we can estimate from the batch data, from the overall volume of ethanol blended into the gasoline pool as reported by the Energy Information Administration (EIA) in each of those years, we are able to estimate the volume of ethanol splash-blended into the conventional gasoline pool. For adjusting the gasoline property data, the additional amount of ethanol splash-blended into the gasoline pool was assumed to be blended downstream of refineries into the non-CBOB conventional gasoline pool at 10 volume percent (we did not include the data for higher ethanol blends (i.e., E85) nor did we assume any ethanol blended above 10 percent ethanol). Because we don't know which batches of gasoline were splash-blended with ethanol, we could only adjust the national average

[19] Most conventional gasoline produced at a refinery is shipped by pipeline, barge or ship to its downstream location and ethanol is blended in at that downstream location. This conventional gasoline would not be reported by refiners to contain ethanol. E10 gasoline sold off a refinery's rack, which comprises a smaller portion of the gasoline sold each year, is likely to be reported with ethanol included. Refiners report these batches, allowing us to distinguish them in the data.

gasoline properties for this splash-blended ethanol, and did not adjust the conventional gasoline data which summarizes the range of gasoline properties for individual conventional gasoline batches. The volume of gasoline reported was increased to include the volume of ethanol blended downstream of the refinery. These adjusted volumes are reflected in the volume of gasoline reported in Table 6, and are used when volume-weighting gasoline properties to calculate national-average gasoline properties.

Two types of adjustments were made to the gasoline properties to account for the downstream blending of ethanol. For sulfur, olefins, aromatics and benzene, these gasoline properties were adjusted assuming that they were reduced by simple dilution. Thus, these properties were lowered to account for the blending of ethanol by multiplying the gasoline parameter by 0.902 (ethanol contains 2% by volume of denaturant which is gasoline or gasoline-like) to reflect the change that would happen when denatured ethanol is blended into gasoline at 10 volume percent.

For RVP, E200, E300 and API gravity, the adjustment accounts for the non-ideal blending behavior of ethanol. The adjustments for RVP, E200, E300 and API gravity were made based on a statistical analysis performed of the data derived by the American Petroleum Institute's (API) ethanol blending study.[20] RVP is adjusted using the equation: $RVP(E10) = RVP(E0) + 6.2371 * RVP(E0)^{-0.794}$. E200 is adjusted using the equation: $E200(E10) = 0.6988 * E200(E0) + 23.182$. E300 is adjusted using the equation: $E300(E10) = 0.8681 * E300(E0) + 12.874$. API Gravity is adjusted using the equation: API gravity(E10) = 0.8251* API gravity(E0) +9.5272. The plots of the data used for developing these equations, the trend lines through that data and the R-squared characterizing the trend lines' fit to the data are shown in Figures 1 - 4.

[20] Determination of the Potential Property Ranges of Mid-Level Ethanol Blends, American Petroleum Institute; April 23, 2010.

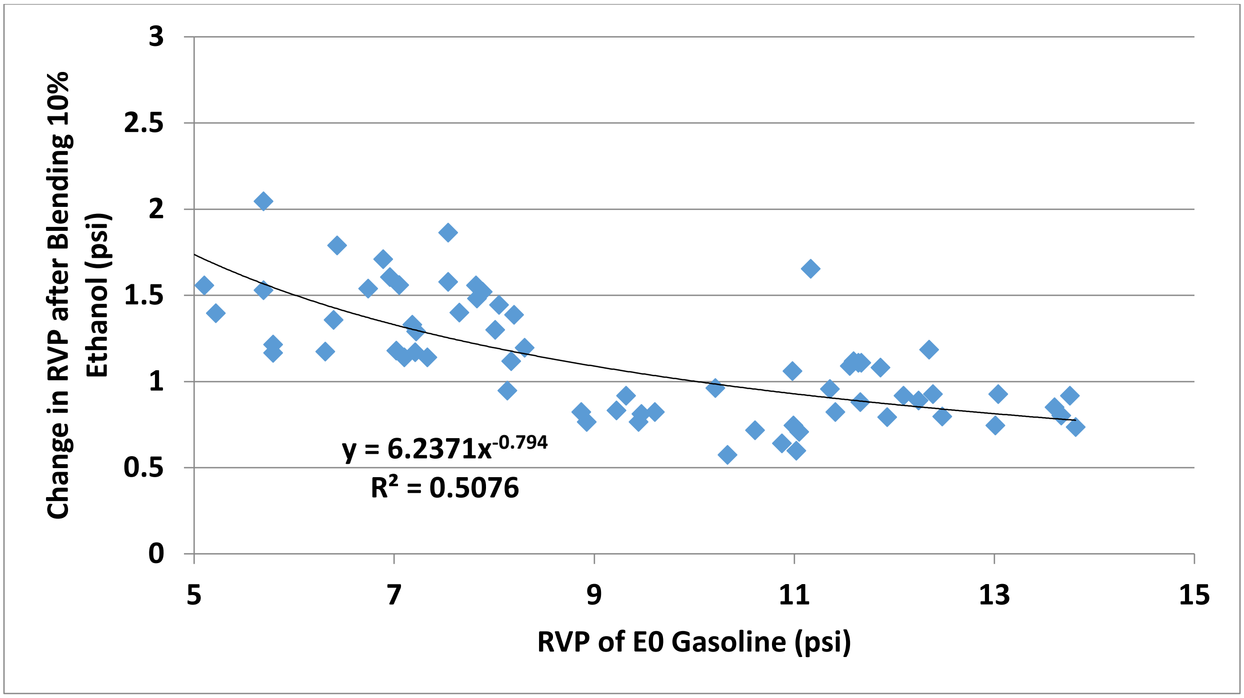

Figure 1 Change in RVP for Blending in 10% Ethanol vs Starting RVP of E0 Gasoline

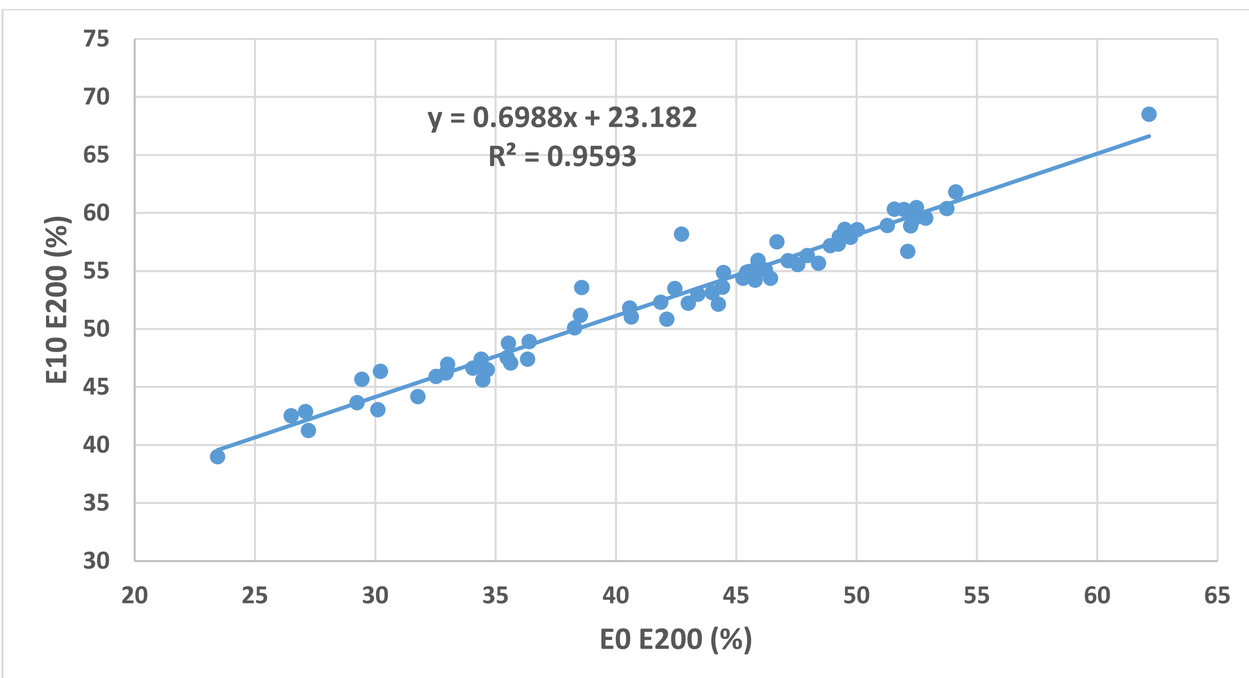

Figure 2 E200 of E10 Gasoline vs E200 of E0 Gasoline

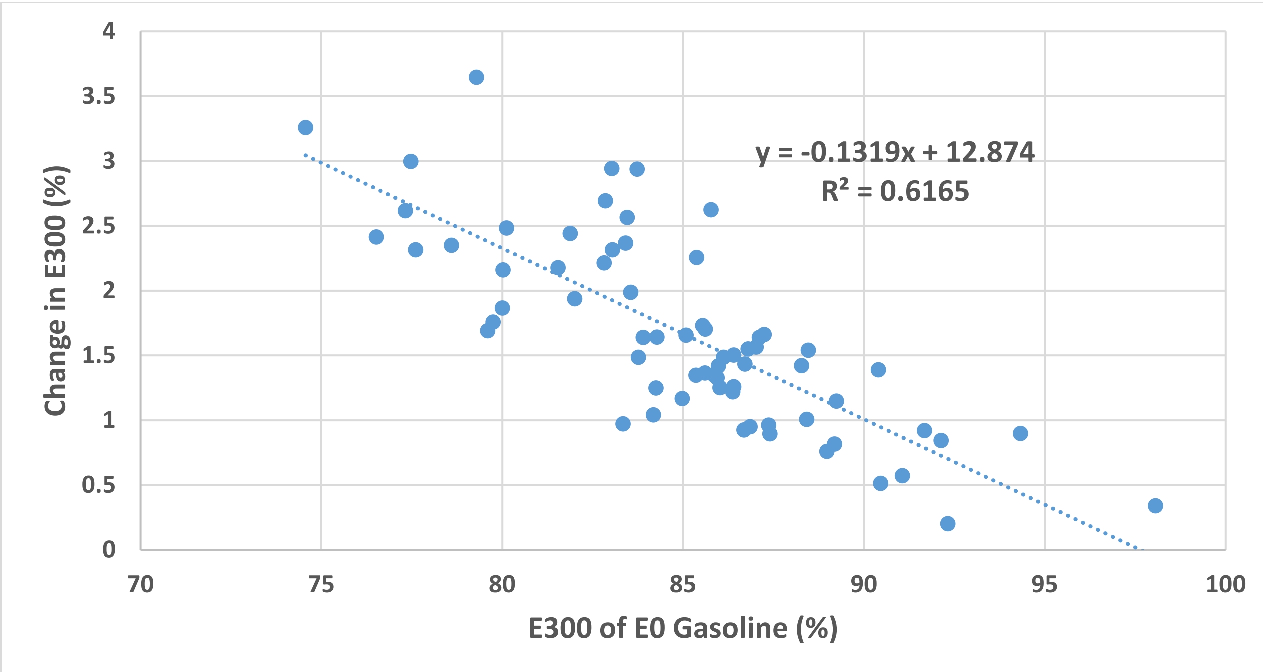

Figure 3 Change of E300 for blending in 10% Ethanol per E300 of E0 Gasoline

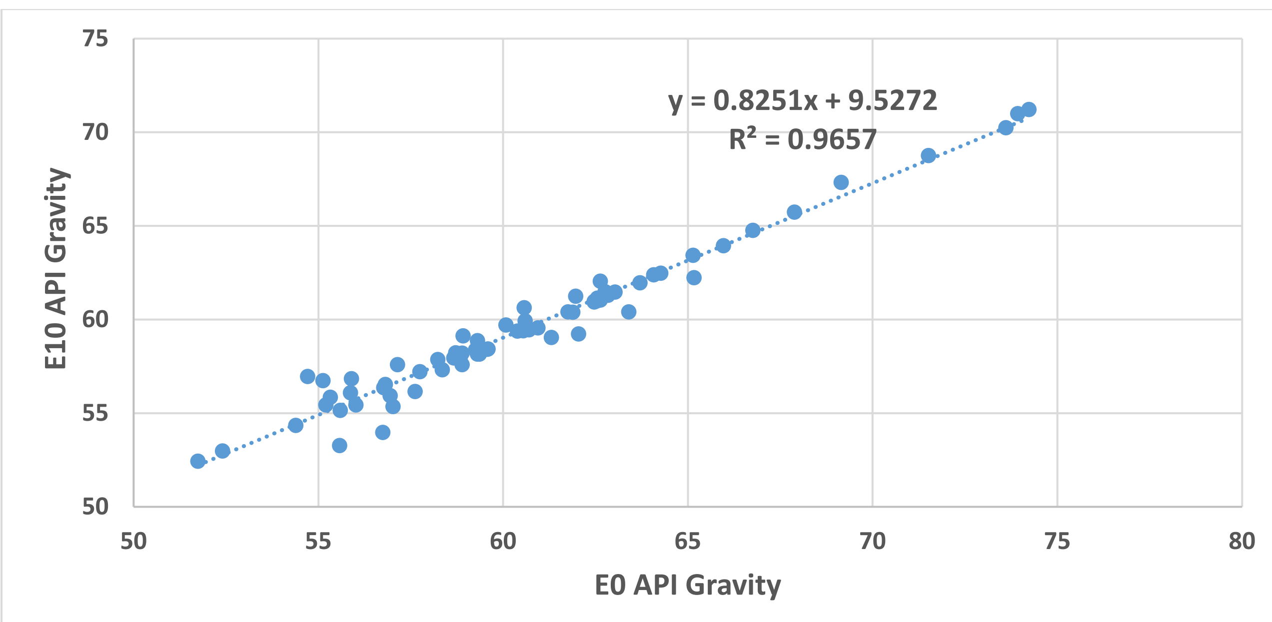

Figure 4 E10 API Gravity vs E0 API Gravity

The weight percent oxygen is reported differently in this report compared to the previous report. Prior to 2006, the weight-percent oxygen average values were calculated only when a weight-percent oxygen value greater than zero was reported. All weight-percent oxygenate values

(Ethanol, MTBE, TAME, etc.) were calculated as a group based on the presence of a reported value for oxygen that was greater than zero. Starting in 2006, because of the much greater use of ethanol which is always blended at 10 volume percent, weight-percent oxygen is reported as an average over the entire gasoline pool for each gasoline type/season subcategory.

Due to limited reporting of T50 and T90 data, complicated by the adjustments to account for the downstream blending of ethanol, T50 and T90 results are not presented starting in 2006.

C. Retail Gasoline Survey Data – RFG Survey Data and Alliance Survey Data

Under the CAA, areas required to use RFG are called RFG "covered areas." Gasoline meeting RFG emissions standards is required to be sold in each covered area. Since most refiners meet the RFG standards on average and not per-gallon, in addition to refinery gate batch reports, the RFG program requires refiners and importers to conduct surveys of gasoline quality in RFG covered areas. If the gasoline in an area fails to meet the RFG standard for a particular RFG pollutant, the standard for that pollutant is made more stringent and the number of surveys that must be conducted in the following year is increased. These surveys are conducted by the RFG Survey Association according to a statistical sampling plan approved by EPA and involve sampling gasoline at retail gasoline stations. The samples are tested for the relevant gasoline properties, and the emissions performance of the gasoline is calculated to determine if the gasoline complies with the RFG standards. Therefore, the survey data provides much information regarding the quality of gasoline sold at retail gasoline stations in RFG covered areas. The information contained in this report relating to trends in gasoline properties and emissions performance at retail gasoline stations is based on the data obtained from the RFG surveys. This report, therefore, provides a unique picture of gasoline quality at retail stations in RFG covered areas. Using the most recent RFG survey information, we compare the 2006 - 2016 batch data to the 2006-2016 RFG Survey data, and we also report city-specific RFG survey information.

The RFG Survey data are subject to regulatory requirements which help ensure the quality of the data submitted to EPA. EPA has a Quality Assurance Project Plan in place for the survey program. The survey regulations provide for exclusion of samples from a specific fuel property average if a sample exceeds a per-gallon minimum or maximum standard for that fuel property plus an enforcement tolerance. These violations are rare and do not have much effect on survey averages. EPA did not apply any further data screening criteria to the survey data for this report (2006 to 2016).

It should be noted that EPA's RFG survey database, like the refinery batch data, does not contain information on California gasoline which also would be subjected to the RFG program if California did not put in place its own reformulated gasoline program. Within this report, when we speak of U.S. gasoline, we refer to non-California gasoline covered by EPA’s standards.

The Alliance of Automobile Manufacturers North American Fuel Survey© is conducted twice every calendar year.[21] Sampling takes place in winter (January of the calendar year) and summer (July of the calendar year). The survey is conducted by an expert independent laboratory contractor, which also oversees collection of the fuel samples tested. No advance notice is provided to stations sampled. The Alliance of Automobile Manufacturers North American Fuel Survey data reflect a "snapshot" of market fuel properties from retail stations sampled in various cities. The number of stations sampled varies from city to city, and cities and stations can vary from survey to survey, though every effort is made to sample from the same service stations every year. The cities and stations sampled are not selected to meet statistical criteria, or on the basis of market share, but do tend to focus urban areas. Station selections are not based on RFG or CG status. The survey examines the quality of commercially available gasoline and diesel fuel from selected retail service stations located in the United States, Canada and Mexico. For gasoline, the survey covers two grades of unleaded gasoline (regular and premium octane grade) typically from 29 U.S. cities.

At the time we drafted this report, we only had Alliance survey data up to the year 2015. Thus, for this report, we compare the 2006 – 2015 batch data to the 2006 to 2015 Alliance survey data. The one exception is benzene as we were only able to report Alliance data up to 2013 since the Alliance stopped testing for benzene in 2013.

[21] The survey reports are available from the Alliance at www.autoalliance.org.

Chapter 4. EPA Regulations Affecting Gasoline Properties

A. RFG Program

Congress required that EPA establish the Reformulated Gasoline program (RFG) program in 211(k) of the 1990 Amendments to the Clean Air Act (CAA 1990). Congress required RFG to be sold in cities with the worst ozone non-attainment problems, but also allowed other cities with significant smog problems to opt into the RFG program. RFG is currently required in 17 states and the District of Columbia and about 27 percent of gasoline, not including California, is subjected to the RFG standards. In the 1990 Amendments, Congress also required that non-RFG, or conventional gasoline, sold in the rest of the country become no more polluting than gasoline sold in 1990. This requirement ensured that refiners did not "dump" fuel components that are restricted in RFG into conventional gasoline that would cause environmentally harmful emissions.

The RFG program phased in from 1995 through 2000 and compliance was managed through the use of motor vehicle emission models, the final version of which was named the Phase II Complex Model. The RFG program established emissions performance standards for volatile organic compounds (VOCs), nitrogen oxides (NOx), and toxics. These standards were based on percent reductions from the average tailpipe and evaporative emissions of these pollutants in 1990 model year vehicles operated on a specified baseline gasoline (see below for a summary of the gasoline properties in the RFG baseline). To comply with the VOC, NOx and toxics standards, refiners adjusted various gasoline properties including: aromatics, olefins, sulfur, Reid Vapor Pressure (RVP), benzene, oxygen and distillation points. The RFG program also established a maximum benzene standard of 1.0 volume percent, and an oxygen minimum standard of 2.0 weight percent. To comply with the hydrocarbon standard, refiners primarily lowered the RVP of their gasoline. To meet the NOx standard, refiners primarily lowered the sulfur content of their gasoline. To comply with the toxics standard, refiners primarily lowered the benzene and aromatics levels of their gasoline. For conventional gasoline, the program established emissions standards for exhaust toxics and NOx designed to ensure that an individual refinery's or importer's gasoline will not have higher levels of these pollutants than the refinery's or importer's 1990 gasoline. These standards for conventional gasoline are called the anti-dumping standards.

To demonstrate compliance with the RFG and anti-dumping standards, refiners and importers were required to measure the relevant gasoline properties in each batch of gasoline they produce or import, using a prescribed regulatory test method, to calculate the emissions level of each pollutant (hydrocarbons, NOx and toxics) in each batch of gasoline using the Complex Model. Since most refiners comply with annual average standards instead of per-gallon limits, the calculated emission results for each batch for each regulated pollutant are volume weighted over the course of the year to determine if the gasoline is in compliance.

There have been several changes in subsequent fuels regulations (many of which are discussed below) which affected compliance with the RFG program. The Energy Policy Act of 2005 repealed the RFG oxygen content requirement. This triggered refiners, who were mostly using MTBE, to switch to using ethanol in their RFG. As a result of the renewable fuels standard (RFS) ethanol has continued to be used in RFG. The 30 ppm Tier 2 gasoline sulfur standards brought down RFG and CG sulfur levels to a much lower level causing the NOx emission performance of RFG to surpass the RFG standards. Thus, the NOx emission performance standard was now deemed met for both RFG and CG if the Tier 2 gasoline sulfur standard was met. The MSAT2 0.62v% benzene standard brought the benzene level of all gasoline down to the level being achieved at the time by RFG. By virtue of meeting the MSAT2 benzene standard refiners were deemed to meet the RFG toxics performance standards.[22]

B. Tier 2

The Tier 2 gasoline sulfur program established by EPA limited the average sulfur content in gasoline to 30 ppm.[23] The Tier 2 program included an initial phase-in period in which gasoline refiners and importers were required to comply with a company-wide annual average sulfur standard of 120 parts per million (ppm) in 2004 and 90 ppm 2005. In 2005, refineries and importers began complying with a 30 ppm annual-average sulfur standard. The program also limited the amount of sulfur that may be present in any gallon of gasoline to 300 ppm in 2004 and 2005, and 80 ppm thereafter. Also, a 95 ppm gasoline cap standard applies at retail stations.

Some refineries had more time to comply with the Tier 2 gasoline sulfur requirements. In the Rocky Mountain states of the United States, and also Alaska, the Tier 2 program created a geographic phase in-area (GPA) because of the smaller refineries located there, and the longer time needed for their compliance. Refineries in the GPA area were provided two additional years to comply. Furthermore, small refiners were granted a delayed phase-in of the Tier 2 sulfur standards, which could be extended in exchange for on-time compliance with diesel fuel sulfur control under a subsequent diesel sulfur rulemaking. Based on the various flexibilities provided, the latest a small refinery could delay compliance with the Tier 2 gasoline sulfur standards was 2011.

Refiners and importers were allowed to generate early sulfur credits during the years 2000 to 2003 for reducing their gasoline sulfur levels from refinery sulfur baselines established under the Tier 2 regulations. Refiners could also create sulfur credits if they over-complied with the annual average sulfur standard in 2005 by producing or importing gasoline with a sulfur level that is lower than 30 ppm. Beginning with 2004 and until the early credits expired, refiners could use the early credits to delay making their capital investments for full compliance with the Tier 2 sulfur standards, or sell them to another refiner which would allow that refiner to delay compliance with the Tier 2 sulfur standards. Once the early credits expired, U.S. refineries (except California gasoline) averaged about 30 ppm, although the credit program allowed some refineries to produce gasoline which averaged more than 30 ppm sulfur (but no higher than 80 ppm), while other refineries averaged less than 30 ppm.

[22] 40 CFR 80.101
[23] 40 CFR 80.195

C. Tier 3

The Tier 3 gasoline sulfur program established by EPA limited the average sulfur content in non-California gasoline to 10 ppm.[24] The 10 ppm gasoline sulfur standard took effect starting in 2017 for non-small refiners, and will take effect in 2020 for small refiners and small volume refineries. Refiners could generate early credits staring in 2014 by reducing their gasoline sulfur levels below 30 ppm. Early credits could be used for compliance by non-small refiners during the years 2017 to 2019. All refineries, including small refiners and small volume refineries, must comply with the 10 ppm Tier 3 sulfur standard starting in 2020.

D. MSAT

The Mobile Source Air Toxics (MSAT) program established requirements for refiners and importers designed to ensure that the average level of toxic air emissions from gasoline did not increase starting in 2001.[25] This program required refiners and importers to establish an individual toxics baseline, separately for RFG and conventional gasoline, based on the average toxics performance of their gasoline during the baseline period 1998 to 2000. Refiners and importers also must establish a total baseline volume based on their volume of gasoline production or imports during the baseline period. The volume of gasoline produced or imported during the year, up to the refiner's or importer's baseline volume can be no more polluting than the refiner's or importer's MSAT baseline level for that type of gasoline (RFG or conventional). Any volume produced or imported in excess of the refiner's or importer's individual MSAT baseline volume can be no more polluting than the RFG toxics standard or the refiner's or importer's conventional gasoline anti-dumping toxics baseline level, as applicable. The MSAT program likely had little effect on gasoline properties because it was designed to prevent increases in toxics emissions, not reduce them.

E. MSAT2

The MSAT2 program superseded the MSAT program by establishing a 0.62 volume-percent benzene limit on refiners' non-California gasoline.[26] The 0.62 volume-percent MSAT2 benzene standard took effect starting in January 1, 2011 for non-small refiners, and January 1, 2015 for small refiners. Refiners could generate early credits starting in 2007 by reducing their gasoline benzene levels below their average gasoline benzene levels during the two-year period of 2004 and 2005. Early credits could be used for compliance by non-small refiners during the years 2011 to 2013, and by small refiners during the years 2015 – 2017. Consequently, by January 1, 2018 the standard will be fully phased-in. In addition to the 0.62 volume-percent standard, a 1.3 volume-percent maximum average benzene standard also applies, starting in 2011 for large refiners and 2016 for small refiners. Thus, although a refinery could show compliance with the 0.62 volume percent standard through the use of credits, the 1.3 volume-percent maximum

[24] 40 CFR 80.1603
[25] Subpart J Gasoline Toxics, 40 CFR part 80
[26] 40 CFR 80.815

average standard requires every refinery to average no more than 1.3 volume-percent benzene in any year.

F. RFS1

The Energy Policy Act (EPAct) required EPA to establish renewable fuel consumption standards outlined in the Act. EPA established the RFS program in 2007.[27] The Act specified that 4 billion gallons of renewable fuels must be used in 2006, ramping up to 7.5 billion gallons in 2012. However, due to the rising price of crude oil and the use of corn-based ethanol as a replacement of methyl tertiary butyl ether in RFG, the use of renewable fuels, and in particular ethanol, increased faster and higher than mandated by RFS1.

G. RFS2

The Energy Independence and Security Act (EISA) amended the RFS1 program to increase renewable fuels volume requirements, and subdivided the volumes into 4 different standards. The renewable fuels standards are: cellulosic biofuels, biomass-based diesel fuel, advanced biofuel and total renewable fuels. To qualify for use in a specific renewable fuels category, each renewable fuel must meet specified greenhouse pollutant reduction thresholds. EPA revised the RFS program regulations in 2010 pursuant to EISA.[28] The renewable fuels volume standards established by EPA for each year since 2010 are summarized in Table 3.

	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Cellulosic (Mil Gals)	6.5	0	0	0.8	33	123	230	311
Biomass-Based Diesel (Bil Gals)	0.65	0.8	1.0	1.28	1.63	1.73	1.9	2.0
Advanced Biofuel (Bil Gals)	0.95	1.35	2.0	2.75	2.67	2.88	3.61	4.28
Renewable Fuel (Bil Gals)	12.95	13.95	15.2	16.55	16.28	16.93	18.11*	19.28

* This standard for 2016 has been remanded back to the Agency by the D.C. circuit.

Table 3 Summary of Renewable Fuels Standards

[27] 40 CFR 80.1405
[28] 40 CFR 80.1405

Chapter 5. Marketplace-Based Changes in Gasoline Properties

While many of the changes in gasoline properties have been driven by the fuel regulations described above, the marketplace is always changing and these changes have brought about shifts in gasoline properties as well. The changes in gasoline properties caused by the marketplace are more difficult to discern because the marketplace does not seek to affect gasoline properties directly. Instead, as the marketplace changes, refineries adjust and operate differently which can cause changes in gasoline properties.

One likely change in gasoline properties attributable to the marketplace is the observed increase in E300 and E200. These distillation qualities of gasoline may have increased because the demand of diesel fuel and other distillate has been increasing faster than the demand in gasoline. One way refineries can increase the production of diesel fuel is to change their distillation columns in their refineries to cut more of the heaviest portion of the gasoline pool into the distillate pool. This action would remove a portion of the gasoline pool which boils above 300 degrees Fahrenheit, and therefore increase E300 and also E200. An increase in E200 and E300 is also affected by the increased blending of ethanol. Not only does ethanol blending expand the gasoline pool which decreases the gasoline portion of the E10 gasoline pool, and refiners must compensate for that, but all of ethanol boils less than 200 degrees Fahrenheit and this directly increases E200, and increases E300 by a much smaller amount.

E200 and E300 levels decreased after 2013 and the most likely explanation is that a large volume of diesel fuel came into the world market by several large refineries in the Middle East and Asia which were designed to predominantly produce diesel fuel over gasoline. This caused the world diesel fuel prices to fall and U.S. refiners altered their refinery production to produce less diesel fuel and more gasoline, thus, temporarily reversing the previous trend.

The decrease in aromatics is also likely affected by the marketplace. Although aromatics are naturally occurring in crude oil, most aromatics in gasoline are produced by a refinery unit called the reformer which produces aromatics to improve the octane rating of the gasoline pool. Reformers use a precious metal catalyst to convert branched chain and cyclical hydrocarbons in a reactor at low to medium pressures to aromatics such as toluene, xylene and benzene, and also produce hydrogen and light hydrocarbons as byproducts. A key reason why the marketplace is causing lower aromatics production by reformers is because of a series of economic factors which disfavor reforming. Although the hydrogen produced by reformers as a byproduct has a valuable use in the refinery, hydrogen from steam-methane reformers, fueled by very cheap natural gas, is currently a much lower cost supply for hydrogen than reformers. Also, reformers produce a certain amount of light hydrocarbons, such as methane and ethane which have a much lower value than if those hydrocarbons stayed in gasoline. These light hydrocarbons cannot be blended into the gasoline pool and are therefore burned as fuel gas in refinery heaters in lieu of natural gas. Both of these losses were much less of an issue when natural gas was priced at or near parity with crude oil, but in recent years, natural gas has been priced much lower. These economic issues which are now discouraging reforming join an issue which has always discouraged reforming, and that is its yield loss. Part of this yield loss is the conversion to light hydrocarbons mentioned above, but the other part of the yield loss occurs when reformers convert branched and cyclic hydrocarbons to aromatics which have a higher density and thus lower volume. Decreased volume is a cost to refiners because their input cost increases for the same volume of gasoline output.

While reforming has become more expensive, the cost of producing other high octane blendstocks have decreased making them more cost-competitive with reforming. The first high octane blendstock which has been priced lower than reformate is ethanol. When the first RFS program was phasing in, increasing crude oil prices provided an incentive to refiners to blend in lower priced, high octane ethanol. Thus, ethanol use was increasing faster than the RFS standards from 2006 to 2012.

The second high-octane blendstock which the marketplace is causing to replace reformate is alkylation. Alkylation reacts isobutylene with isobutane or normal butane to produce a low sulfur, high octane gasoline blendstock that can be blended into gasoline. What has made alkylation more cost-competitive for blending into gasoline is the decrease in the price for reactants, butane and isobutene. The increased use of hydraulic fracturing has increased the production of light hydrocarbons such as four carbon butane and isobutene, which has driven down their prices. As alkylate's production cost has decreased, alkylate is displacing the production of aromatics by reformers, thus lowering the content of aromatics in the gasoline pool.

Another marketplace impact on gasoline properties is caused by the lower relative price of light gasoline blendstocks. Hydraulic fracturing has increased the production of light hydrocarbons such as butane. This has created a market incentive for refiners or blenders to blend as much butane into the gasoline pool, marginally increasing the RVP of gasoline.

The marketplace has likely impacted other gasoline properties, but such changes are perhaps offset by other changes, masked or constrained by the changes described above, or simply not large enough to be seen in the data. For example, because of the long term trend for increasing sulfur in crude oil, one could expect gasoline sulfur levels to increase over time as well. However, our Tier 2 and Tier 3 gasoline sulfur standards have limited gasoline sulfur to much lower levels, thus, the increasing content of sulfur in crude oil is not be observed in our gasoline data.

Chapter 6. Summary of Gasoline Property and Volume Data

This section presents data on trends in gasoline properties and volume, and discusses how the various fuels regulations shaped the fuel properties. The first section contains an overview of the trend in fuel properties and discusses how the fuel programs shaped those properties. The second section shows the trend in gasoline volume. The third section provides a series of figures which further illustrates fuel property trends by parsing the data in a variety of ways. This third section also compares the batch data to RFG and Alliance survey data. Finally, this section presents the results of various analyses of the data investigating potential causes of differences in fuel properties (e.g., refinery size or configuration).

A. Overall Changes in Gasoline Properties

Table 4 and Table 5 summarize the U.S. gasoline properties for 1990, 2000 and 2016 for summer and winter, respectively. The reason for choosing 1990 is to show the gasoline properties before the RFG program was implemented. The year 2000 was chosen to show how the RFG program affected gasoline properties and resulted in different gasoline properties between RFG and CG areas. Finally, the 2016 gasoline properties are chosen because they are the most recent gasoline properties available with the batch reports, and it shows how the subsequent fuel programs, after the RFG program, have affected gasoline properties and reduced the gasoline property differences between CG and RFG. The 1990 gasoline properties are not from batch data since there were no requirements to test and report the properties of gasoline batches to EPA until 1995.[29] Instead, the 1990 gasoline properties are the baseline gasoline properties established for the RFG program.[30] The year 2000 and 2016 gasoline property data are from batch data.

Table 6 summarizes the annual average gasoline properties for all U.S. gasoline for each year from 1997 to 2016.

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[29] 40CFR80.65

[30] The Clean Air Act baseline established for the RFG program by Congress was determined to underestimate the quantity of olefins in the gasoline pool. The values for summertime and wintertime gasoline olefins reported in the tables are the best estimated values for actual olefin levels in U.S. gasoline in 1990 as estimated for the RFG rulemaking documents.

	1990	2000		2016 RFG		2016 CG	
Property	**Baseline**	**RFG Average**	**CG Average**	**Average**	**95%**	**Average**	**95%**
Sulfur (ppm)	339	126	324	23.1	48.2	22.5	51.0
Benzene (vol%)	1.53	0.59	1.15	0.51	0.86	0.63	1.27
RVP (psi)	8.7	6.78	8.27	7.1	7.47	9.08	10.0
Aromatics (vol%)	32	19.3	28.5	17.12	27.3	21.76	32.1
E200 (vol%)	41	47.6	45.2	47.9	54.8	53.0	61.4
E300 (vol%)	83	84.7	80.7	85.6	92.0	84.8	91.1
Olefins (vol%)	13.1	10.6	11.8	10.5	18.7	8.38	16.4
Ethanol (vol%)	0.6	1.14	0.84	9.61	9.97	9.28	9.8

Table 4 Summary of Summertime Gasoline Properties (ethanol adjusted)

	1990	2000		2016 RFG		2016 CG	
Property	**Baseline**	**RFG Average**	**CG Average**	**Average**	**95%**	**Average**	**95%**
Sulfur (ppm)	339	200	293	24.4	48	23.0	55.0
Benzene (vol%)	1.64	0.65	1.08	0.51	0.84	0.58	1.13
RVP (psi)	11.5	12.1	12.1	13.1	14.9	12.6	15.0
Aromatics (vol%)	26.4	19	24.8	16.4	25.1	18.8	28.7
E200 (vol%)	50	56.3	50.4	58.1	62.5	56.2	62.8
E300 (vol%)	83	86.1	83.4	87.0	92.7	86.6	93.0
Olefins (vol%)	11.9	11.8	12	9.16	18.8	8.12	17.0
Ethanol (vol%)	0.6	1.22	1.19	9.7	10.1	9.28	9.8

Table 5 Summary of Wintertime Gasoline Properties (ethanol adjusted)

Year	Volume	Oxygen	API Gravity	Ethanol	MTBE	TAME	Sulfur	Aromatics	Olefins	Benzene	RVP	E200	E300	T50	T90
	Million Gallons	Wt%		Vol%	Vol%	Vol%	ppm	Vol%	Vol%	Vol%	Psi	Vol%	Vol%	F	F
1997	107,220	0.72	60.0	0.31	2.89	0.22	312.6	24.7	12.2	1.01	10.34	49.3	82.5	201.5	331.4
1998	112,950	1.05	60.0	0.80	3.65	0.36	272.7	24.8	11.2	1.00	10.35	49.0	82.6	202.0	329.5
1999	114,776	1.08	60.0	0.97	3.45	0.29	283.8	24.8	11.5	1.00	10.33	49.1	82.6	201.9	330.2
2000	115,574	1.07	60.0	1.07	3.27	0.35	270.2	24.6	11.7	0.99	10.23	49.2	83.0	201.7	327.8
2001	117,153	1.07	59.6	1.05	3.36	0.37	264.1	24.9	12.5	1.02	10.17	48.9	83.0	203.5	327.9
2002	120,802	1.08	59.8	1.14	3.27	0.39	259.4	24.7	11.7	0.97	10.16	48.9	82.8	203.5	329.1
2003	121,617	1.17	59.4	1.33	3.43	0.30	243.8	24.7	11.6	1.00	10.20	49.0	82.6	202.8	330.6
2004	122,166	1.39	60.1	2.02	3.35	0.24	112.0	24.5	11.3	0.98	10.21	49.3	82.7	202.3	330.0
2005	119,666	1.38	60.3	2.23	2.89	0.23	94.8	24.5	11.7	1.04	10.18	49.7	83.4	201.2	326.9
2006	123,178	1.19	60.1	2.91	0.64	<0.01	49.2	24.7	11.1	1.04	10.15	49.1	83.7	-	-
2007	122,403	1.27	60.2	3.44	0.02	<0.01	39.9	24.4	11.2	1.04	10.20	49.6	83.8	-	-
2008	114,032	2.02	60.8	5.54	<0.01	<0.01	34.2	22.5	10.5	1.02	10.33	52.0	85.8	-	-
2009	115,404	2.62	60.3	7.20	<0.01	<0.01	33.3	22.0	10.3	0.97	10.47	52.7	84.8	-	-
2010	116,286	3.13	60.4	8.65	<0.01	<0.01	32.4	21.2	10.0	0.89	10.54	53.8	85.3	-	-
2011	121,131	3.13	60.7	8.72	<0.01	<0.01	30.0	20.2	9.8	0.70	10.64	54.7	86.0	-	-
2012	119,696	3.24	61.0	9.01	<0.01	<0.01	29.4	19.6	9.6	0.63	10.73	55.2	86.3	-	-
2013	119,689	3.33	61.3	9.21	<0.01	<0.01	27.2	19.1	9.5	0.59	10.82	55.7	86.9	-	-
2014	123,005	3.34	61.4	9.23	<0.01	<0.01	25.3	18.8	9.3	0.59	10.95	55.6	87.0	-	-
2015	125,386	3.43	-	9.38	<0.01	<0.01	23.4	19.0	9.0	0.58	10.83	55.0	86.6	-	-
2016	125,000	3.48	-	9.57	<0.01	<0.01	23.1	19.3	8.6	0.58	10.60	54.4	85.9	-	-

Table 6 Summary of Annual Average Gasoline Properties Between 1997 and 2016

RFG

Comparing the gasoline properties for year 2000 with those of the year 1990 in Table 4 and Table 5 reveals the impact that the RFG program had on gasoline properties. The RFG NOx standard lowered summertime RFG's sulfur from 339 ppm sulfur down to 126 ppm sulfur. While the RFG NOx standard only applied during the summertime, there was some reduction in wintertime RFG sulfur levels as well. The RFG toxics standard and the associated 1.0 volume percent benzene standard lowered RFG benzene levels to around 0.6 from about 1.6 volume percent, and along with the 2.0 weight percent oxygen standard, lowered aromatics from 26 to 30 volume percent to 19 volume percent. Finally, the RFG hydrocarbon standard lowered the RVP of RFG to about 7 psi.

Tier 2 and Tier 3

Comparing the gasoline properties in Table 4 and Table 5 for the year 2016 with those of the year 2000 reveals the effects that Tier 2 and Tier 3 have had on gasoline properties. The Tier 2 gasoline sulfur program reduced gasoline sulfur levels from the 130 to 300 ppm range down to around 30 ppm. Then the Tier 3 gasoline sulfur program further reduced gasoline sulfur levels to the 22 to 24 ppm range in 2016 due to the effect of the early credit generation program. Once the Tier 3 gasoline sulfur program is phased in, gasoline sulfur levels will be about 97 percent lower than in 1990. While olefins are not directly targeted by Tier 2 and Tier 3, the act of desulfurizing the highest sulfur gasoline blendstocks also reduces the olefin in that stream which has led to a reduction in olefins from a range of 12 – 13 percent down to a range of 8 to 11 percent. Table 6 shows how gasoline sulfur levels changed year-by-year. Over the years from 2000 to 2003, the credit generation program of the Tier 2 gasoline sulfur program caused a modest decrease in gasoline sulfur levels. When the Tier 2 program phased-in over 2004 to 2006, there was a dramatic reduction in gasoline sulfur levels. There were some further modest reductions in gasoline sulfur levels from 2007 to 2011 as the refineries in the Geographic Phase-In Areas (GPA) and small refiners needed to comply with the Tier 2 gasoline sulfur program. Then starting in 2014, gasoline sulfur levels began to decrease further as refiners generated credits for compliance under the Tier 3 sulfur program. The reduction in olefins which is a byproduct of the Tier 2 and Tier 3 sulfur control programs can be seen in the year-by-year olefin data, although the coincident addition of ethanol also played a role.

MSAT2

Comparing the gasoline benzene levels for year 2016 with those for the year 2000 in Table 4 and Table 5 shows how benzene levels decreased in conventional gasoline due to the MSAT2 program. Conventional gasoline benzene levels decreased from over 1 percent to around 0.6 percent. Also, reformulated gasoline benzene levels decreased by over 0.1 percent, likely because RFG refineries opted to further reduce their RFG benzene levels to generate credits for selling to refineries which produce CG. The phase-in of the 0.62 volume percent MSAT2 benzene standard can be observed by the data in Table 6. After the MSAT2 benzene reductions, benzene levels are about 60 percent lower than in 1990. Under the MSAT2 program, refiners could generate early credits starting in 2007 prior to the program start in 2011. While there was a very small reduction in gasoline benzene levels in 2009, refiners clearly relied on 2010 to generate early credits prior to the program's start. The use of early credits in 2011 and 2012 can be seen as gasoline benzene levels stepped down from 2011 to 2012 and again from 2012 to 2013. Because benzene is one of the aromatic compounds which factor in the quantity of total aromatics, the MSAT2 standard also played a role in the decline in total aromatics.

RFS2

The increase in ethanol due to the RFS program can be seen in Tables 4, 5, and 6. The marketplace, and not RFS2 standards, may have been the primary driving force for much of the ethanol which was blended into the gasoline pool when crude oil was priced over $100 per barrel. The RFS2 program forced ethanol into gasoline markets where it is marginally more expensive, particularly when gasoline neared and exceeded 100 percent E10, and helped prevent any backsliding in ethanol use when crude oil prices started their decline in 2014. The addition of ethanol causes an array of changes in gasoline properties, and perhaps the most important is the reduction in aromatics. As high octane ethanol increased in the gasoline pool, it replaced high octane reformate, which is a major source of aromatics in the gasoline pool.

E200 and E300 are also affected by the addition of ethanol. Ethanol boils below 200 Fahrenheit, and also causes some of the hydrocarbons in gasoline which boil above 200 Fahrenheit to boil below 200 Fahrenheit. Ethanol likely contributed to increased E300 values between 2000 and 2016 as well. However, as discussed above, the modest dieselization trend here in the United States also may have contributed to increased E300 over this time period.

Ethanol also has other modest effects in gasoline properties. Ethanol dilutes olefins causing a reduction in that gasoline property. Because refiners comply with the Tier 2 sulfur and MSAT2 benzene standards at the refinery gate, and most ethanol is blended into conventional gasoline downstream of the refinery, the downstream blending of ethanol is likely one important reason why gasoline sulfur and benzene levels at retail are slightly lower than the standards.

B. Gasoline Volume Data

In addition to the gasoline property data, refiners report the volume of each batch of gasoline produced and imported into the United States. This volume is aggregated and summarized here.

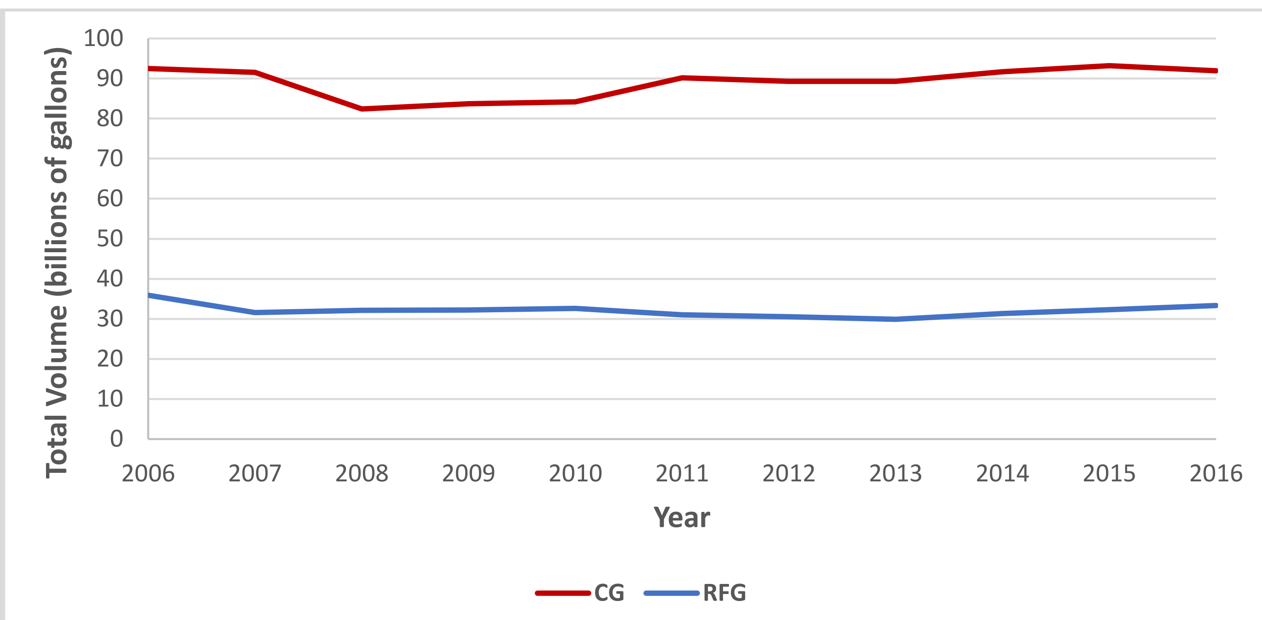

Figure 5 Annual Volume of Gasoline Produced (includes ethanol)

Figure 5 shows that total gasoline production and imports (thus, supply which corresponds to gasoline demand) decreased after the recession which began in 2008. Gasoline supply increased in 2011, dipped slightly in 2012 and increased slightly through 2015. With the improving U.S. economy and much lower crude oil prices in 2015, one might expect that gasoline demand would have spiked in 2015, and clearly it did not. It could be that the phase-in of EPA's motor vehicle greenhouse emission standards, which started in 2011, and which has effectively improved the fuel efficiency of newly sold vehicles, offset the effect of additional motor vehicle use on gasoline consumption due to the more favorable economic conditions. Figure 6 shows the gasoline production by regular and premium gasoline grades.

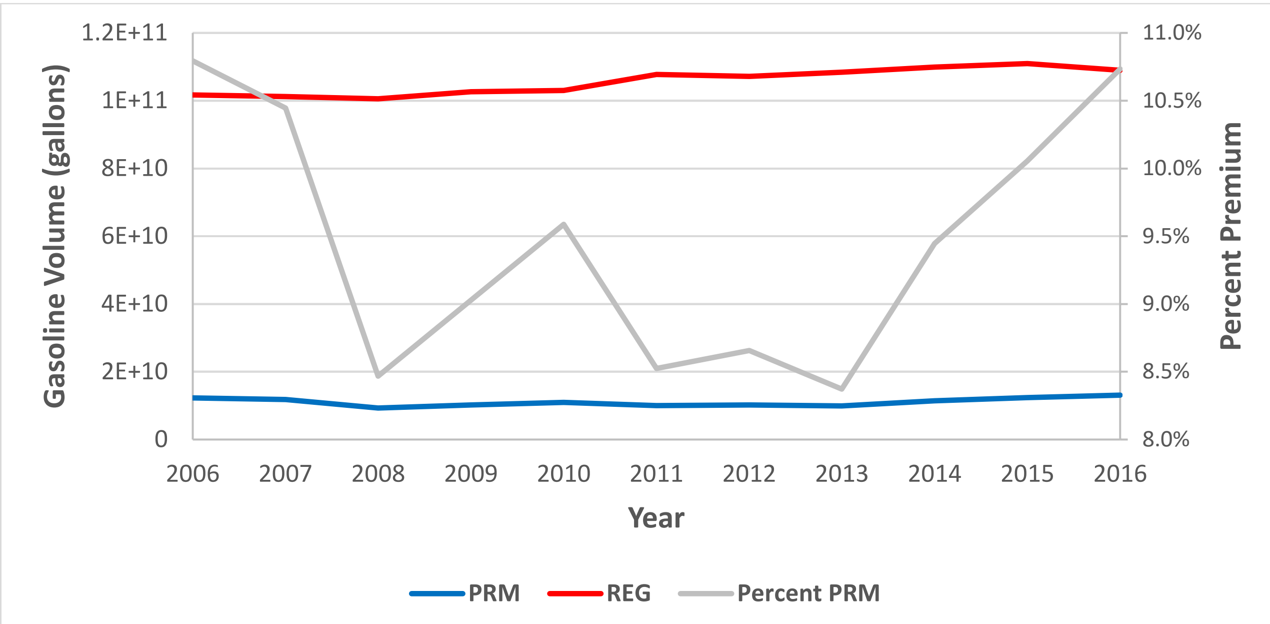

Figure 6 Batch Volume by Grade

Figure 6 shows that premium gasoline demand fell from over 10.5 percent to about 8.5 percent of total gasoline demand as the price of crude oil increased in 2007 and 2008, and as the great recession eroded purchasing power. Premium demand stayed low, aside from a spike up in 2010, until after 2013 when premium gasoline demand started to increase again. The decrease in crude oil prices which started in 2014 and continued further in 2015 is the likely a significant reason for the recent rise in premium demand, though not all of the premium produced may be sold at retail as premium as it is increasingly blended downstream to make other fuel grades as well.

Figure 7 summarizes the volume of conventional gasoline produce by refineries which only produce conventional gasoline versus those refineries which produce both conventional and reformulated gasoline. Figure 7 also summarizes the total conventional gasoline supplied, which includes the imported batches of conventional gasoline.

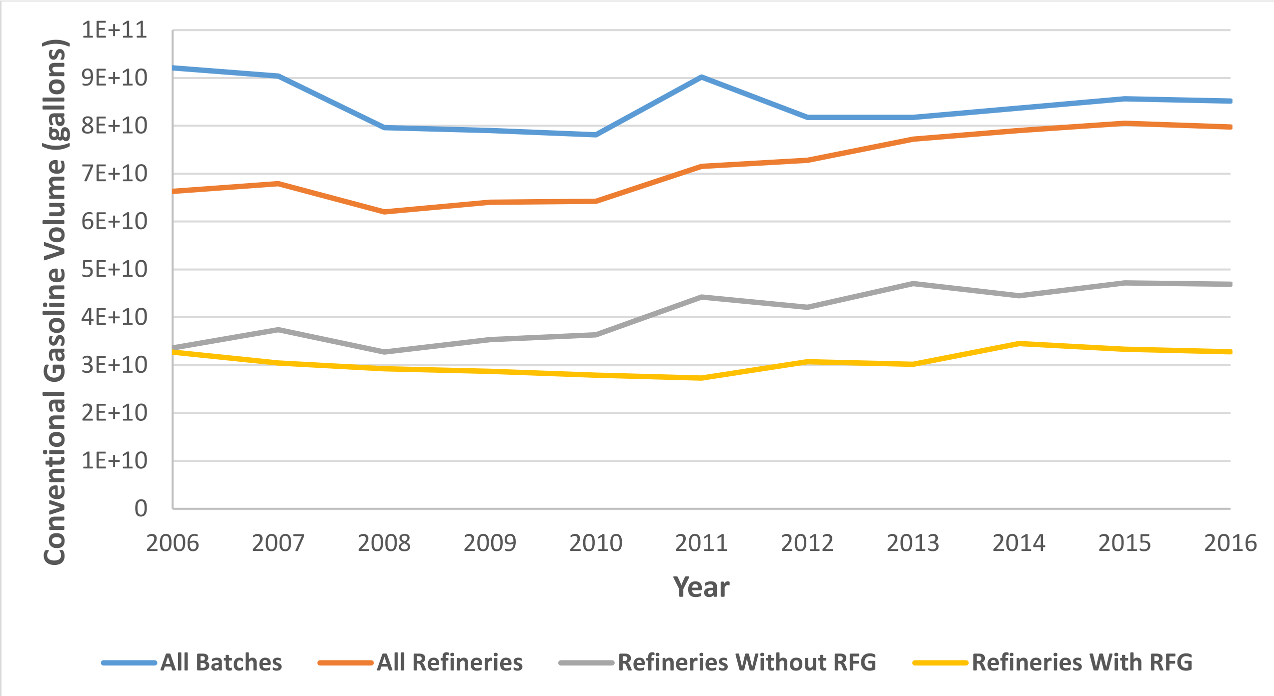

Figure 7 Total Volume Conventional Gasoline Produced by Refinery Type

Figure 7 shows how the supply of conventional gasoline changed over this 11-year period. After the great recession began in 2008, conventional gasoline demand dropped off, stabilized at a lower level for a few years, and began to come back starting in 2011. The dwindling volumetric difference between the "All Batches" volume and the "All Refineries" volume shows that imported gasoline volume decreased from 2006 to 2015. Figure 7 also shows that a greater portion of the conventional gasoline pool was being produced by refineries which only produced conventional gasoline. This last fact was more important early on because, as Figure 9 below shows, refineries which produced CG in addition to RFG tended to produce a lower sulfur CG than those refineries which produced only CG.

Figure 8 shows the percent ethanol in the reformulated and conventional gasoline pools, and it also shows the reported percentage of CBOB and refinery-blended conventional E10 gasoline of the conventional gasoline pool. The volume of ethanol blended into the conventional gasoline pool is estimated by subtracting the quantity of ethanol blended into the RFG pool (calculated from the batch report data) from the total volume of ethanol EIA reports is blended into the U.S. gasoline pool.

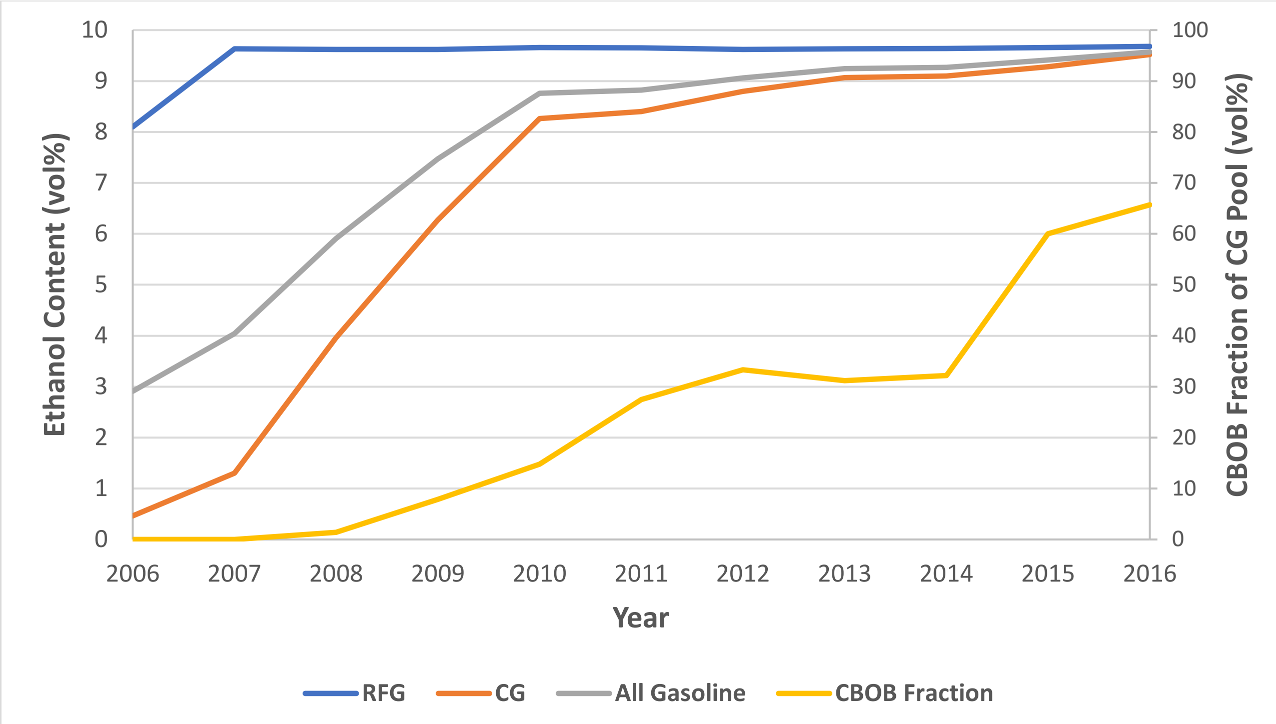

Figure 8 Ethanol Content of Reformulated and Conventional Gasolines

Figure 8 shows that over 80 percent of reformulated gasoline was E10 in 2006, and almost all RFG was E10 in 2007 and thereafter. Less than 10 percent of the conventional gasoline pool was E10 in 2006 and increased steadily to over 80 percent in 2010. From 2010 to 2016, the ethanol in the CG pool increased further to about 97 percent E10 in 2016. Perhaps the most surprising information in Figure 8 is that despite that the conventional gasoline pool contains nearly 100 percent ethanol in 2015 and 2016, about 30 percent of the conventional gasoline is reported as E0, meaning that it is not reported as a CBOB and is not reported as being blended with ethanol at the refinery. Some of this may be actual E0 which is not just produced as E0 but sold as E0 at retail. However, we believe that most all of this is sold as E10 at the refinery rack, but not reported as E10 because the refinery uses in-line blending to blend in the ethanol downstream of the refinery terminal tank and thus, there is no opportunity to retest the gasoline batch after if leaves the refinery terminal. We believe that the refinery does not report this as a CBOB because it is not resold as a CBOB.

C. Gasoline Property Figures

This section contains dozens of figures depicting U.S. gasoline properties from 2006 to 2016. The figures parse the data in different ways, comparing summer gasoline versus winter gasoline, RFG versus conventional and premium grade versus regular grade. The figures also show batch-by-batch summaries of the gasoline properties with the batches sorted from lowest values to highest values, as well as box and whisker diagrams and histograms showing the volumetric 25% median and 75% points. Additional figures compare the gasoline properties from batch data with that from the RFG and Alliance surveys (Alliance data is shown up to 2015; 2016 data was not available yet). RFG survey data is also presented city-by-city, except for those cities in PADD 2 which are aggregated together to avoid the potential risk of revealing gasoline property data from a specific refinery, which is considered confidential business information. Additional figures plot refinery-specific average gasoline properties. One set of refinery-specific figures show minimum and maximum gasoline batch gasoline property levels for individual refineries and another set of similar figures for groups of five refineries together based on volume and shows the min and max values along with the average based on gasoline production volume. Another group of refinery-specific figures plots refinery average properties against each refinery's crude oil sulfur and API gravity (only shown for 2011 which is the only year for which we have crude oil data), and against each refinery's complexity index. Finally, average gasoline properties are tabulated and shown separately for refineries with and without specific refinery units to evaluate whether specific refinery units affect gasoline properties – the refinery units included in this analysis are: alkylation, aromatics extraction, coker, fluidized catalytic cracker (FCC), hydrocracker, isomerization, gasoline desulfurization, heavy gas or vacuum gas oil desulfurization, residual fuel desulfurization, and the reformer.

A general set of observations can be made after reviewing these figures.

- Two of the conclusions made above are reinforced:
    - Sulfur, benzene, olefins and aromatics have decreased over time, and E200 and E300 have increased.
    - The gasoline property differences between RFG and CG created by the RFG program have significantly diminished.
- Premium gasoline is typically lower in sulfur, benzene, olefins, RVP and E200, but higher in aromatics and E300, than regular grade gasoline.
- The PADD-average differences in sulfur and benzene have decreased significantly, while the other properties have experienced only modest changes.
- Gasoline property levels can vary widely from batch-to-batch,
    - Establishing an average gasoline property standard (i.e., sulfur, benzene) will reduce the average levels of that gasoline property, but the batch-to-batch levels still vary widely.
    - Per-gallon cap standards (RVP, 80 ppm sulfur cap) reduce the batch-to-batch variability.
- Although the RFG and the Alliance spot surveys do not comprehensively measure actual average gasoline properties, their results are typically reasonably close to the batch data and for the most part the surveys do a very good job capturing trends in the changes of gasoline properties.
    - A source of the difference between the Alliance data and the batch data is the Alliance's sampling of both regular and premium grade gasoline where offered at the subject stations (premium gasoline as high as 50% of the samples for some cities), which is not proportionate to the relative volume of retail sales of regular versus premium gasoline which is consumed (premium is about 10% of the gasoline consumed).

    - Unlike the batch data, the gasoline property retail survey data provide an indication of the gasoline properties in certain retail markets.
- Despite differences in the API gravity and sulfur content of the crude oil refined by each refinery, these crude oil qualities have no obvious correlation with the properties of the gasoline produced by U.S. refineries.
- Refinery size and complexity index have no clear correlation with any of the gasoline properties.
- Except for a few cases, the use of a specific refinery unit type is not associated with a strong correlation with gasoline properties. The exceptions are:
    - Refineries with fluidized catalytic cracker (FCC) units have higher sulfur, much higher olefins, but lower aromatics and E300.
    - Refineries with reformers have higher aromatics.
    - Refineries with alkylation units have lower aromatics and E300.
    - Refineries with aromatics extraction units have lower benzene.

Additional gasoline property-specific comments about the following figures is presented at the beginning of each gasoline property subsection.

a. Sulfur

Highlights for the following sulfur figures:

- The sulfur trends figures show the decline in gasoline sulfur levels due to Tier 2 and Tier 3
- The larger sulfur differences in previous years for summer versus winter, RFG versus CG and between PADDS are essentially gone
- Figures 19 through 26 show that, although refinery gasoline sulfur averages have shifted lower, the variance in batch sulfur levels has continued.
- Like Figure 18, Figure 21 shows how the high sulfur gasoline phased out due to the imposition of the 80 ppm cap standard and the phase-out of small refiner and hardship provisions – 95 percent of gasoline is below 50 ppm.
- Premium grade gasoline sulfur levels remain consistently below those of regular grade.
- The survey data and batch data align very well over time.
- The Alliance survey reports lower sulfur levels but this may be driven by the disproportionate sampling of premium gasoline.
- Figures 28 to 31 shows that, refinery size, complexity index, crude oil API gravity or crude oil sulfur content have no discernable impact on gasoline sulfur levels; the exception is very small refineries with no fluidized catalytic cracker unit which have inherently low sulfur levels as depicted in Figure 32.

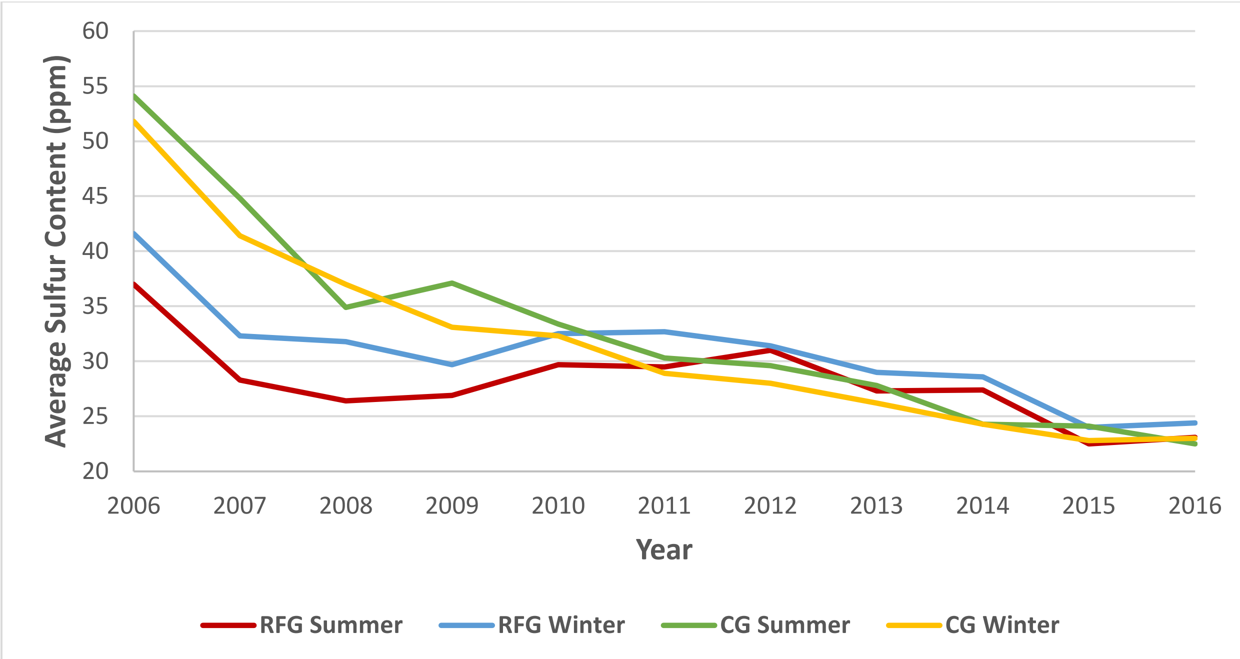

Figure 9 Sulfur Trends Summer versus Winter (ethanol-adjusted)

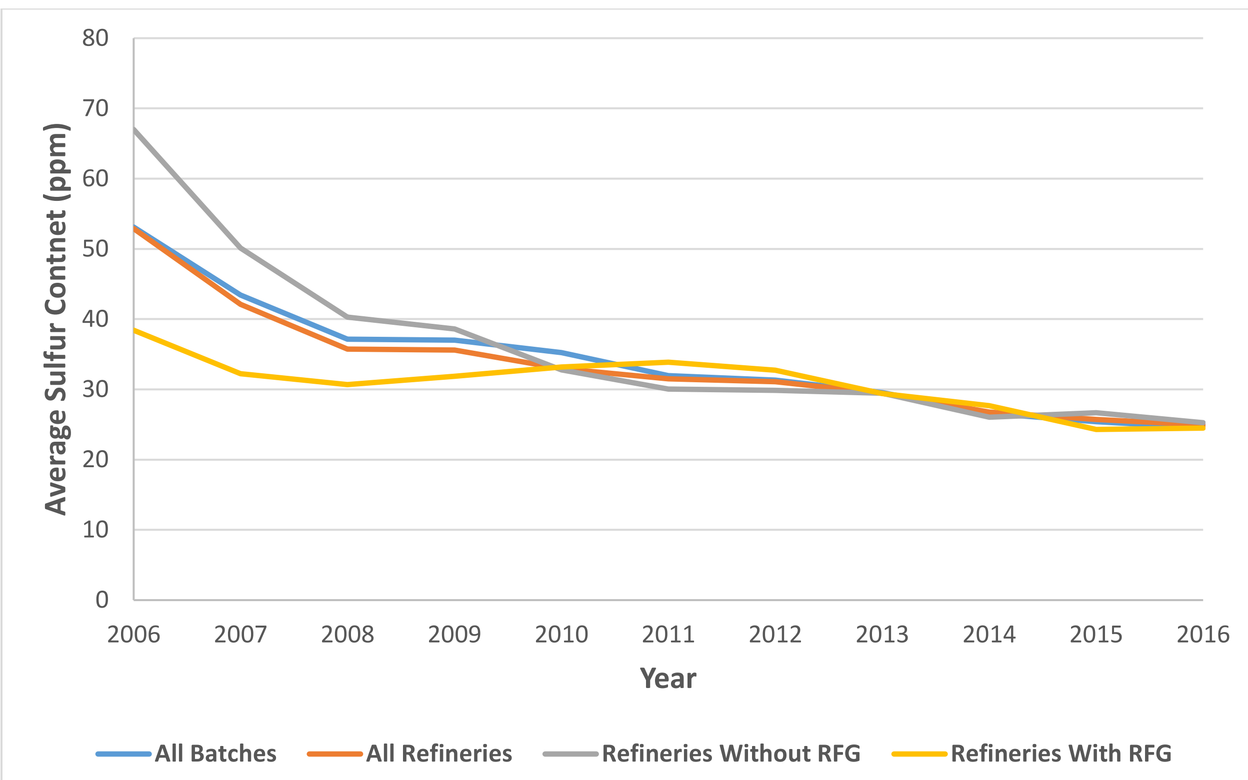

Figure 10 Average CG Sulfur Content by Refinery Type (not ethanol-adjusted)

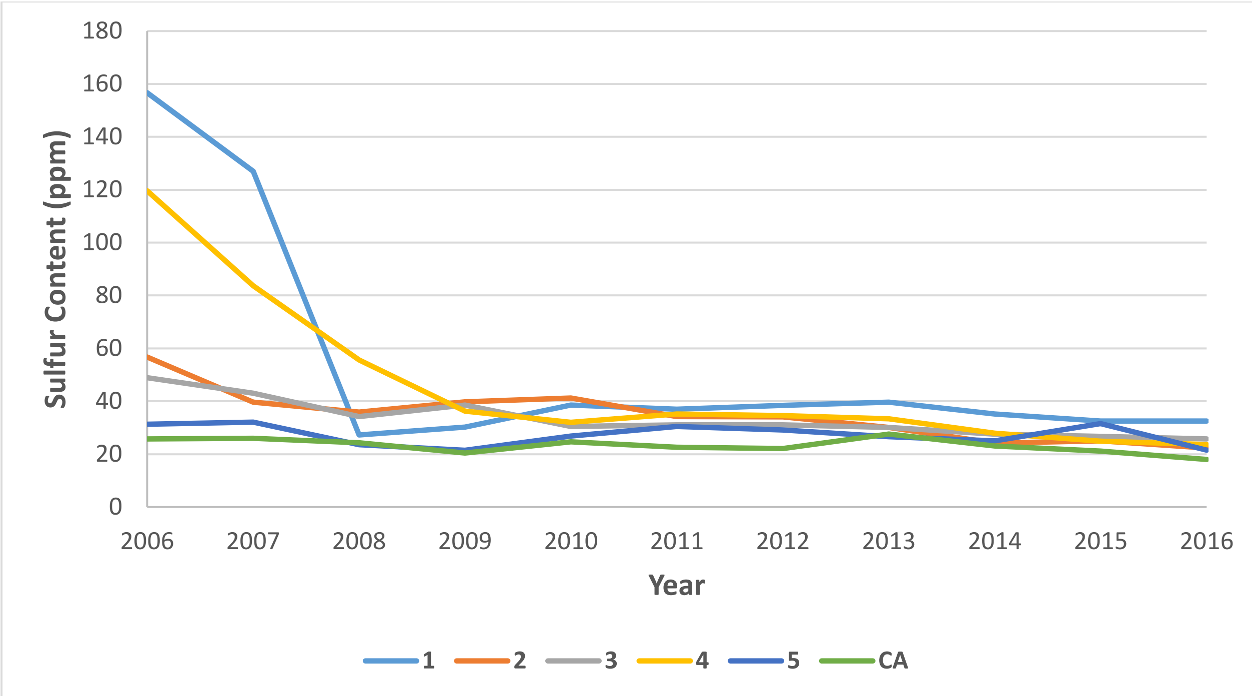

Figure 11 CG Summer Sulfur by PADD (not ethanol-adjusted)

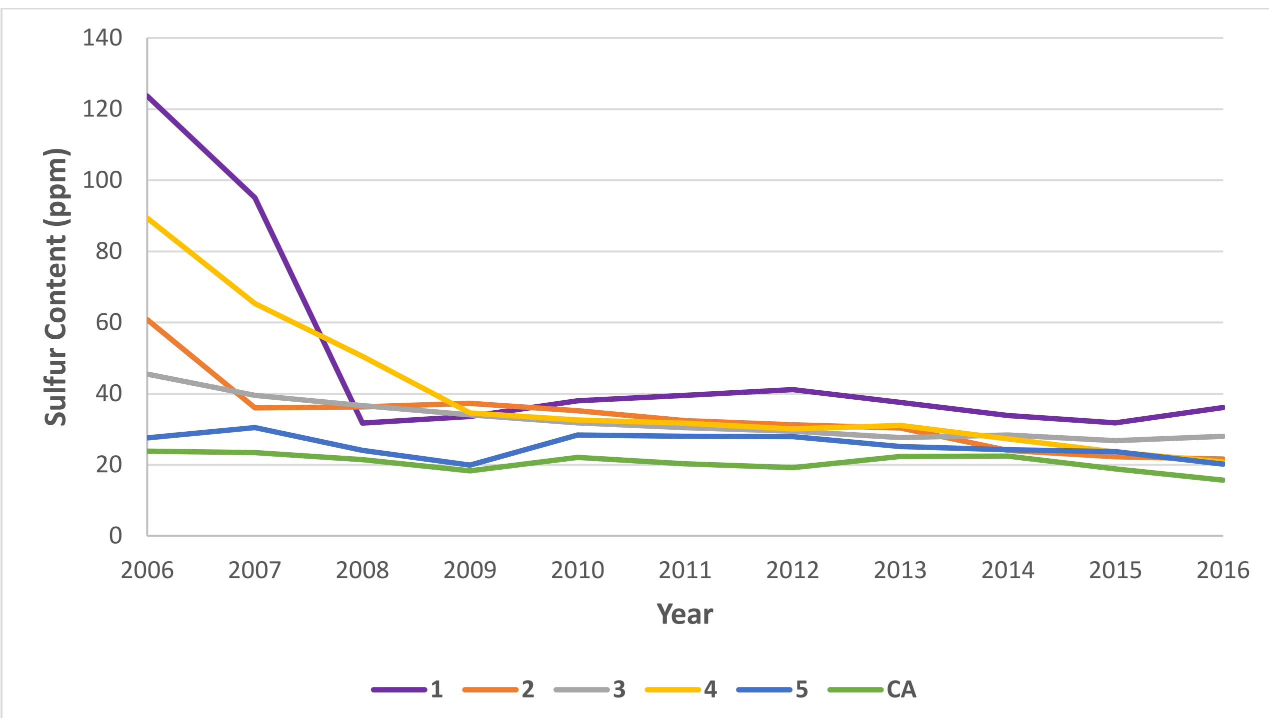

Figure 12 CG Winter Sulfur by PADD (not ethanol-adjusted)

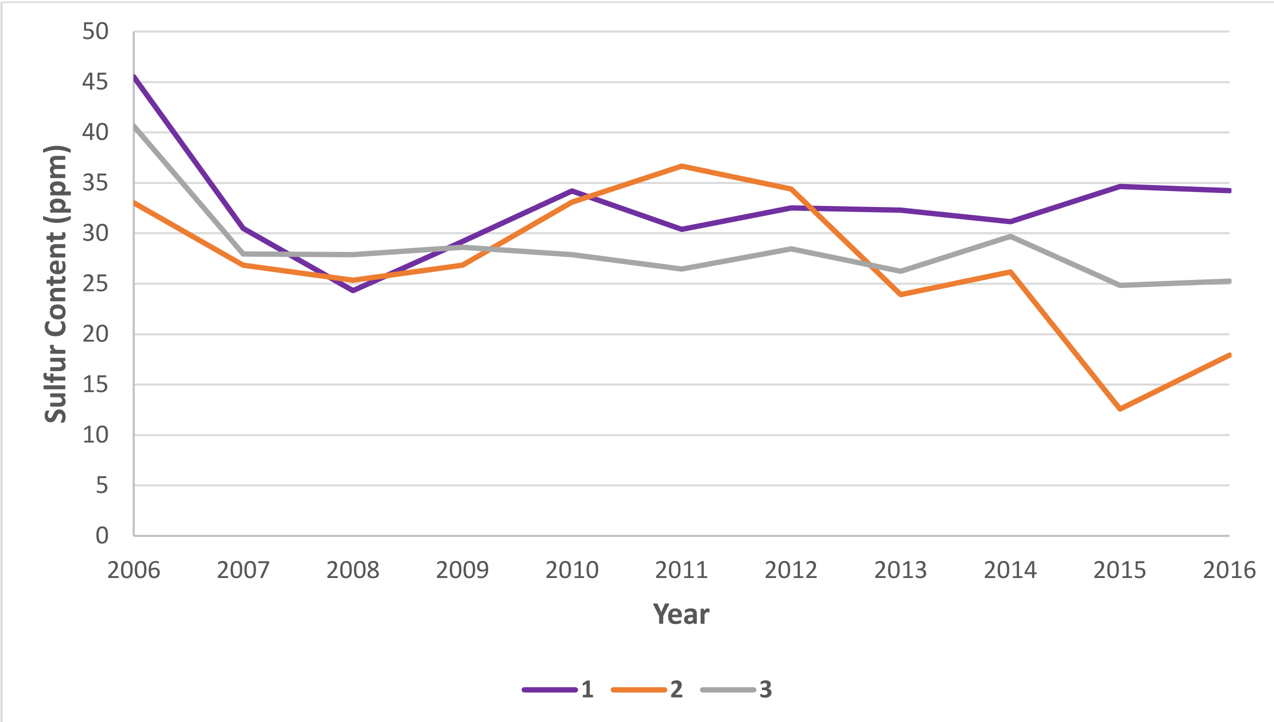

Figure 13 RFG Summer Sulfur by PADD Produced from Batch Data

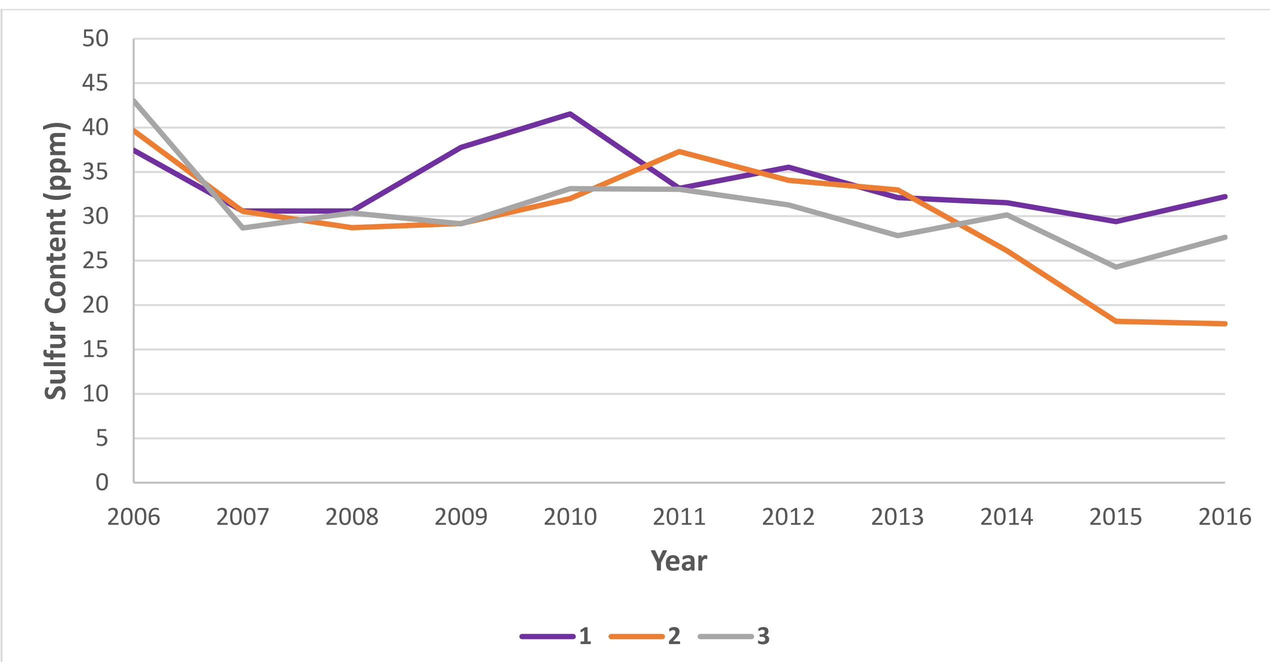

Figure 14 RFG Winter Sulfur by PADD Produced from Batch Data

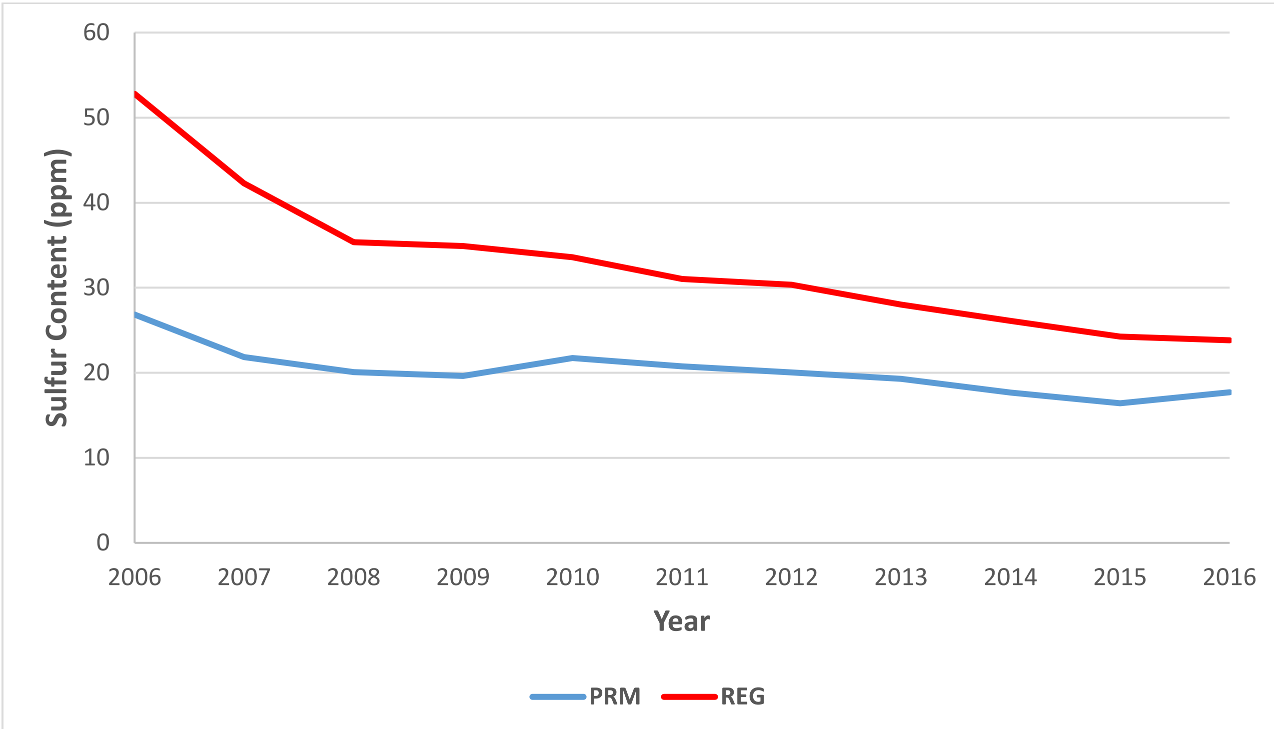

Figure 15 Regular versus Premium Sulfur in CG and RFG

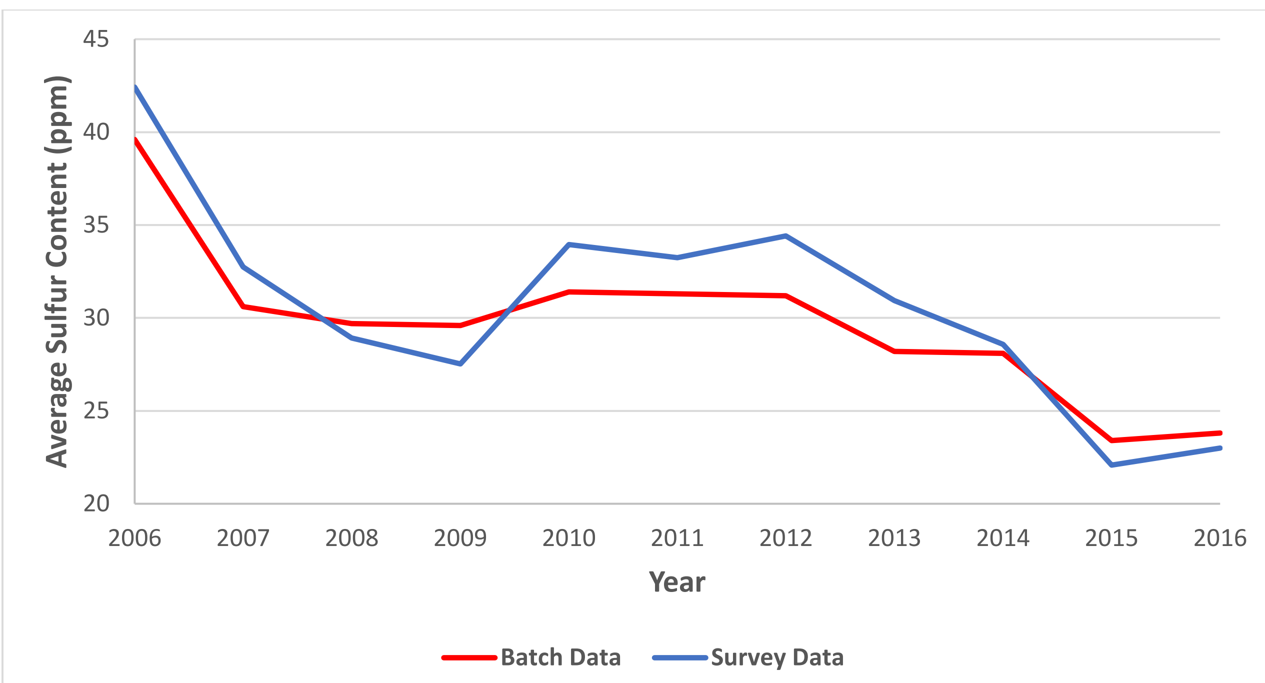

Figure 16 Sulfur RFG Batch versus Survey

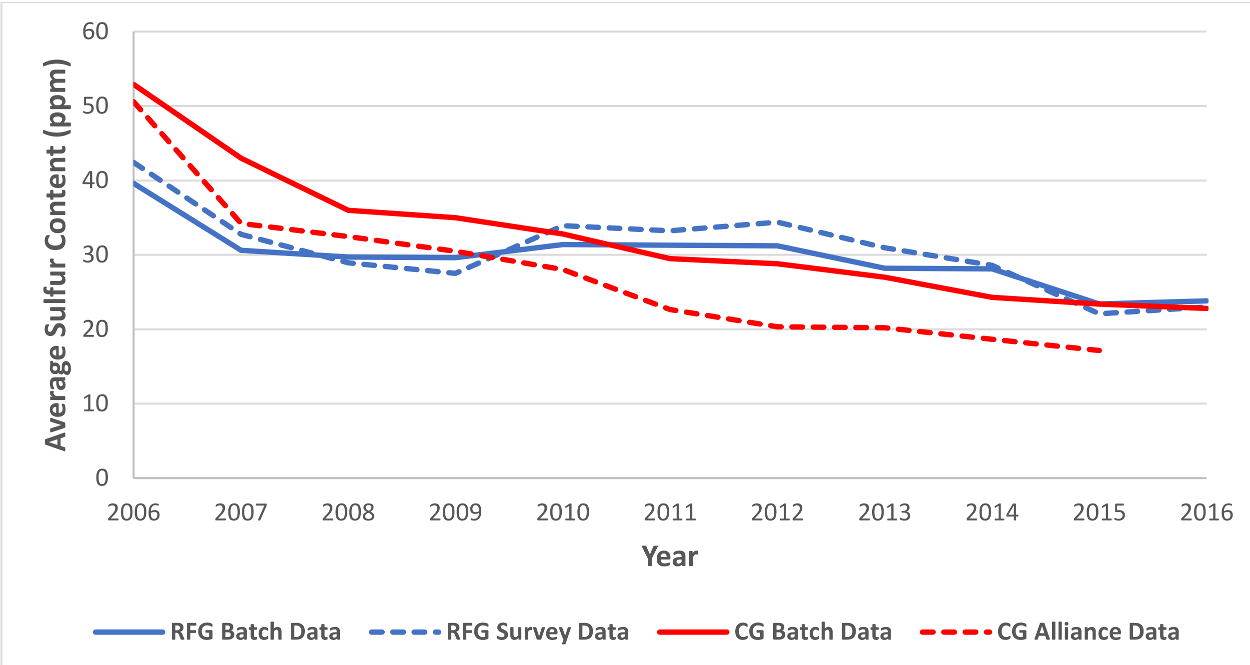

Figure 17 Comparing Batch, Survey, and Alliance data (ethanol-adjusted)

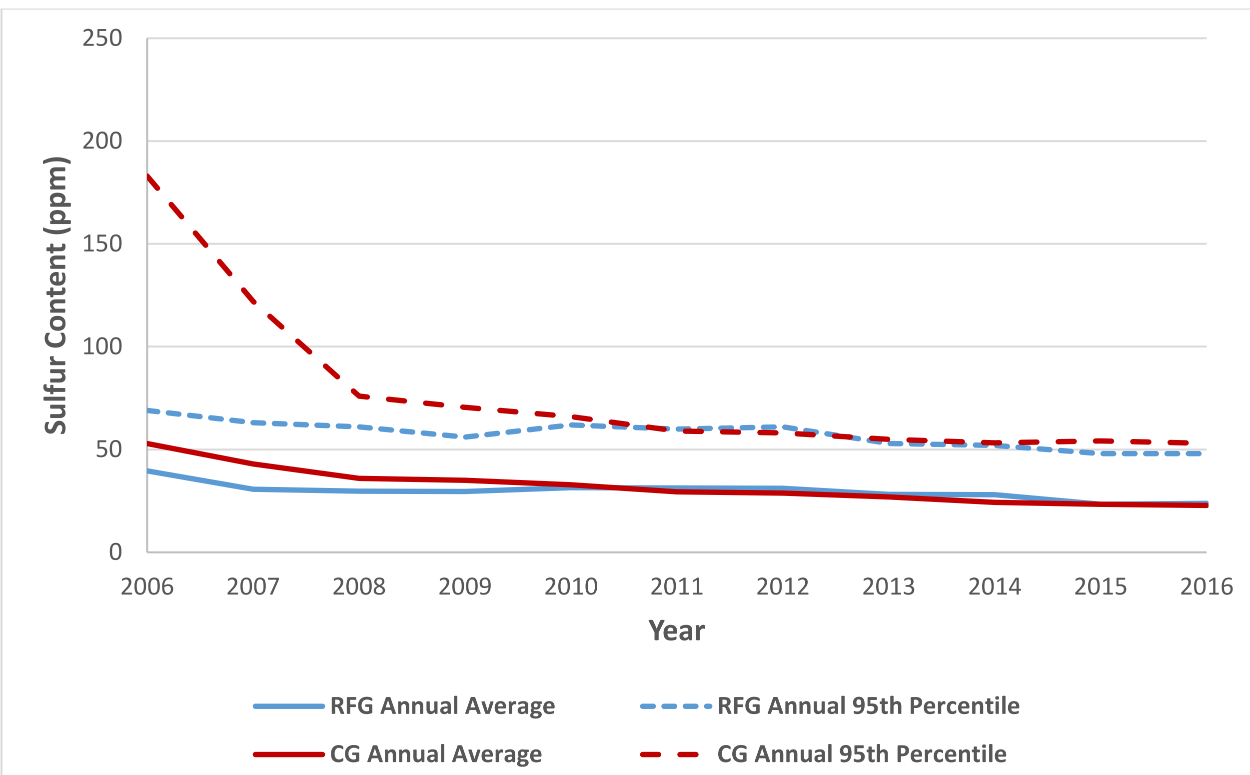

Figure 18 Sulfur Trends 95th Percentile versus Average (ethanol-adjusted)

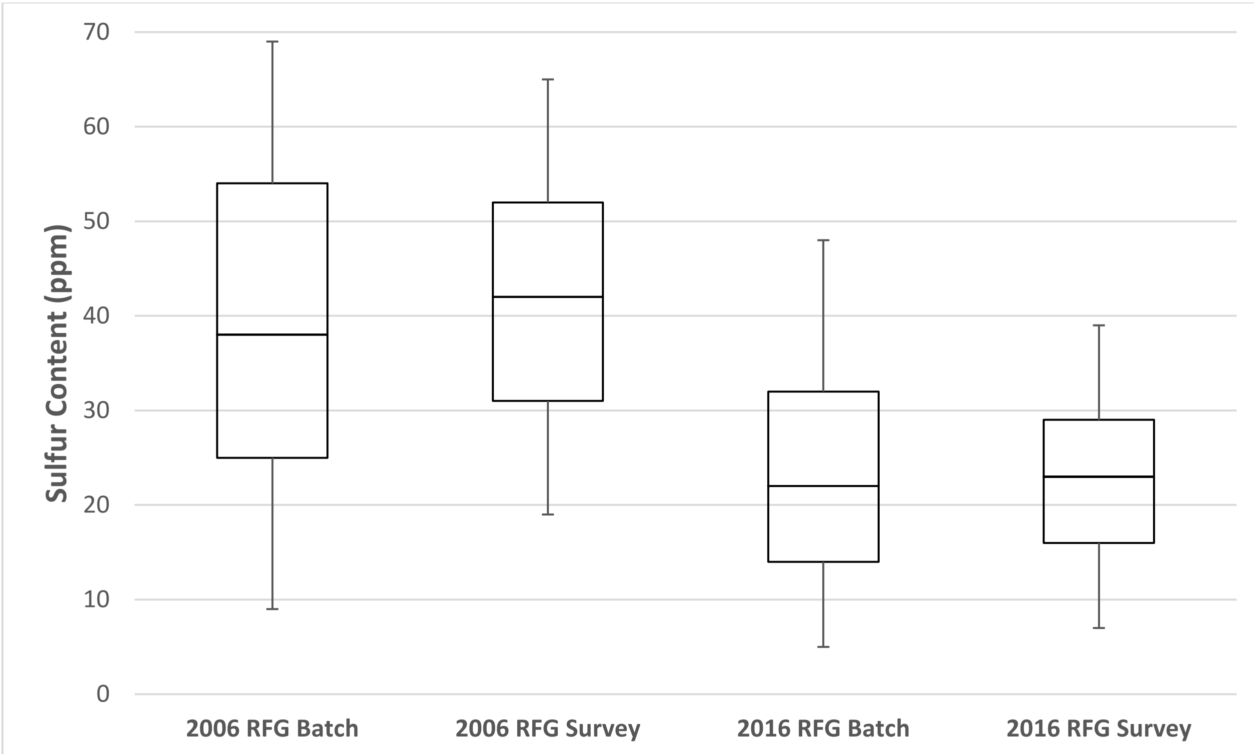

Figure 19 Sulfur RFG Box and Whiskers (5%, 25%, median, 75%, 95%)

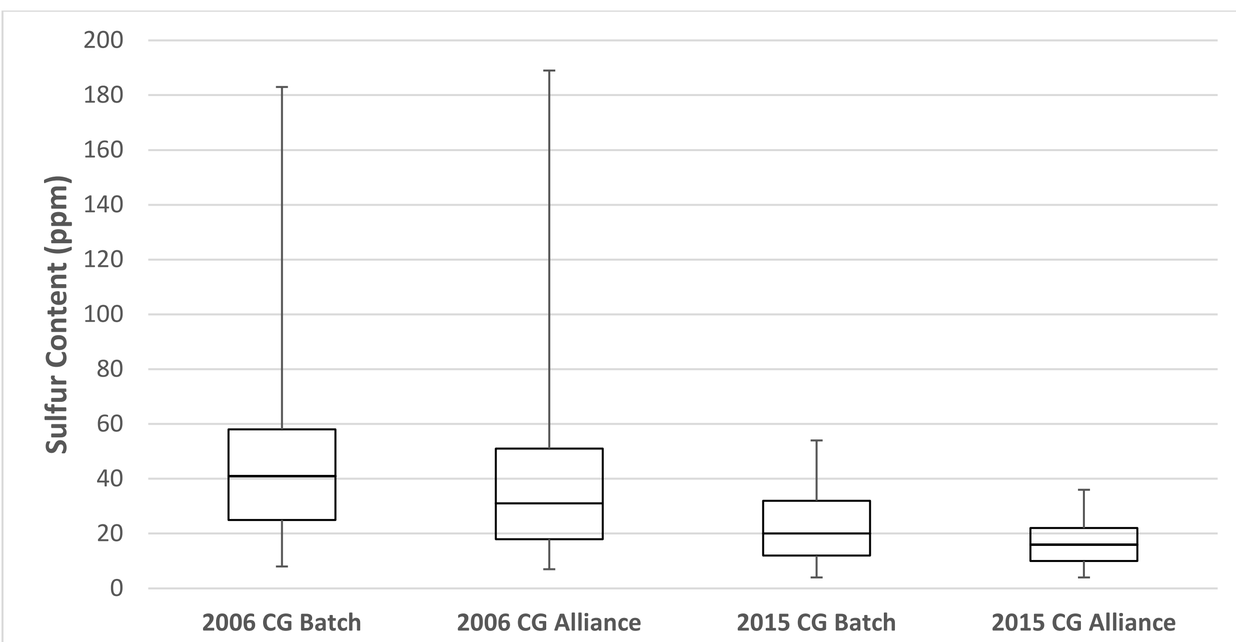

Figure 20 Sulfur CG Box and Whiskers (5%, 25%, median, 75%, 95%) (ethanol-adjusted)

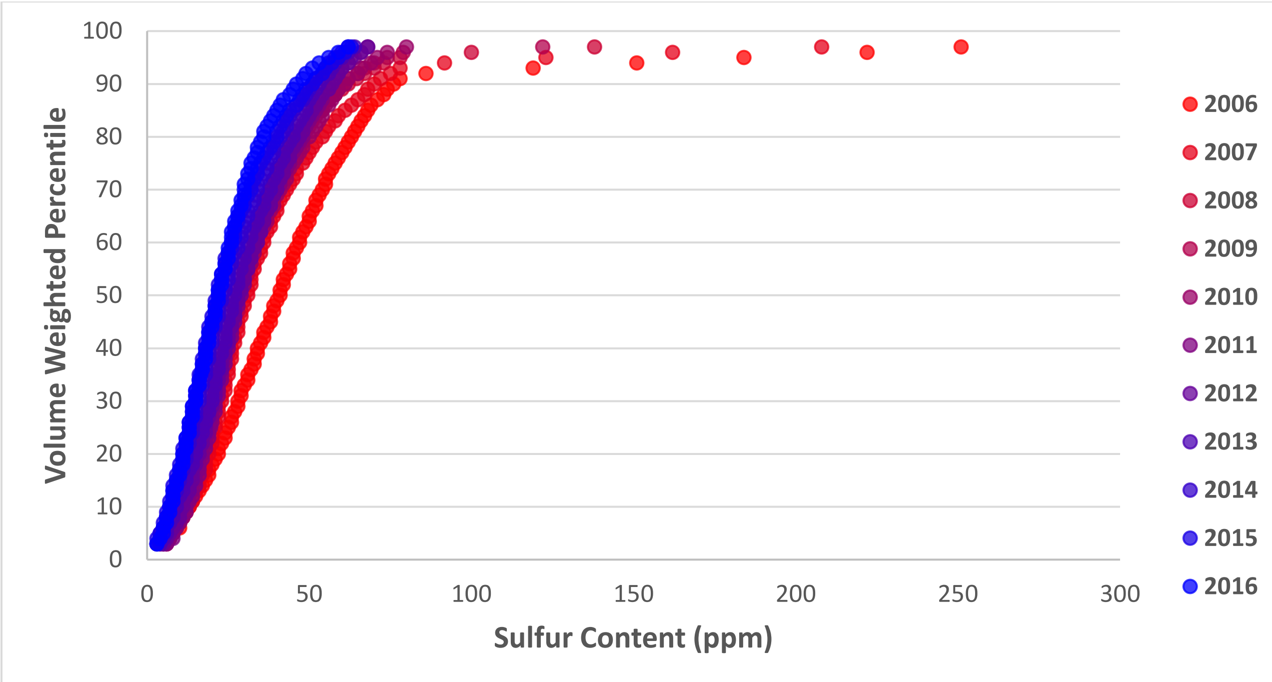

Figure 21 Sulfur Layered Percentile CG (3 to 97%) (not ethanol-adjusted)

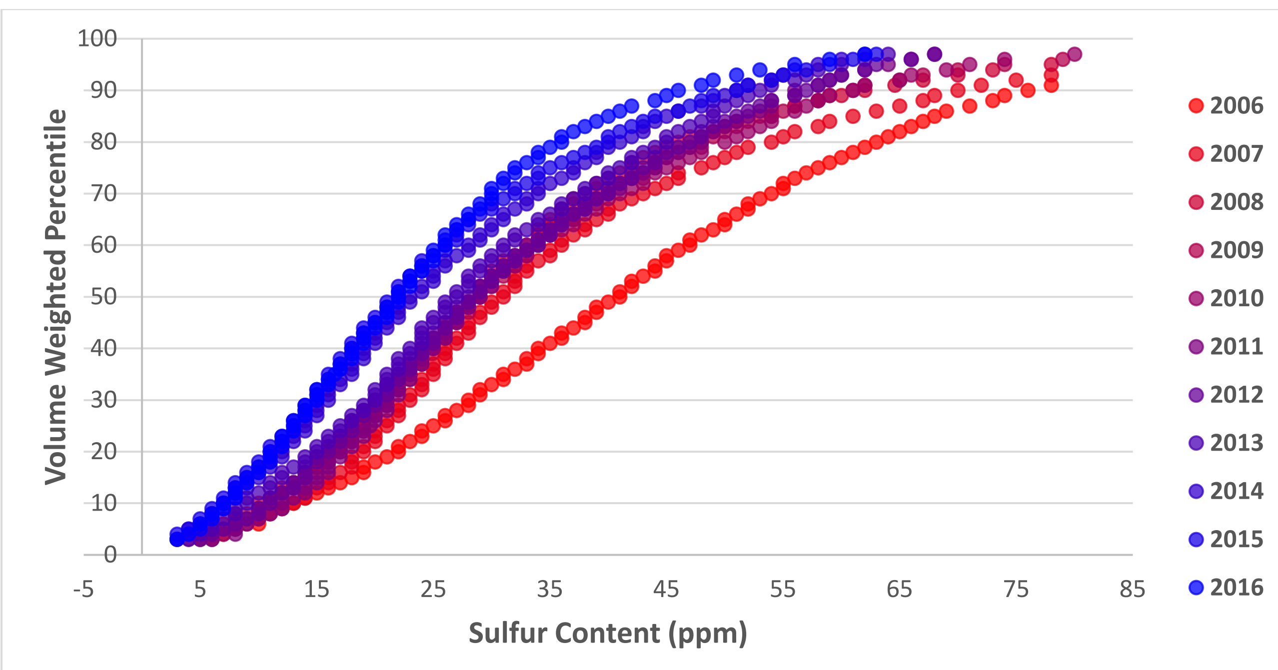

Figure 22 Sulfur Layered Percentile CG (Zoomed-In) (not ethanol-adjusted)

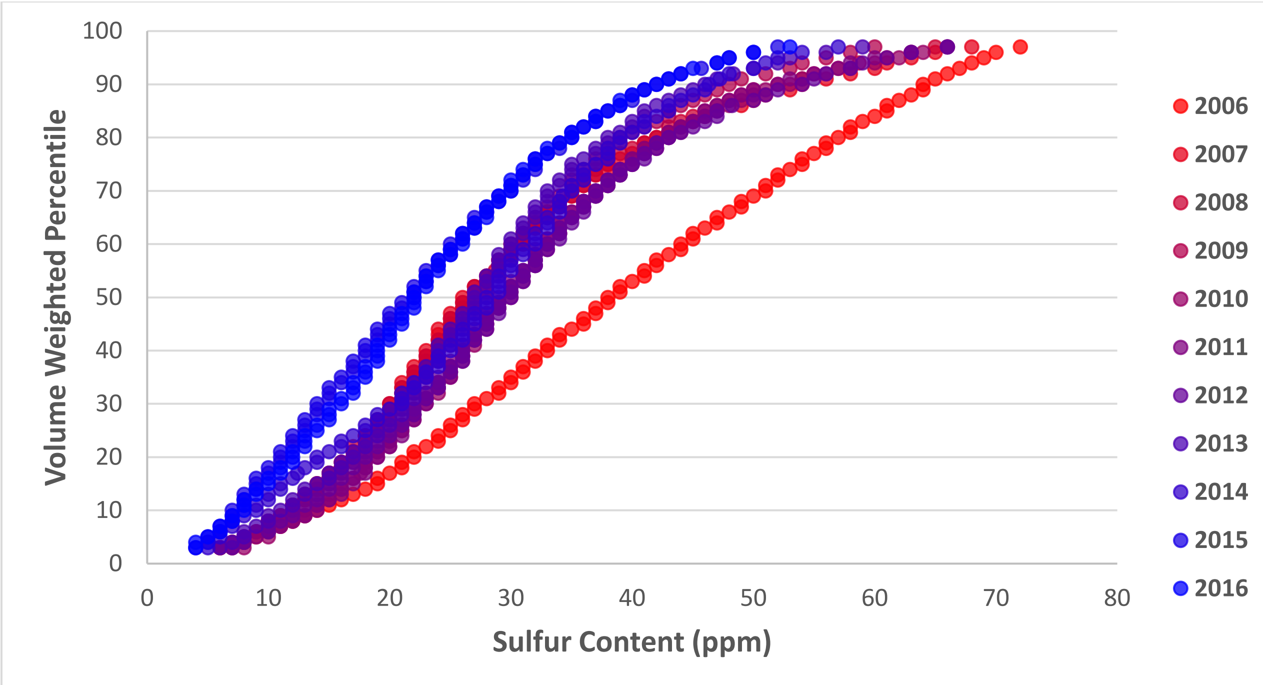

Figure 23 Sulfur Layered Percentile RFG (3 to 97%)

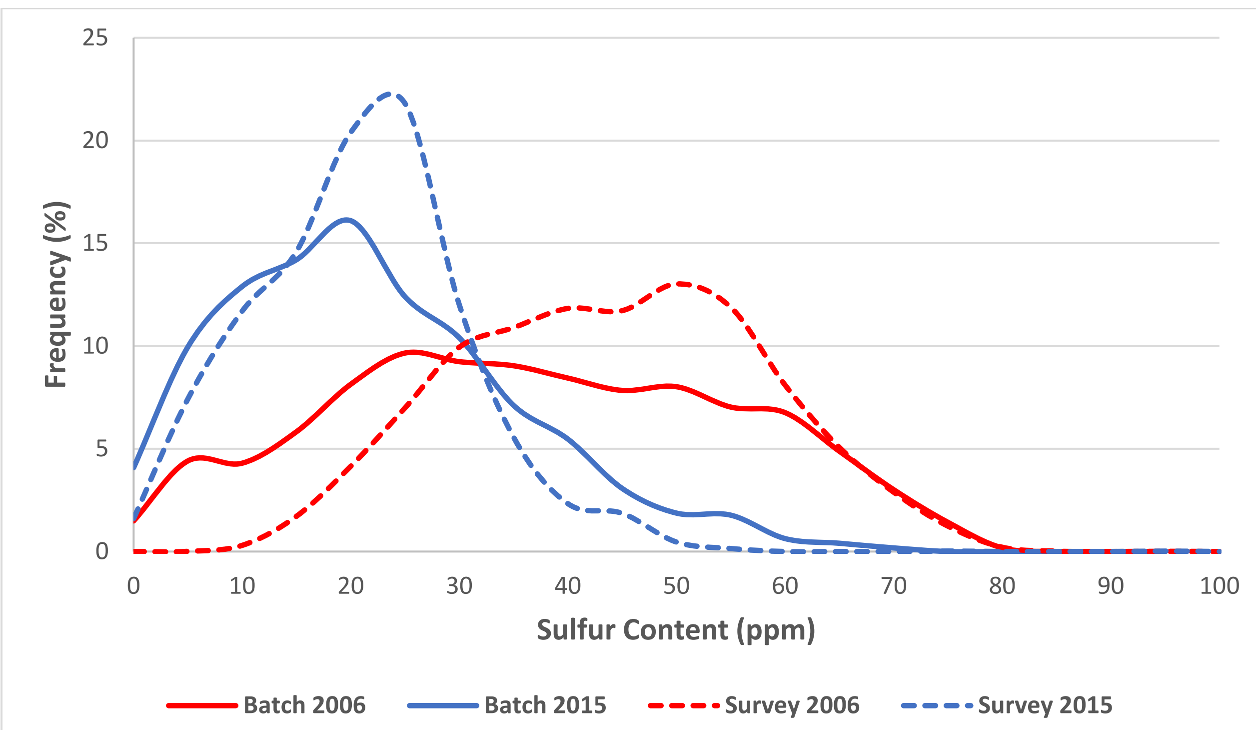

Figure 24 Sulfur RFG 2006 versus 2015 Histogram (bucket size = 5 ppm)

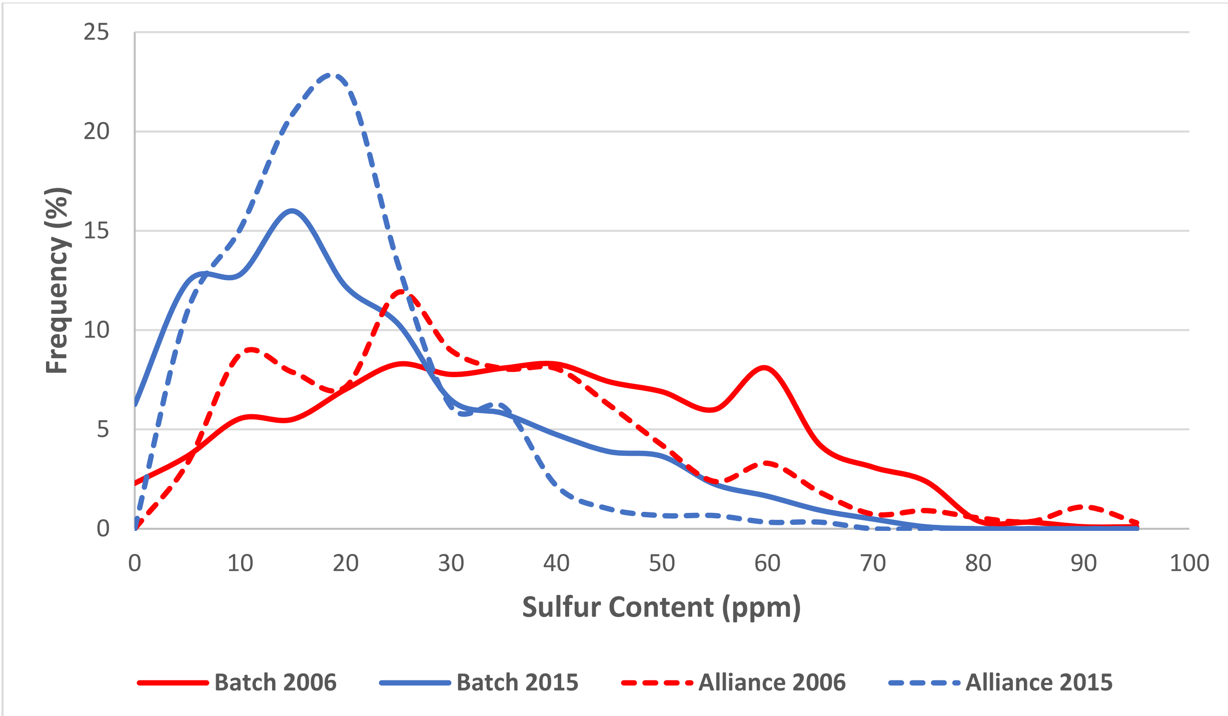

Figure 25 Sulfur CG 2006 versus 2015 Histogram (bucket size = 5 ppm) (ethanol-adjusted)

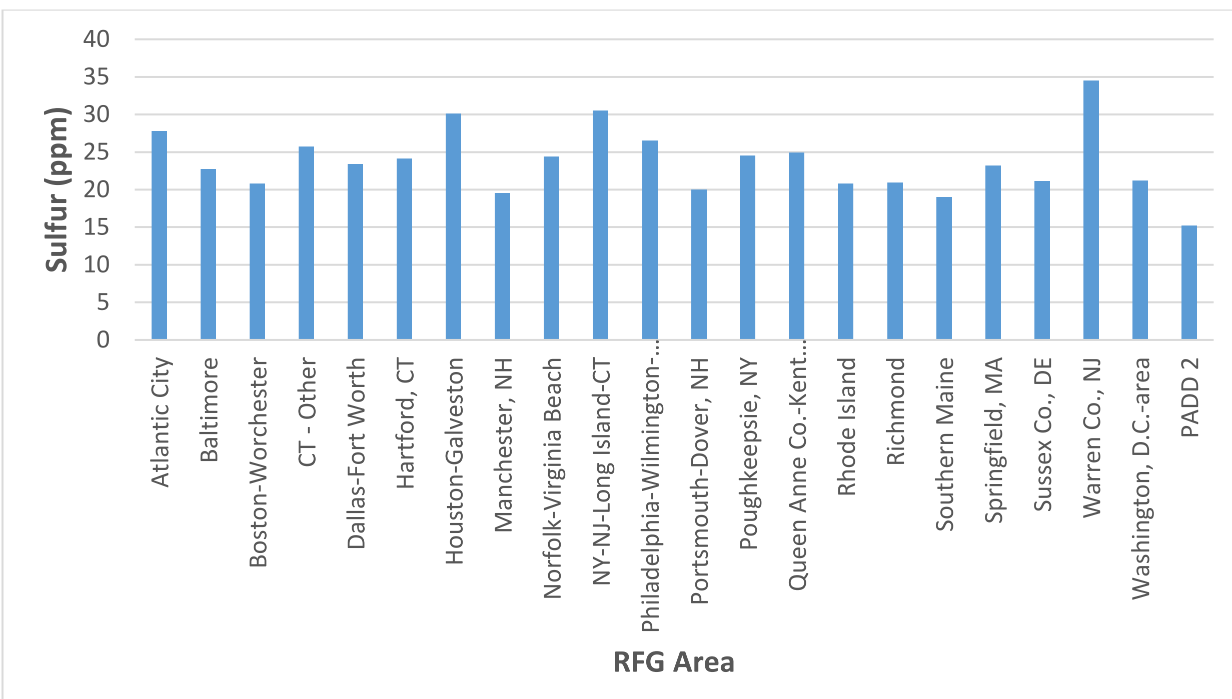

Figure 26 Summertime Sulfur Levels by RFG Area in 2016 from RFG Survey Data

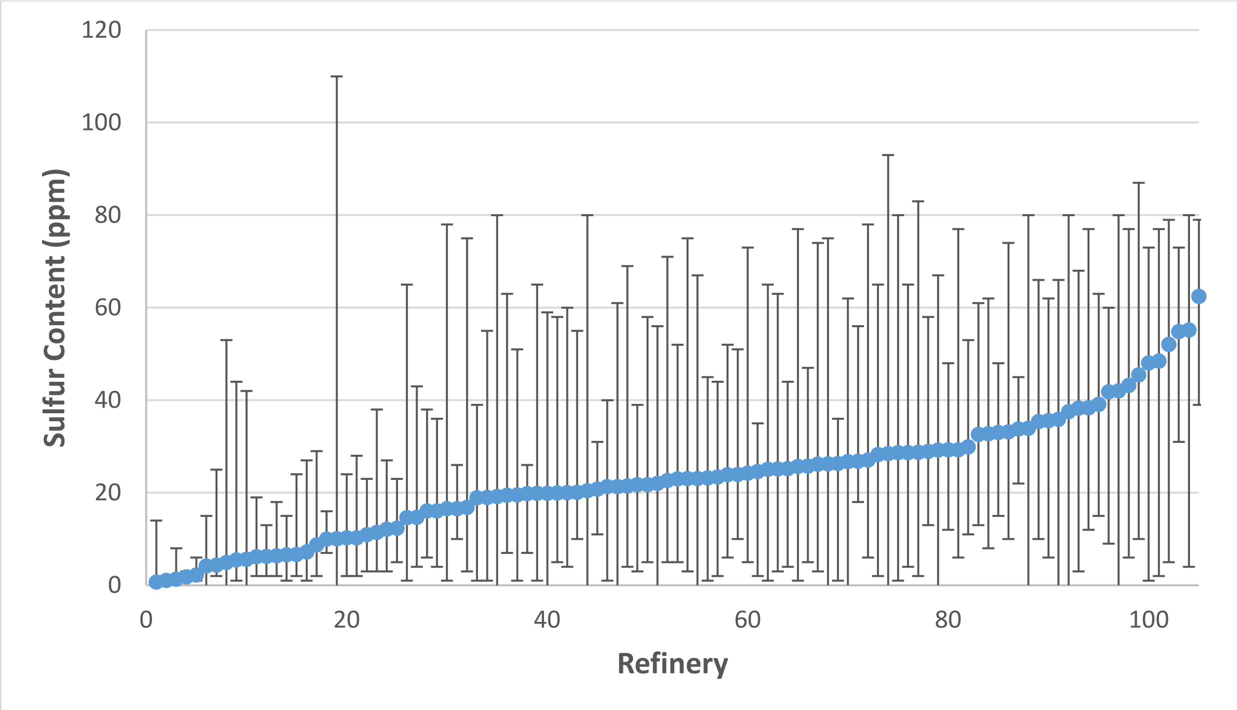

Figure 27 Sulfur content by individual refinery from lowest to highest average (average, minimum and maximum for CG and RFG in 2016; not ethanol-adjusted)

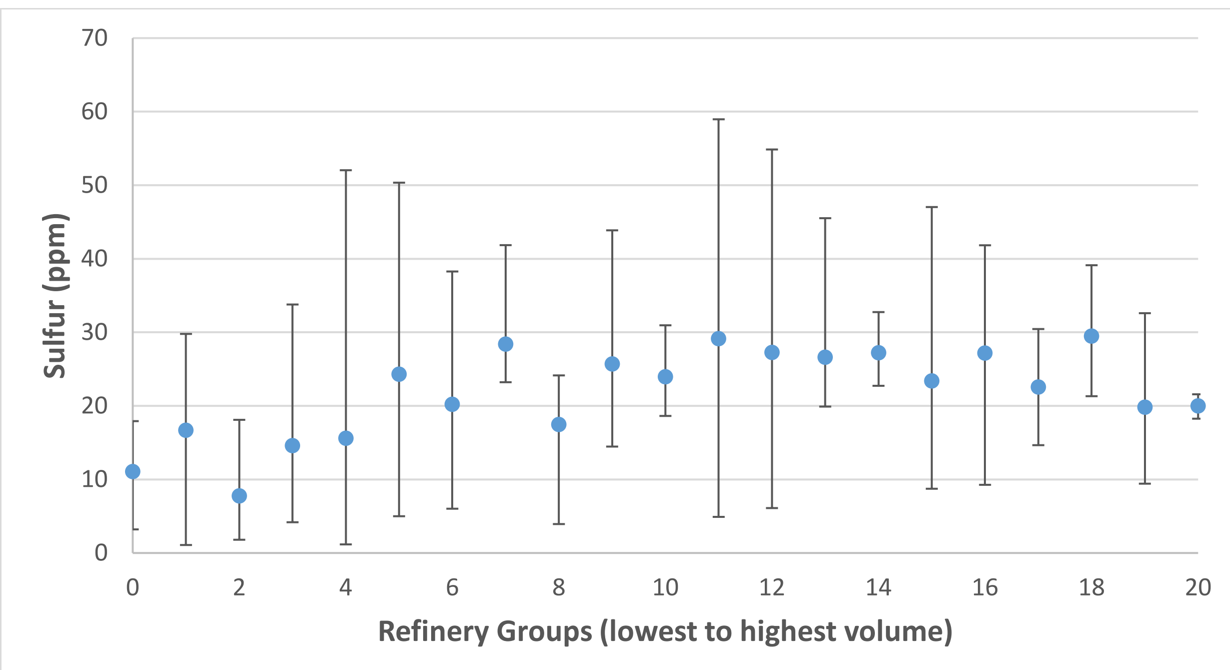

Figure 28 Sulfur content for refineries grouped by volume output (groups of five refineries; average of the average, minimum and maximum values for CG and RFG 2016; not ethanol-adjusted)

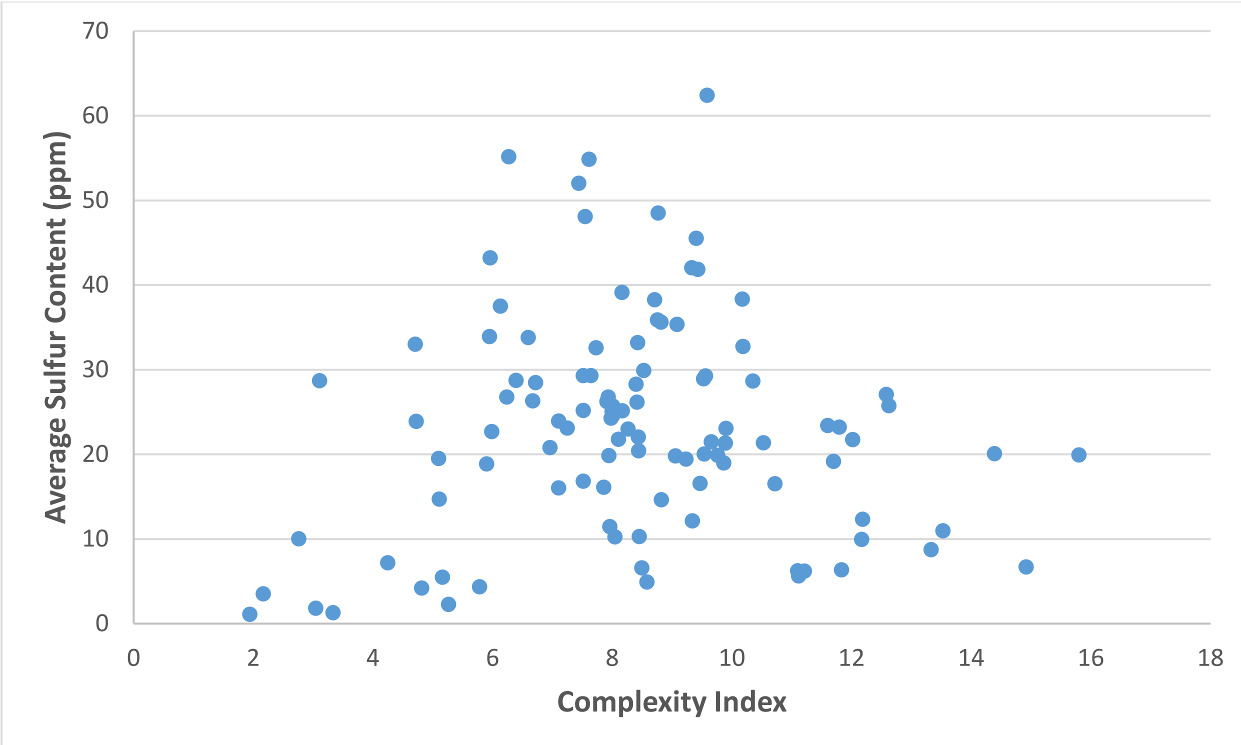

Figure 29 Average Gasoline Sulfur Content by Refinery Complexity Index in 2016 (not ethanol-adjusted)

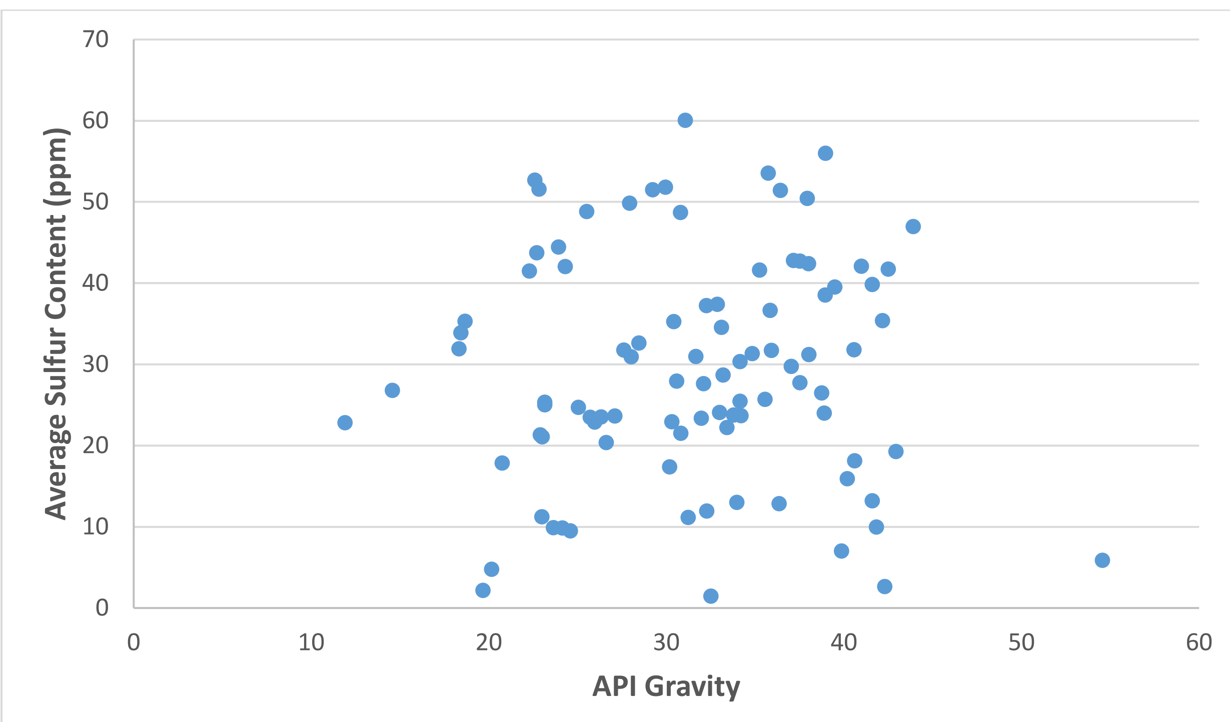

Figure 30 Gasoline Sulfur Content by Crude Oil API Gravity in 2011 (not ethanol-adjusted)

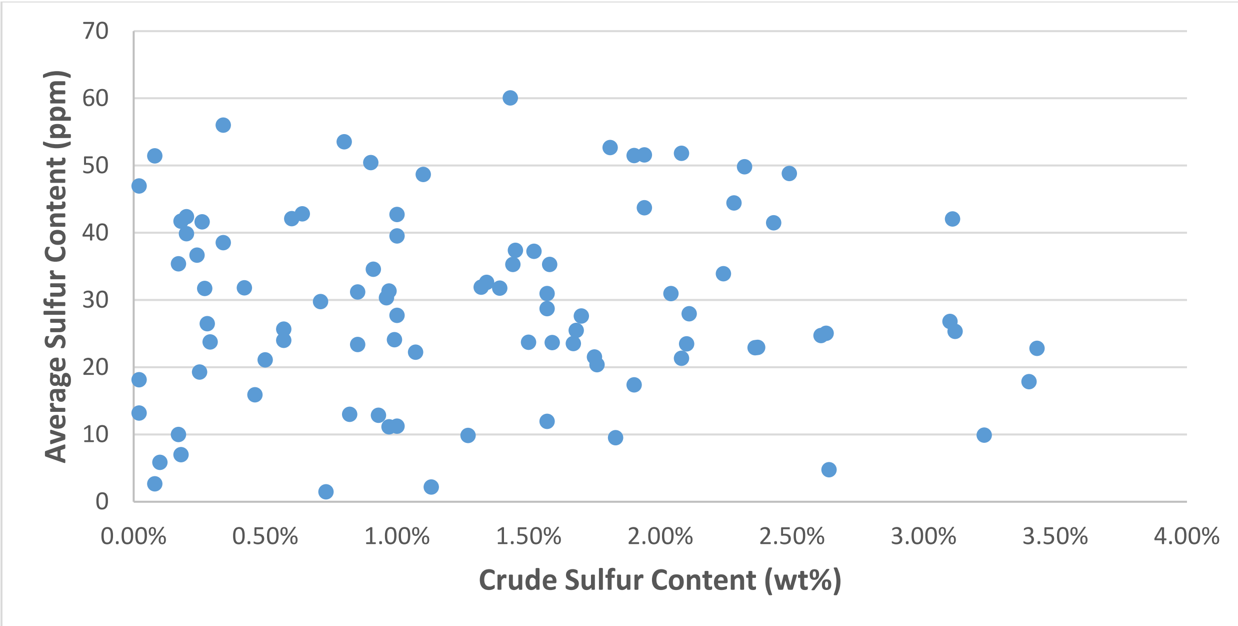

Figure 31 Gasoline Sulfur Content by Crude Oil Sulfur Content in 2011 (not ethanol-adjusted)

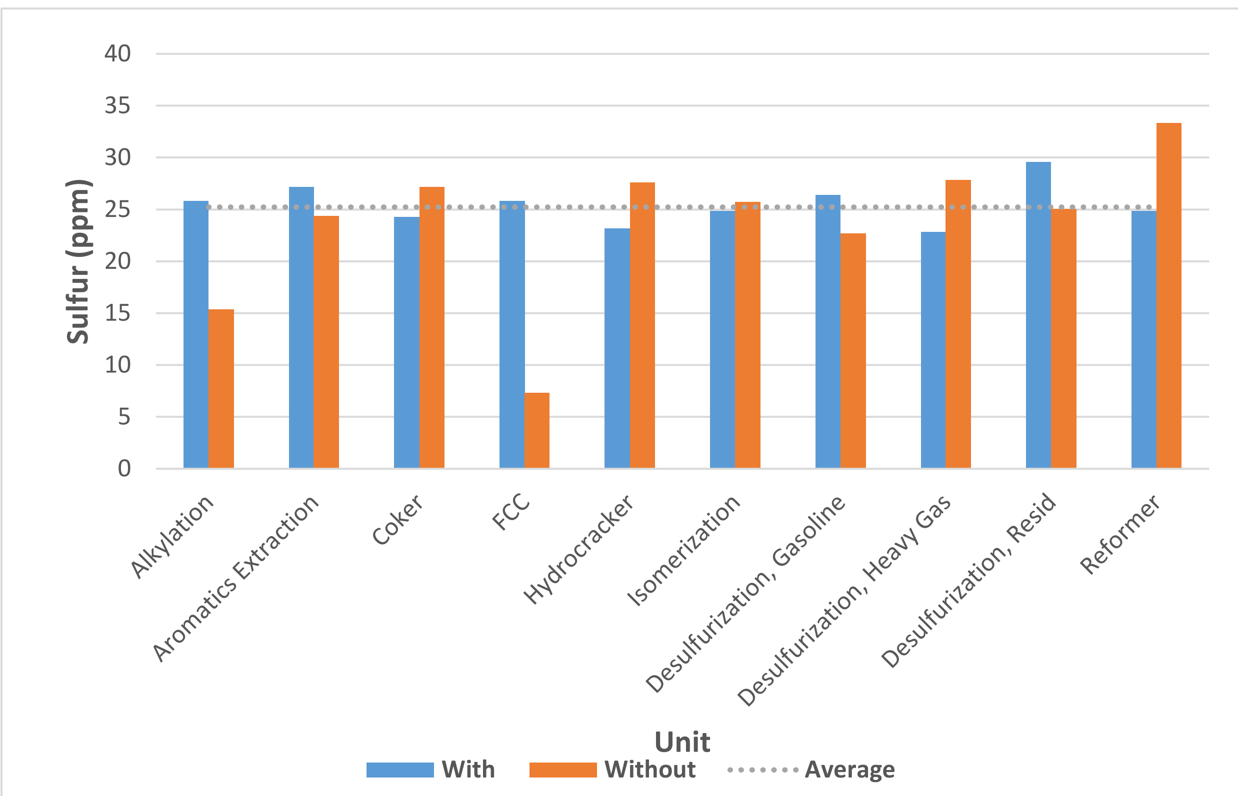

Figure 32 Average Sulfur Content by Refinery Unit Type in 2016 (not ethanol-adjusted)

b. Benzene

Highlights for the following benzene figures:

- Figure 33 shows that benzene levels were lower due to the RFG standards, and following MSAT2, benzene levels for CG have decreased closer to that of RFG – RFG benzene levels decreased further due to MSAT2.
- Almost all gasoline batches now have benzene levels less than 1 volume percent.
- Regional benzene level differences are now minor compared to years past, though PADD 1 and 4 benzene levels remain slightly higher.
- Benzene levels in PADD1 had a temporary increase during the Great Recession and prior to the implementation of MSAT2.
- Figures 43 through 48 show that, although refinery gasoline benzene averages have shifted lower, the variance in batch benzene levels has continued.
- Various Figures show that most high benzene gasoline phased out due to the imposition of both the 0.62 and the 1.3 volume percent average and maximum-average standards, respectively, yet a small number of high benzene level batches still remain.
- Despite being higher in aromatic, premium grade gasoline benzene levels are consistently below those of regular grade.
- The RFG and Alliance survey data and batch data align very well over time.
- Figures 50 to 53 show that, refinery size, complexity index, crude oil API gravity or crude oil sulfur content have no discernable impact on gasoline benzene levels.
- Figure 53 shows that refineries without reformer units and refineries with aromatics extraction units have comparatively low benzene levels.

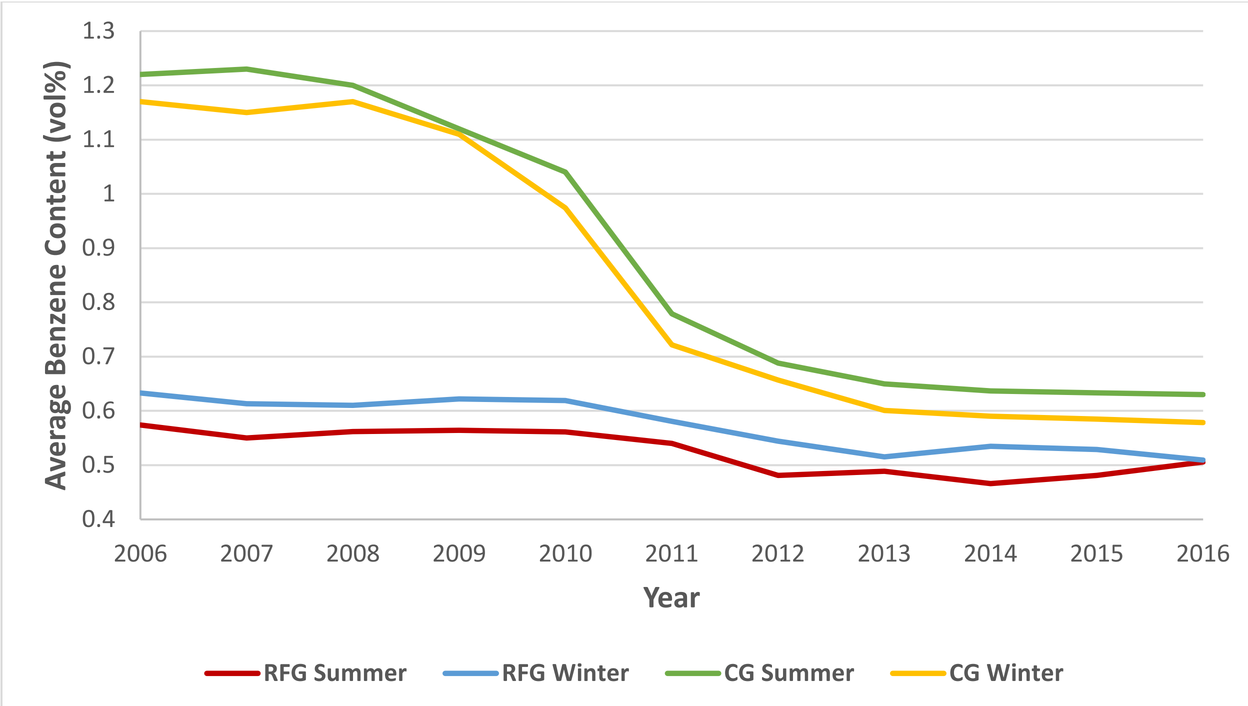

Figure 33 Benzene Trends Summer versus Winter (ethanol-adjusted)

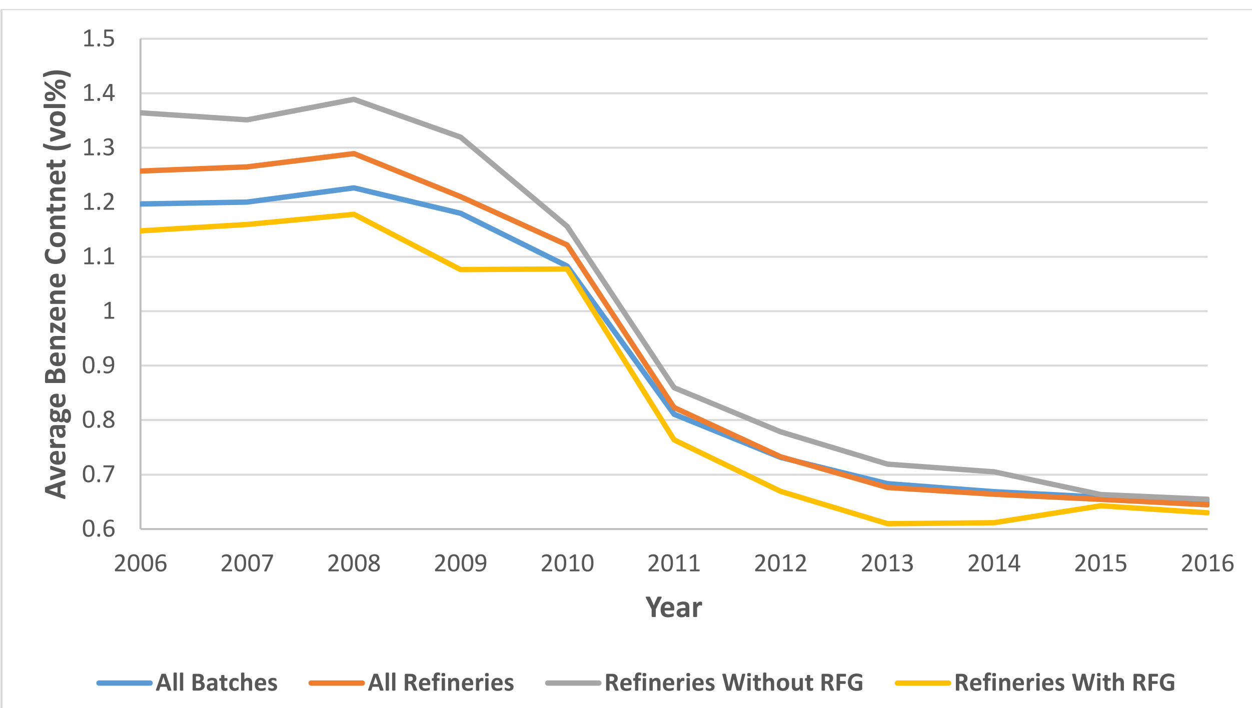

Figure 34 Average CG Benzene Content by Refinery Type (not ethanol-adjusted)

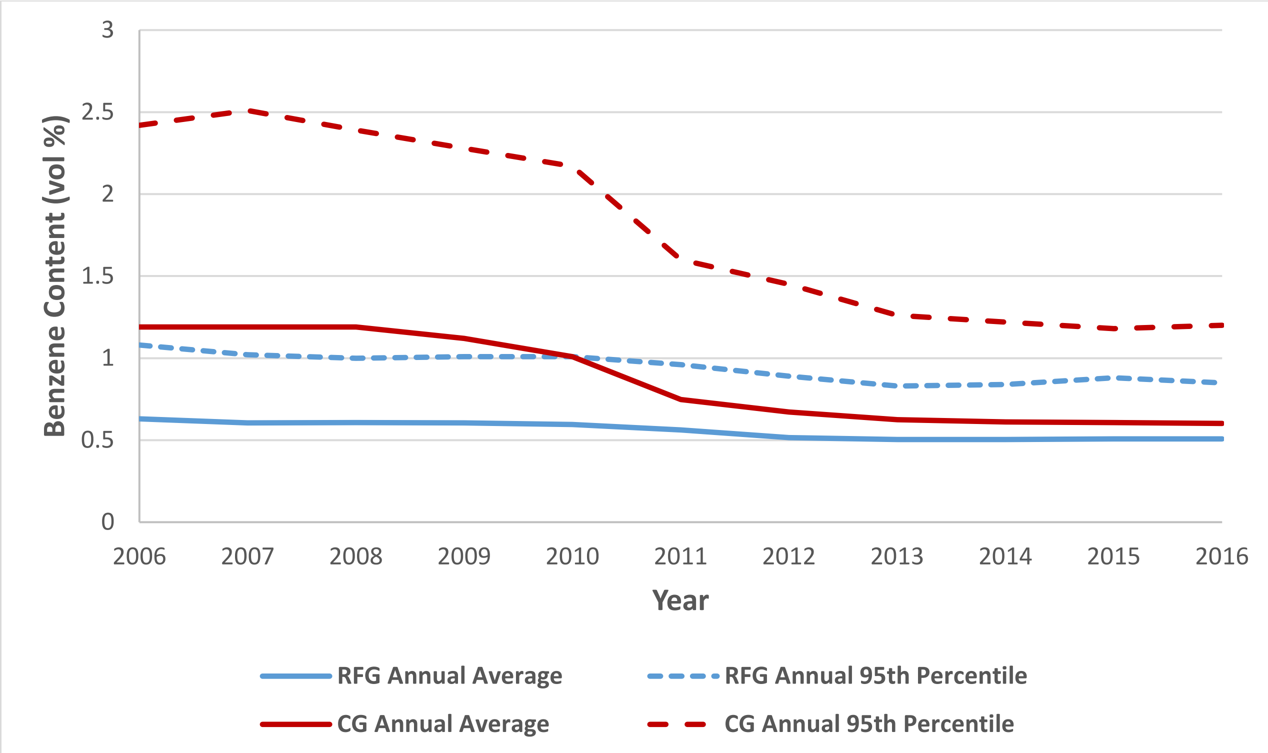

Figure 35 Benzene Trends 95th Percentile versus Average (ethanol-adjusted)

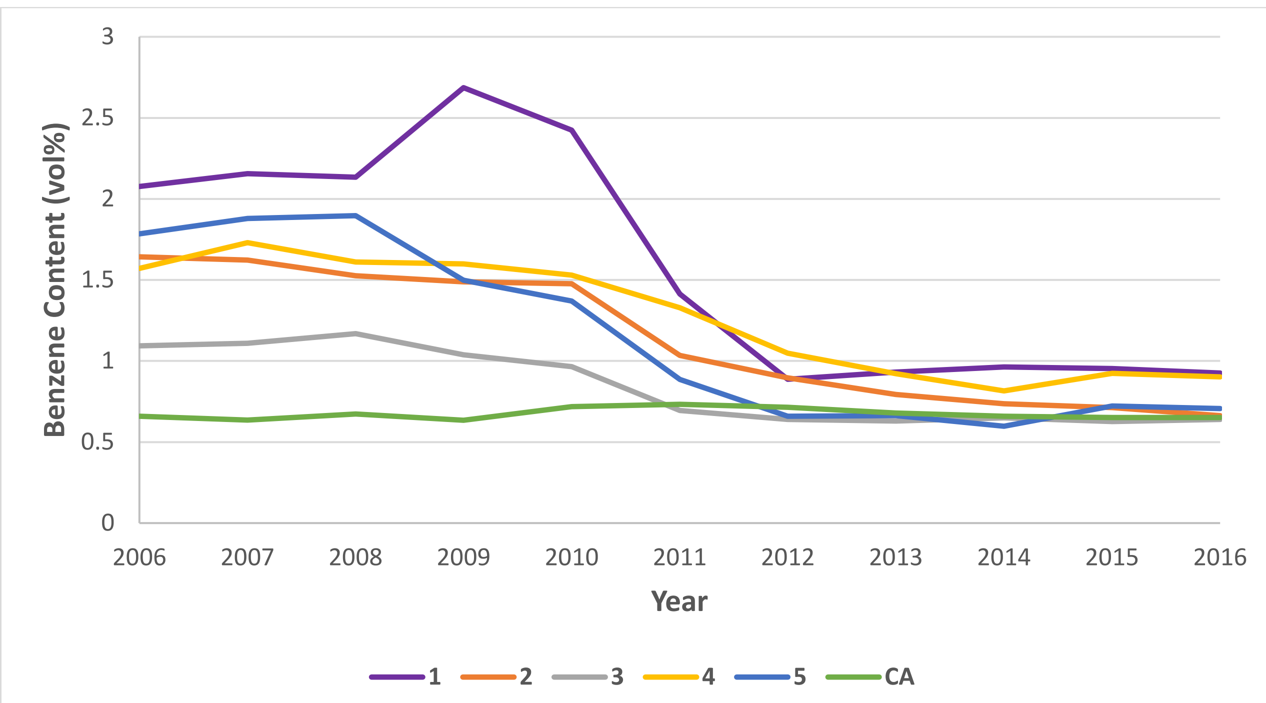

Figure 36 CG Summer Benzene by PADD (not ethanol-adjusted)

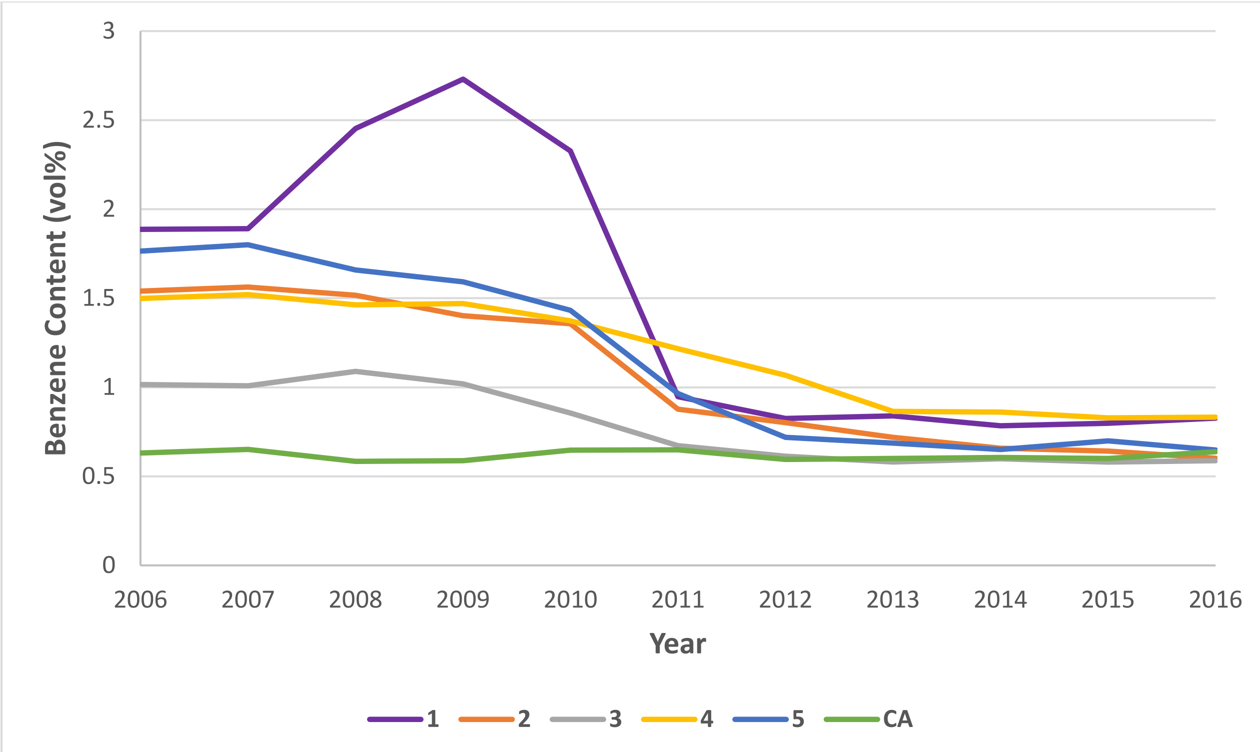

Figure 37 CG Winter Benzene by PADD (not ethanol-adjusted)

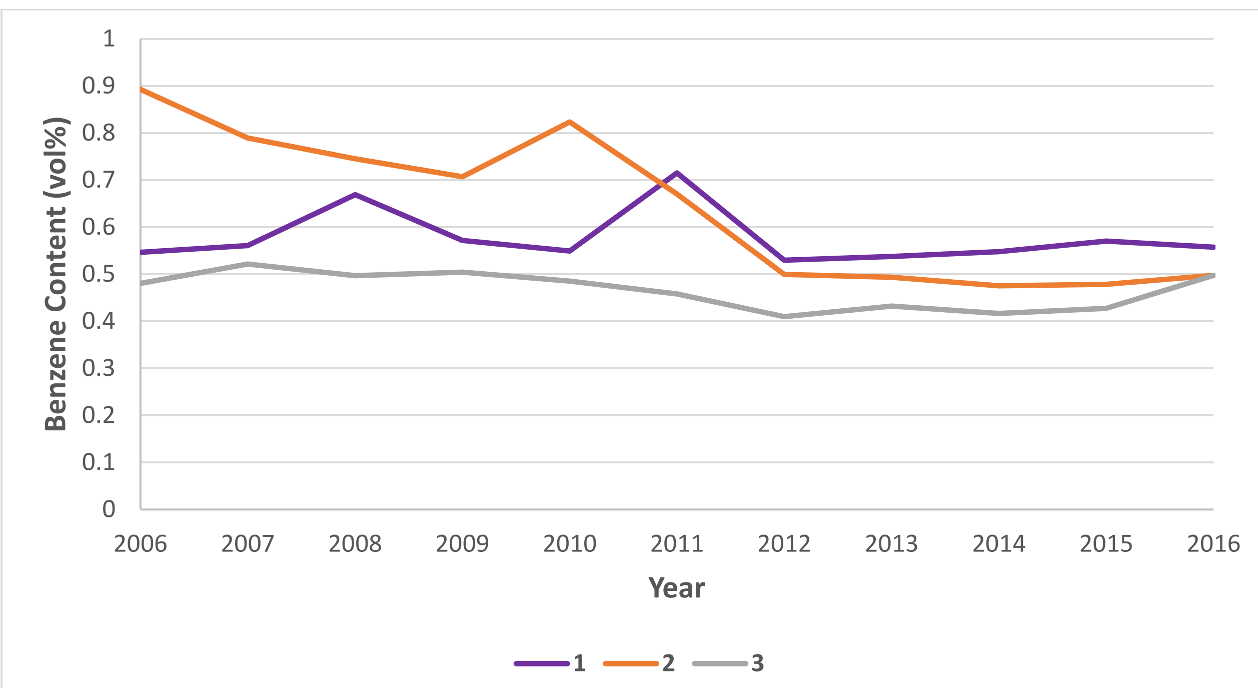

Figure 38 RFG Summer Benzene by PADD Produced from Batch Data

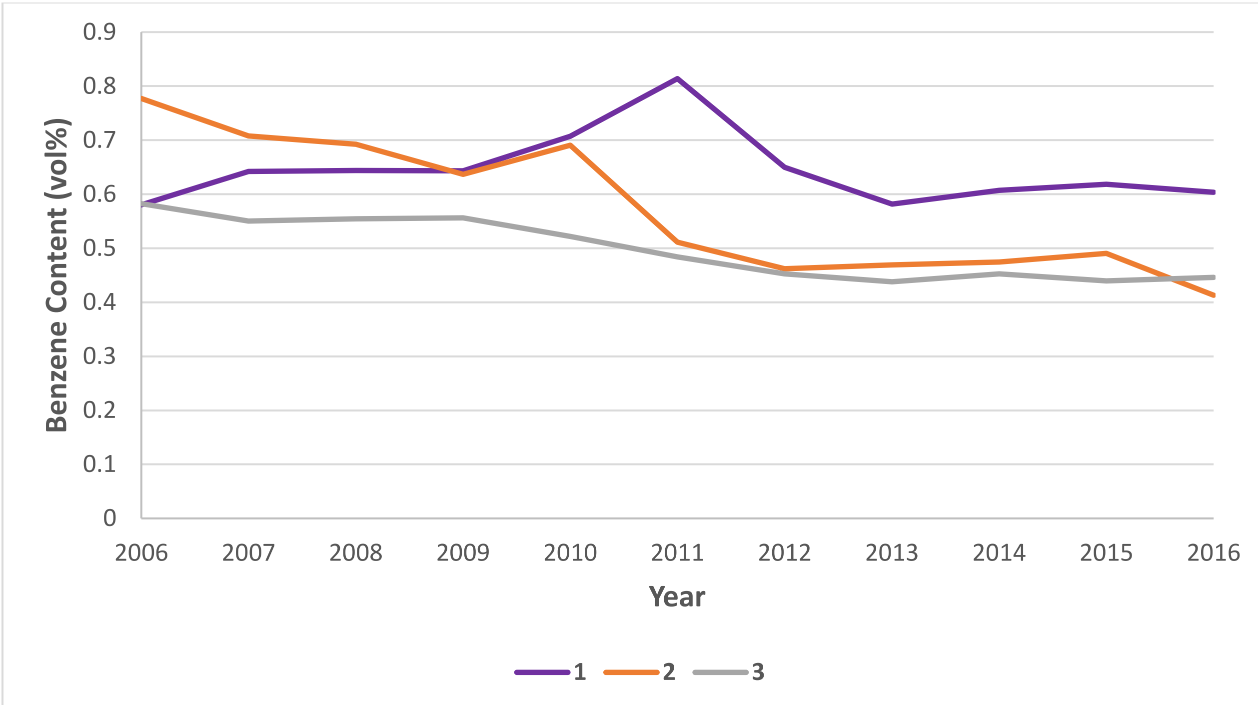

Figure 39 RFG Winter Benzene by PADD Produced from Batch Data

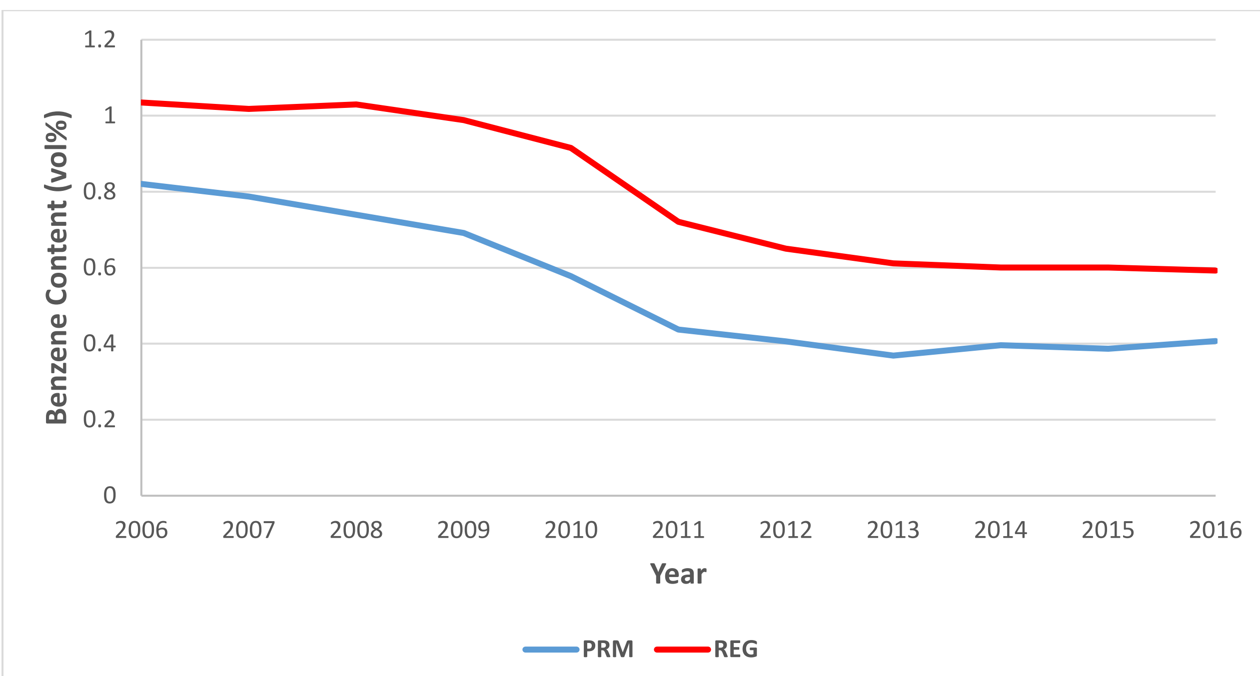

Figure 40 Regular versus Premium CG and RFG Benzene (ethanol-adjusted)

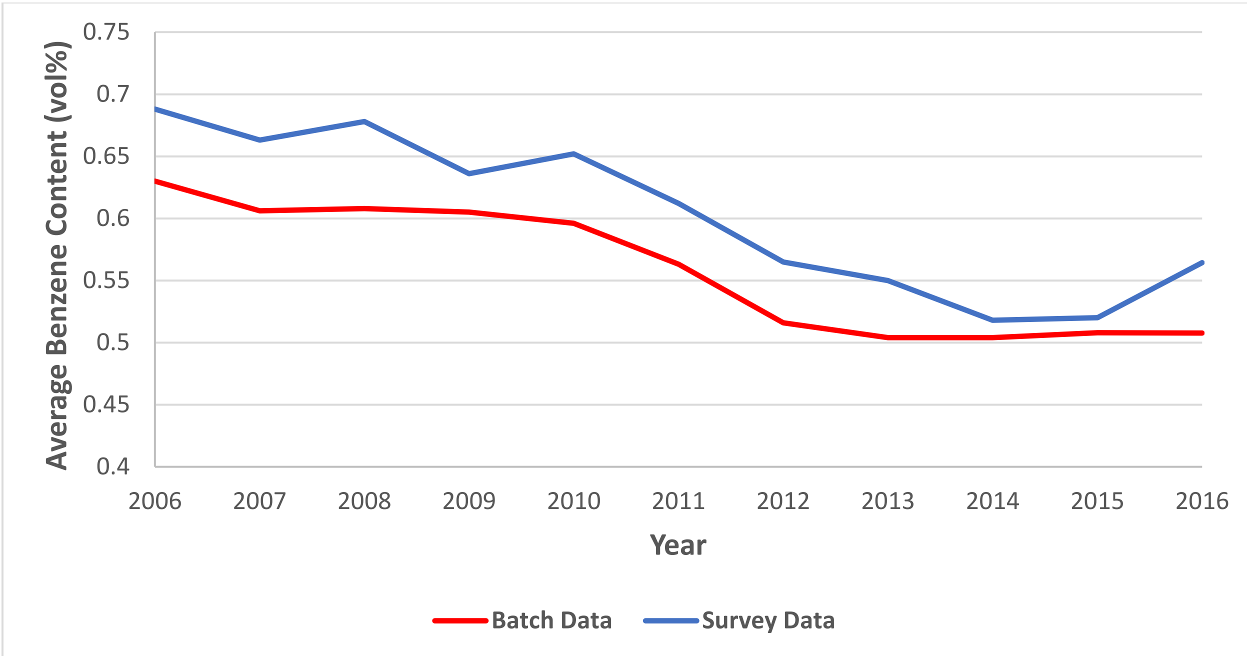

Figure 41 Benzene RFG Batch versus Survey (ethanol-adjusted)

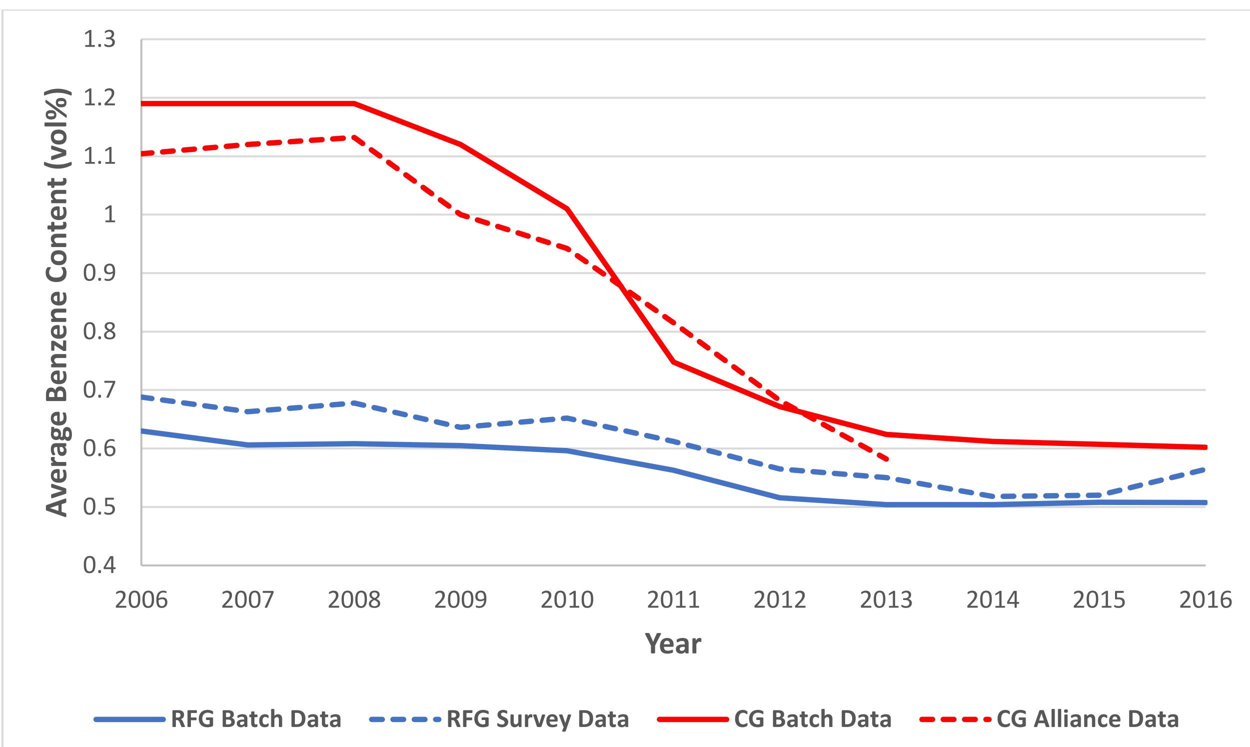

Figure 42 Comparing Batch, Survey, and Alliance data (ethanol-adjusted)

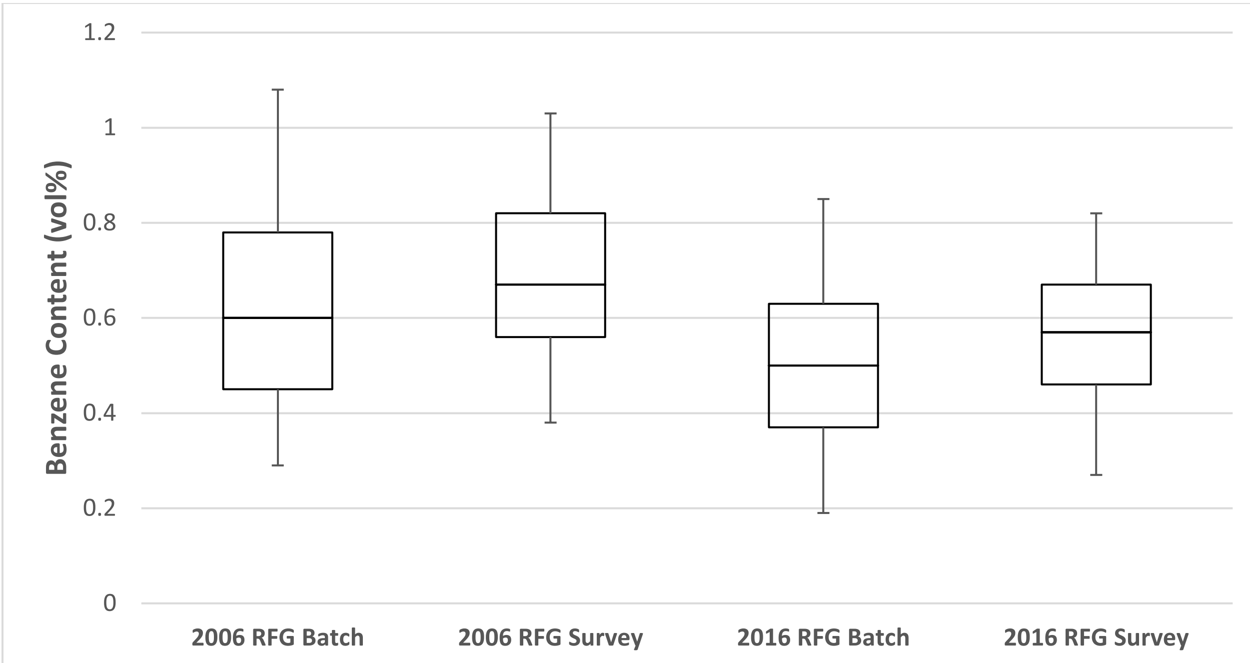

Figure 43 Benzene RFG Box and Whiskers (5%, 25%, median, 75%, 95%)

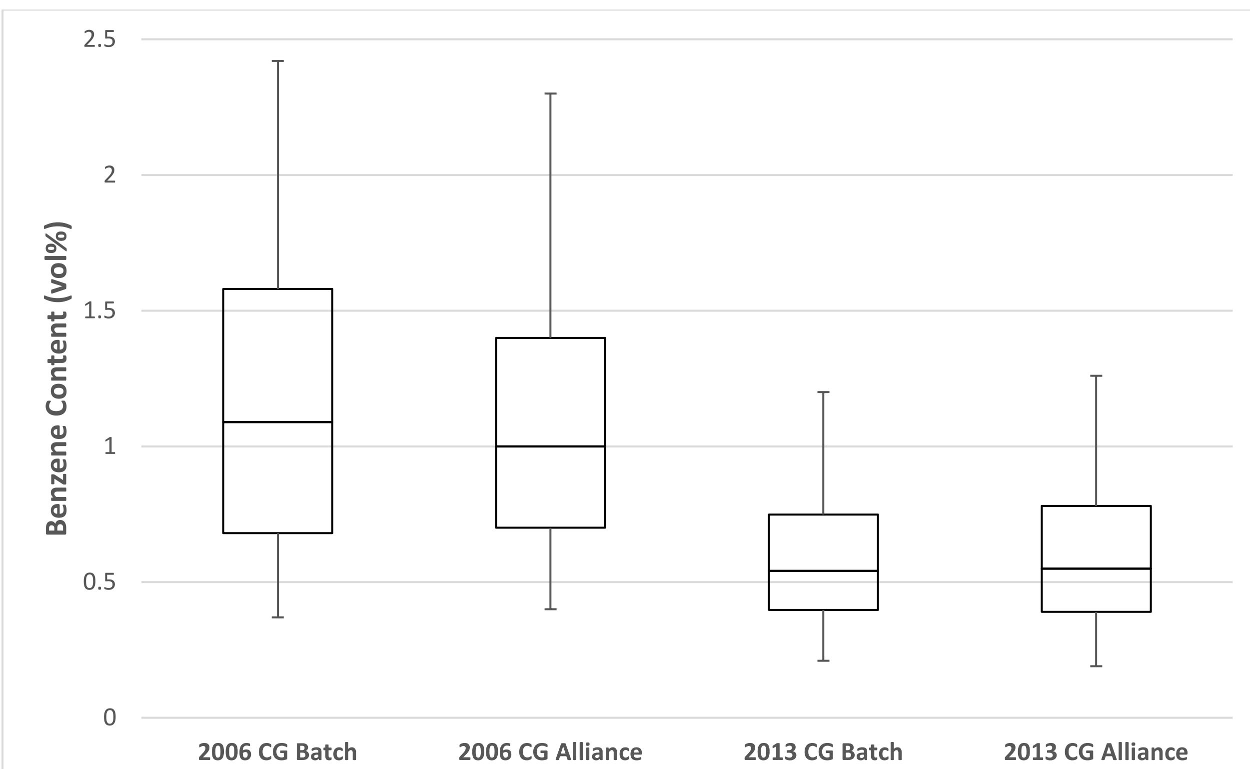

Figure 44 Benzene CG Box and Whiskers (5%, 25%, median, 75%, 95%; ethanol-adjusted)

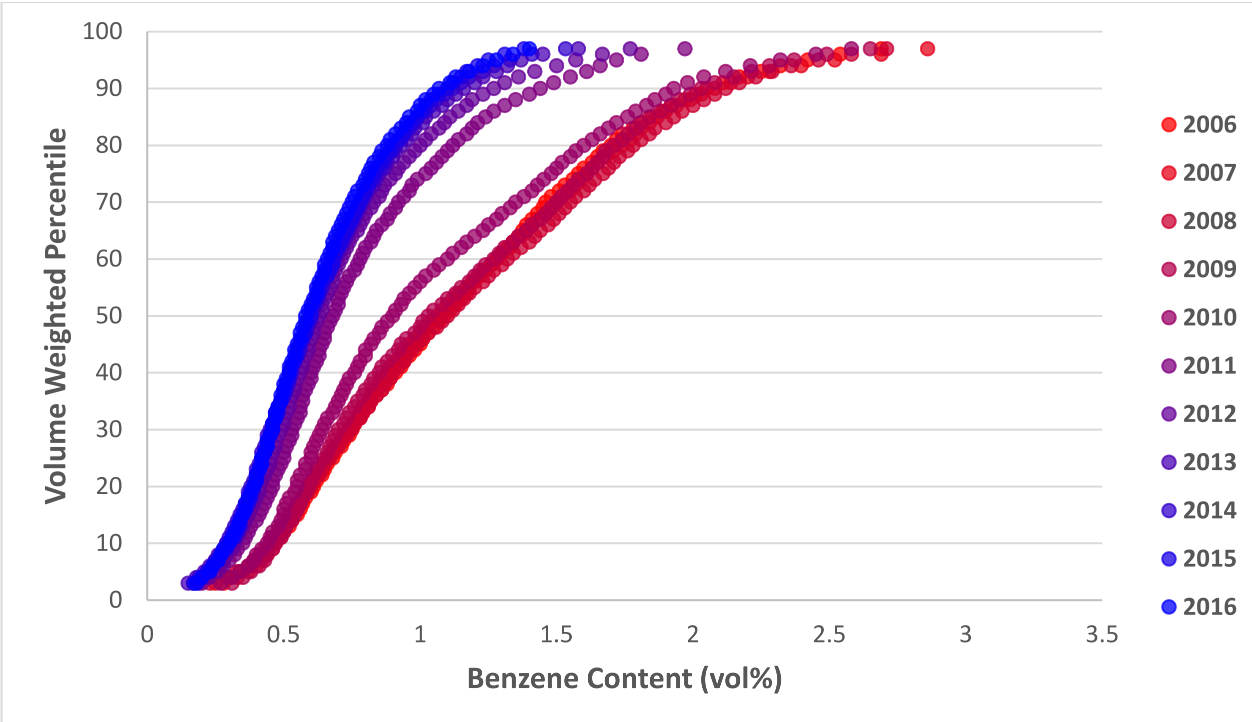

Figure 45 Benzene Layered Percentile CG (not ethanol-adjusted)

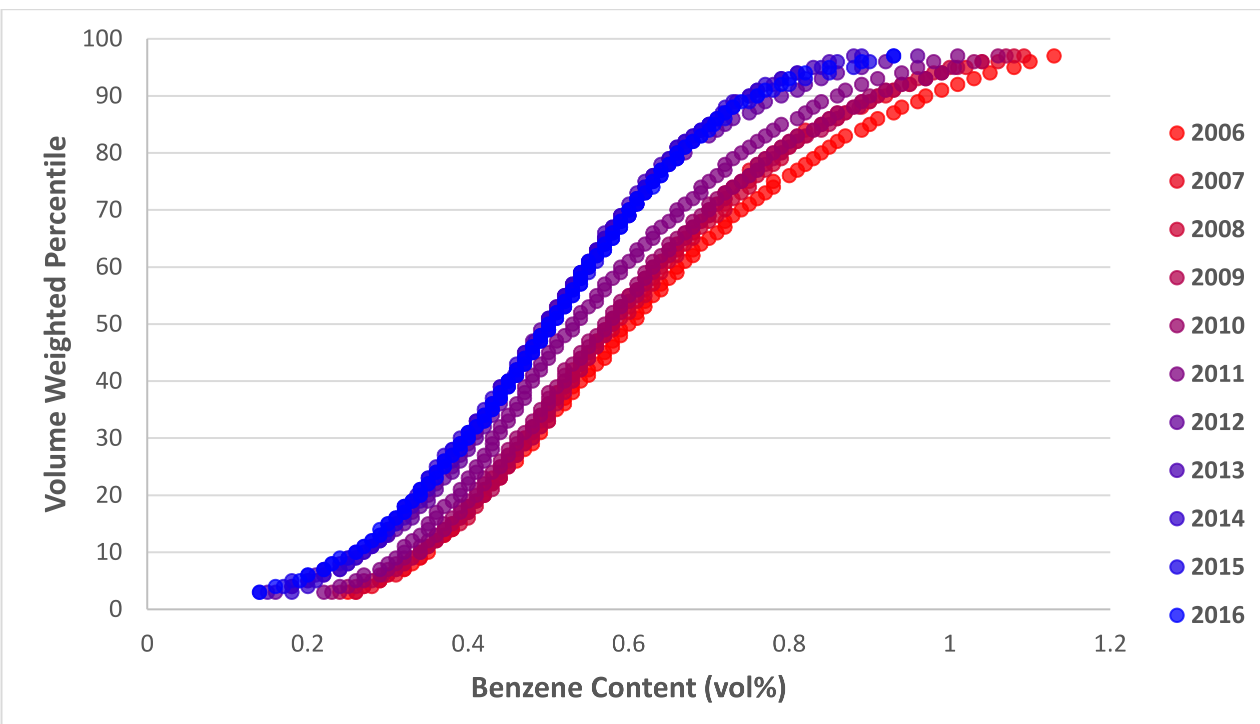

Figure 46 Benzene Layered Percentile RFG

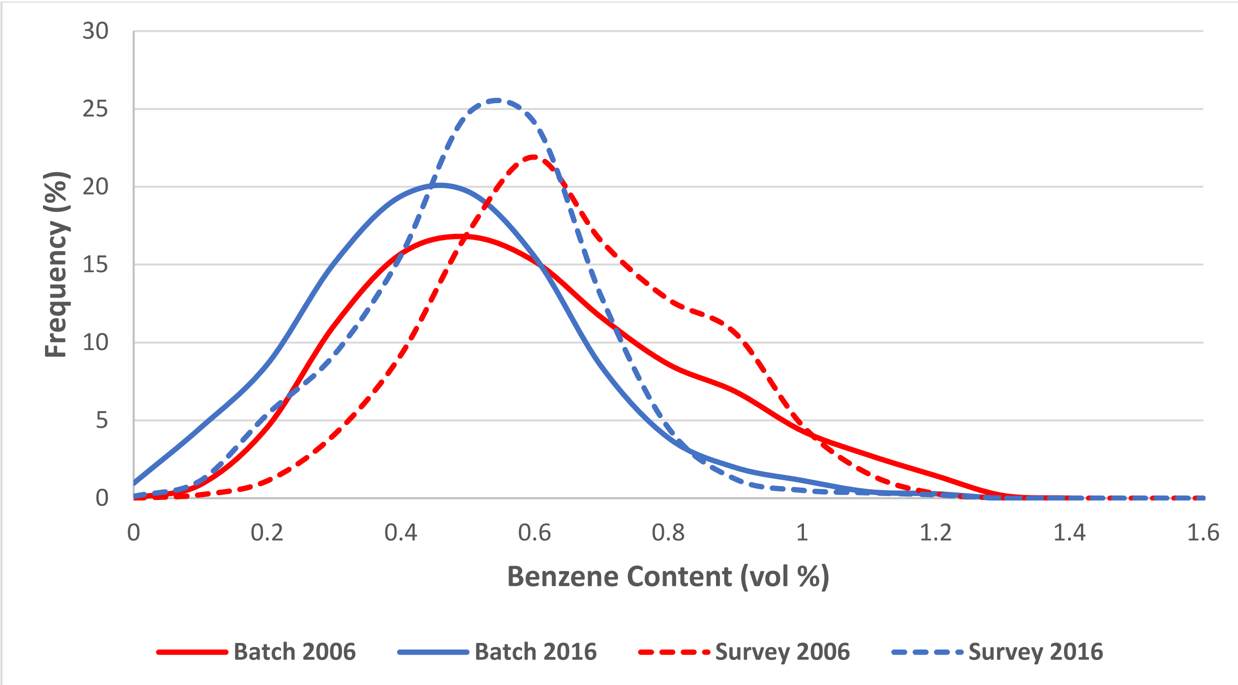

Figure 47 Benzene RFG 2006 versus 2016 Histogram (bucket size = 0.1 vol%) (ethanol-adjusted)

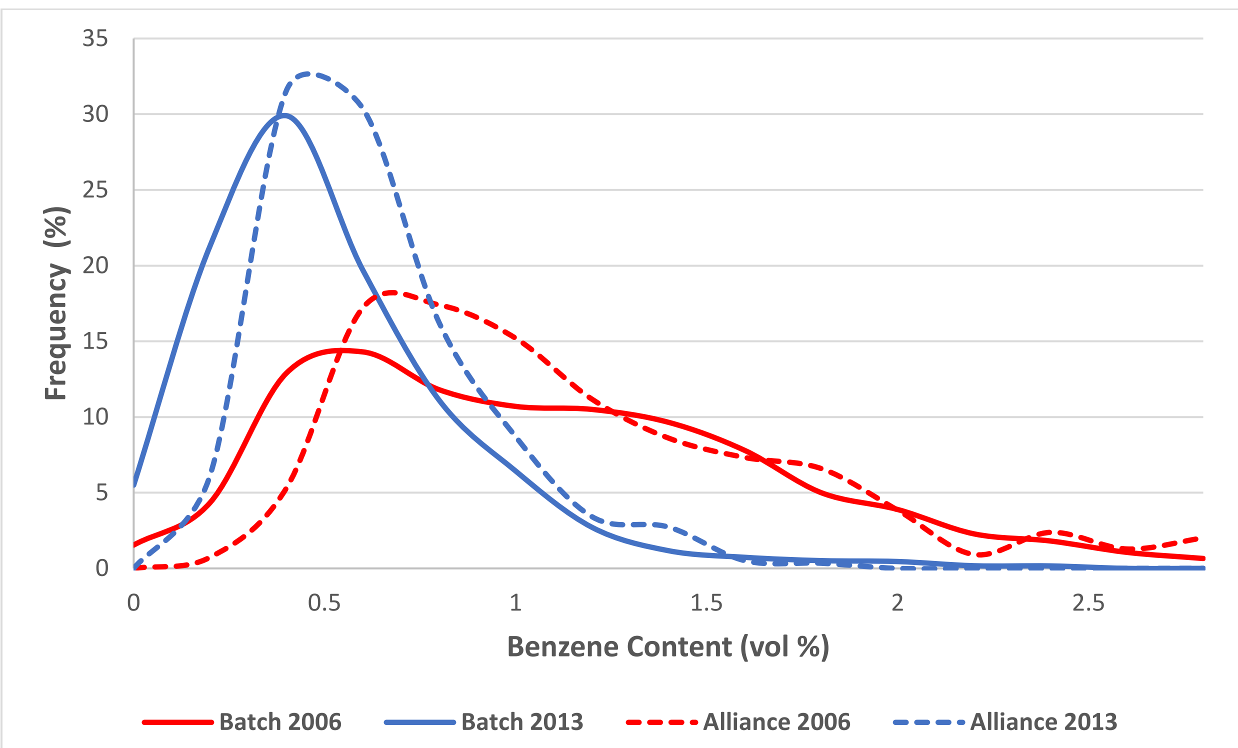

Figure 48 Benzene CG 2006 versus 2013 Histogram (bucket size = 0.1 vol%) (ethanol-adjusted)

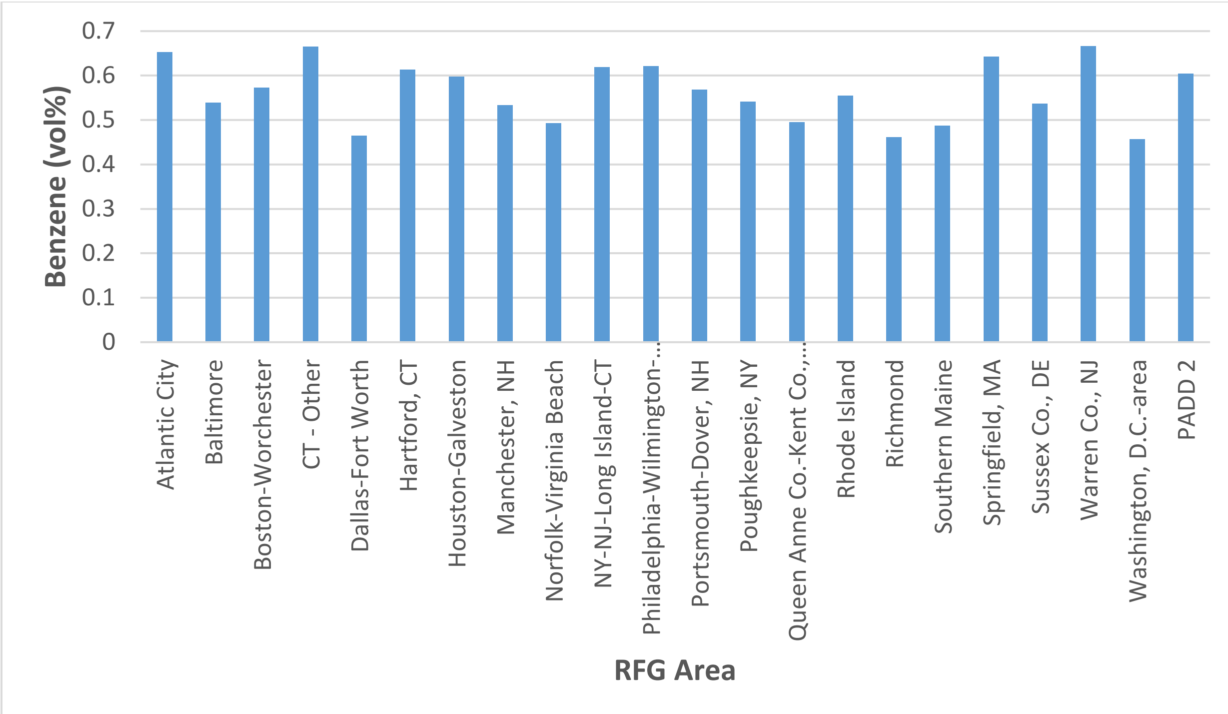

Figure 49 Summertime Benzene Levels by RFG Area in 2016 from RFG Survey Data

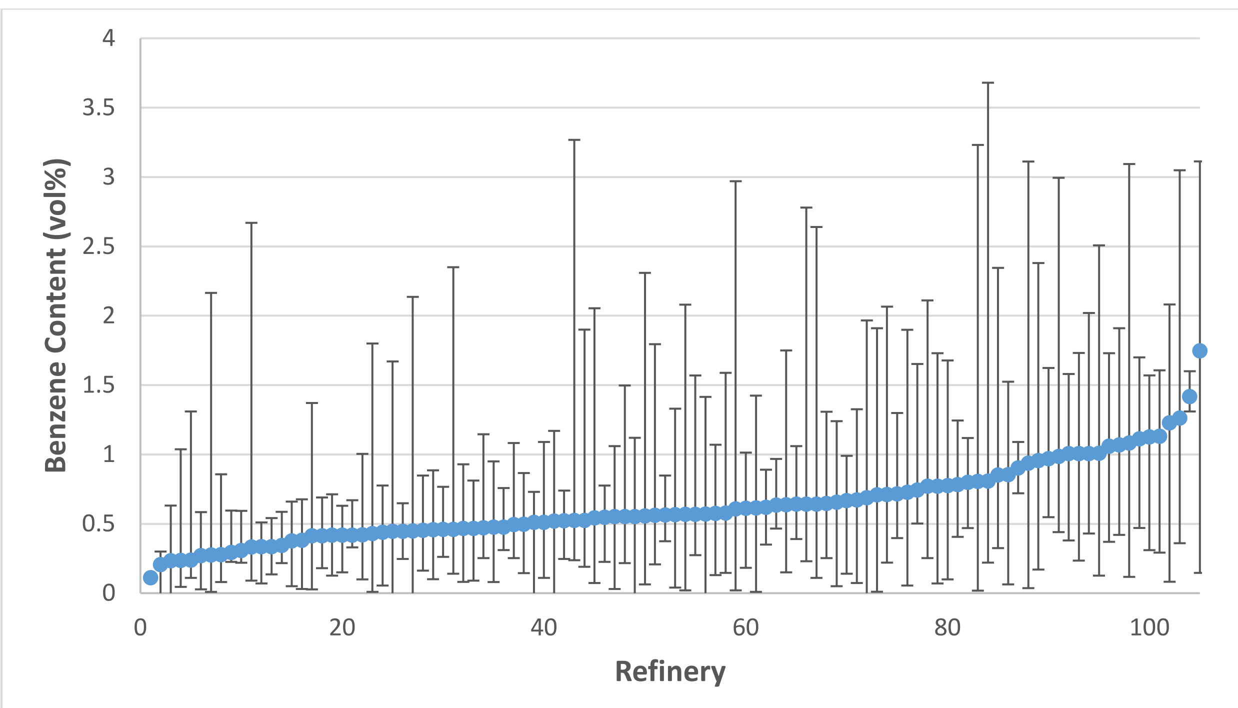

Figure 50 Benzene content by individual refinery from lowest to highest average (average, minimum and maximum for CG and RFG in 2016; not ethanol-adjusted)

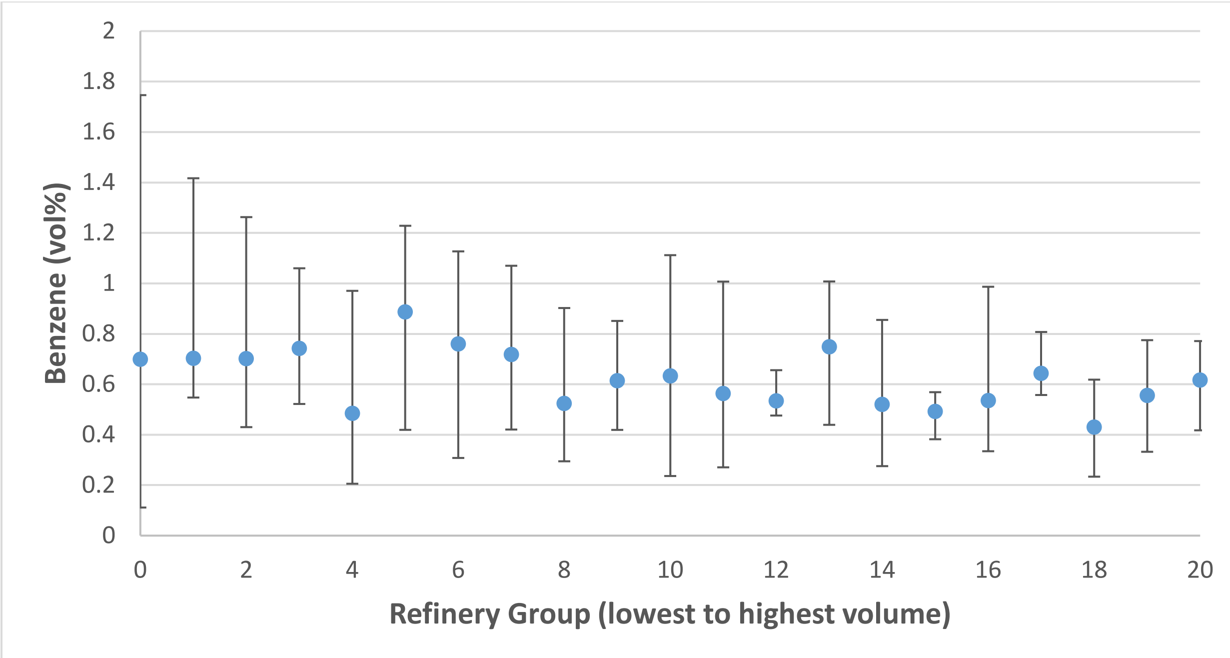

Figure 51 Benzene content for refineries grouped by volume output (groups of five refineries; average of the average, minimum and maximum values for CG and RFG 2016; not ethanol-adjusted)

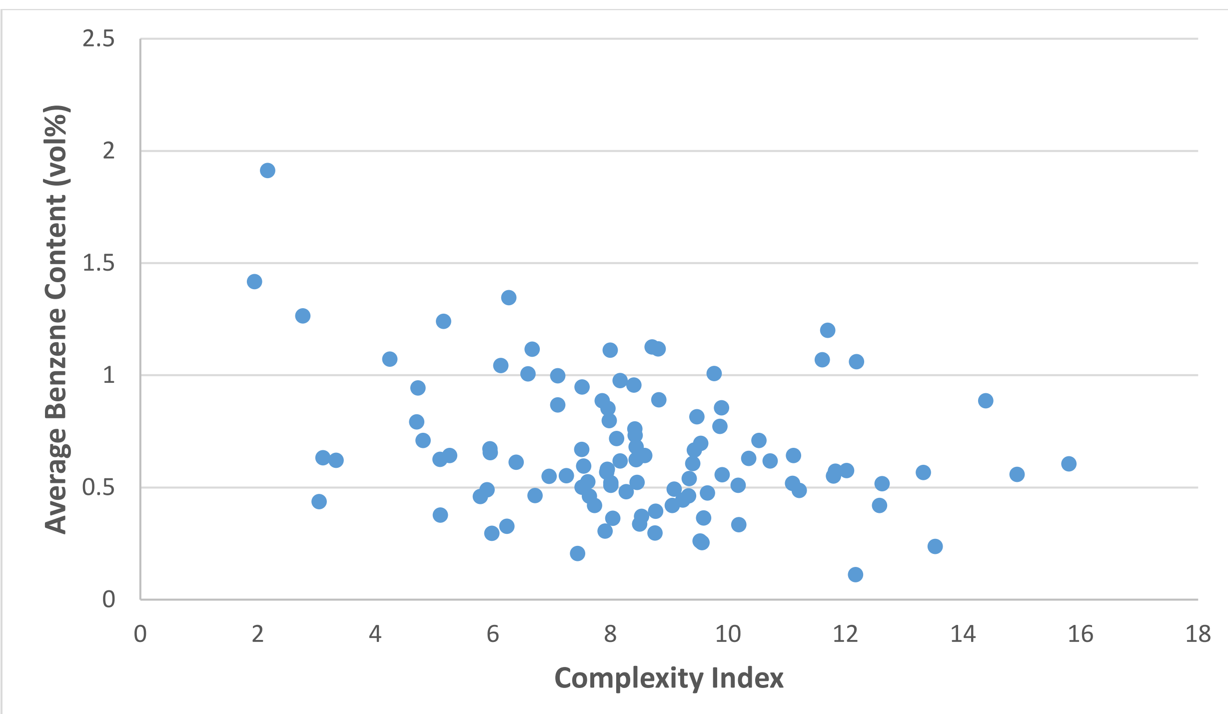

Figure 52 Average Gasoline Benzene Content by Refinery Complexity Index in 2016 (not ethanol-adjusted)

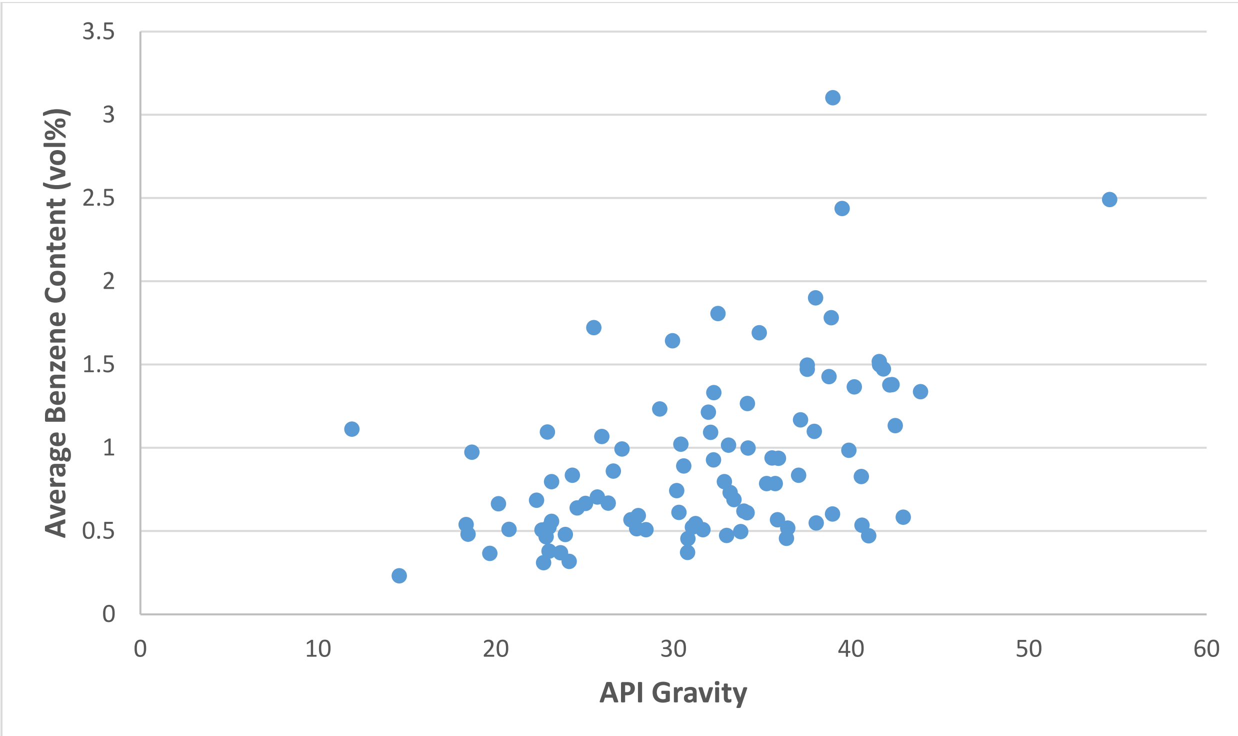

Figure 53 Gasoline Benzene Content by Crude Oil API Gravity (not ethanol-adjusted)

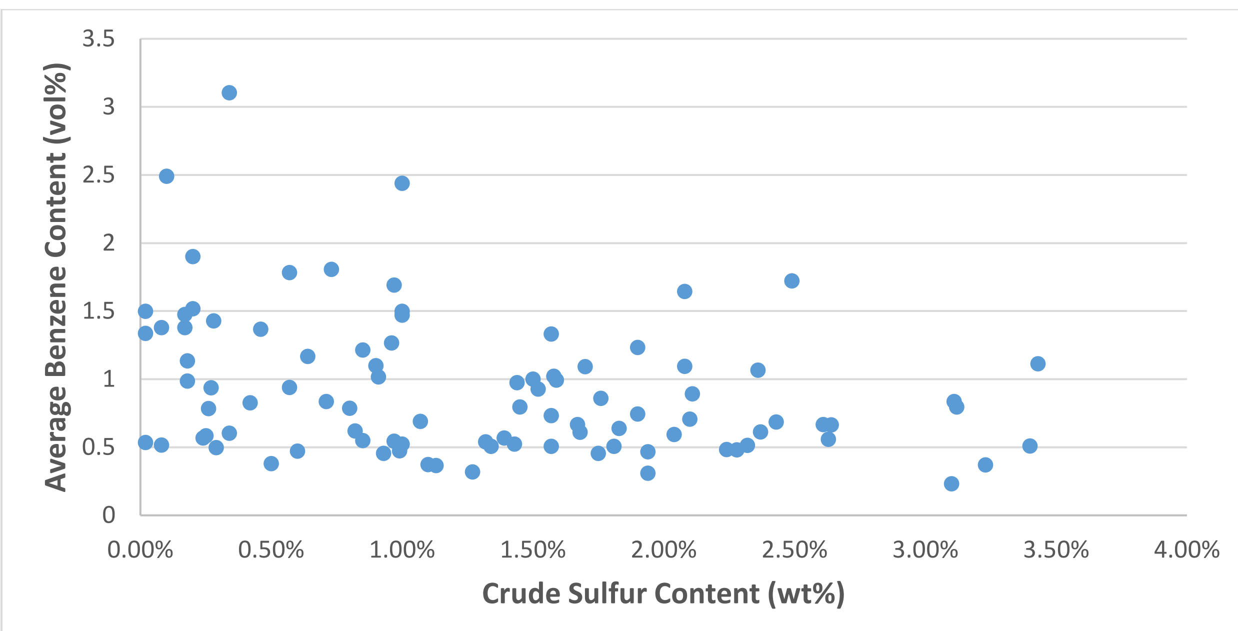

Figure 54 Gasoline Benzene Content by Crude Oil Sulfur Content in 2011 (not ethanol-adjusted)

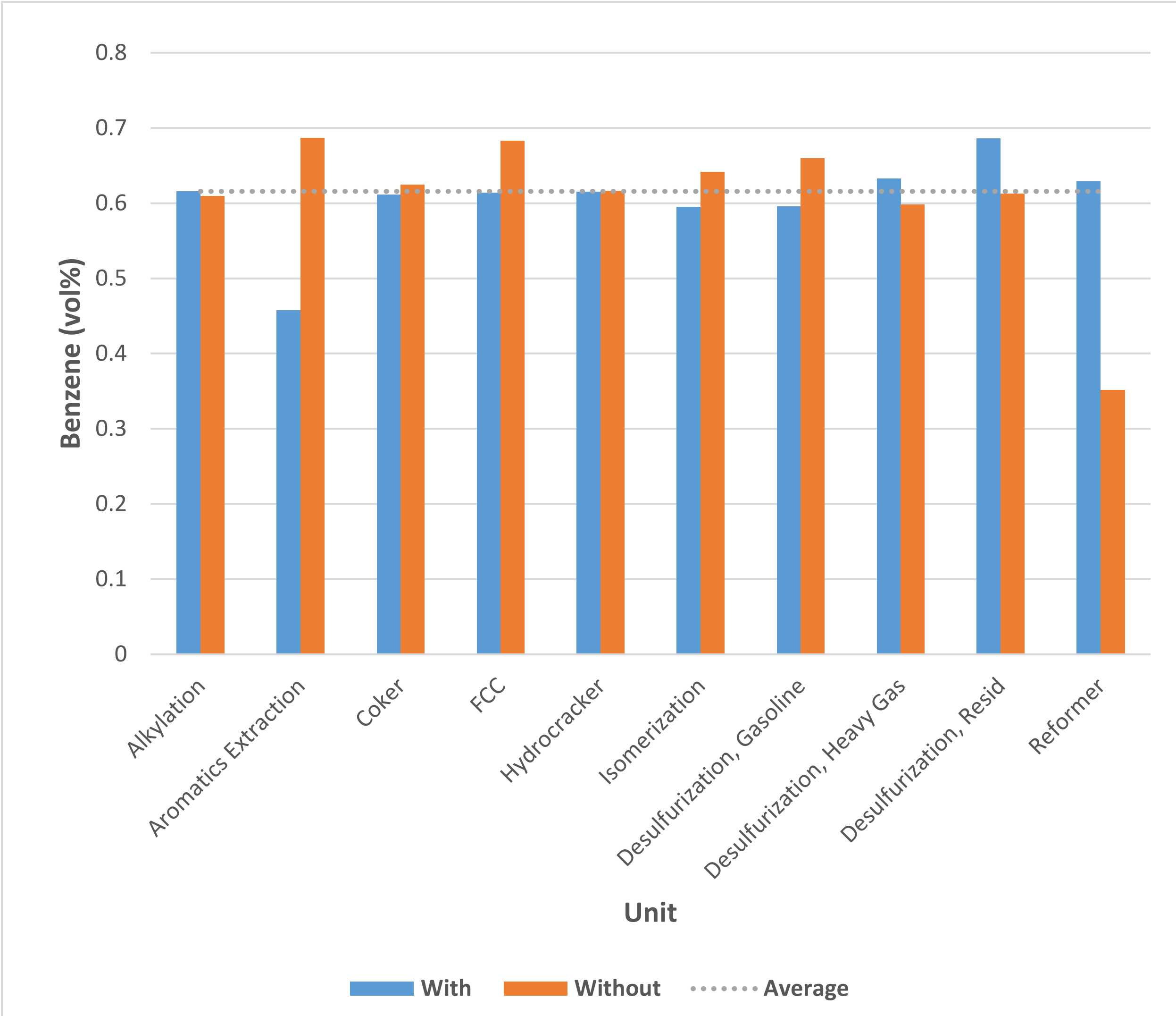

Figure 55 Average Benzene Content by Refinery Unit Type in 2016 (not ethanol-adjusted)

c. Aromatics

Highlights for the following aromatics figures:

- Figure 56 shows that aromatics levels were lower due to the RFG standards, and following the increased use of ethanol, aromatics levels for CG have decreased closer to that of RFG.
- Aromatics levels in the CG gasoline continued to track lower as ethanol has entered the gasoline pool.
- The continued decrease in RFG aromatics levels over time, which was almost completely E10 back in 2006, is likely due to the market forces described above in Section 5.
- Figures 68 through 71 show that, although refinery gasoline aromatics averages have shifted lower, the variance in batch aromatics levels has continued.
- Premium grade gasoline aromatics levels remain consistently above those of regular grade due to the higher octane specifications of premium gasoline.
- The RFG survey and Alliance survey data align very well with the batch data over time.
- Figures 74 to 77 show that, refinery size, complexity index, crude oil API gravity or crude oil sulfur content have no discernable impact on gasoline aromatics levels.
- Figure 78 shows that refineries with reformer units, and refineries without fluidized catalytic cracker units and without alkylation units have comparatively higher aromatics levels.

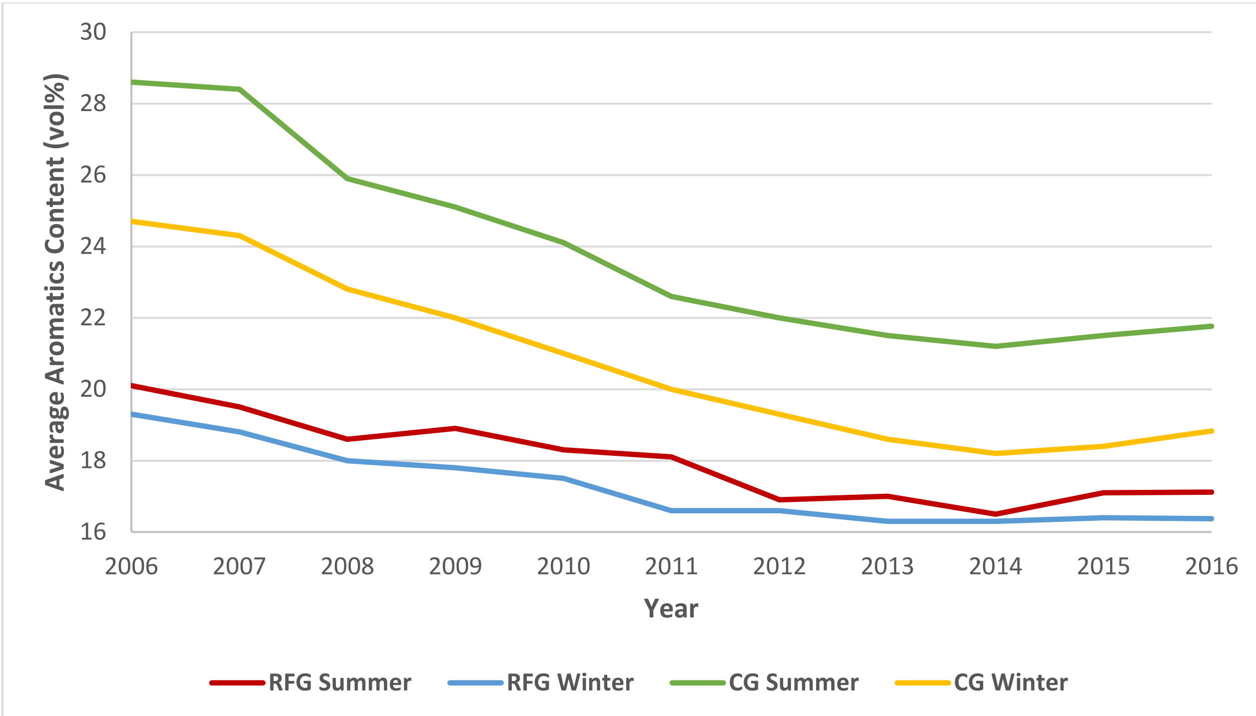

Figure 56 Aromatics Trends Summer versus Winter (ethanol-adjusted)

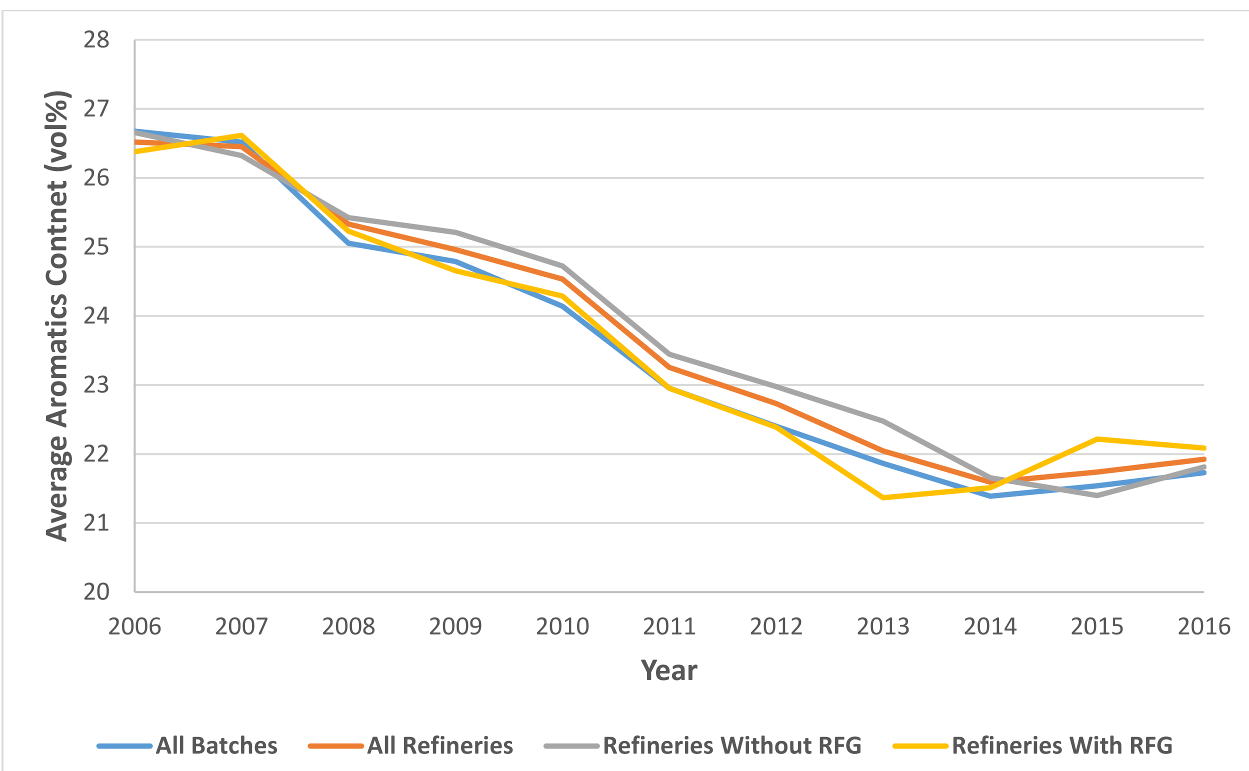

Figure 57 Average CG Aromatics Content by Refinery Type (not ethanol-adjusted)

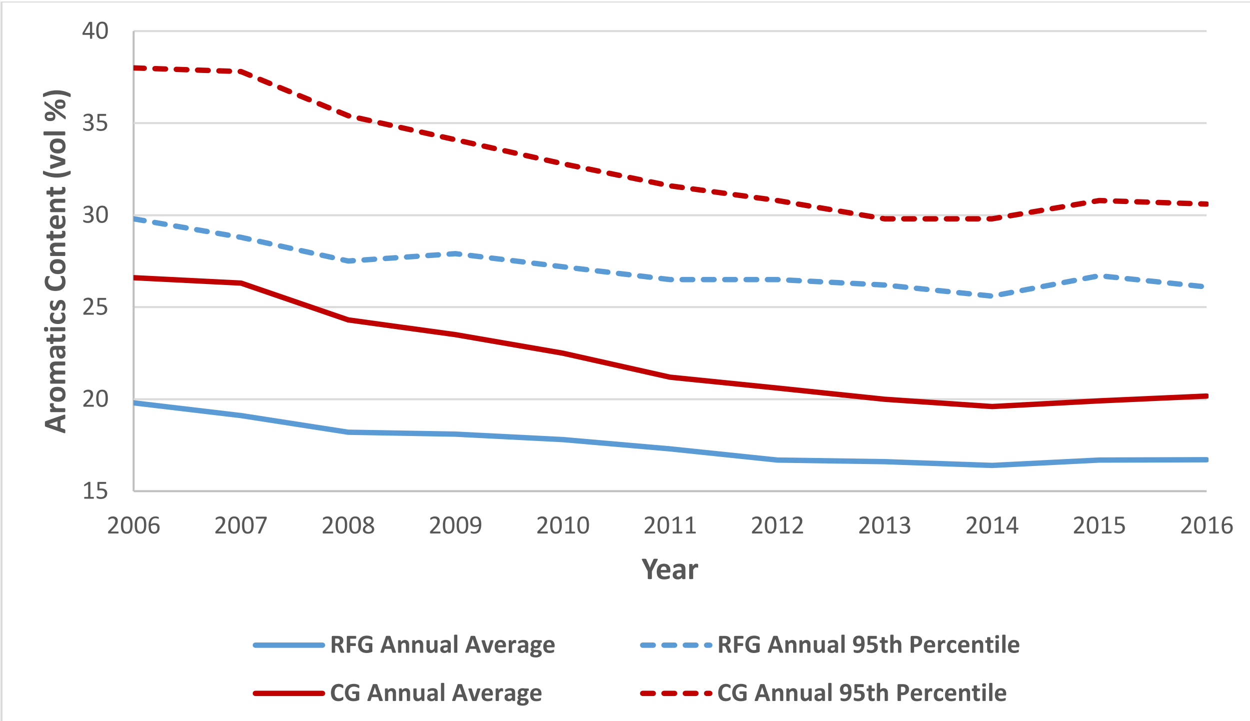

Figure 58 Aromatics Trends 95th Percentile vs Average (ethanol-adjusted)

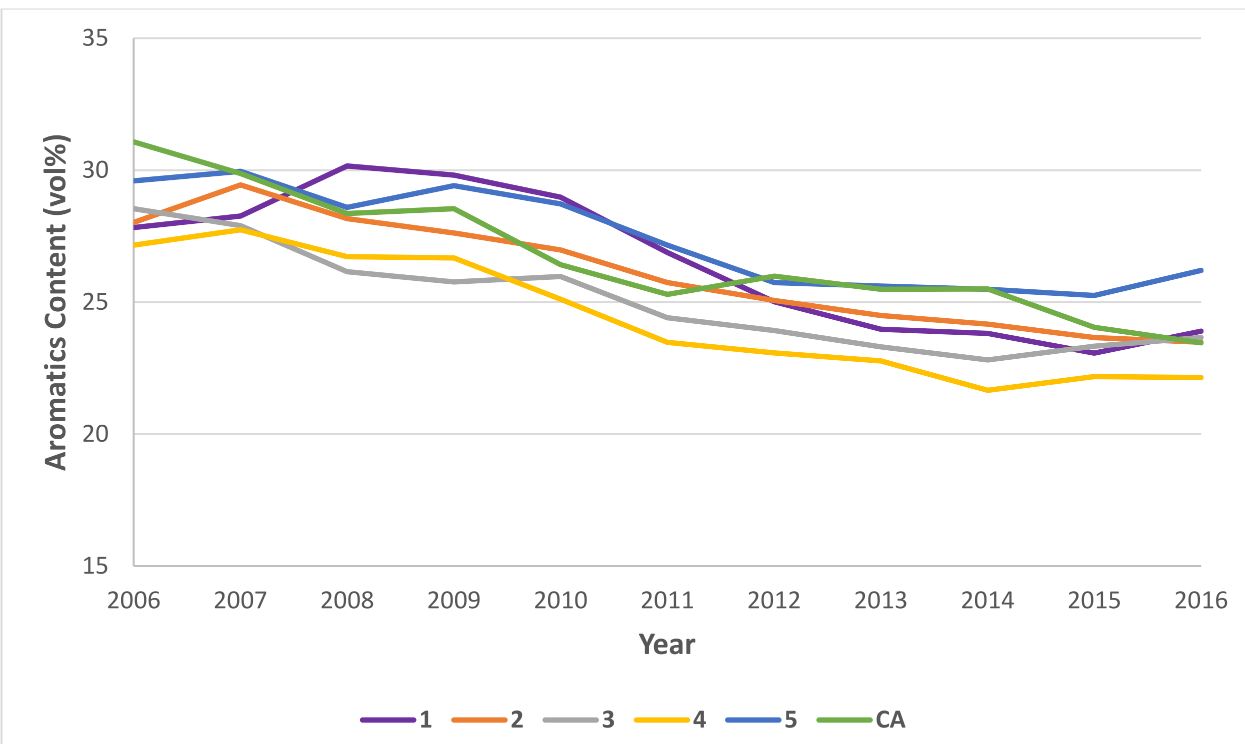

Figure 59 CG Summer Aromatics by PADD (not ethanol-adjusted)

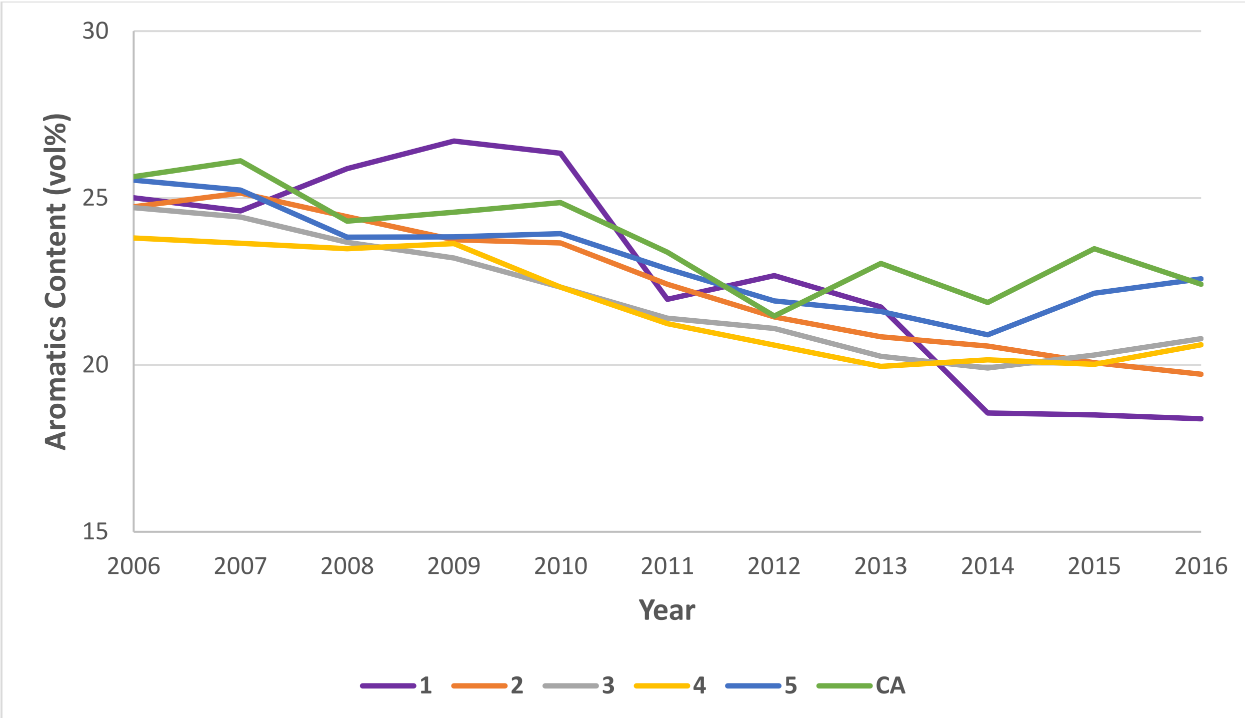

Figure 60 CG Winter Aromatics by PADD (not ethanol-adjusted)

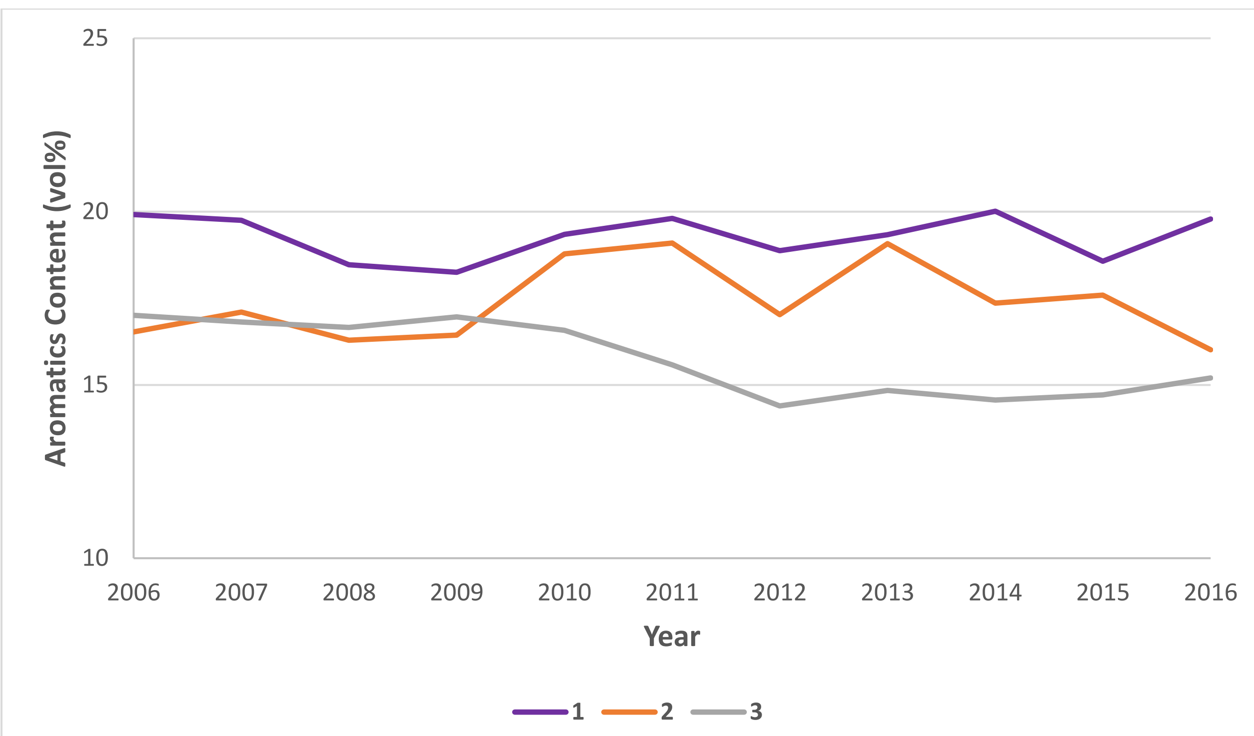

Figure 61 RFG Summer Aromatics by PADD Produced from Batch Data

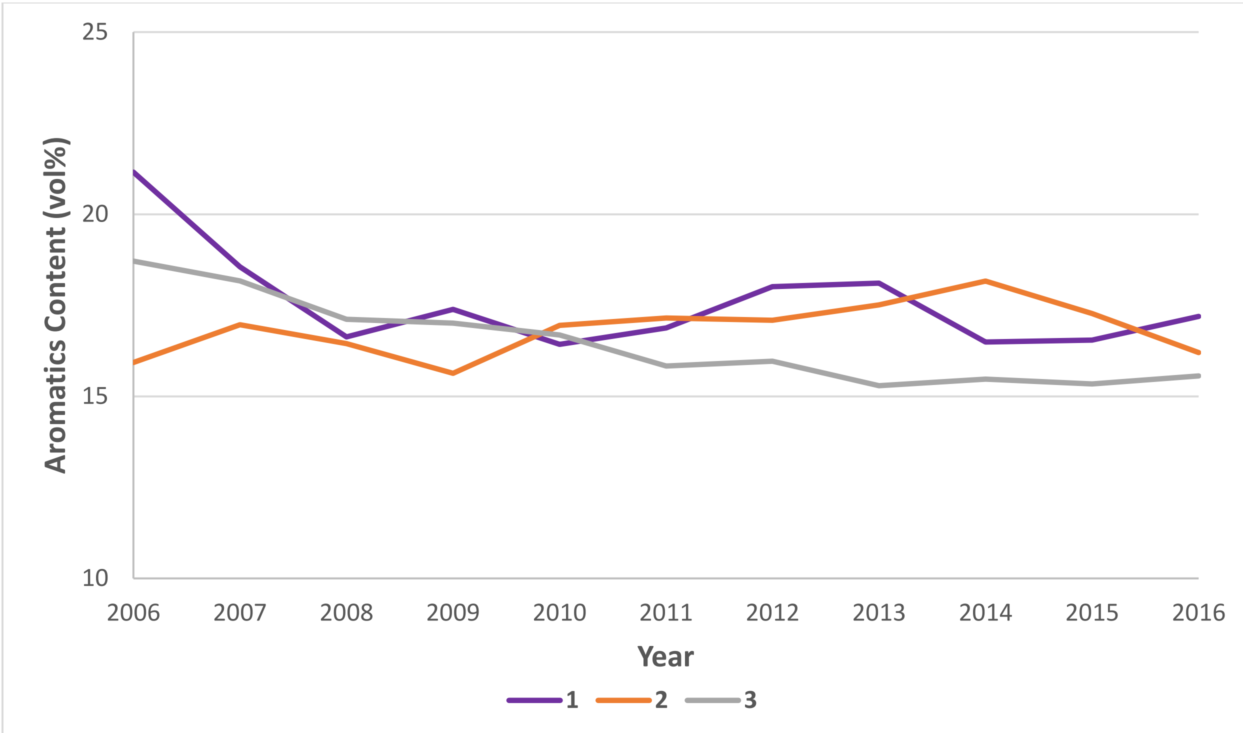

Figure 62 RFG Winter Aromatics by PADD Produced from Batch Data

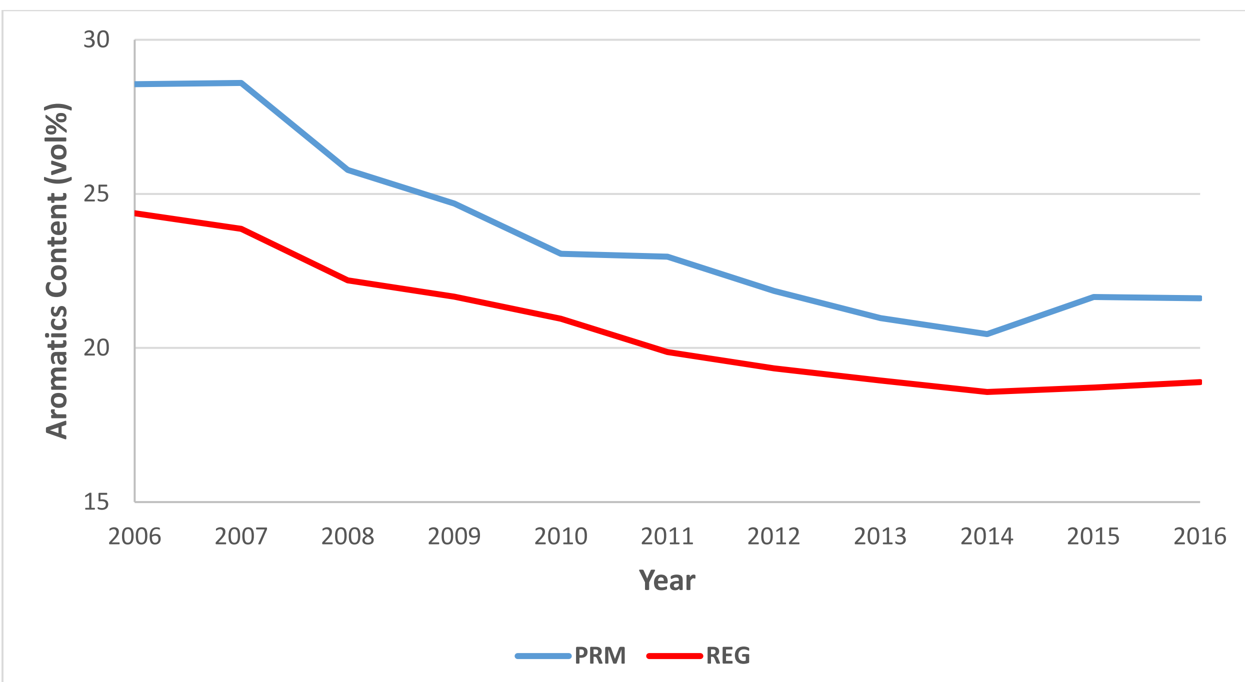

Figure 63 Regular versus Premium CG and RFG Aromatics (ethanol-adjusted)

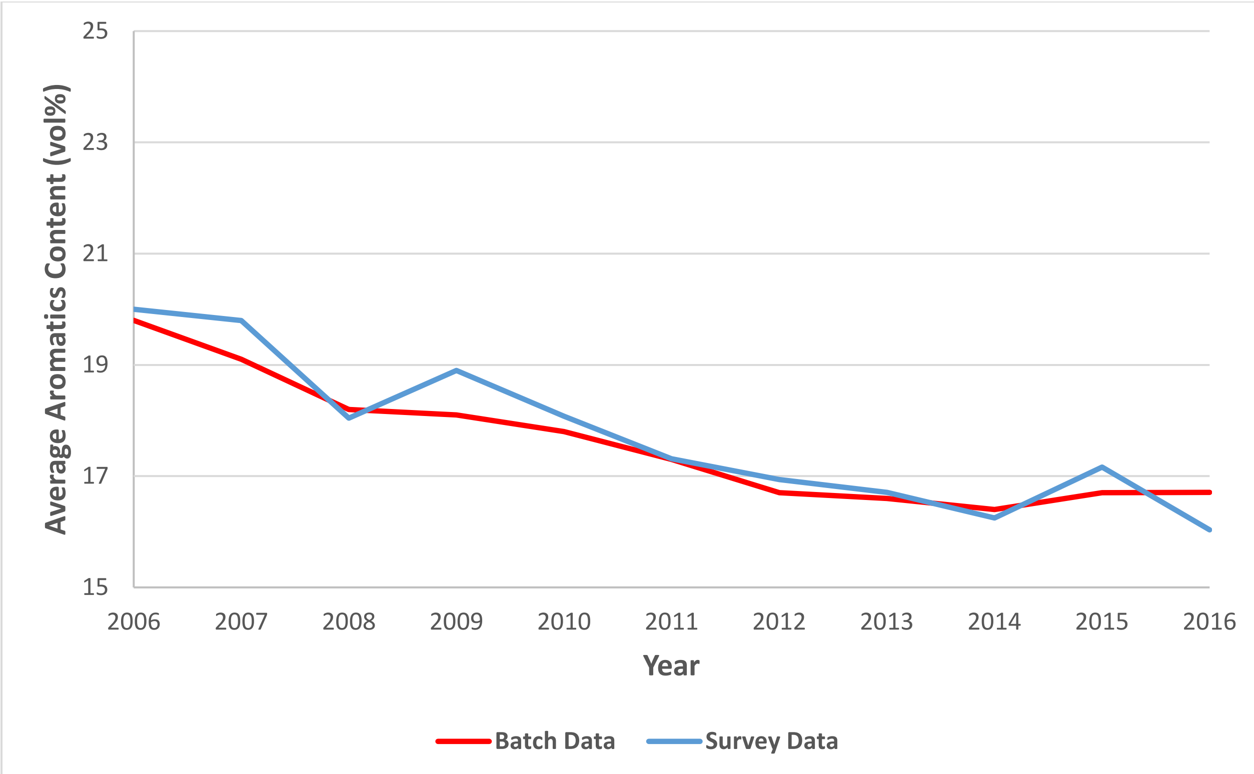

Figure 64 Aromatics RFG Batch versus Survey

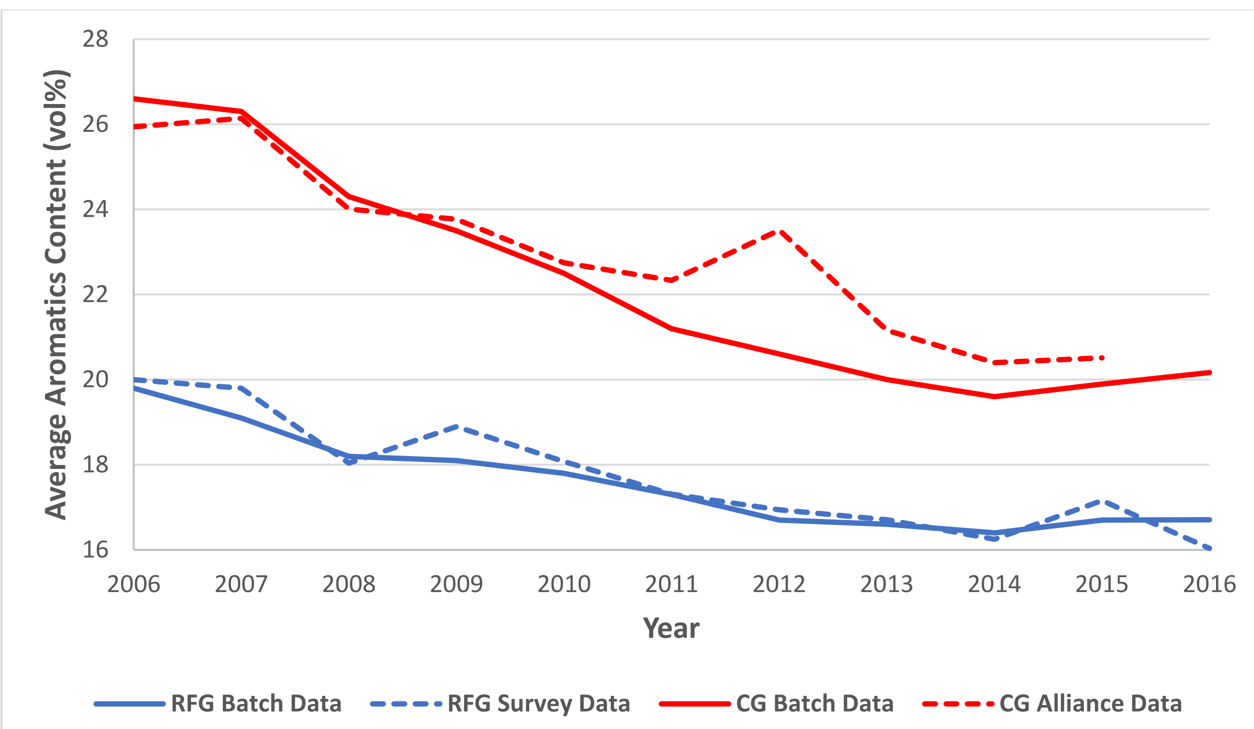

Figure 65 Comparing Batch, Survey, and Alliance data (ethanol-adjusted)

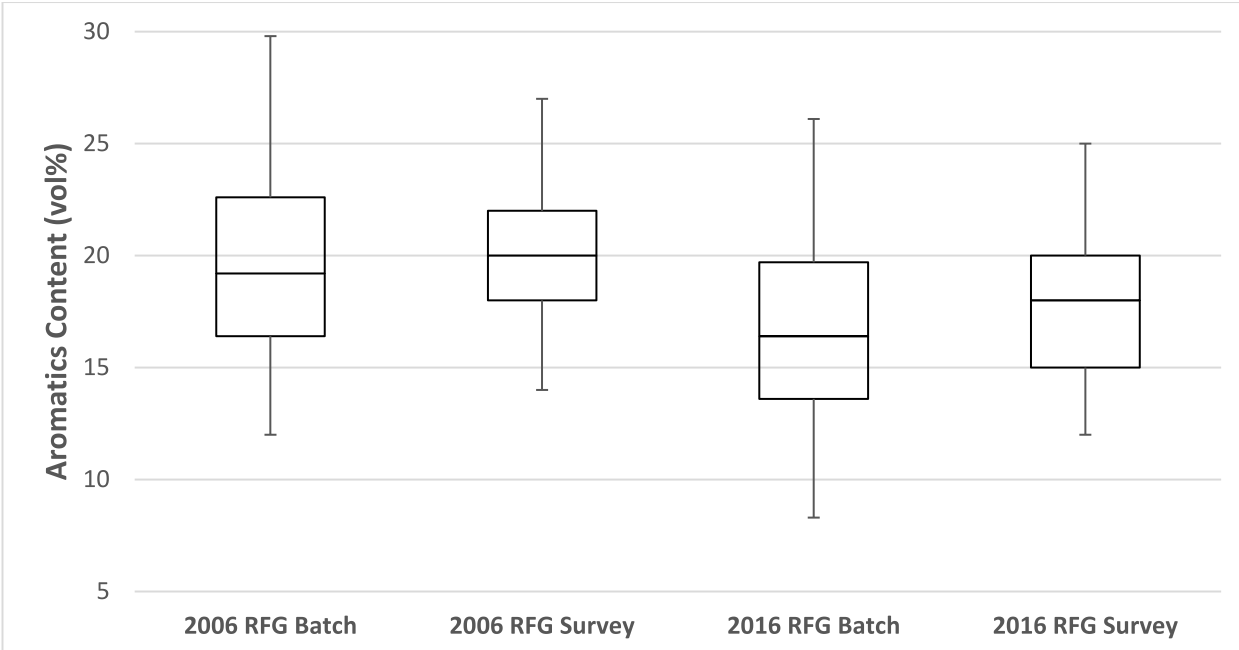

Figure 66 Aromatics RFG Box and Whiskers (5%, 25%, median, 75%, 95%)

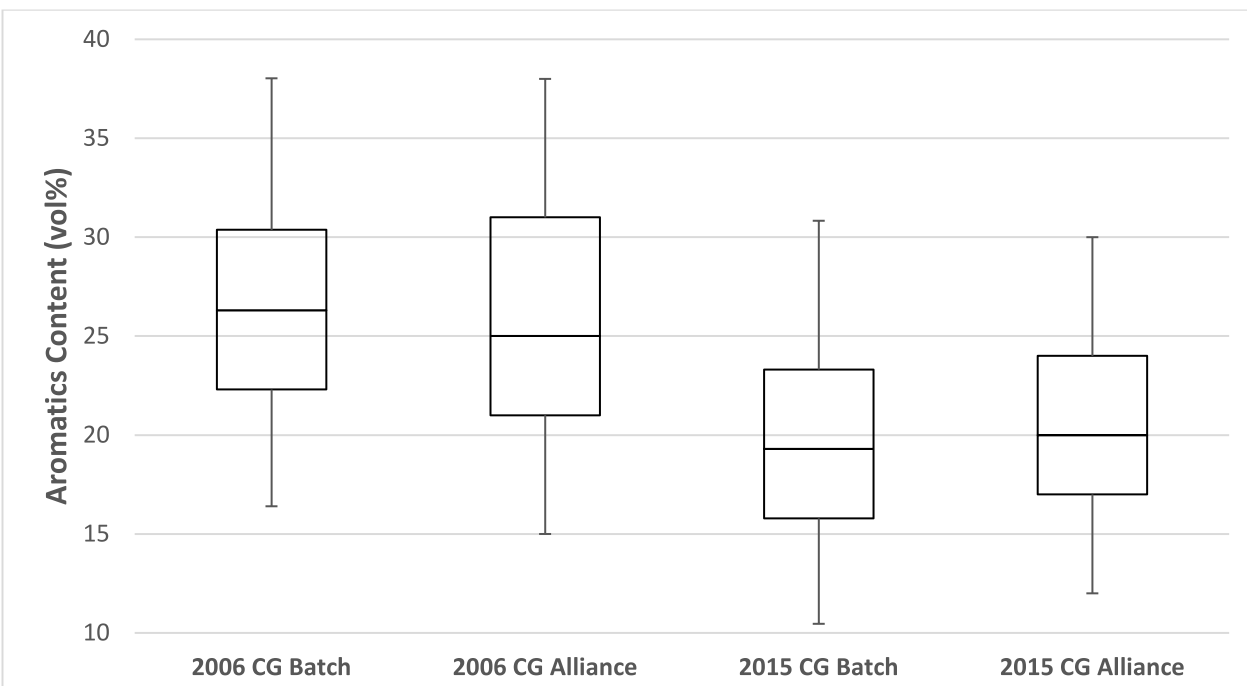

Figure 67 Aromatics CG Box and Whiskers (5%, 25%, median, 75%, 95%; ethanol-adjusted)

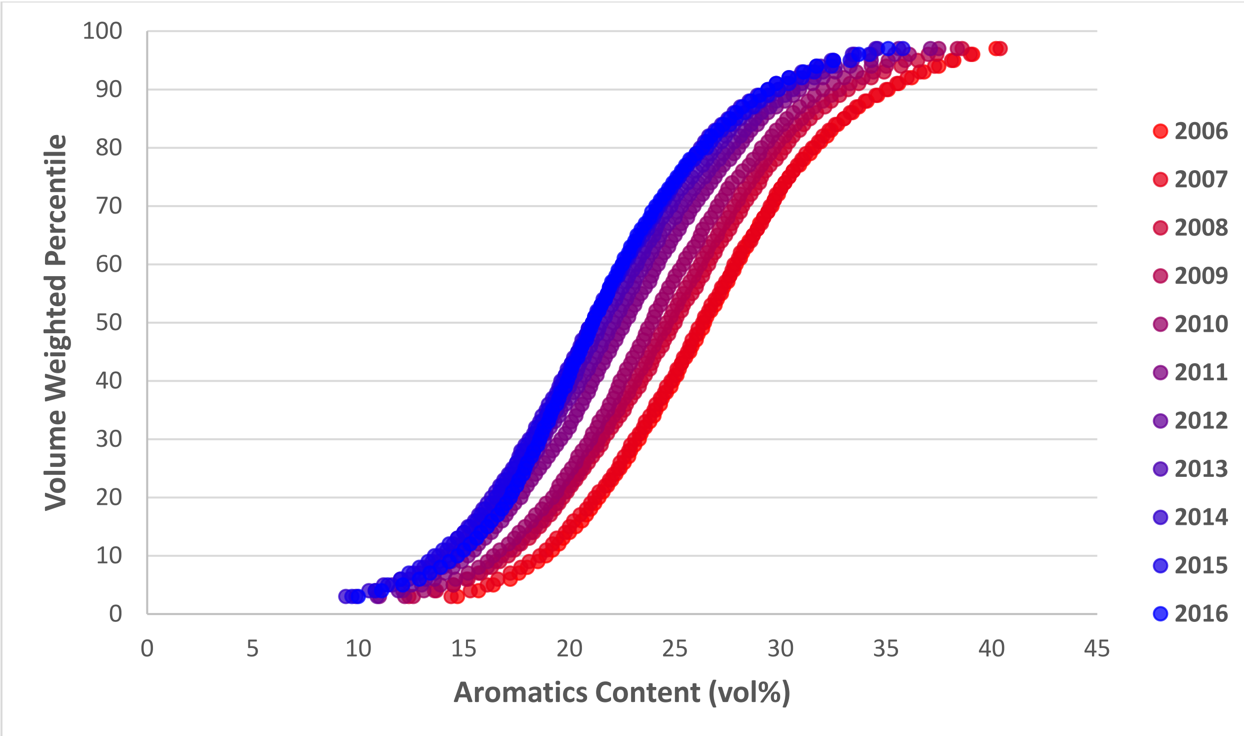

Figure 68 Aromatics Layered Percentile CG (not ethanol-adjusted)

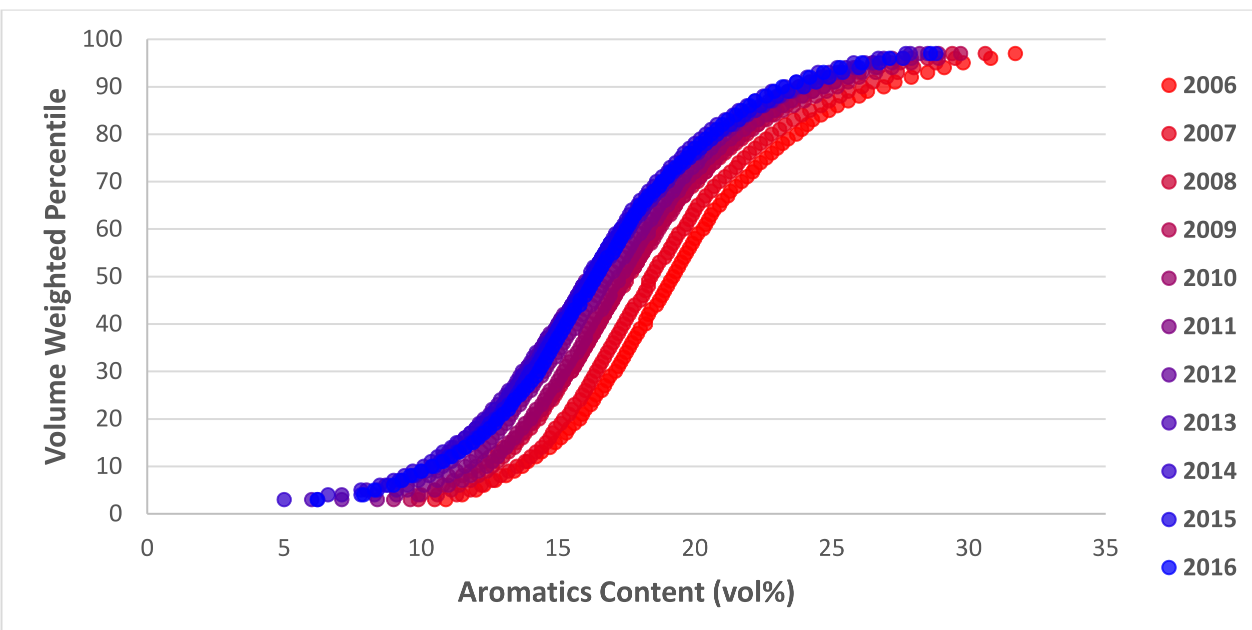

Figure 69 Aromatics Layered Percentile RFG

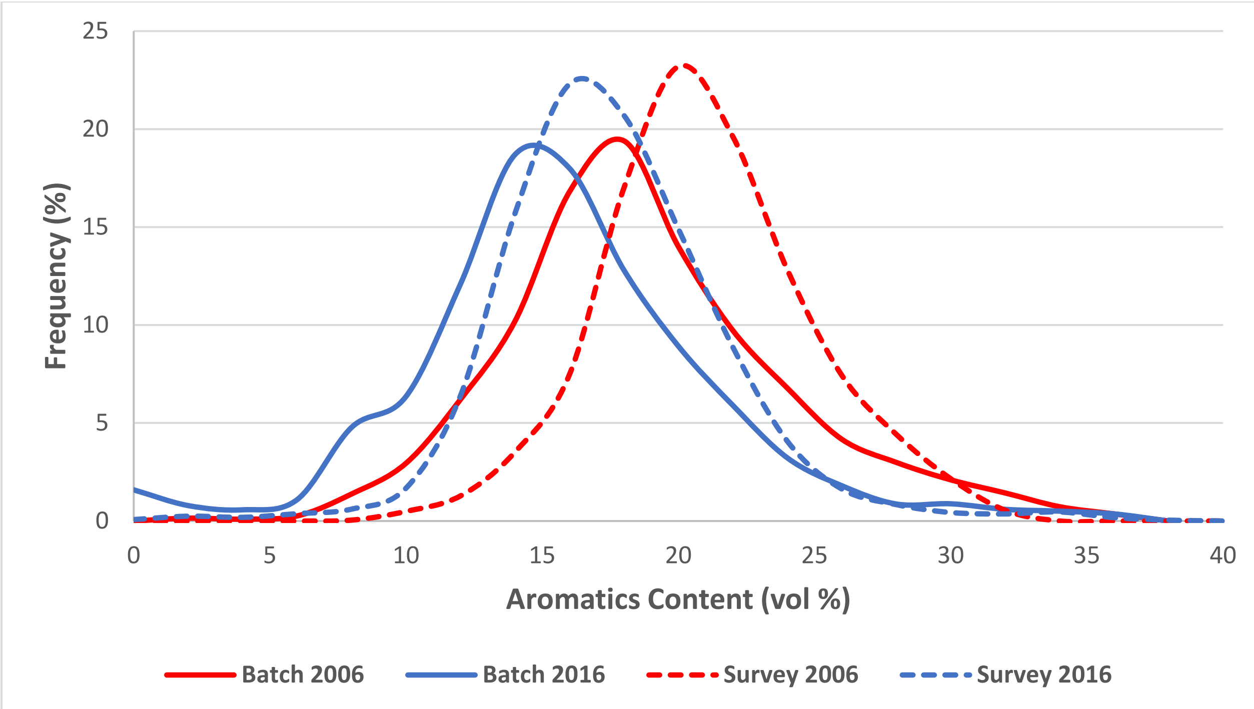

Figure 70 Aromatics RFG 2006 versus 2016 Histogram (bucket size = 0.1 vol%)

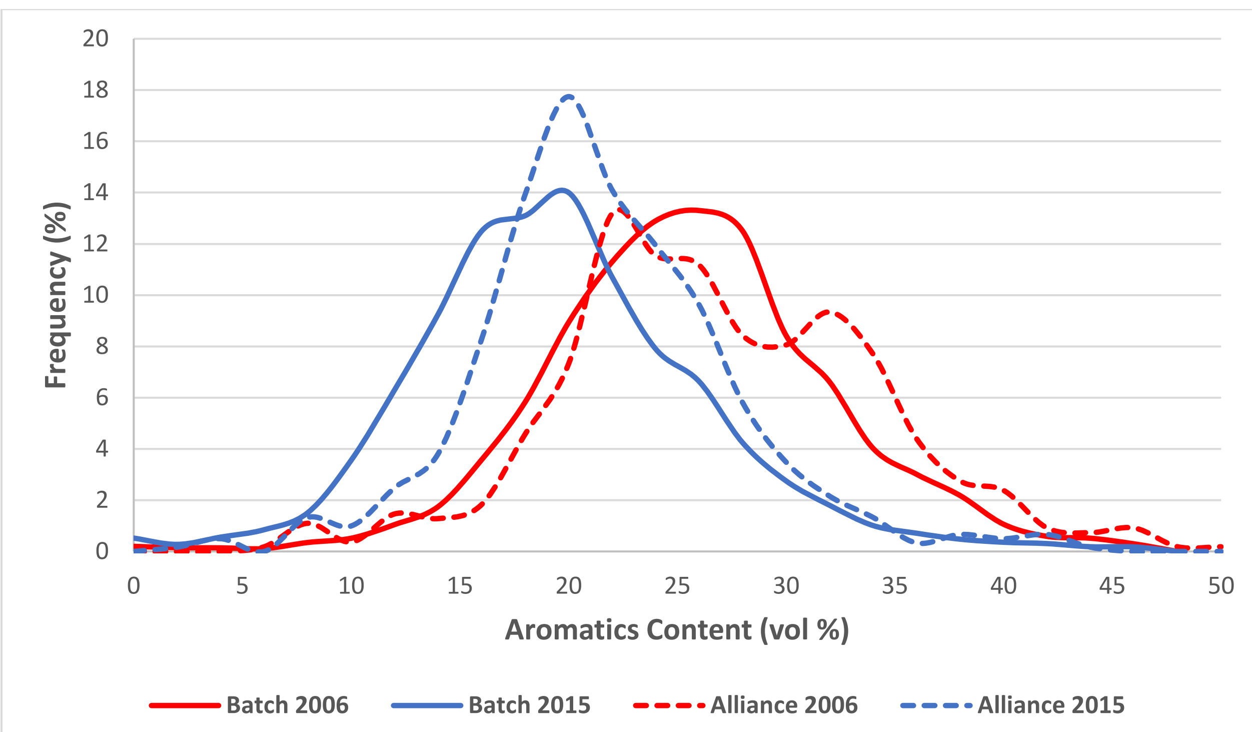

Figure 71 Aromatics CG 2006 versus 2015 Histogram (bucket size = 0.1 vol%; ethanol-adjusted)

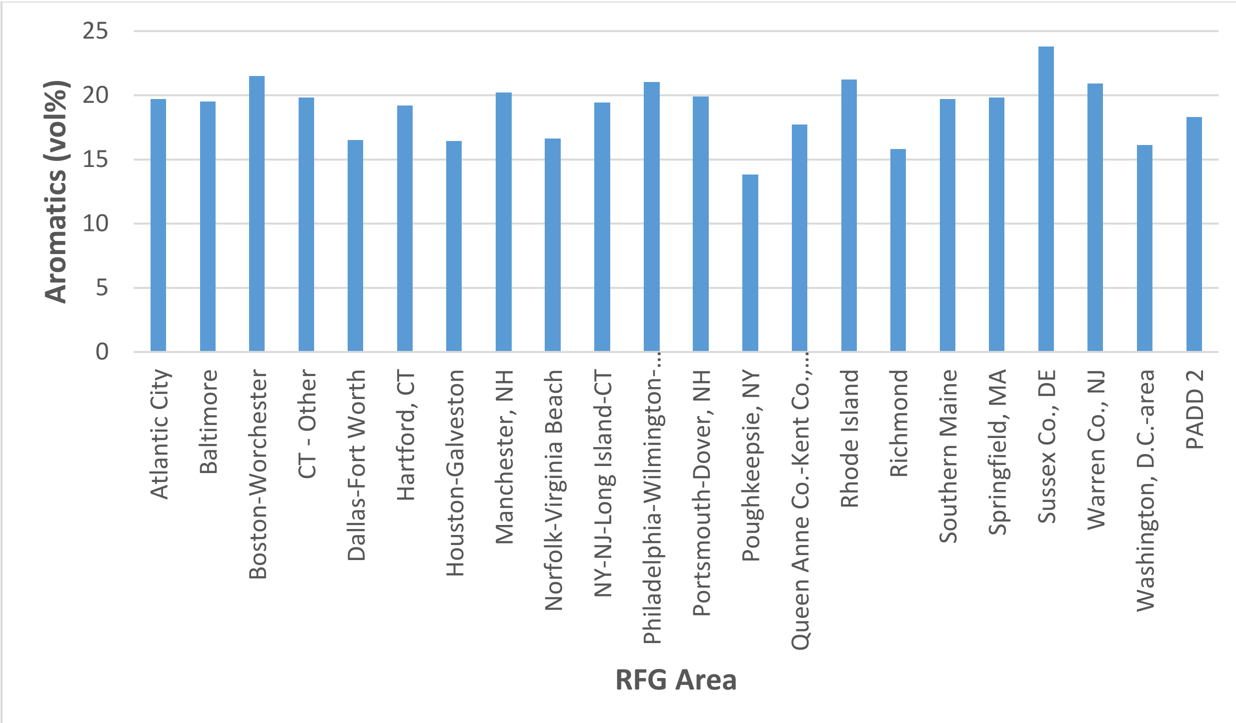

Figure 72 Summertime Aromatics Levels by RFG Area in 2016 from RFG Survey Data

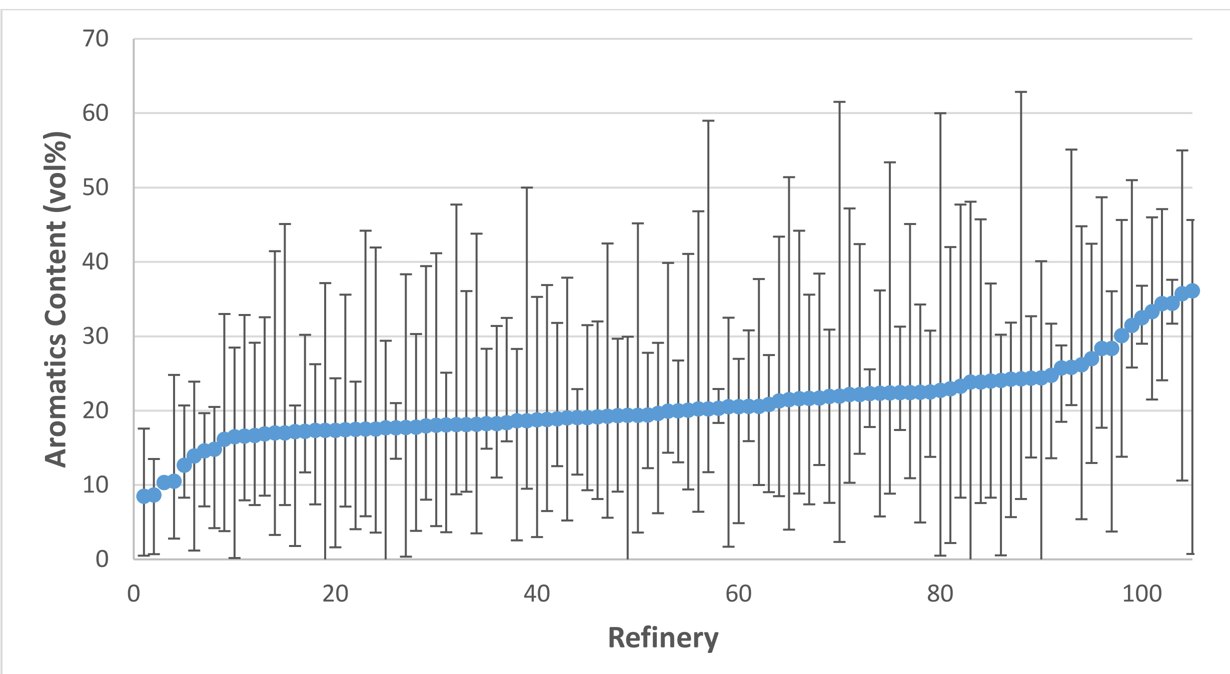

Figure 73 Aromatics content by individual refinery from lowest to highest average (average, minimum and maximum for CG and RFG in 2016; not ethanol-adjusted)

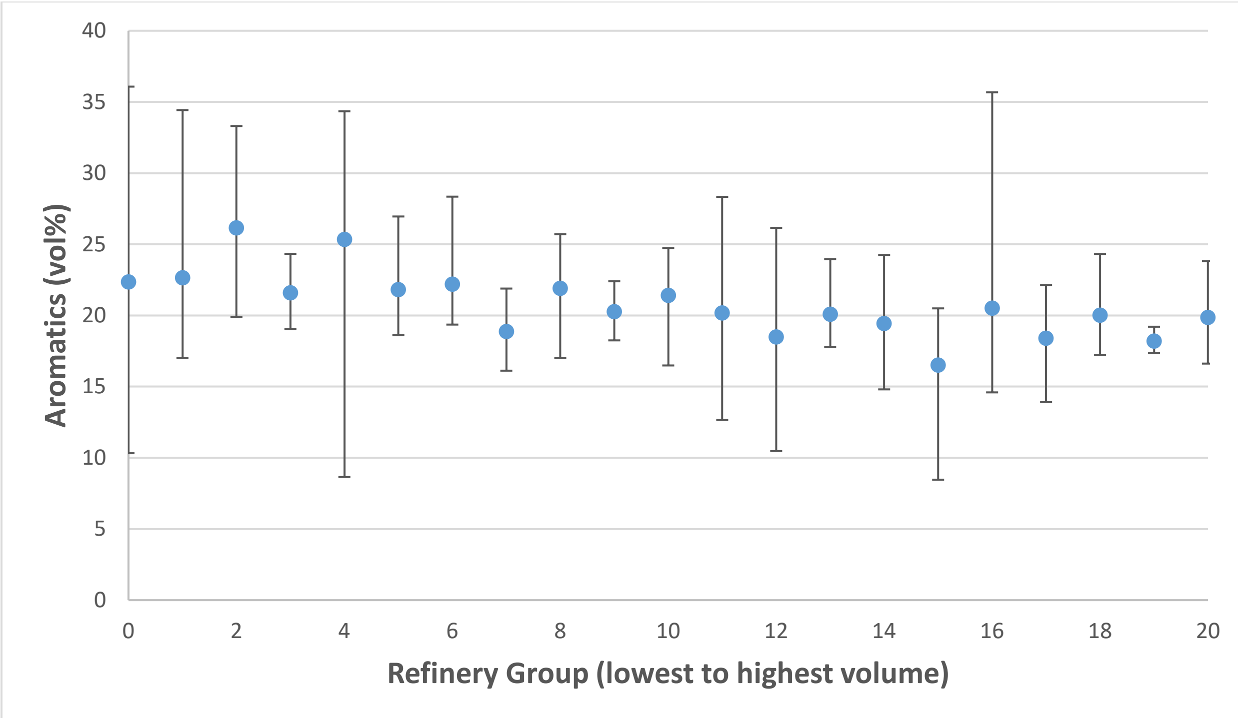

Figure 74 Aromatics content for refineries grouped by volume output (groups of five refineries; average of the average, minimum and maximum values for CG and RFG 2016; not ethanol-adjusted)

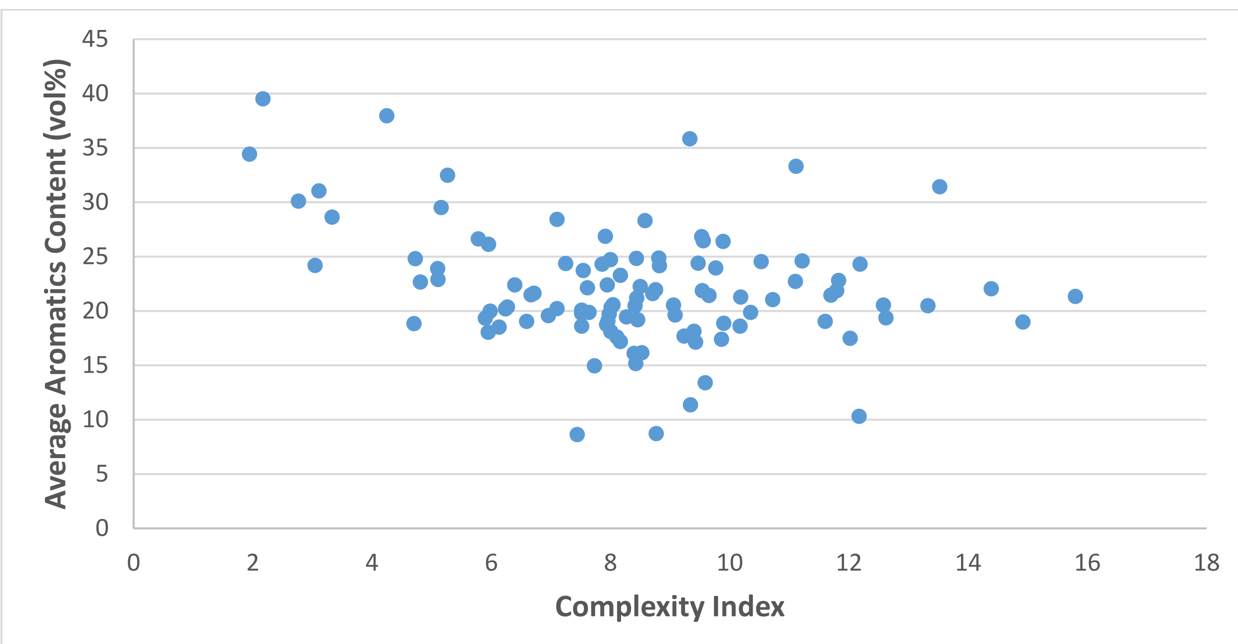

Figure 75 Average Gasoline Aromatics Content by Refinery Complexity Index in 2016 (not ethanol-adjusted)

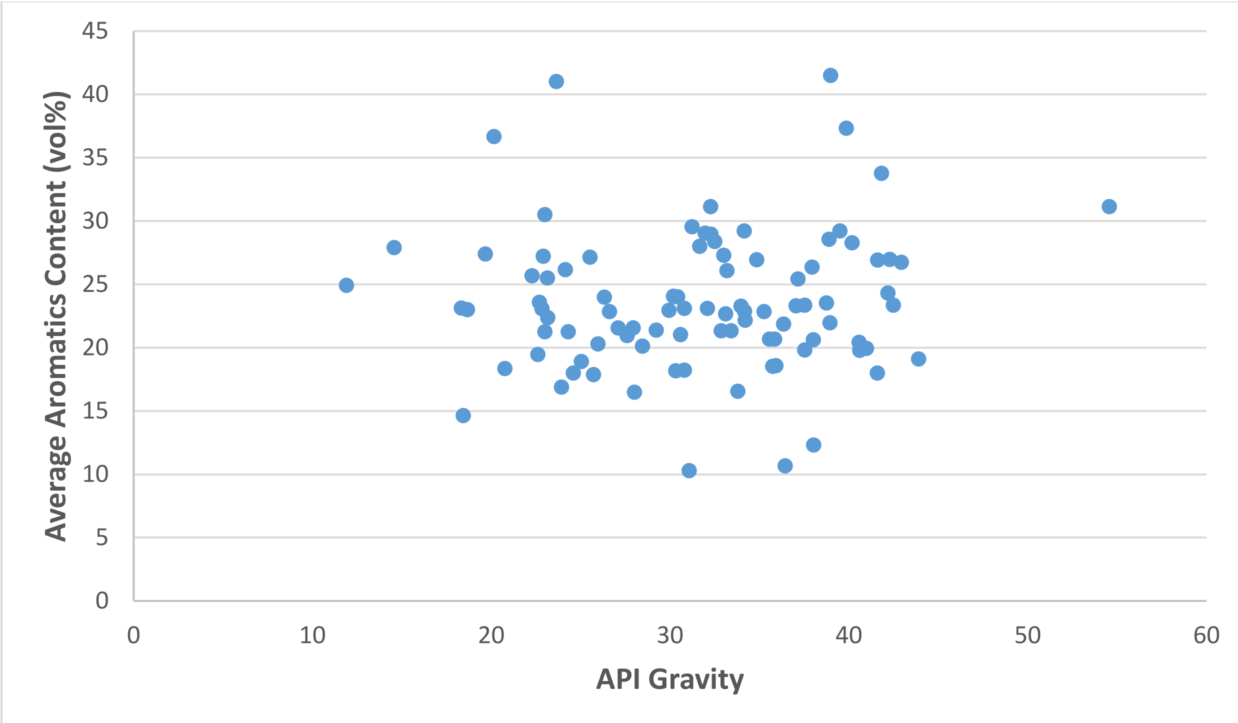

Figure 76 Gasoline Aromatics Content by Crude Oil API Gravity in 2011 (not ethanol-adjusted)

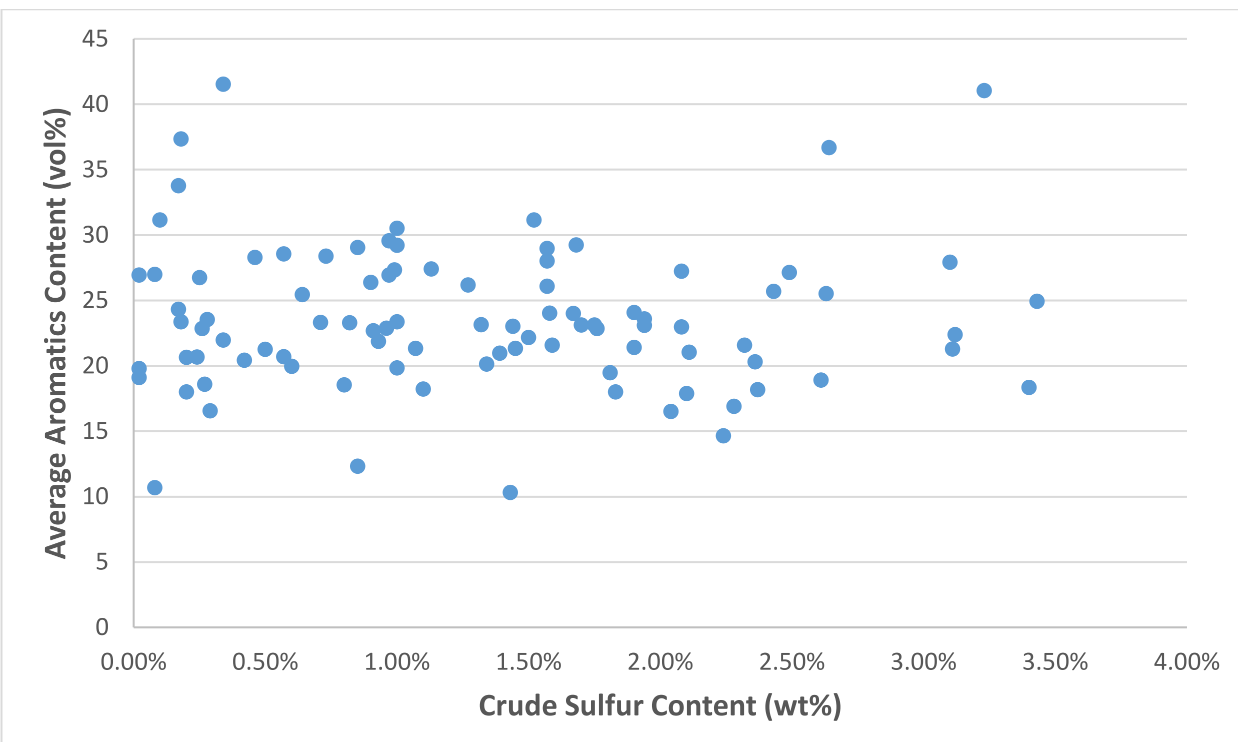

Figure 77 Gasoline Aromatics Content by Crude Oil Sulfur Content in 2011 (not ethanol-adjusted)

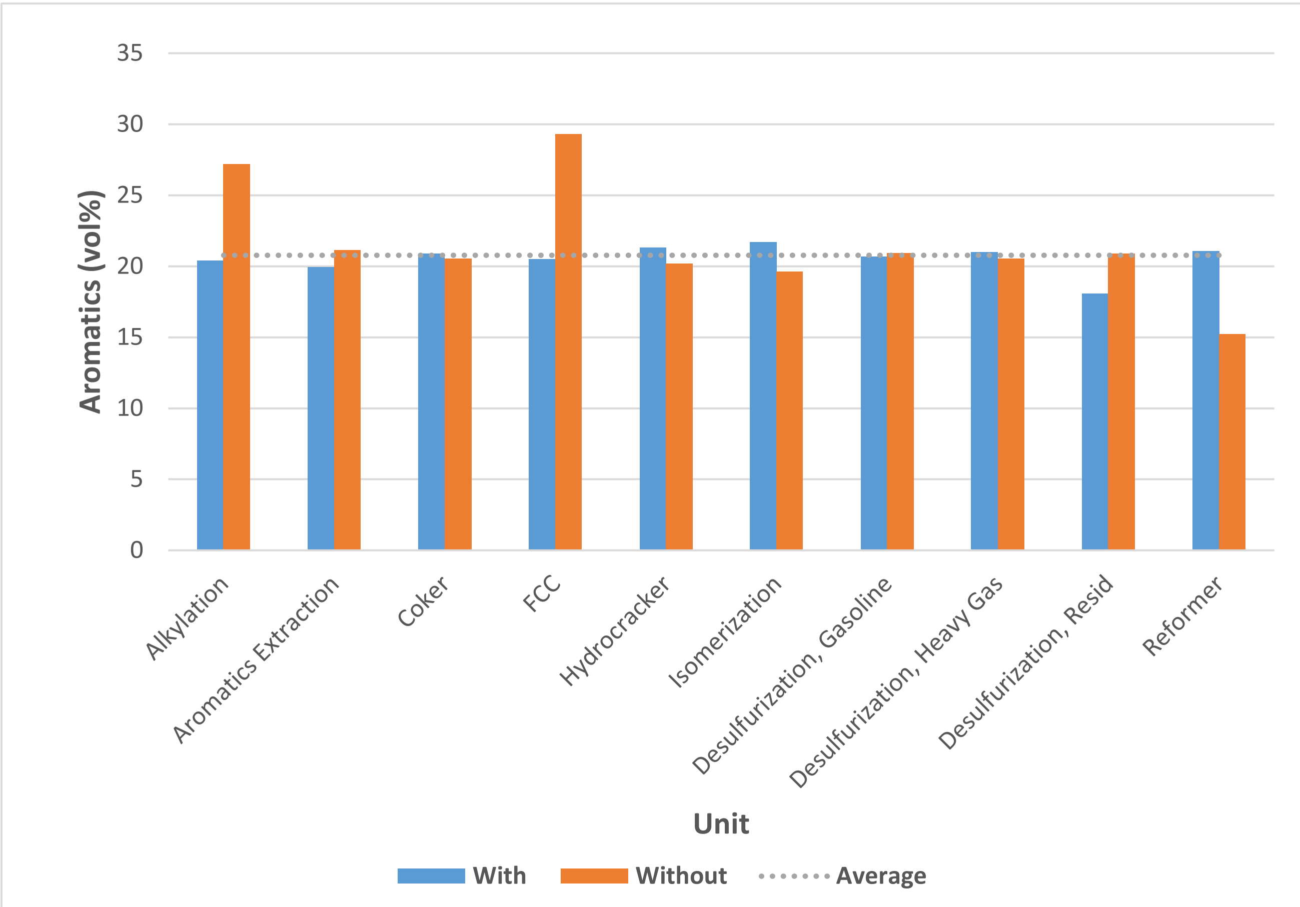

Figure 78 Average Aromatics Content by Refinery Unit Type in 2016 (not ethanol-adjusted)

d. RVP

Highlights for the following RVP figures:

- Except for summertime RFG which is controlled by the RFG hydrocarbon VOC standard, the RVP of wintertime RFG and CG and summertime CG have experienced increases in RVP over time due to the blending of ethanol,
    - Comparisons of the ethanol-adjusted versus not ethanol-adjusted figures highlight the RVP effect of ethanol.
    - The marketplace may have also played a minor factor in increasing RVP levels over time due to the lower relative price of light gasoline blendstocks such as butane.
- A trend for lower sulfur in summertime RFG allowed summertime RFG RVP levels to increase slightly while still meeting the RFG summertime VOC standard.
- Premium gasoline is typically lower in RVP than regular grade gasoline. This may be if premium gasoline is disproportionately sold in urban areas which have RVP controlled to a lower level.
- The unique RVP profile in Figure 90 is due to the variety of RVP standards which apply throughout the United States – this leads to a wide range of RVP levels in the CG pool.
- The RFG survey data show very good agreement with the batch data on RVP levels.
- The Alliance survey is not designed to and does not reflect all the different RVP levels across the country.
    - The stations it surveys result in a greater number of lower RVP cities than would be proportionate nationwide.
- Figures 93 to 96 show that, refinery size, complexity index, crude oil API gravity or crude oil sulfur content have no discernable impact on gasoline RVP levels.
- Refinery unit type does not correlate with RVP differences, and those which seem to show a correlation are likely due to coincidence.

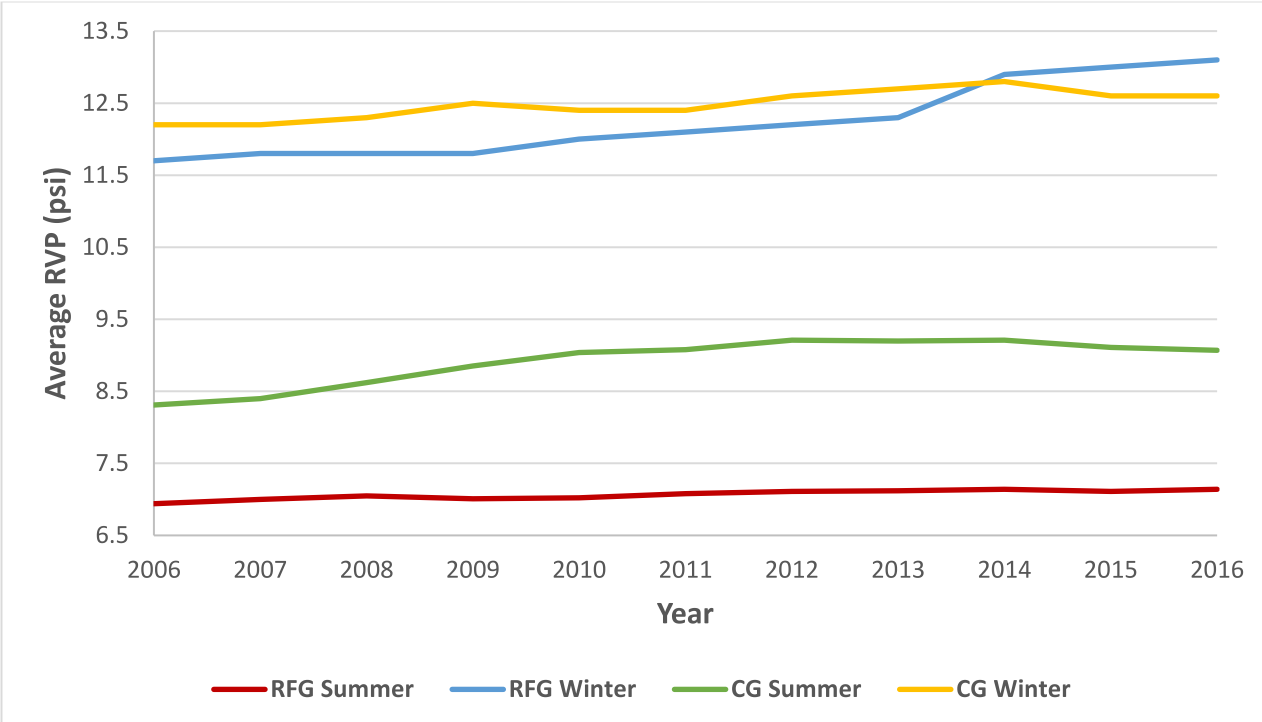

Figure 79 RVP Trends Summer versus Winter (ethanol-adjusted)

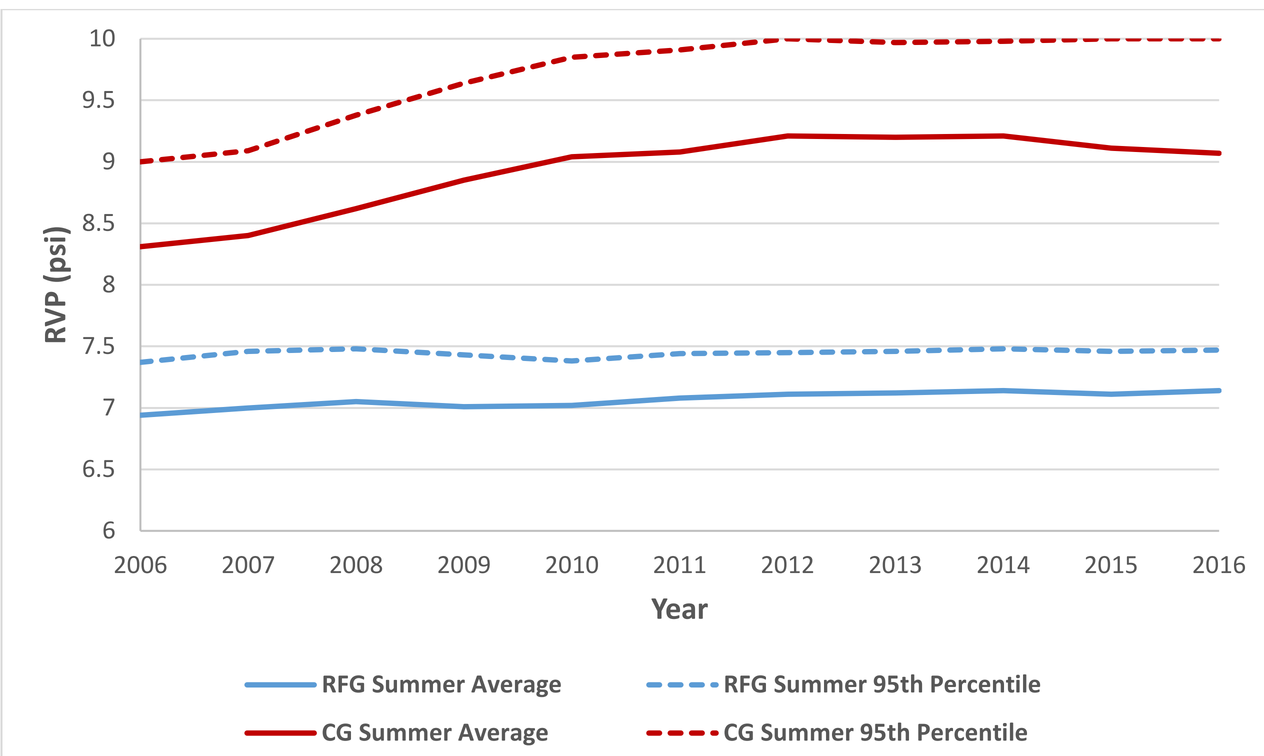

Figure 80 RVP Summer Trends 95th Percentile versus Average (ethanol-adjusted)

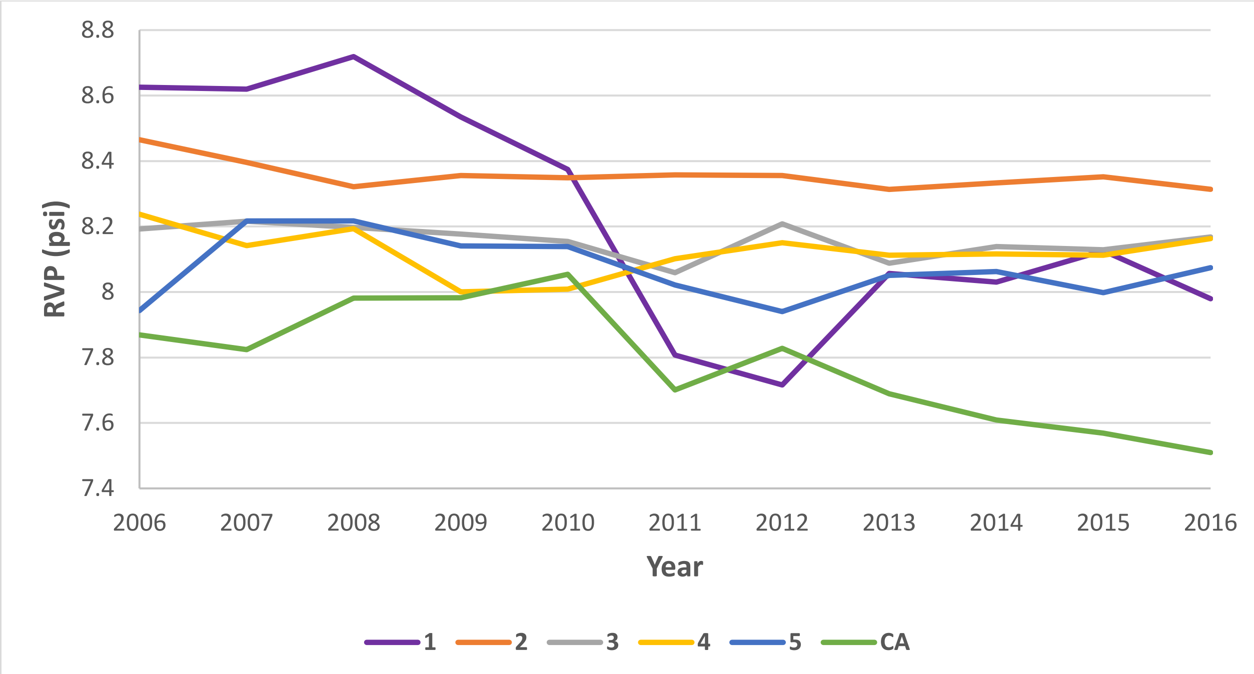

Figure 81 CG Summer RVP by PADD (not ethanol-adjusted)

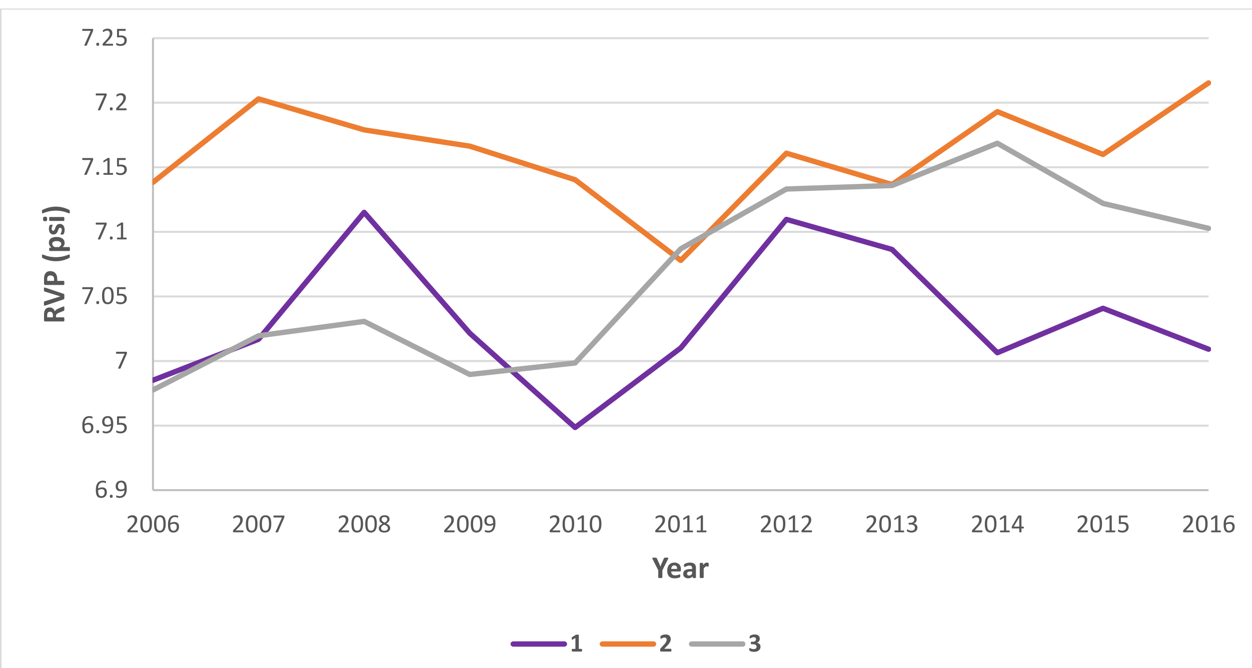

Figure 82 RFG Summer RVP by PADD Produced from Batch Data

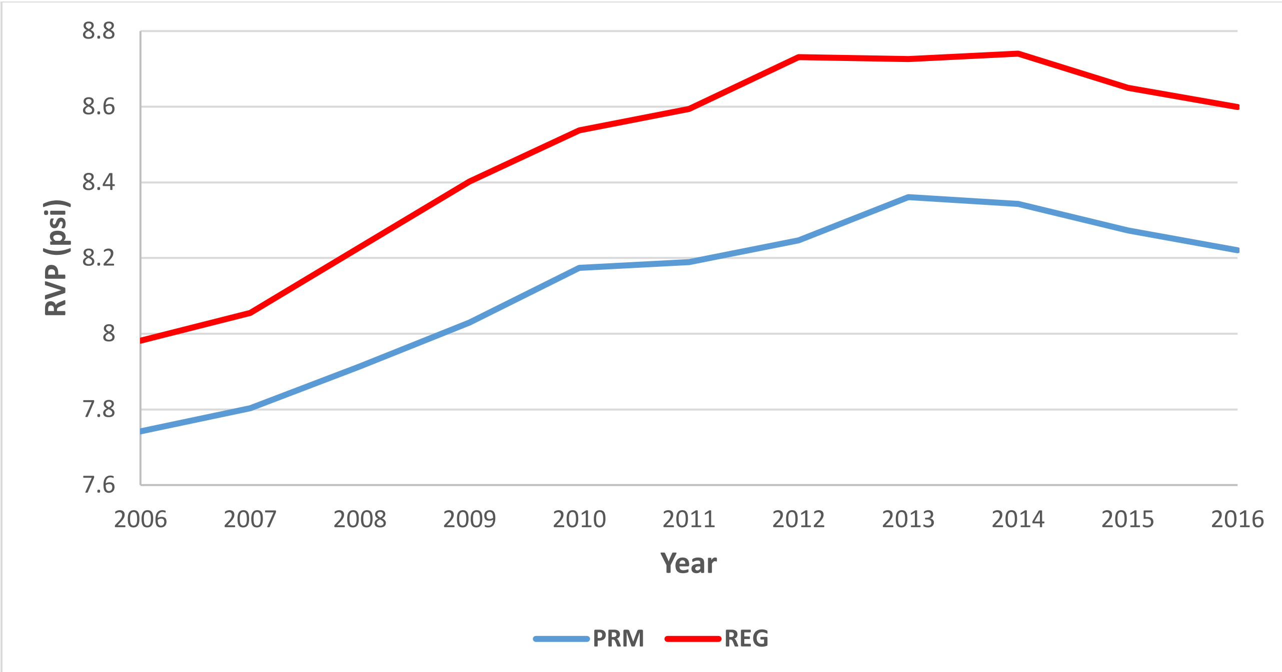

Figure 83 Regular versus Premium CG and RFG Summer RVP (ethanol-adjusted)

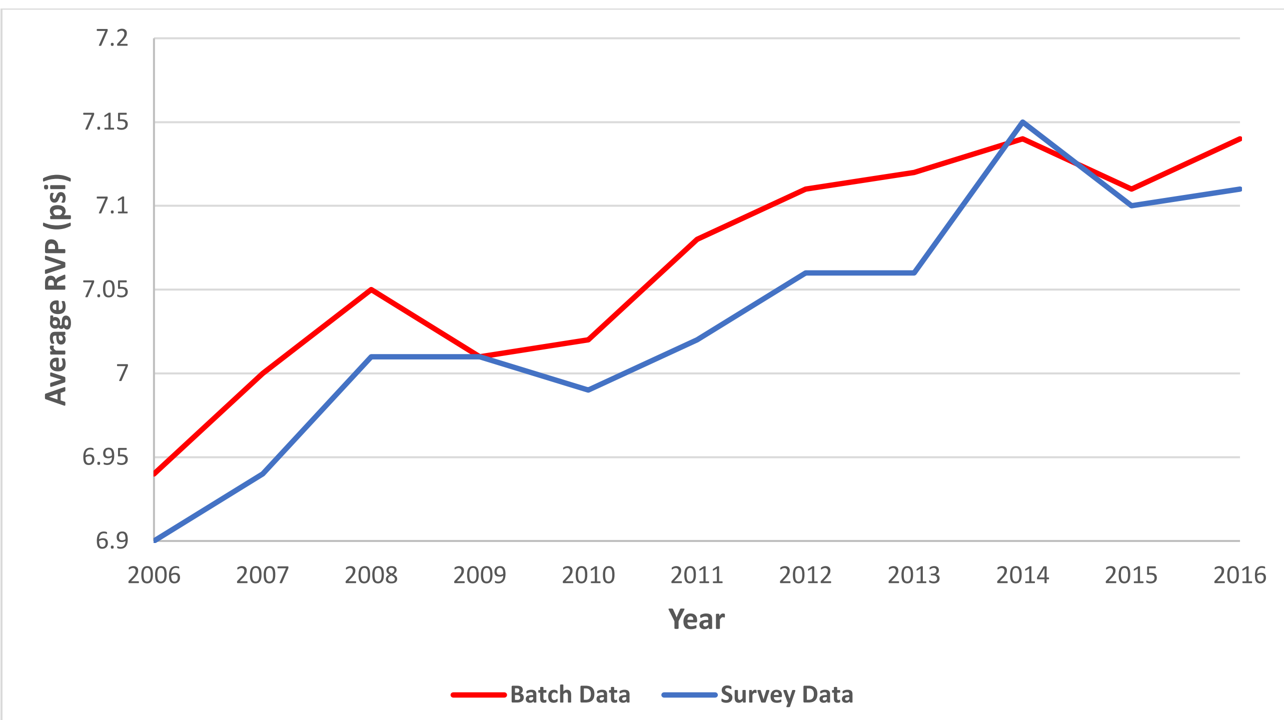

Figure 84 Summer RVP RFG Batch versus Survey

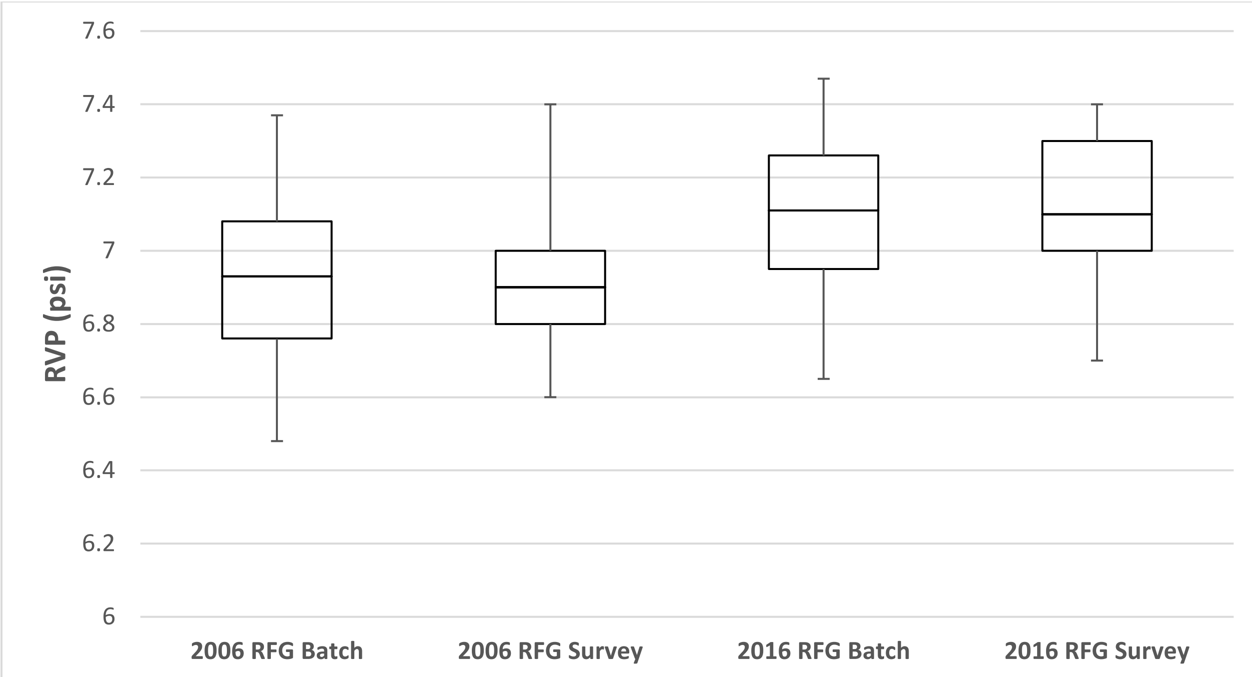

Figure 85 Summer RVP RFG Box and Whiskers (5%, 25%, median, 75%, 95%)

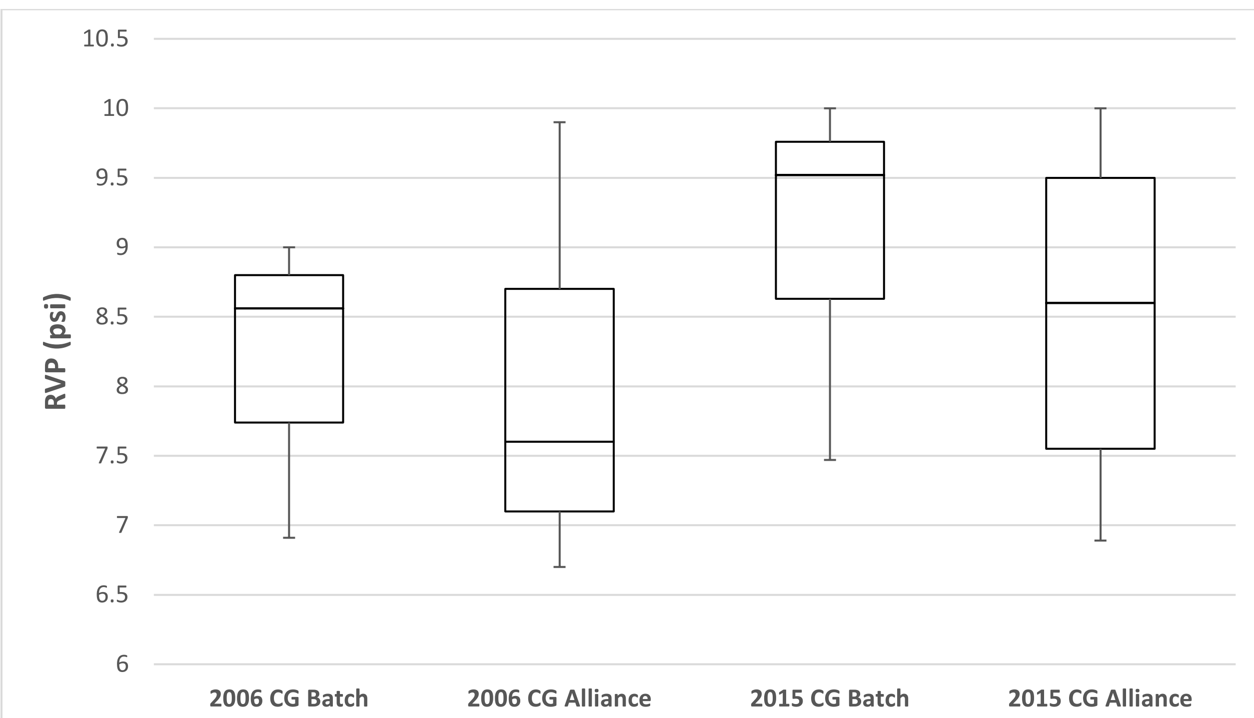

Figure 86 Summer RVP CG Box and Whiskers (5%, 25%, median, 75%, 95%; ethanol-adjusted)

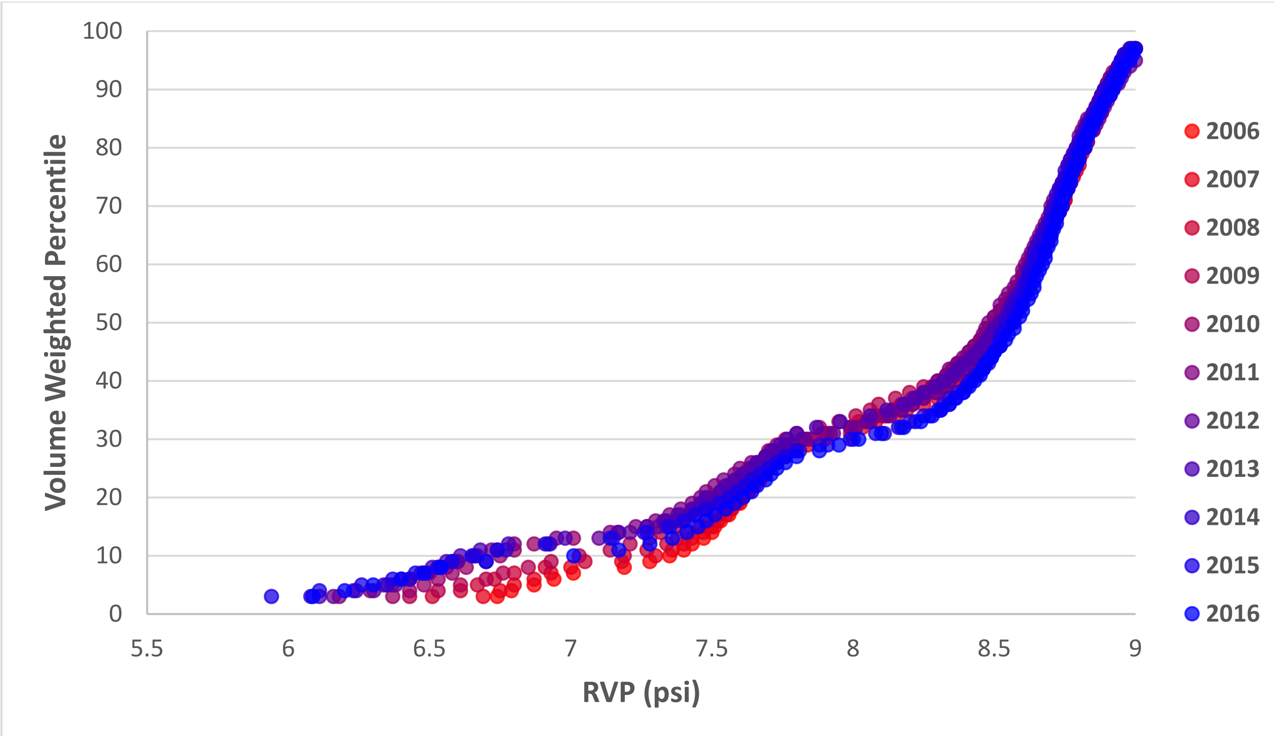

Figure 87 RVP Summer Layered Percentile CG (not ethanol-adjusted)

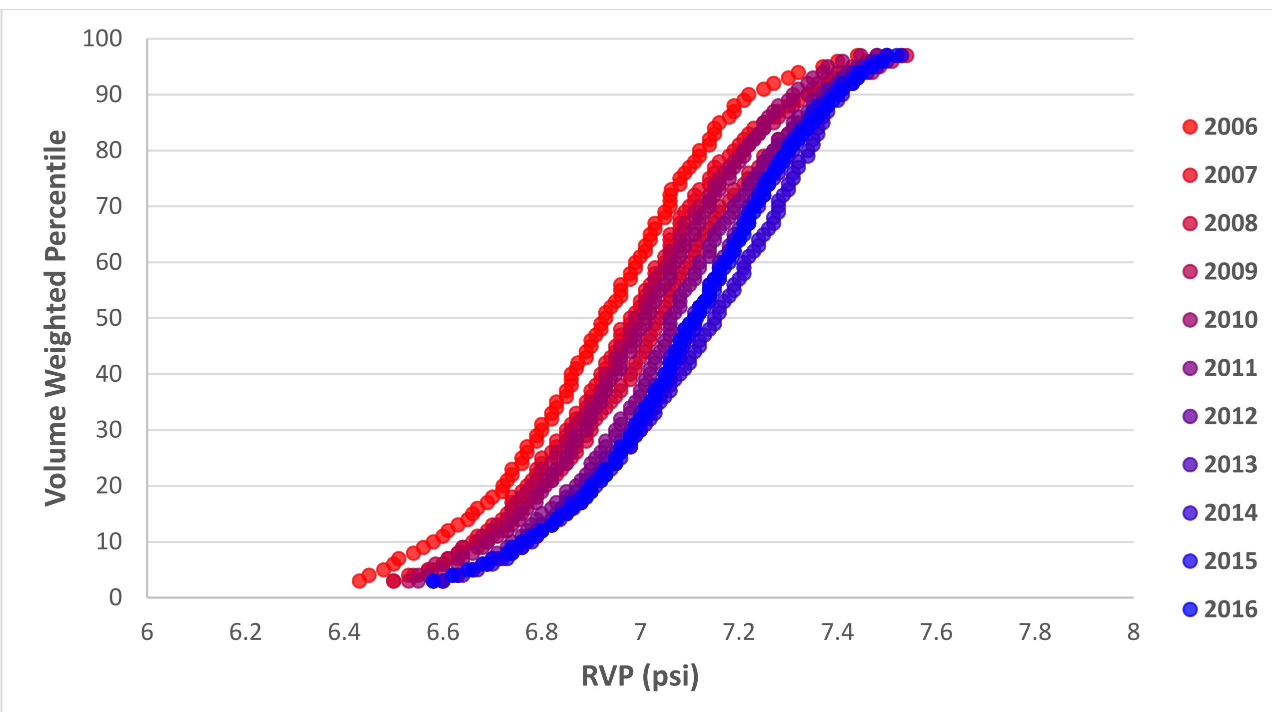

Figure 88 RVP Summer Layered Percentile RFG

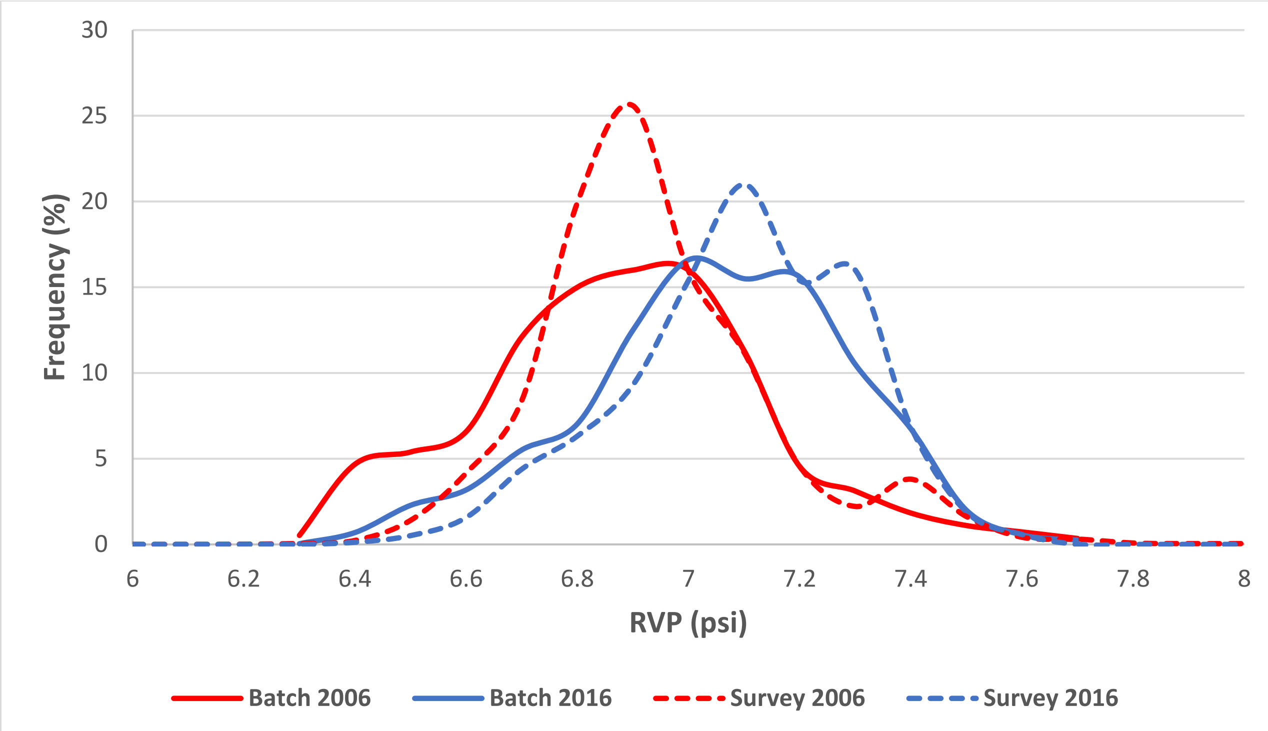

Figure 89 Summer RVP RFG 2006 vs 2016 Histogram (bucket size = 0.1 psi)

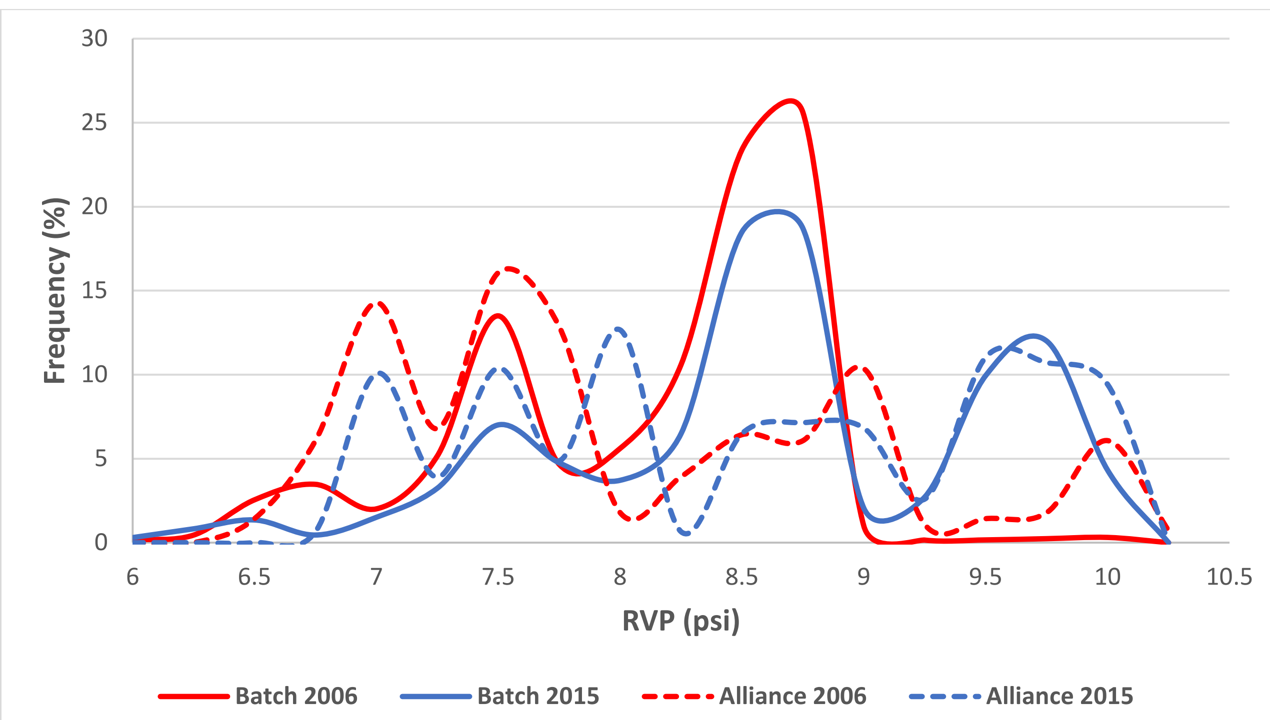

Figure 90 Summer RVP CG 2006 versus 2015 Histogram (bucket size = 0.25 psi; ethanol-adjusted)

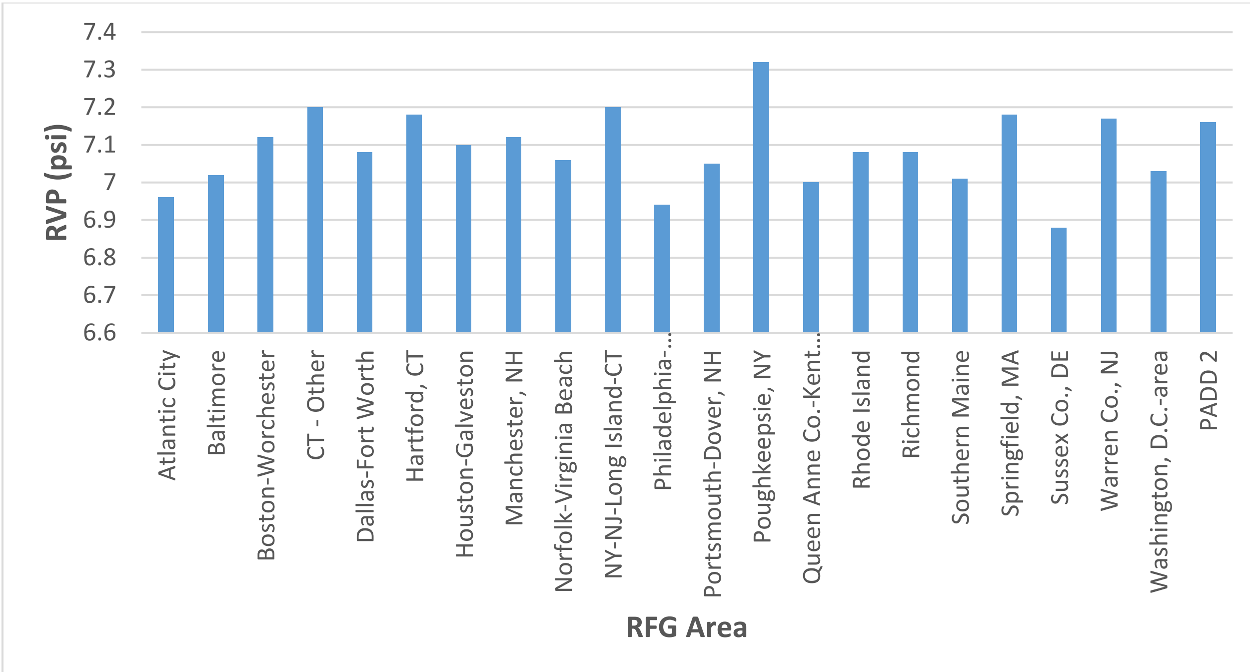

Figure 91 Summer RVP Levels by RFG Area in 2016 from RFG Survey Data

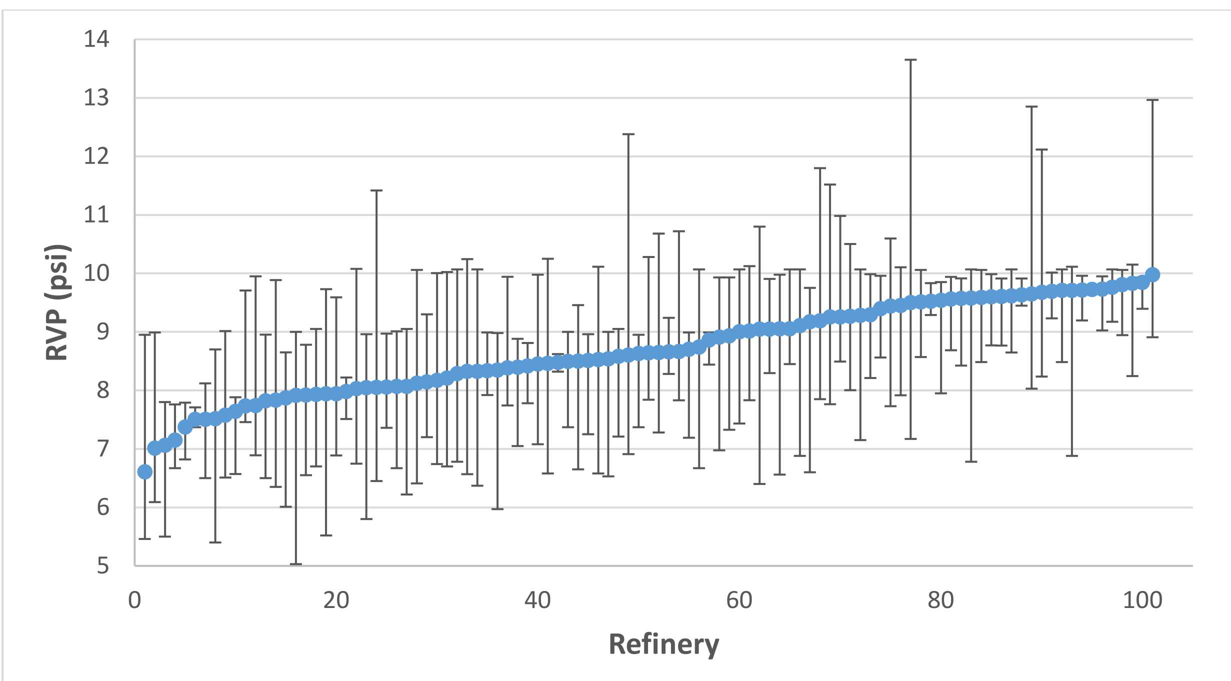

Figure 92 Summer RVP by individual refinery from lowest to highest average (average, minimum and maximum for CG and RFG in 2016; (not ethanol-adjusted)

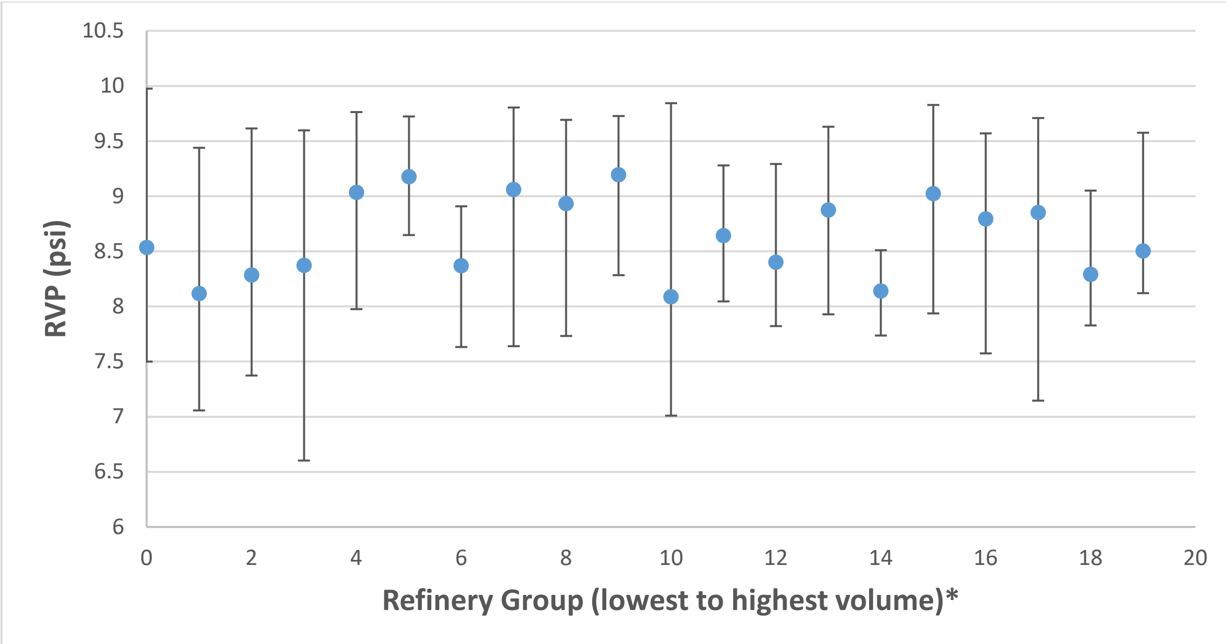

Figure 93 Summer RVP for refineries grouped by volume output (groups of five refineries; average of the average, minimum and maximum values for CG and RFG 2016; not ethanol-adjusted)

*Note: There were a few refinereies that produced gasoline in winter and not summer, which is why there is one fewer group in this plot than for other properties

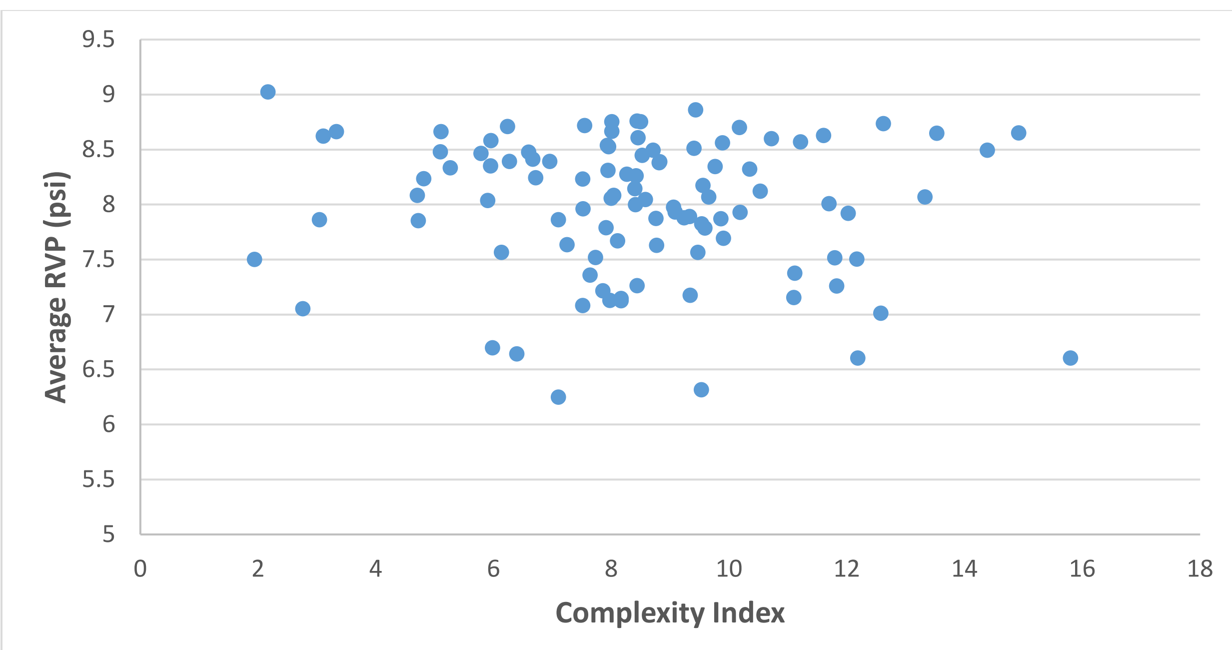

Figure 94 Average Gasoline Summer RVP by Refinery Complexity Index in 2016 (not ethanol-adjusted)

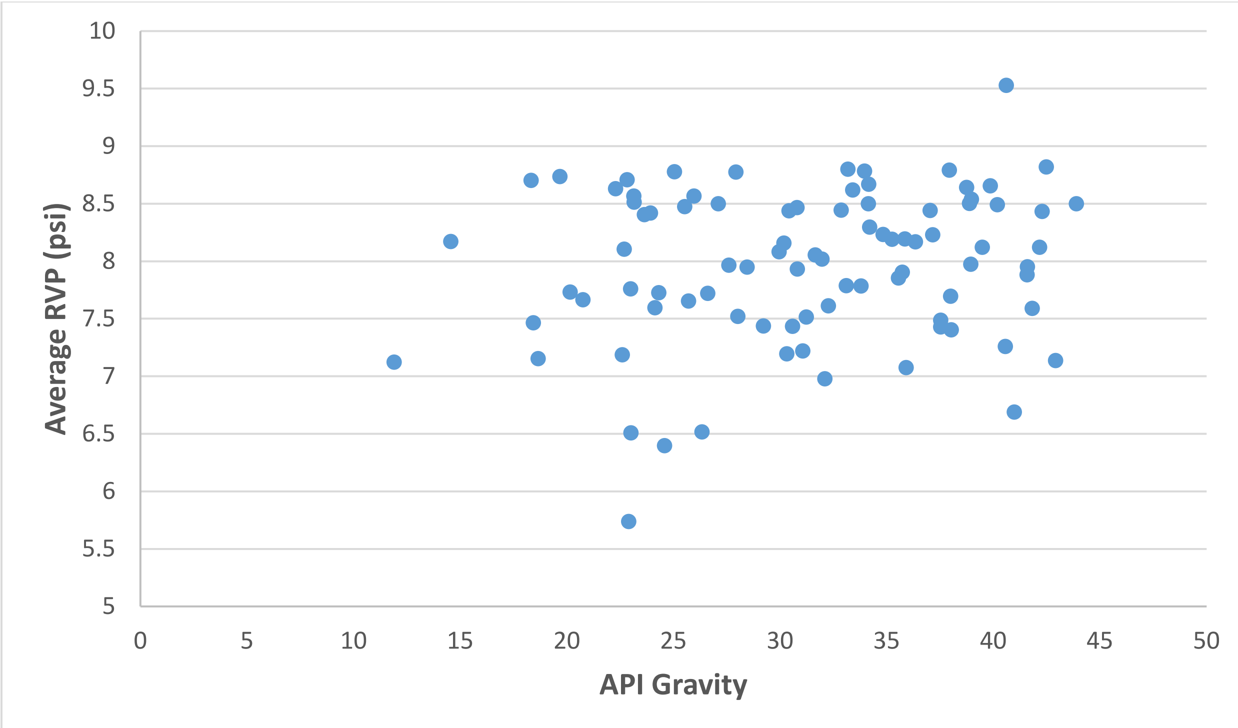

Figure 95 Gasoline Summer RVP Content by Crude Oil API Gravity in 2011 (not ethanol-adjusted)

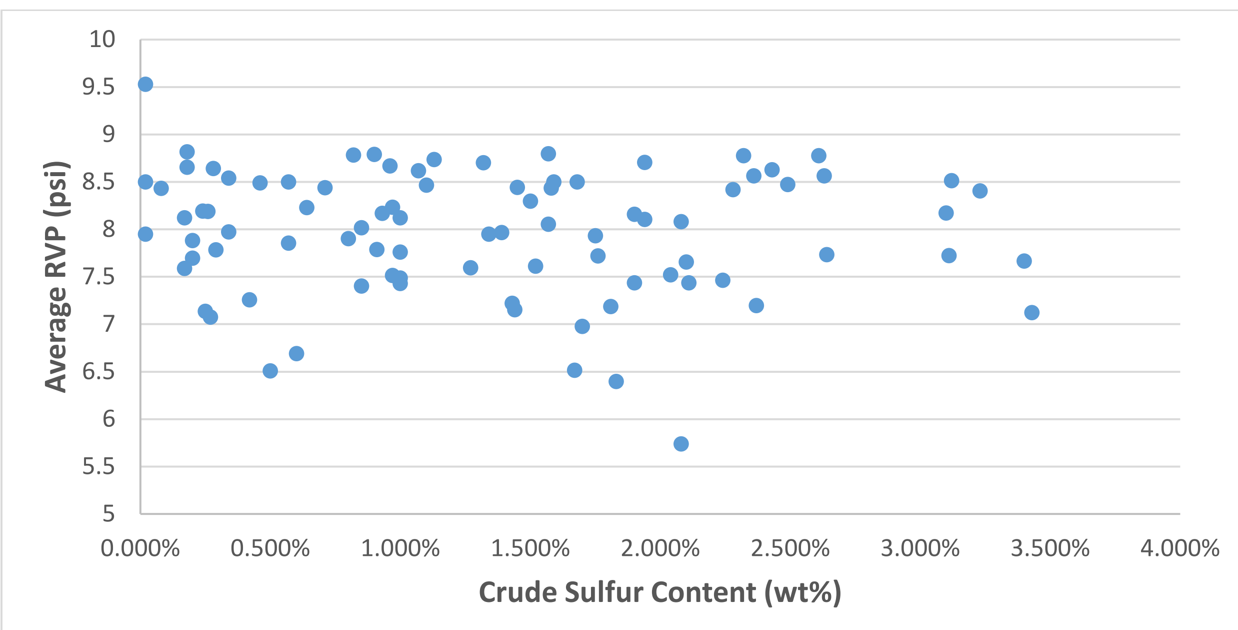

Figure 96 Gasoline Summer RVP Content by Crude Oil Sulfur Content in 2011 (not ethanol-adjusted)

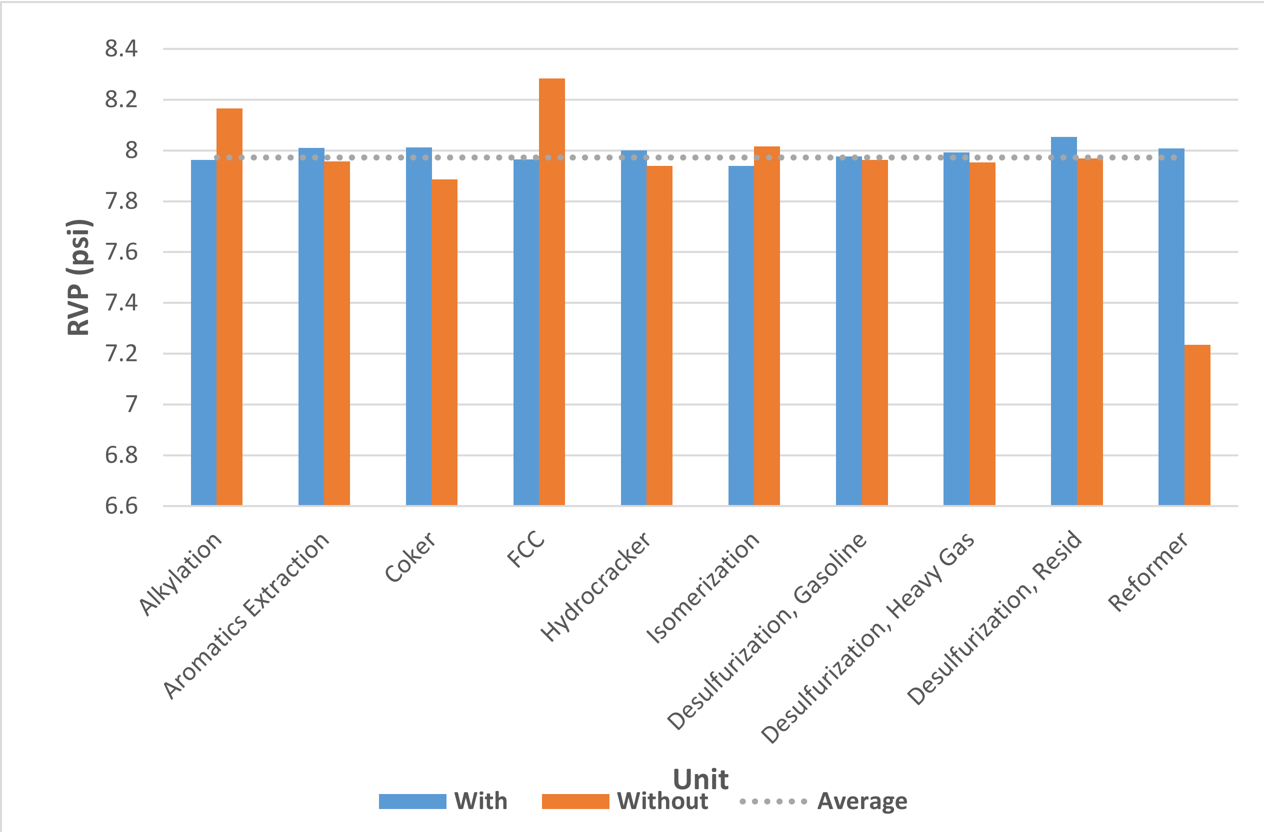

Figure 97 Average Summer RVP Content by Refinery Unit Type in 2016 (not ethanol-adjusted)

e. Olefins

Highlights for the following Olefin figures:

- The presence of olefins in gasoline is almost solely due to the blending of the cracked gasoline produced by the fluidized catalytic cracker unit, which is why the absence of an FCC unit in Figure 119 is associated with very low olefin levels.
- Desulfurization of FCC naphtha to comply with Tier 2 and Tier 3 gasoline sulfur standards has resulted in lower olefin levels in gasoline.
    - The dilution effect of ethanol also leads to the decrease in olefins.
- Premium grade gasoline has lower olefins because premium contains more, higher octane gasoline blendstocks, which do not contain olefins.
- Figure 113 shows that it is common for most all refineries to blend up at least some of their gasoline batches with nearly zero olefins.
    - Gasoline batches can contain zero olefins if they are blended without fluidized catalytic cracker and coker naphtha.
- Figures 115 to 118 show that, refinery size, complexity index, crude oil API gravity or crude oil sulfur content have no discernable impact on gasoline olefin levels.

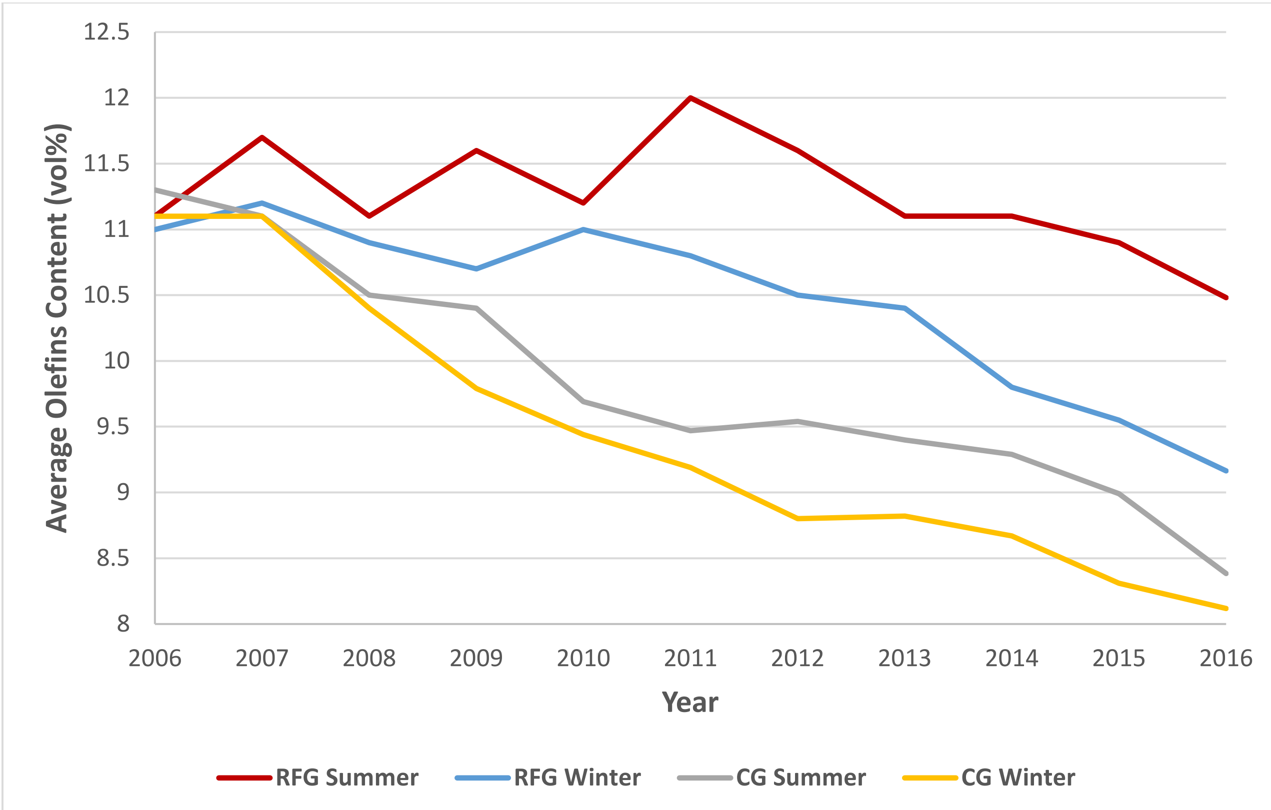

Figure 98 Olefins Trends Summer versus Winter (ethanol-adjusted)

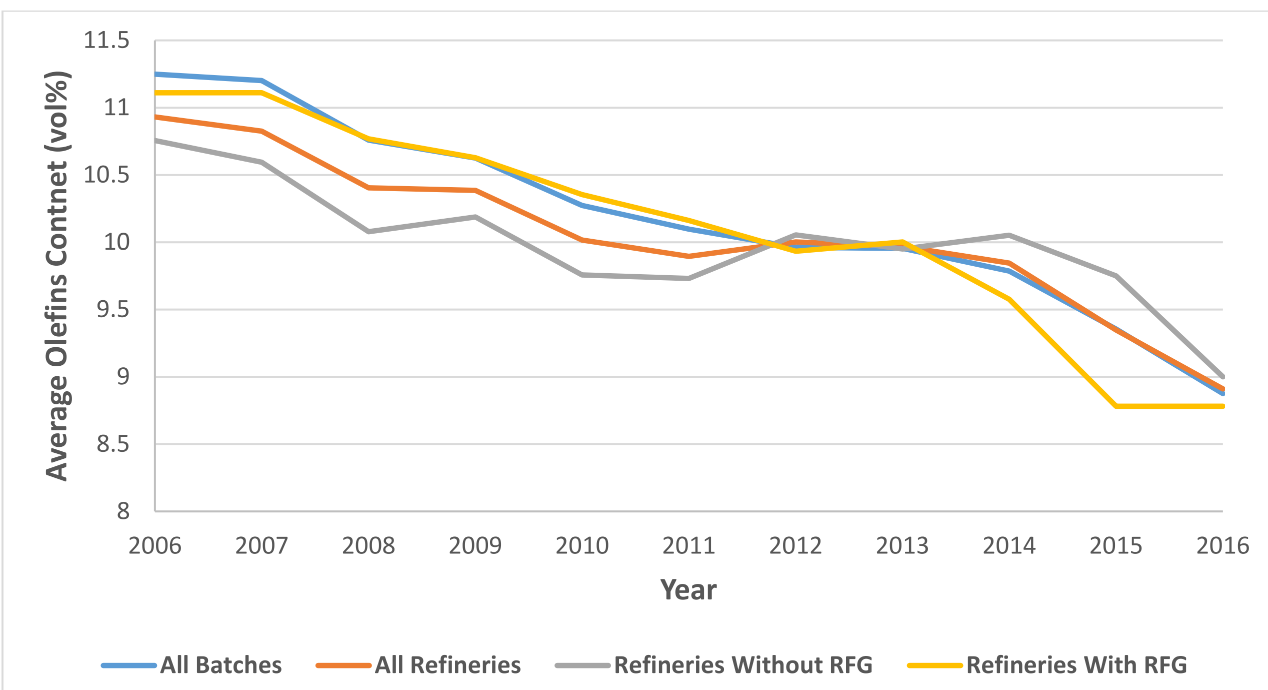

Figure 99 Average CG Olefins Content by Refinery Type (not ethanol-adjusted)

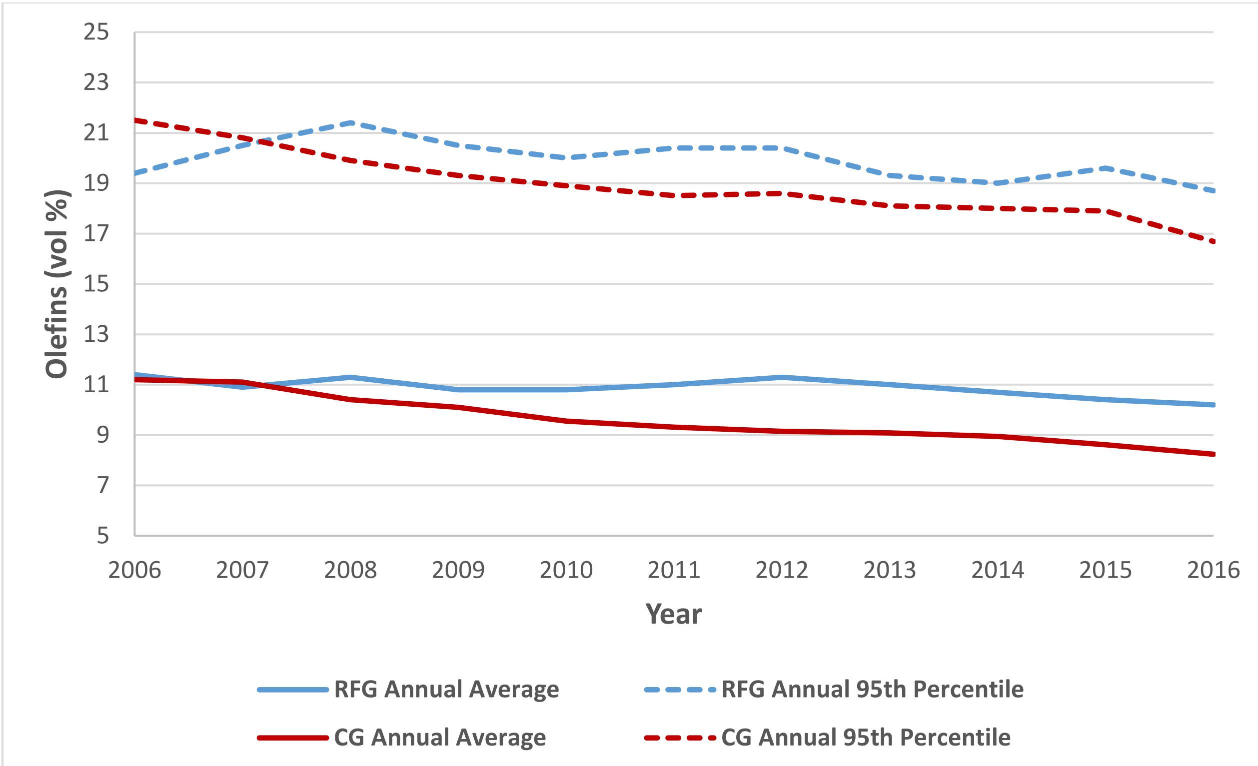

Figure 100 Olefins Trends 95th Percentile versus Average (ethanol-adjusted)

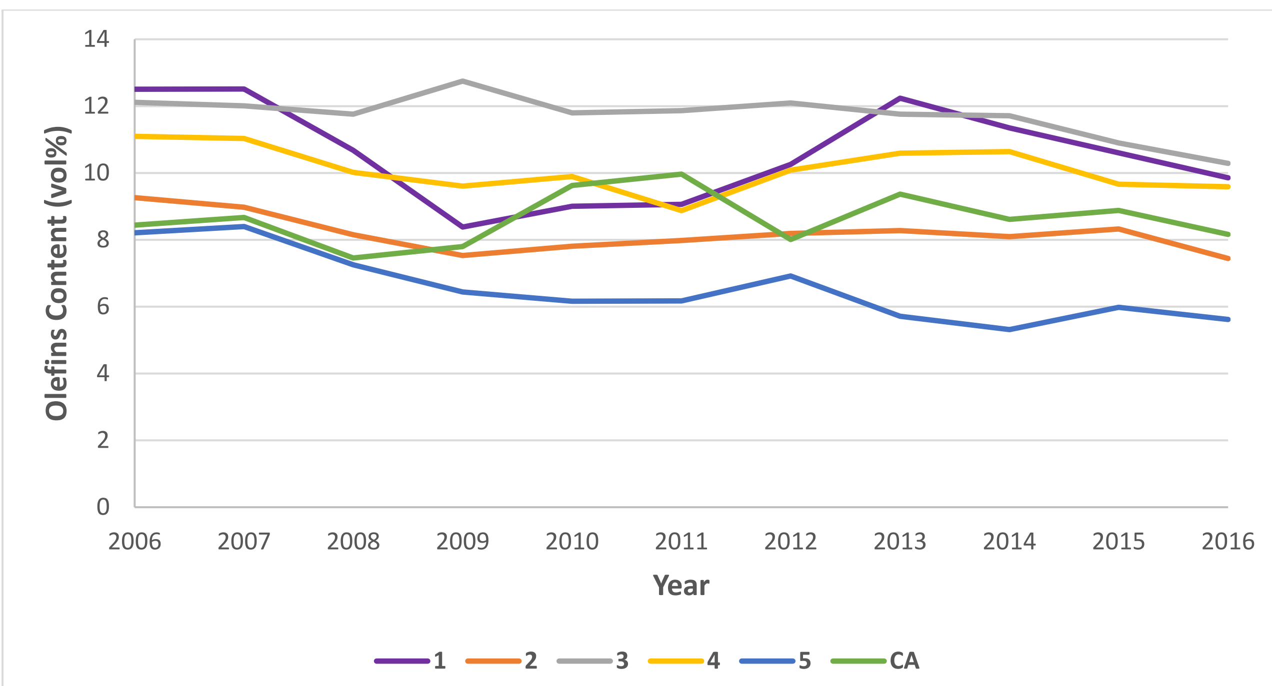

Figure 101 CG Summer Olefins by PADD (not ethanol-adjusted)

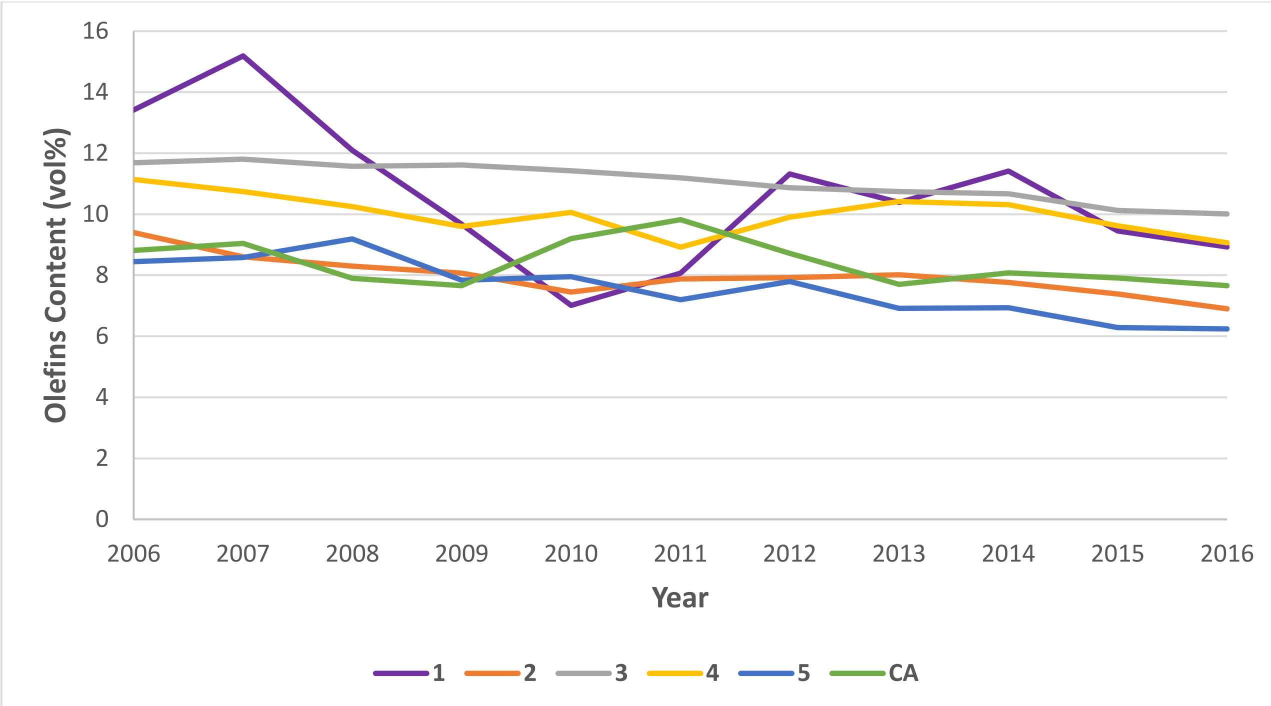

Figure 102 CG Winter Olefins by PADD (not ethanol-adjusted)

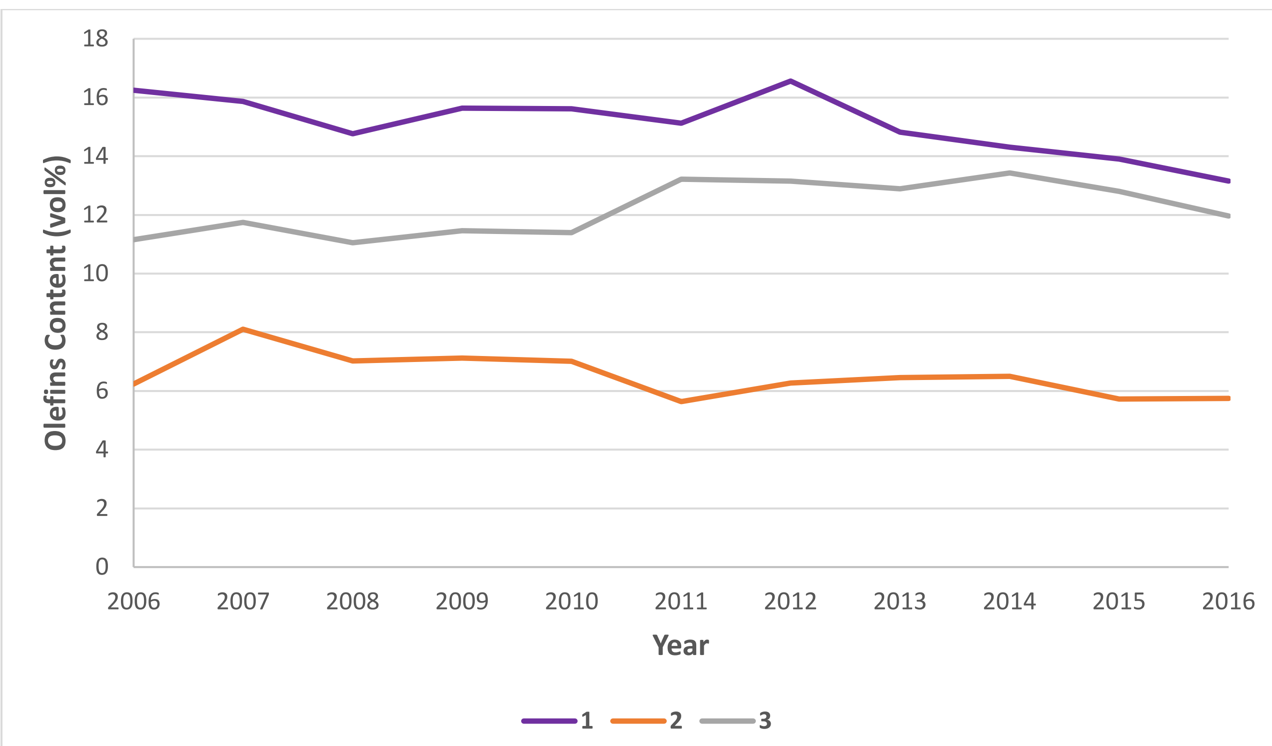

Figure 103 RFG Summer Olefins by PADD Produced from Batch Dat

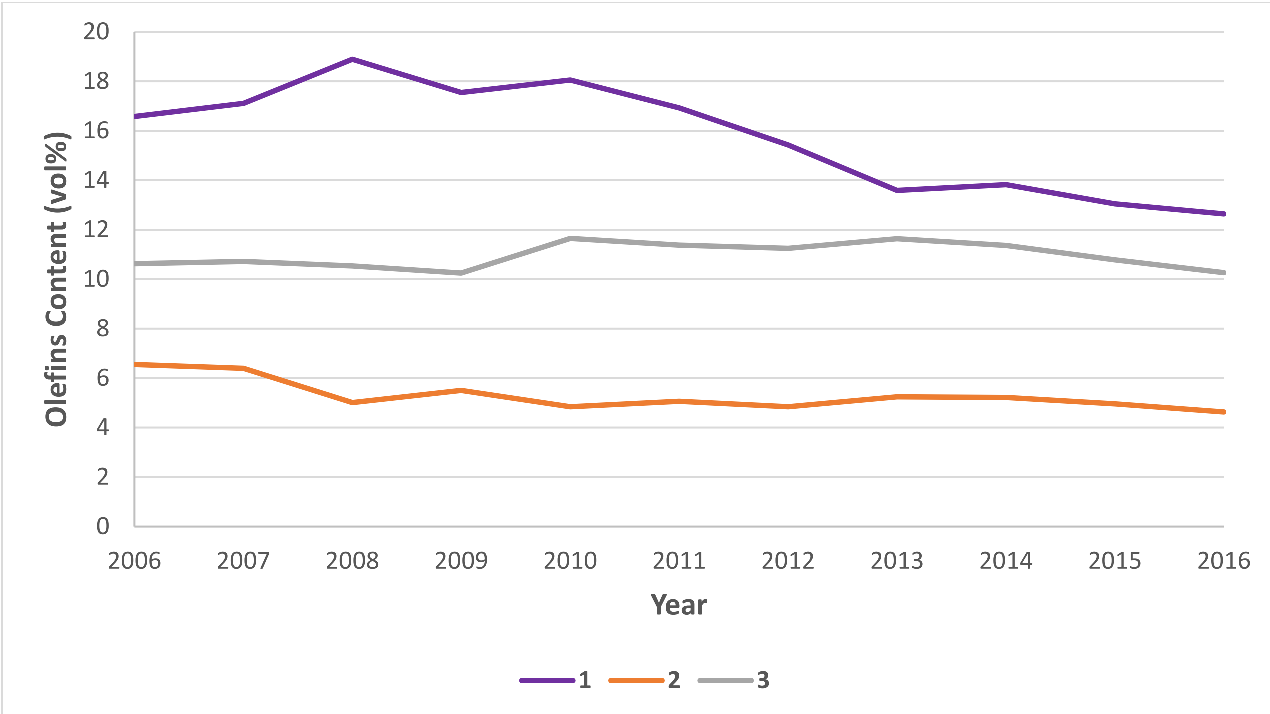

Figure 104 RFG Winter Olefins by PADD Produced from Batch Data

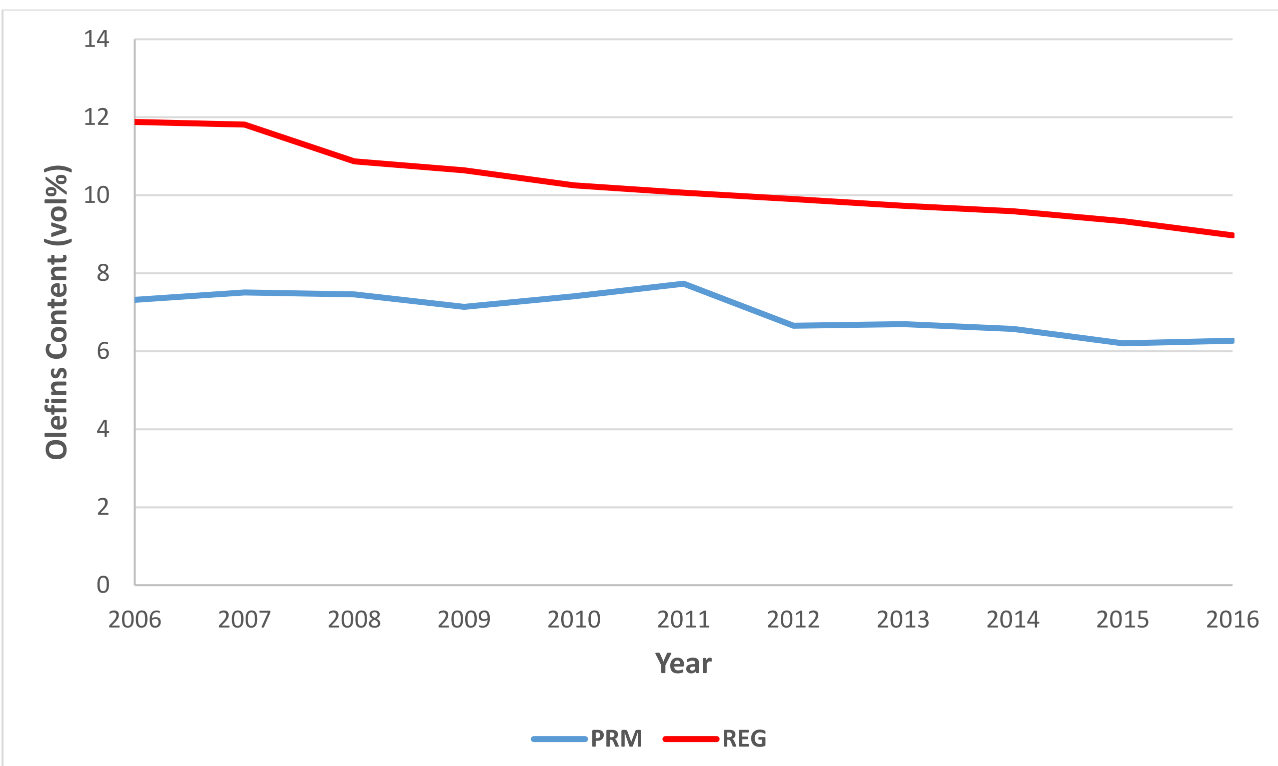

Figure 105 Regular vs Premium CG and RFG Olefins (not ethanol-adjusted)

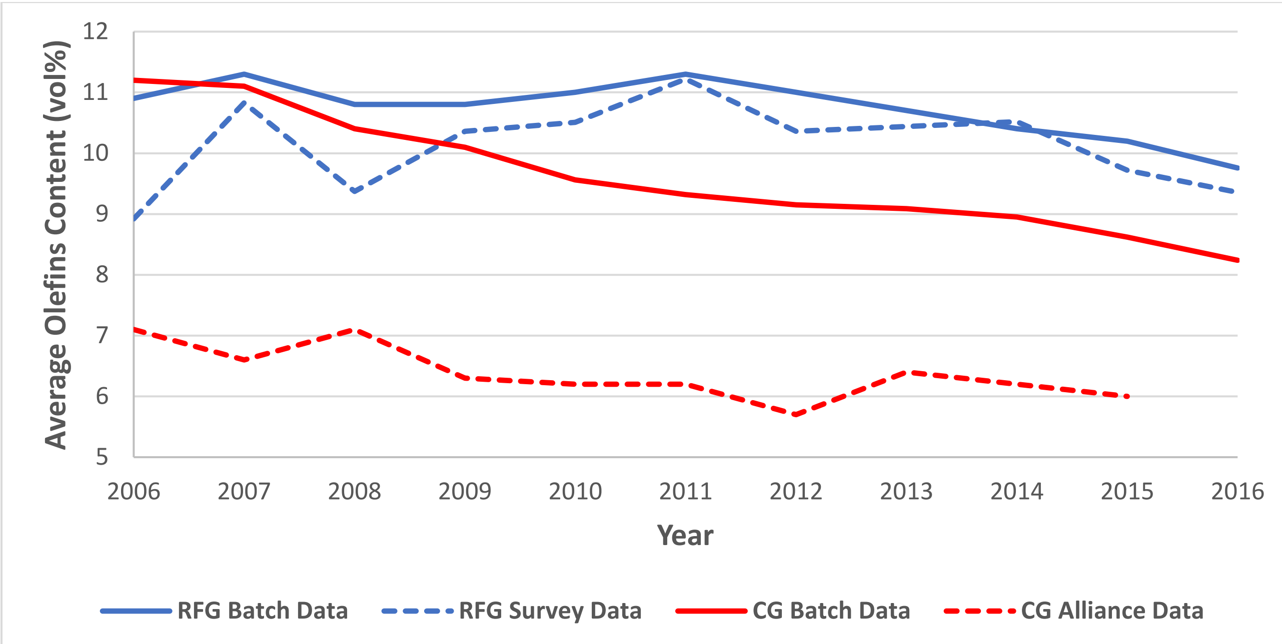

Figure 106 Comparing Batch, Survey, and Alliance data (ethanol-adjusted)

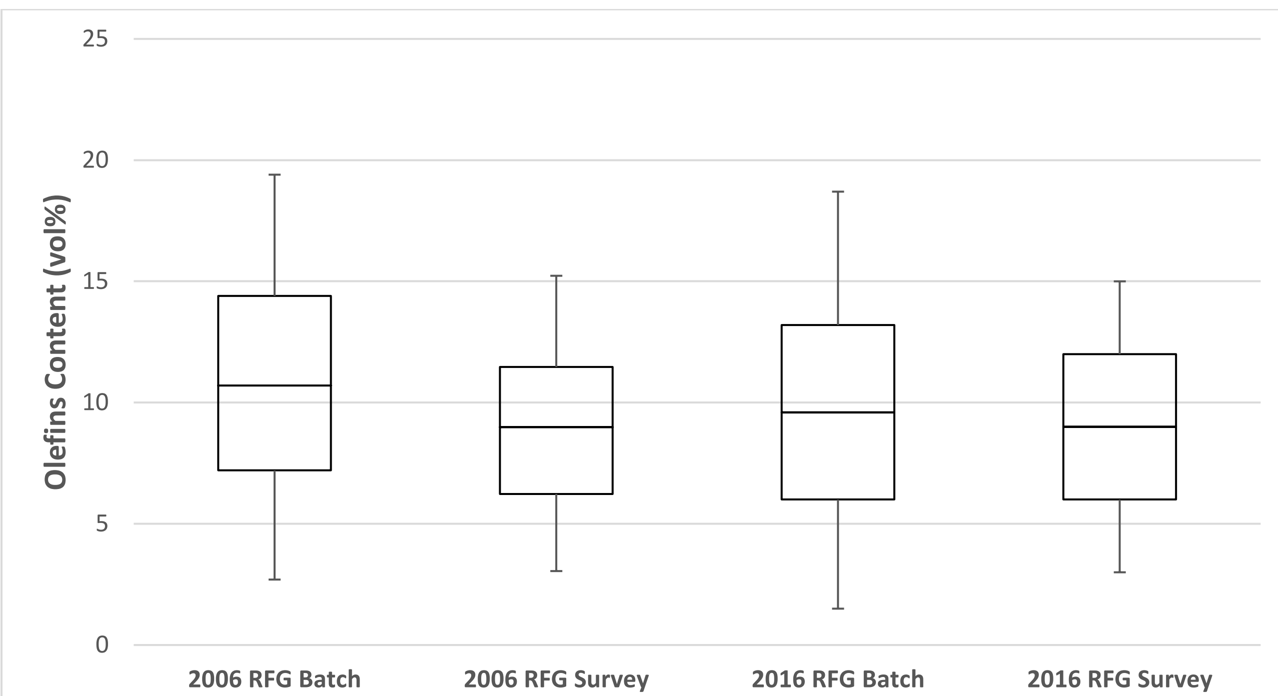

Figure 107 Olefins CG Box and Whiskers (5%, 25%, median, 75%, 95%)

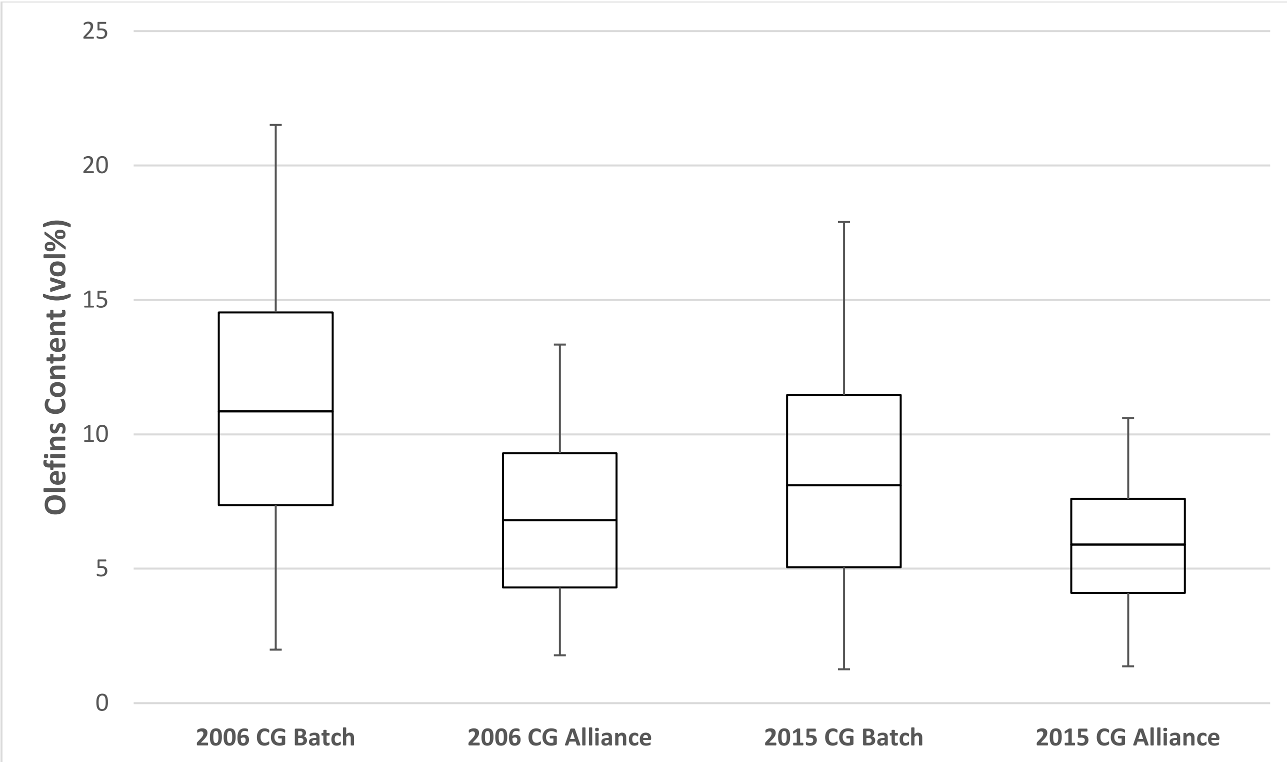

Figure 108 Olefins CG 2006 vs 2015 Histogram (bucket size = 2 %; ethanol-adjusted))

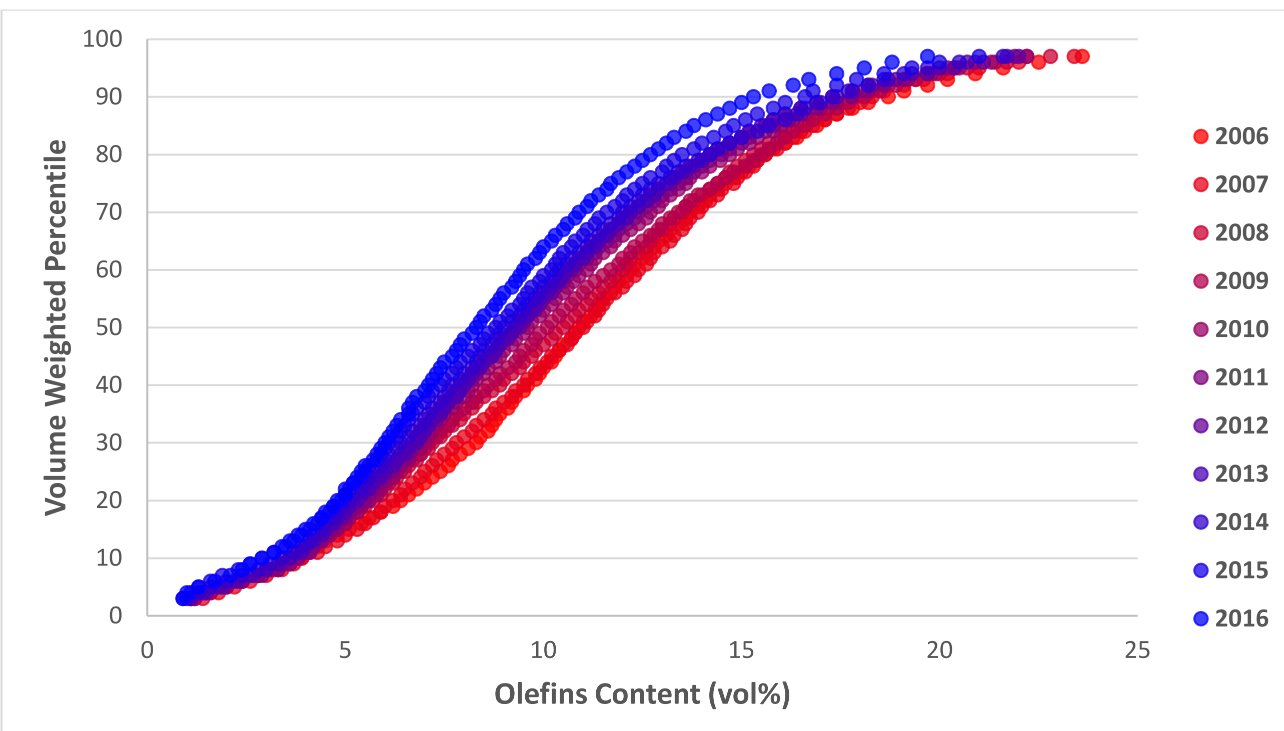

Figure 109 Olefins Layered Percentile CG (not ethanol-adjusted)

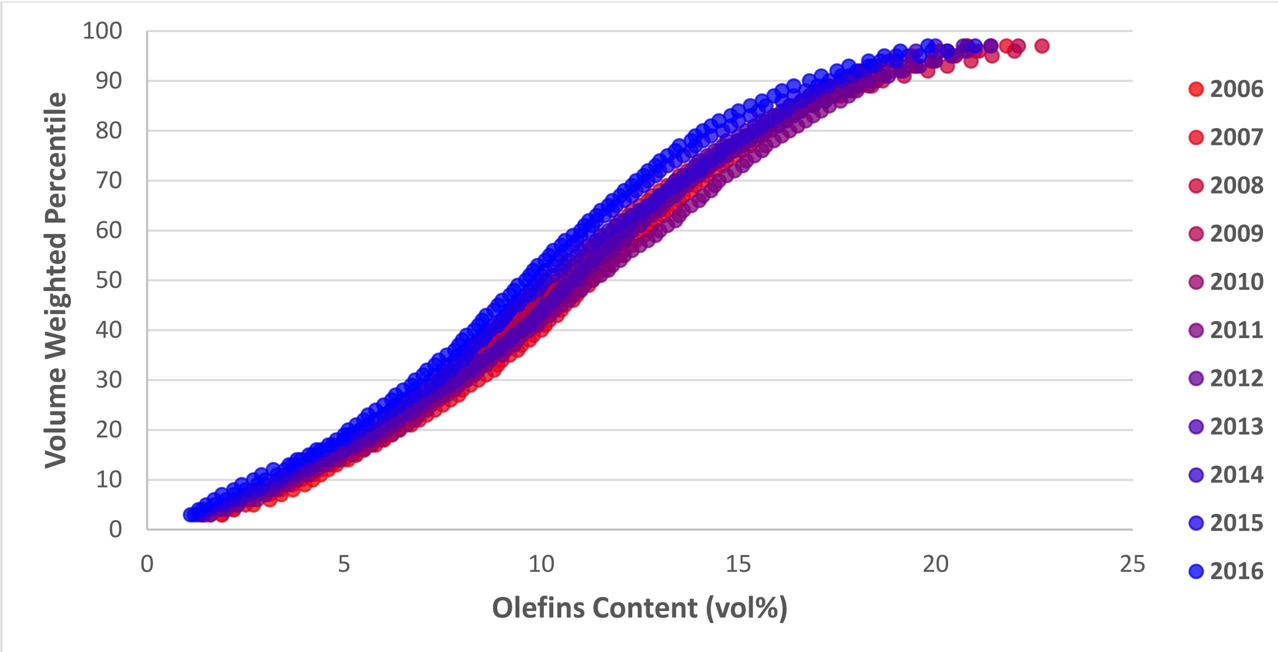

Figure 110 Olefins Layered Percentile RFG (not ethanol-adjusted)

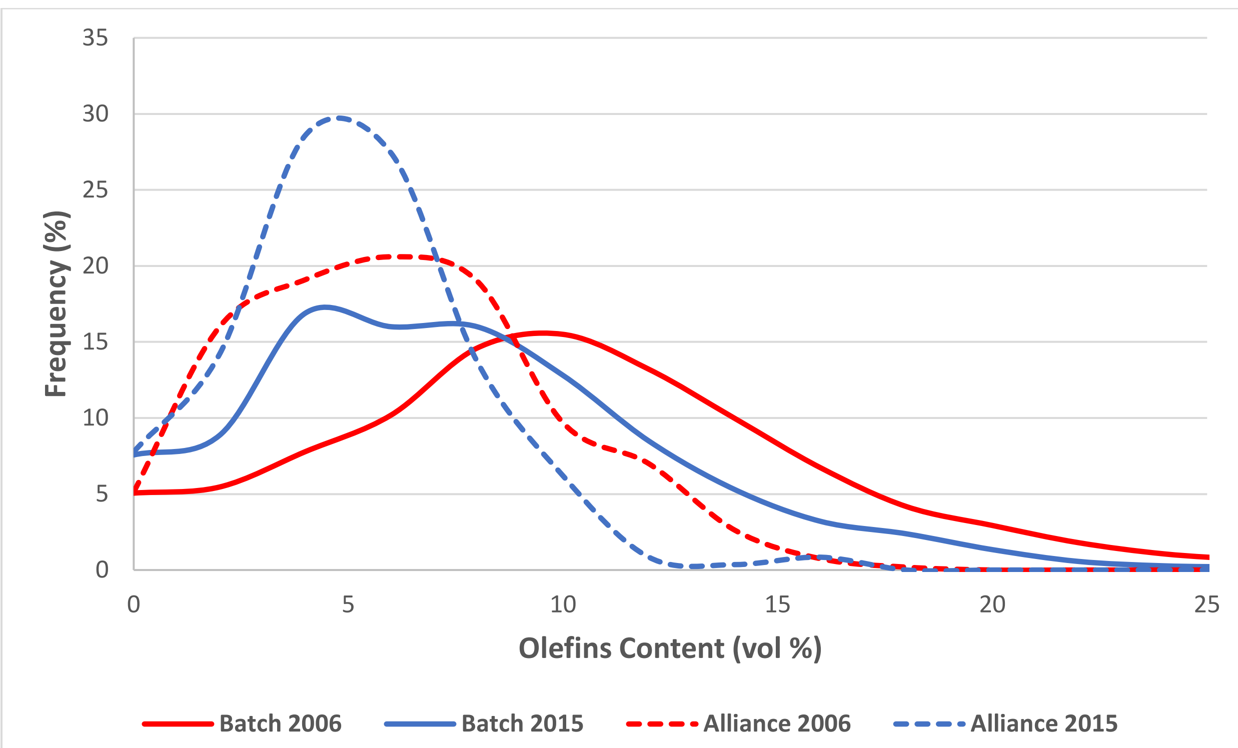

Figure 111 Olefins CG 2006 versus 2015 Histogram (bucket size = 2%, ethanol-adjusted)

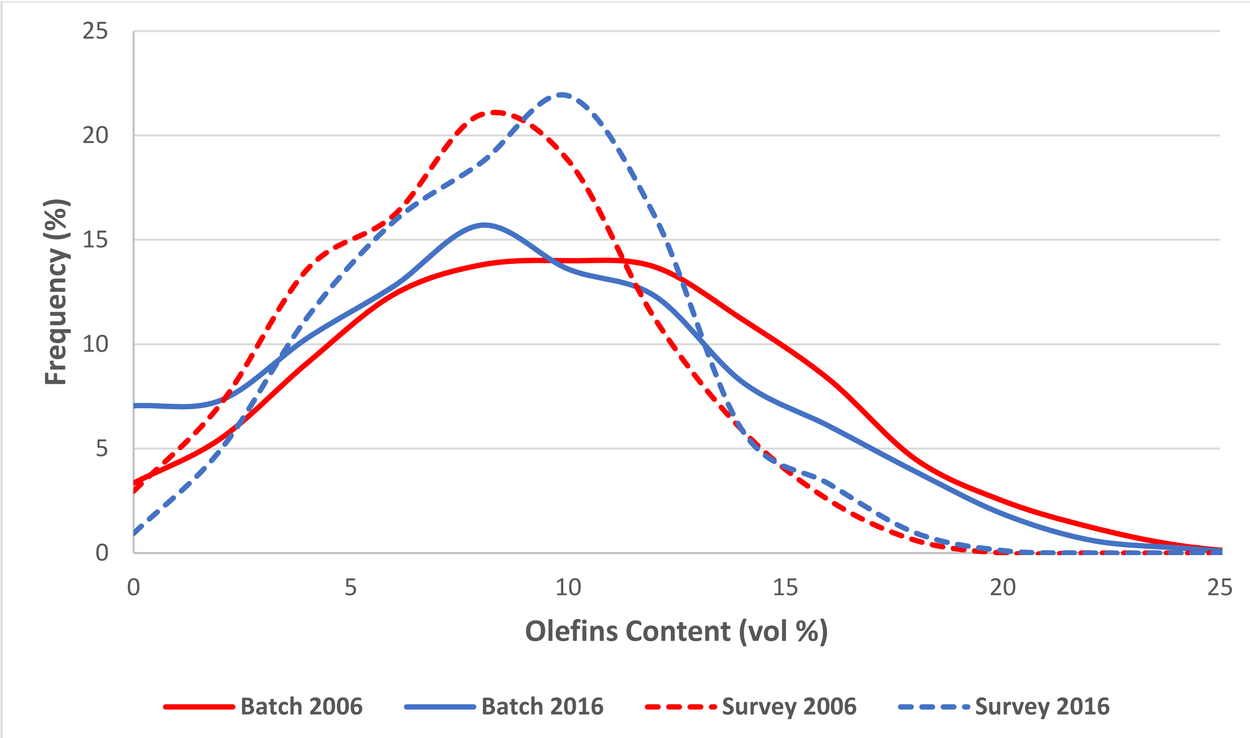

Figure 112 Olefins RFG 2006 versus 2016 Histogram (bucket size = 2%)

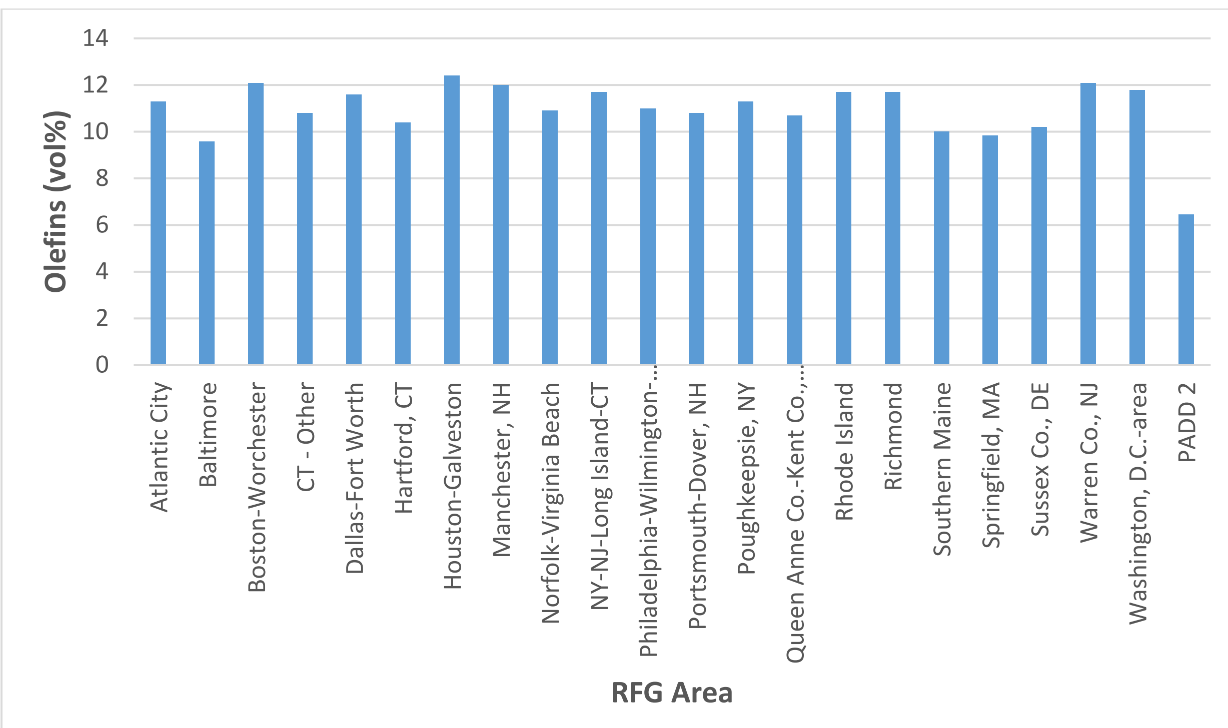

Figure 113 Summer Olefins Levels by RFG Area in 2016 from RFG Survey Data

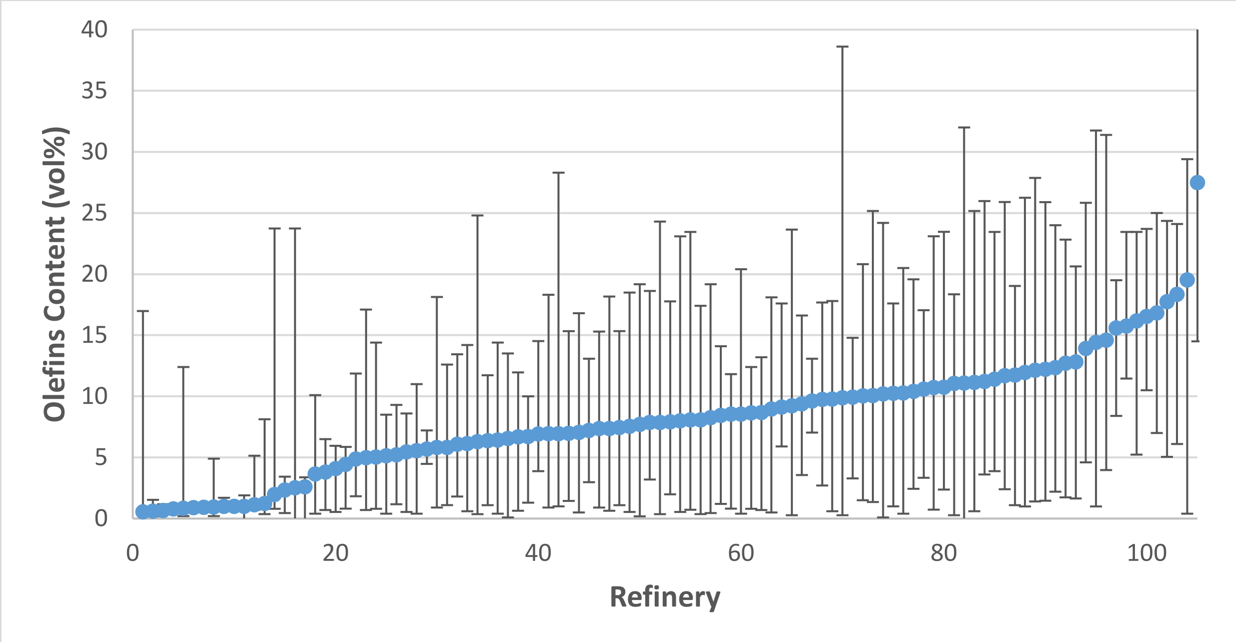

Figure 114 Olefin content by individual refinery from lowest to highest average (average, minimum and maximum for CG and RFG in 2016; (not ethanol-adjusted)

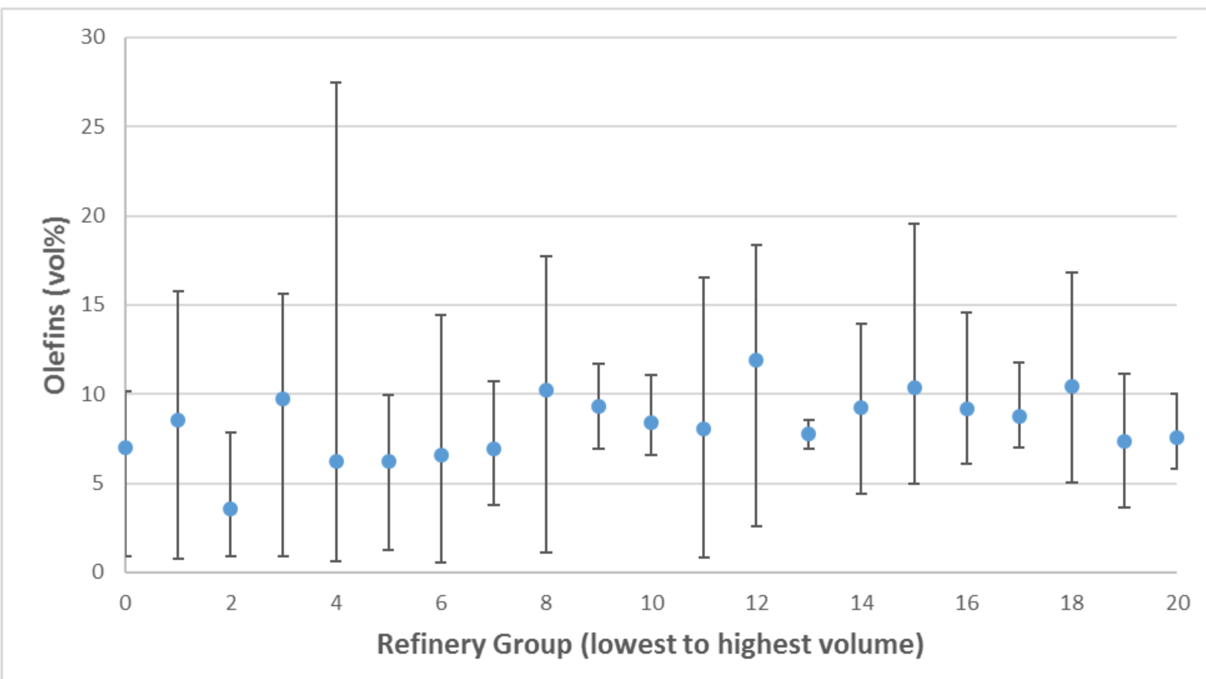

Figure 115 Olefin content for refineries grouped by volume output (groups of five refineries; average of the average, minimum and maximum values for CG and RFG 2016; not ethanol-adjusted)

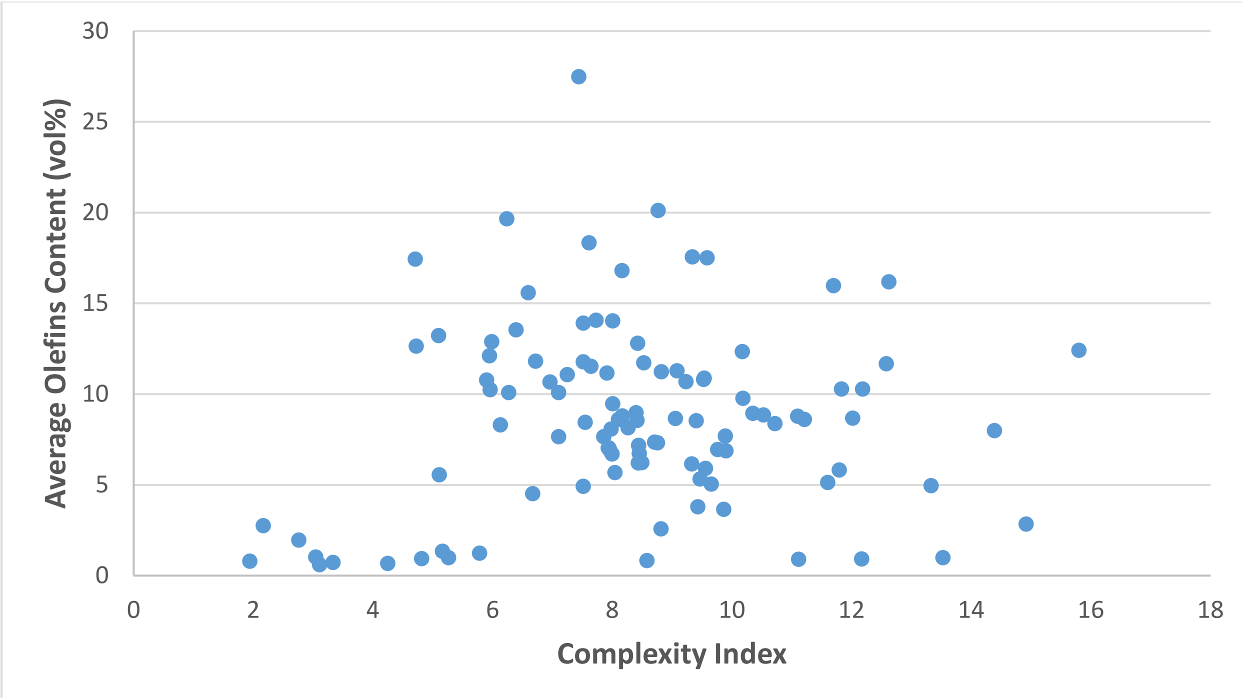

Figure 116 Average Gasoline Olefins Content by Refinery Complexity Index in 2016 (not ethanol-adjusted)

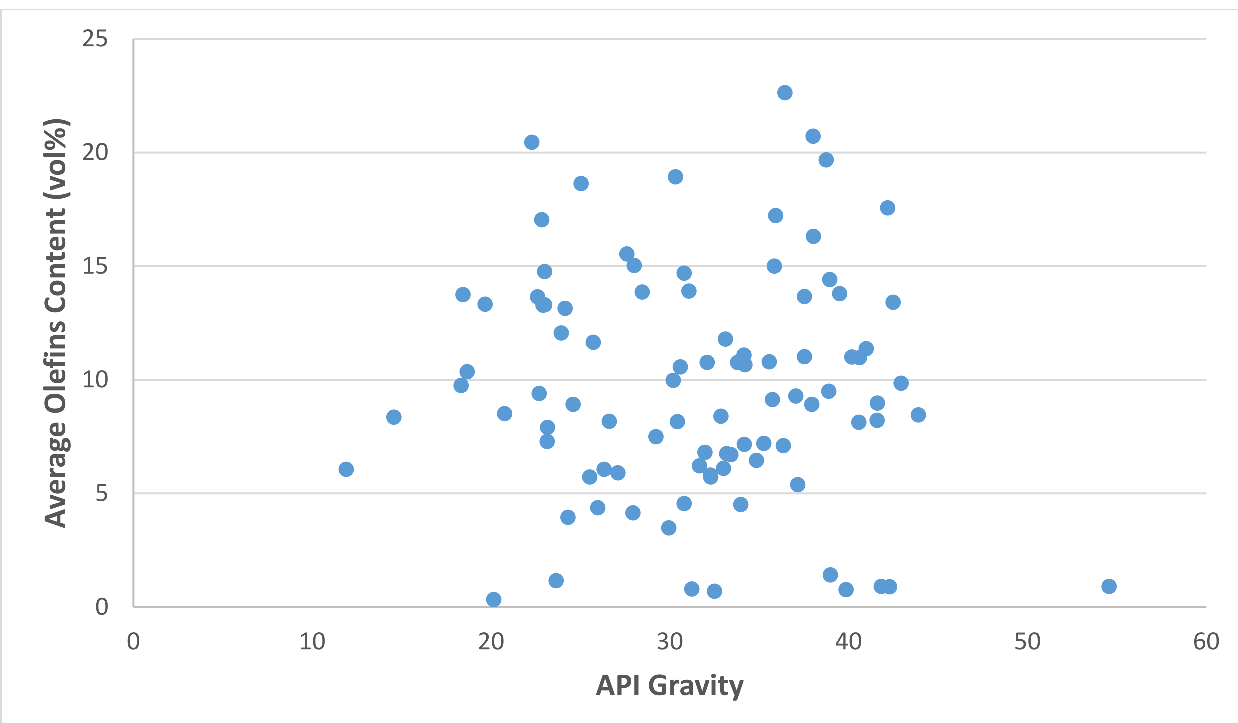

Figure 117 Gasoline Olefins Content by Crude Oil API Gravity in 2011 (not ethanol-adjusted)

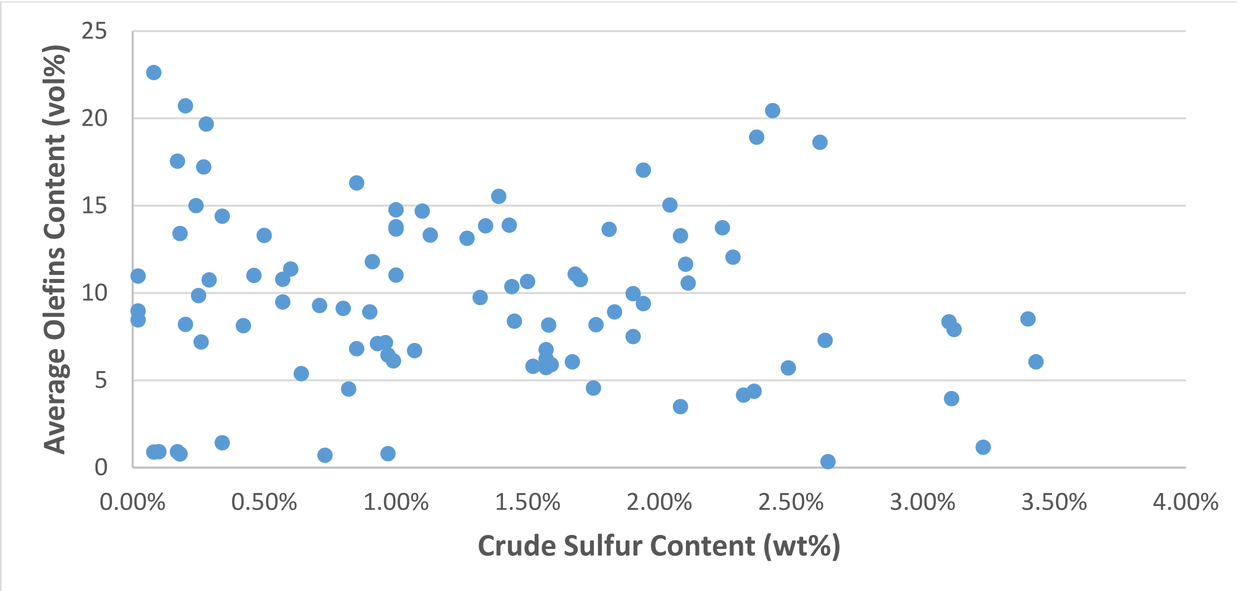

Figure 118 Gasoline Olefins Content by Crude Oil Sulfur Content in 2011 (not ethanol-adjusted)

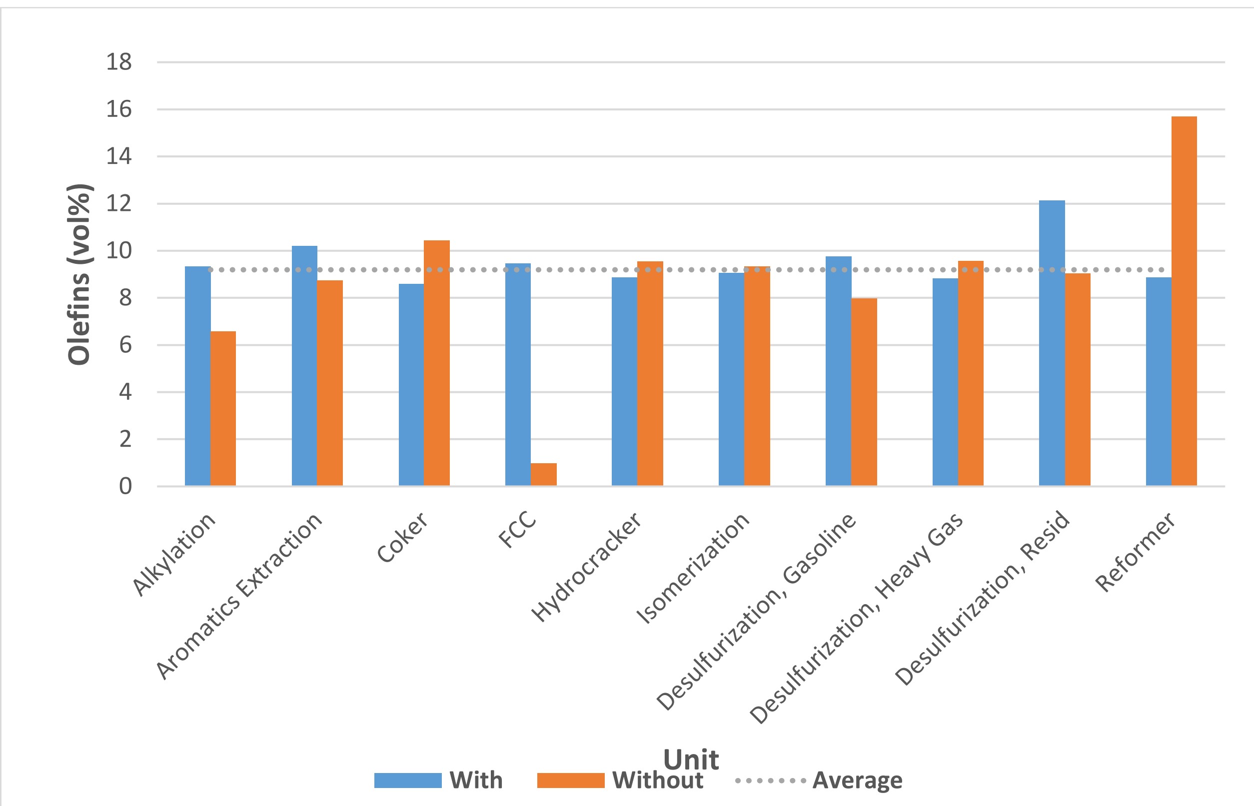

Figure 119 Average Olefins Content by Refinery Unit Type in 2016 (not ethanol-adjusted)

f. E200

Highlights for the following E200 figures:

- Figure 120 shows that winter gasoline is consistently higher in E200 than summer gasoline due to the higher RVP standards which apply in winter allowing for higher butane content.
- Figure 120 also shows that over the period of 2006 to 2013, E200 levels increased predominantly in the CG pool where ethanol blending was increasing.
- The decrease in E200 levels after 2013 is likely due to the market forces described in Section 5 which favored increased gasoline production from U.S. refineries.
- Figures 128 through 134 show that, although refinery gasoline E200 averages have shifted lower, the variance in batch E200 levels has continued.
- Premium grade gasoline E200 levels remain consistently below those of regular grade gasoline, likely due to the blending of higher octane gasoline blendstocks, such as alkylate and reformate, which tend to boil at a higher average temperature and contribute to a lower E200.
- The RFG survey data tracks the RFG batch data very well, although the survey data is somewhat higher in E200.
- Figures 136 to 139 show that, refinery size, complexity index, crude oil API gravity or crude oil sulfur content have no strong impact on gasoline E200 levels.
    - Less complex refineries seem to have a somewhat higher E200.

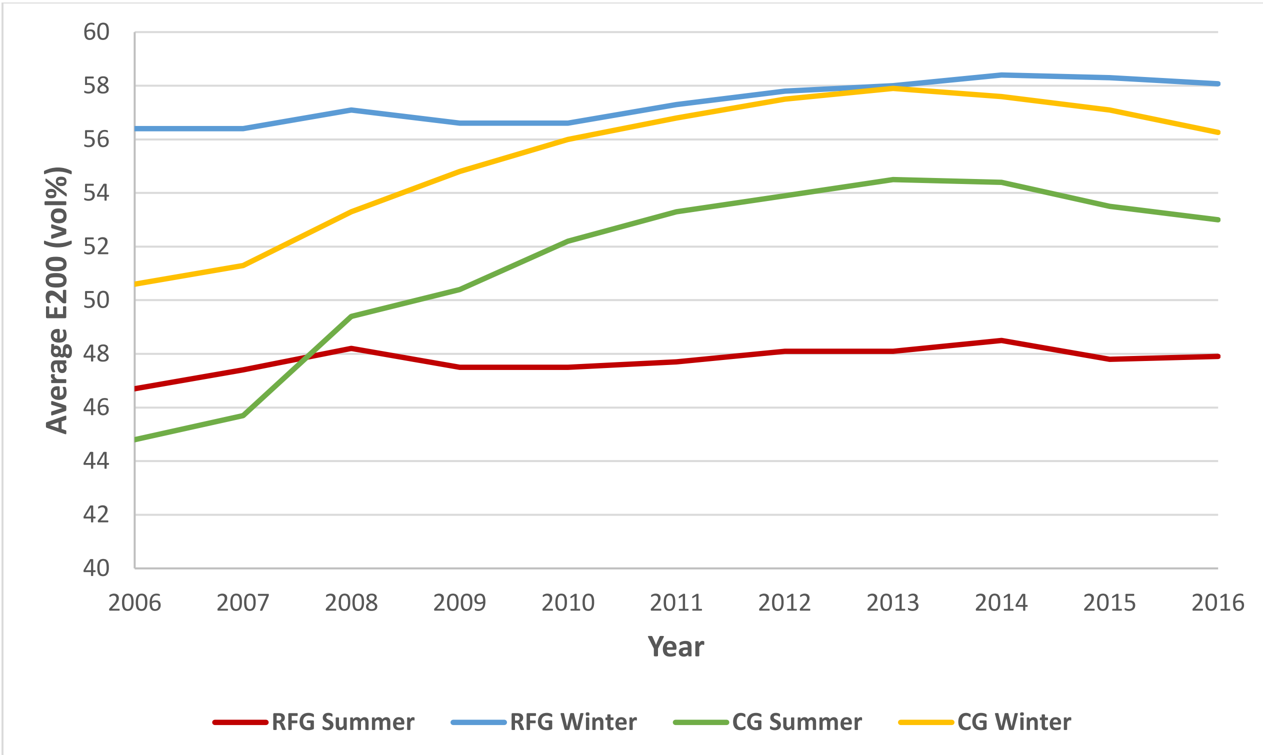

Figure 120 E200 Trends Summer versus Winter (ethanol-adjusted)

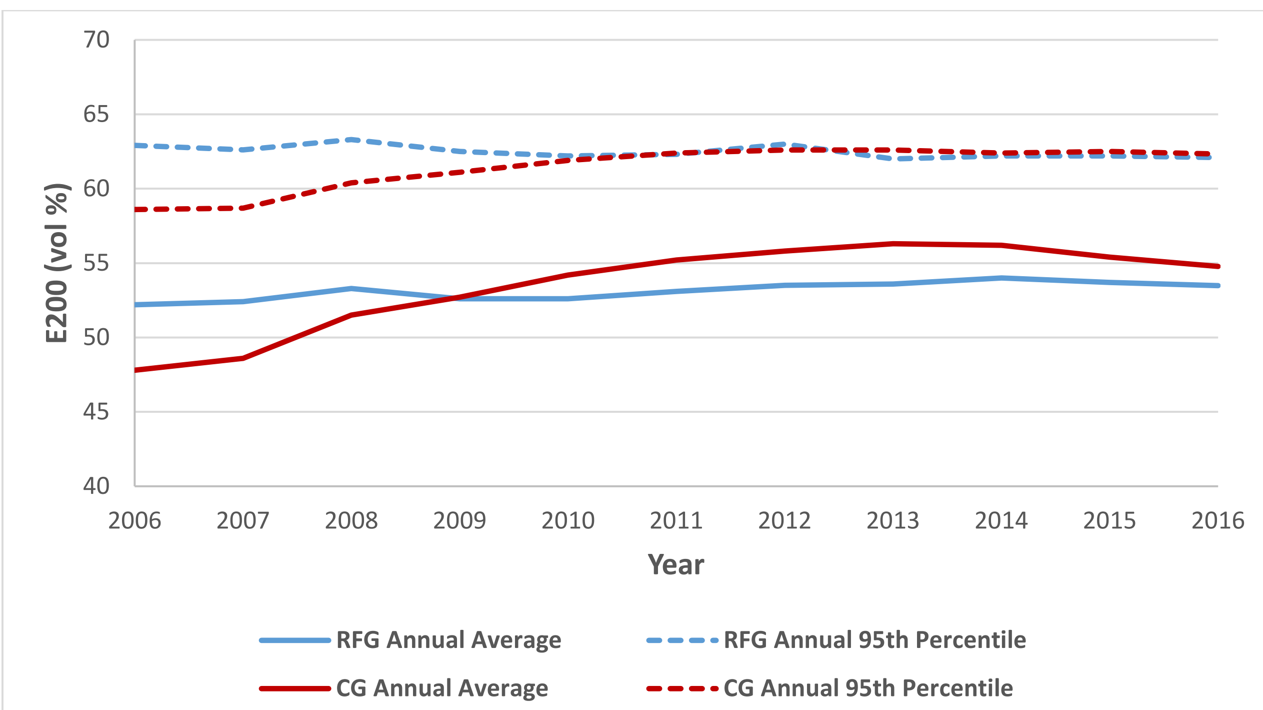

Figure 121 E200 Trends 95th Percentile versus Average (ethanol-adjusted)

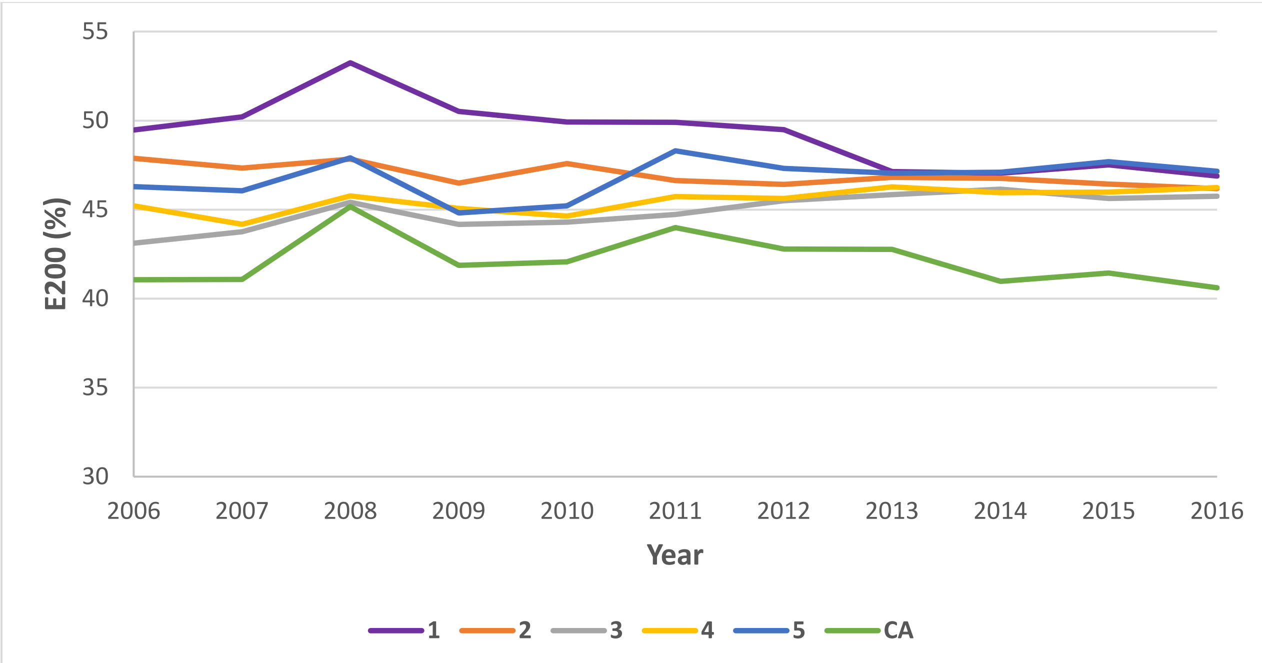

Figure 122 CG Summer E200 by PADD (not ethanol-adjusted)

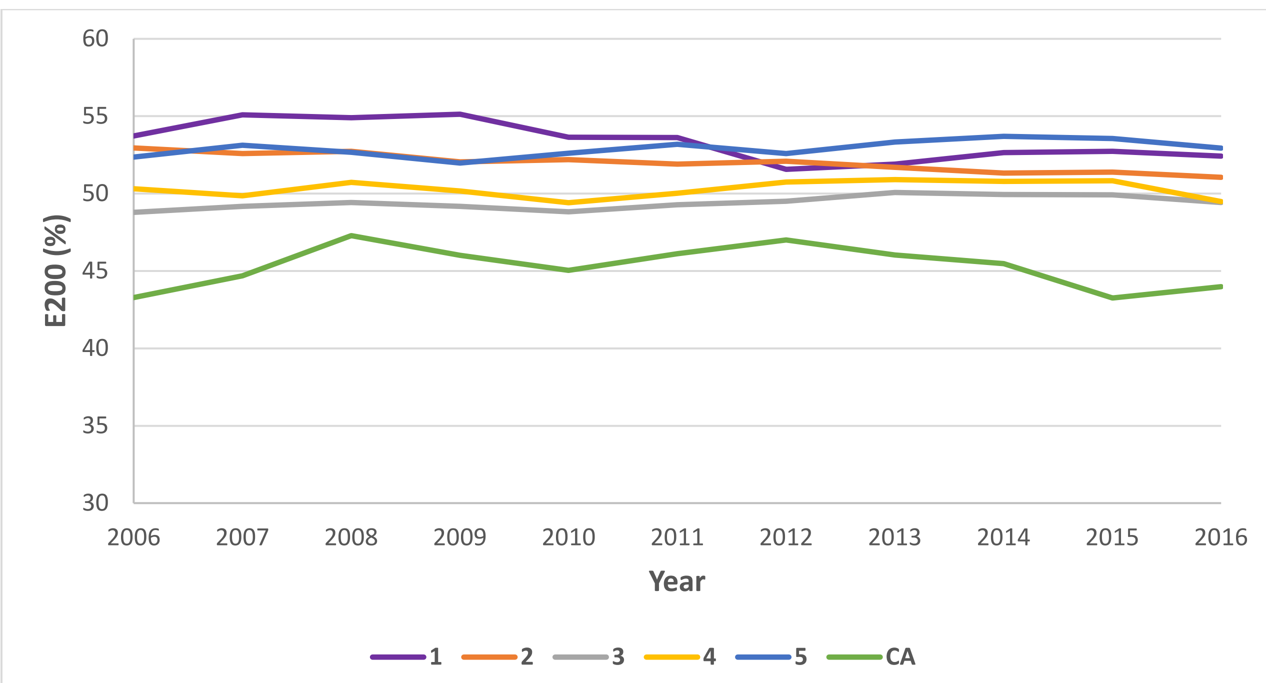

Figure 123 CG Winter E200 by PADD (not ethanol-adjusted)

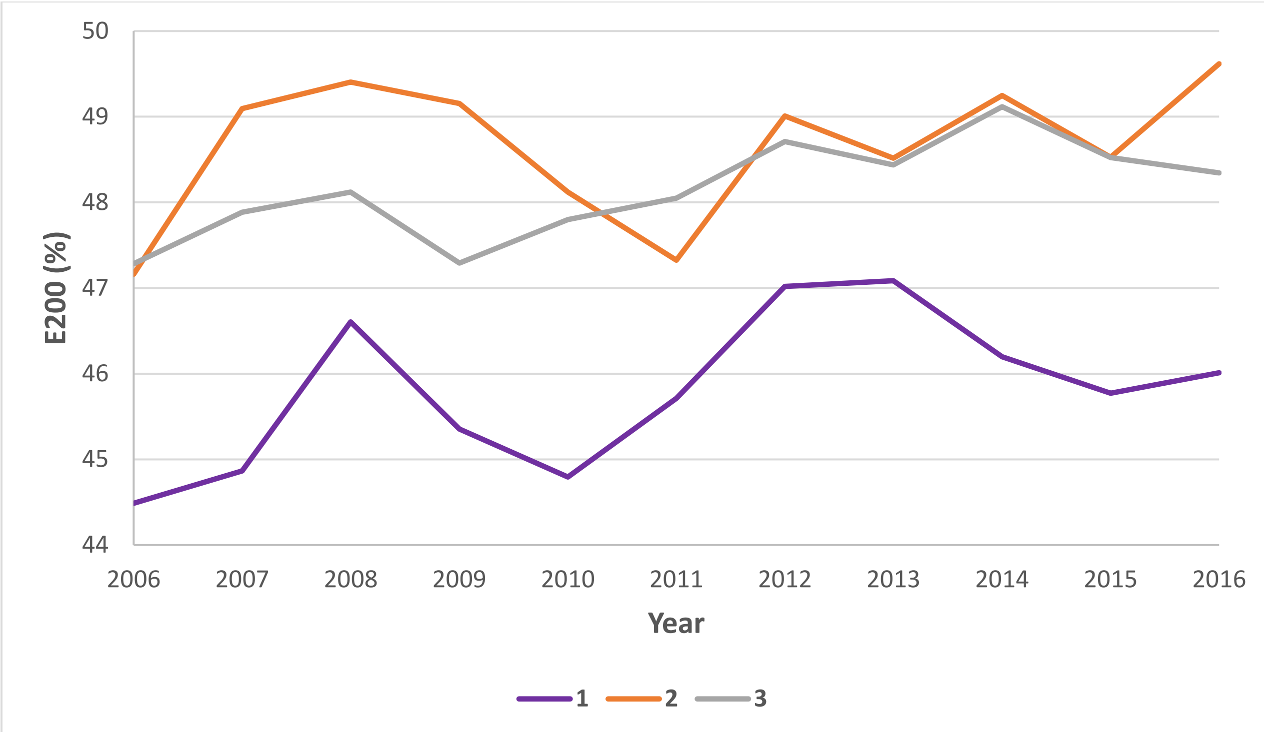

Figure 124 RFG Summer E200 by PADD Produced from Batch Data

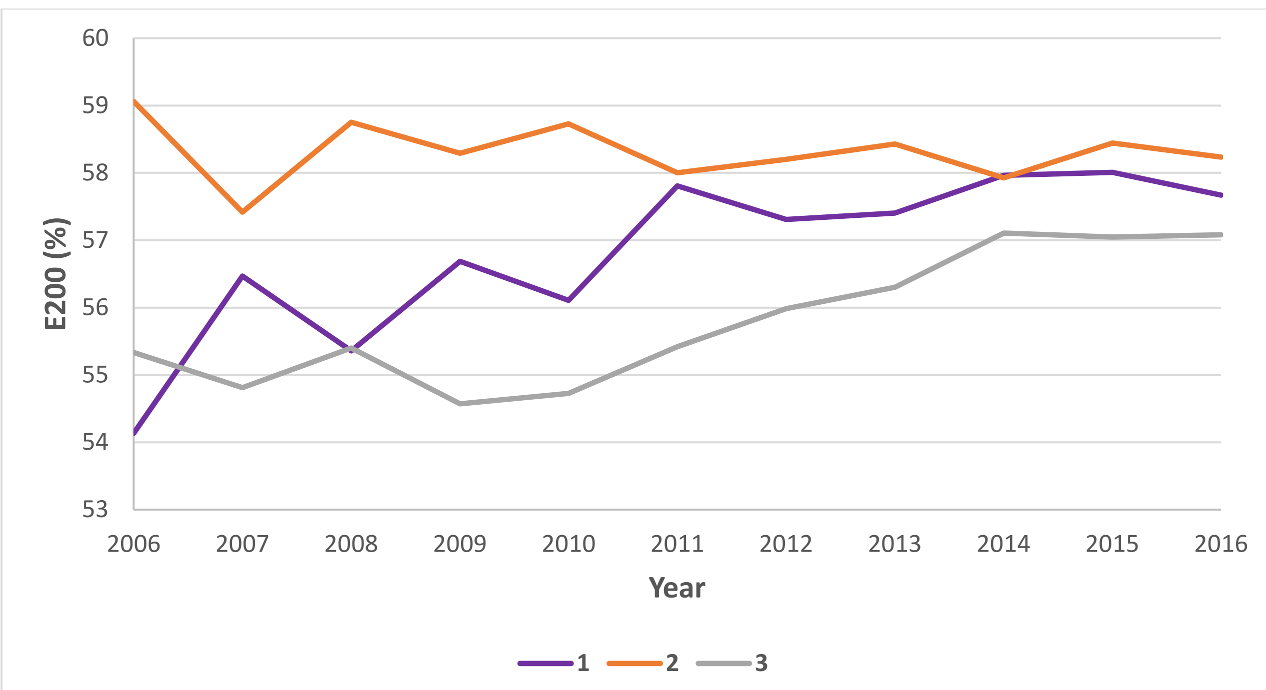

Figure 125 RFG Winter E200 by PADD Produced from Batch Data

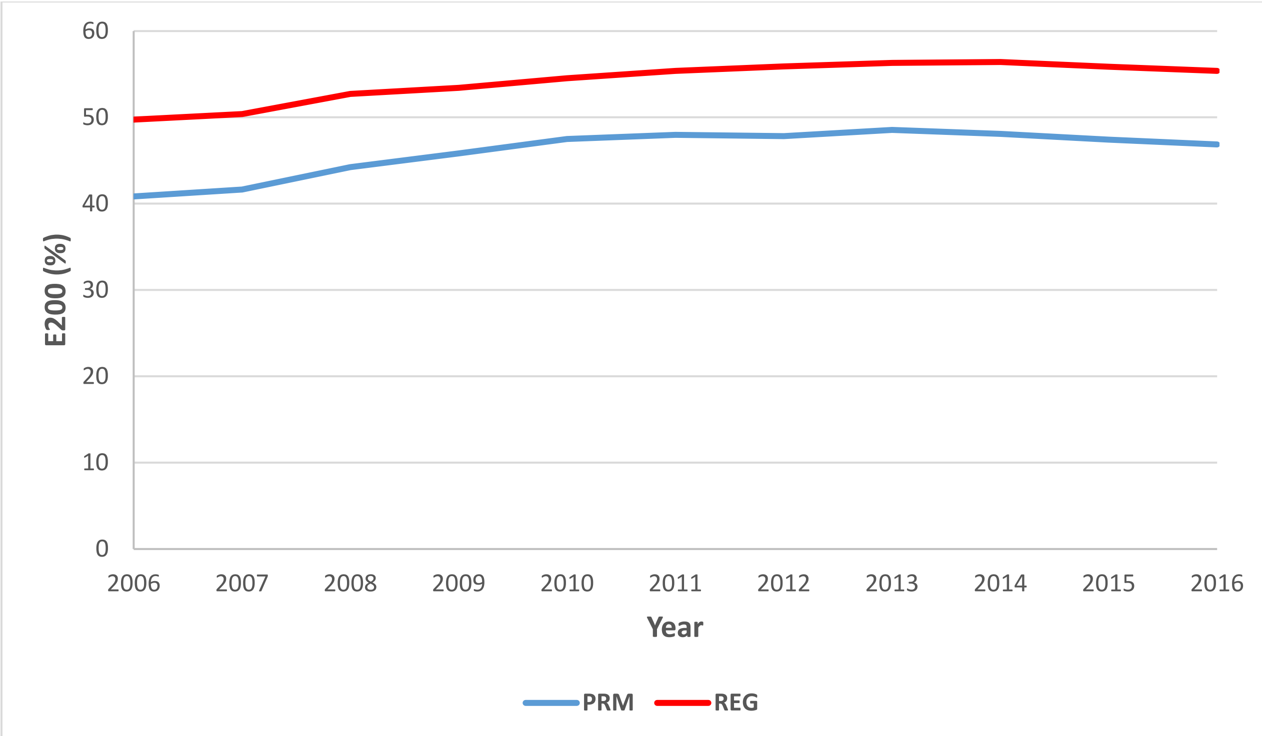

Figure 126 Regular versus Premium CG and RFG E200 (ethanol-adjusted)

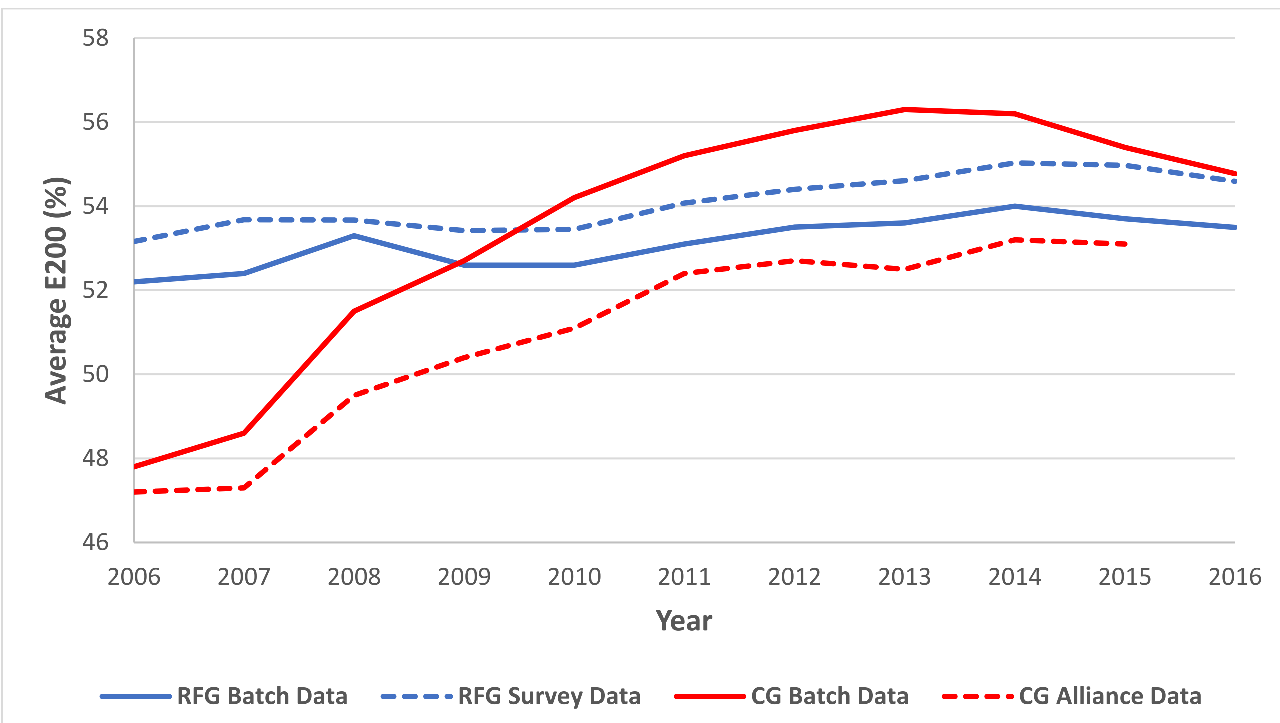

Figure 127 Comparing Batch, Survey, and Alliance data (ethanol-adjusted)

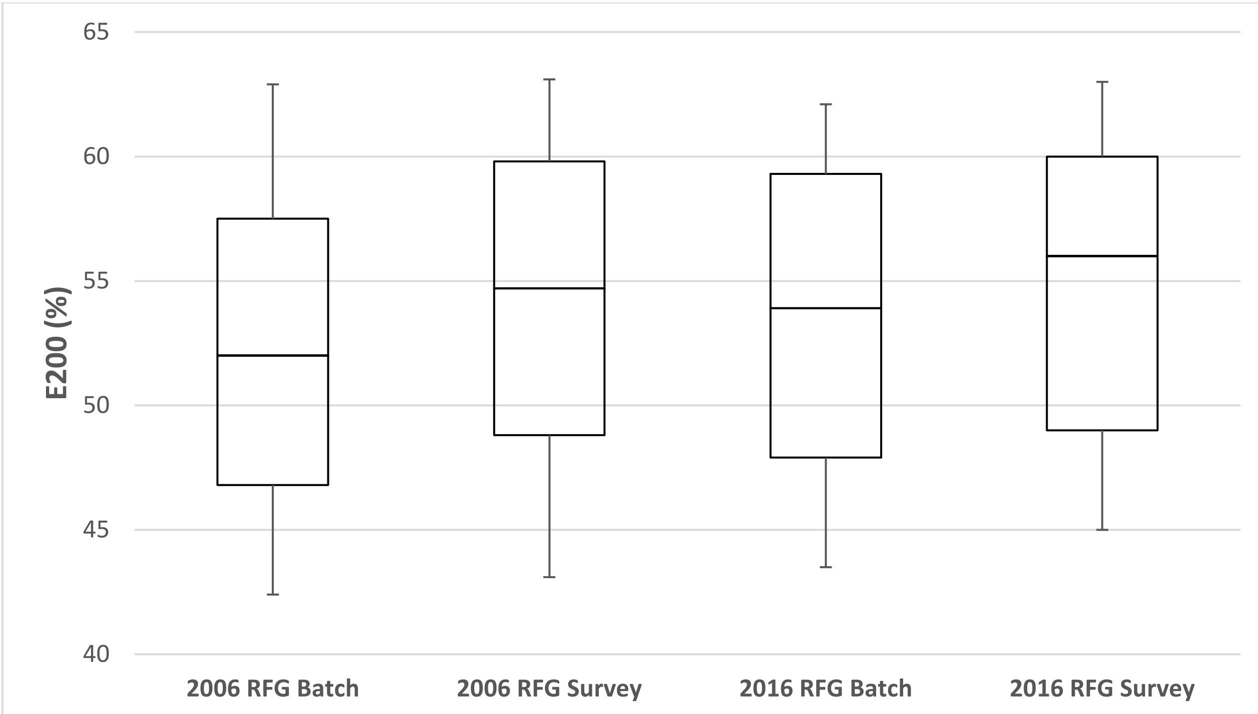

Figure 128 E200 RFG Box and Whiskers (5%, 25%, median, 75%, 95%)

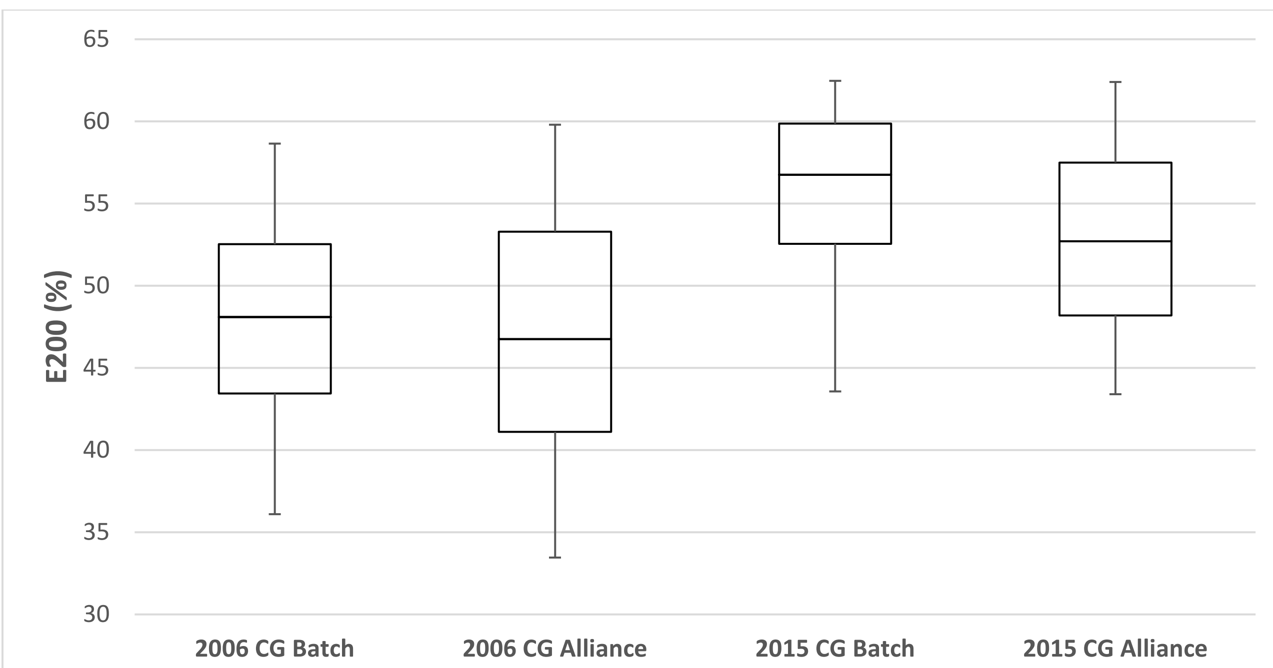

Figure 129 E200 CG Box and Whiskers (5%, 25%, median, 75%, 95%; ethanol-adjusted)

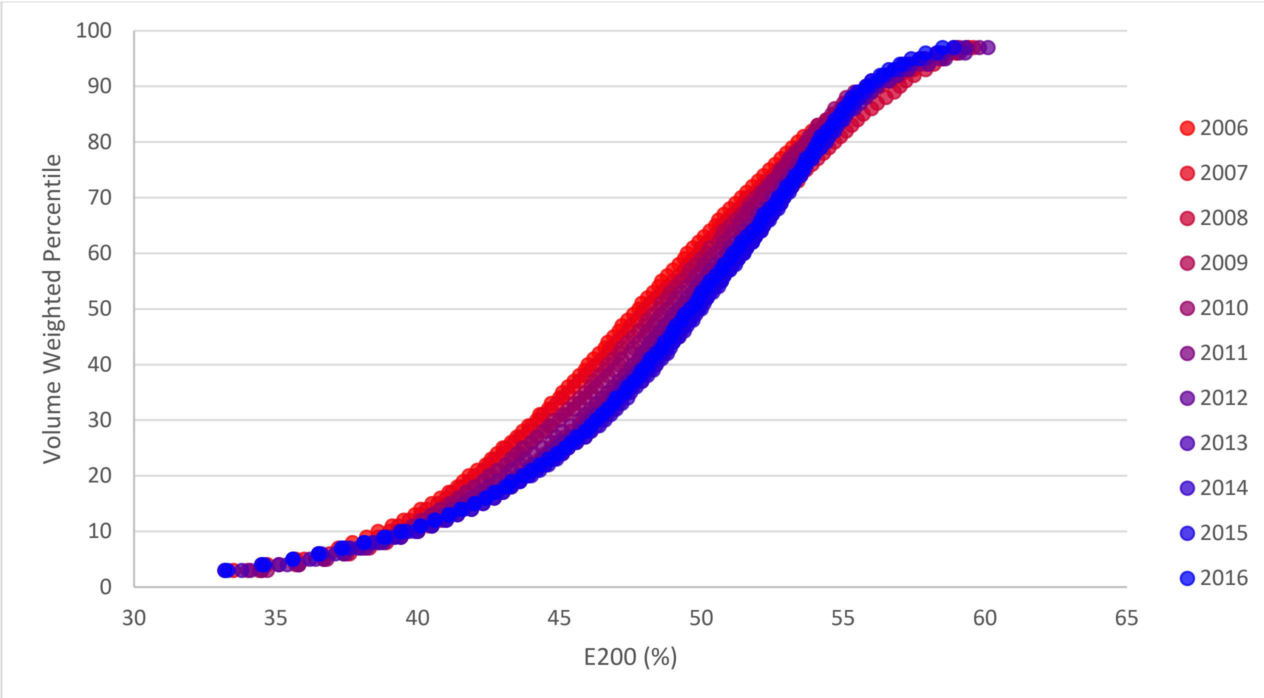

Figure 130 E200 Layered Percentile CG (not ethanol-adjusted)

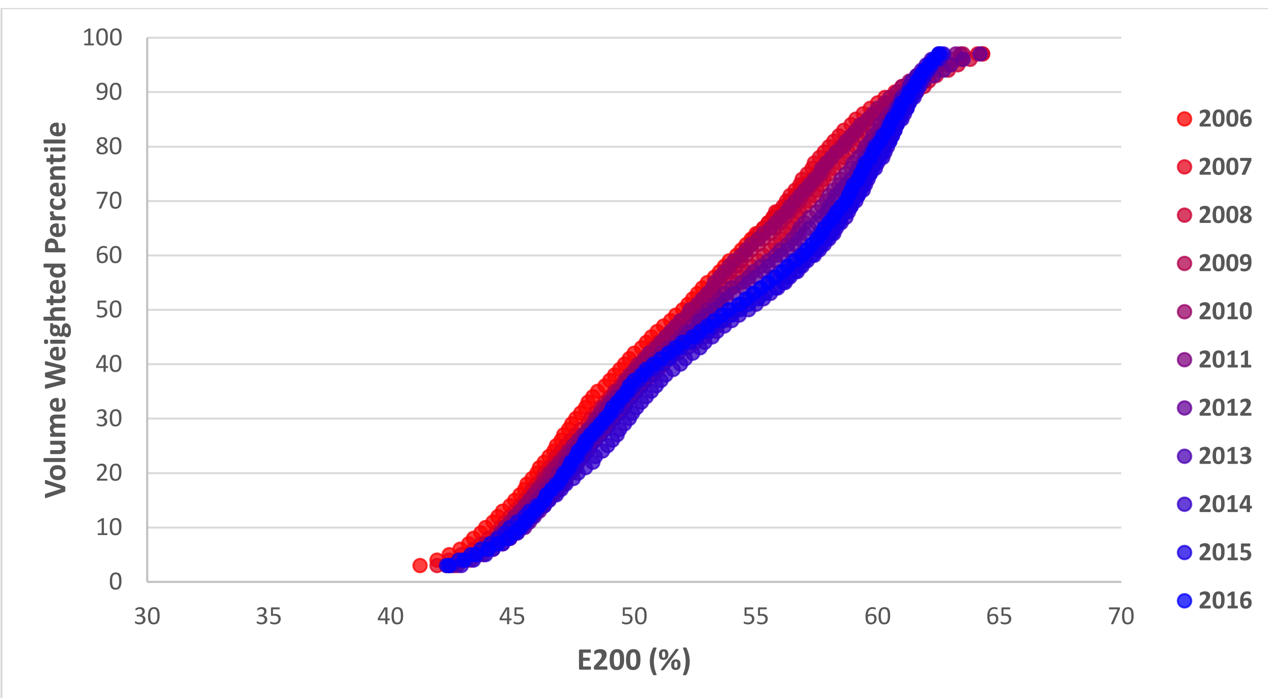

Figure 131 E200 Layered Percentile RFG

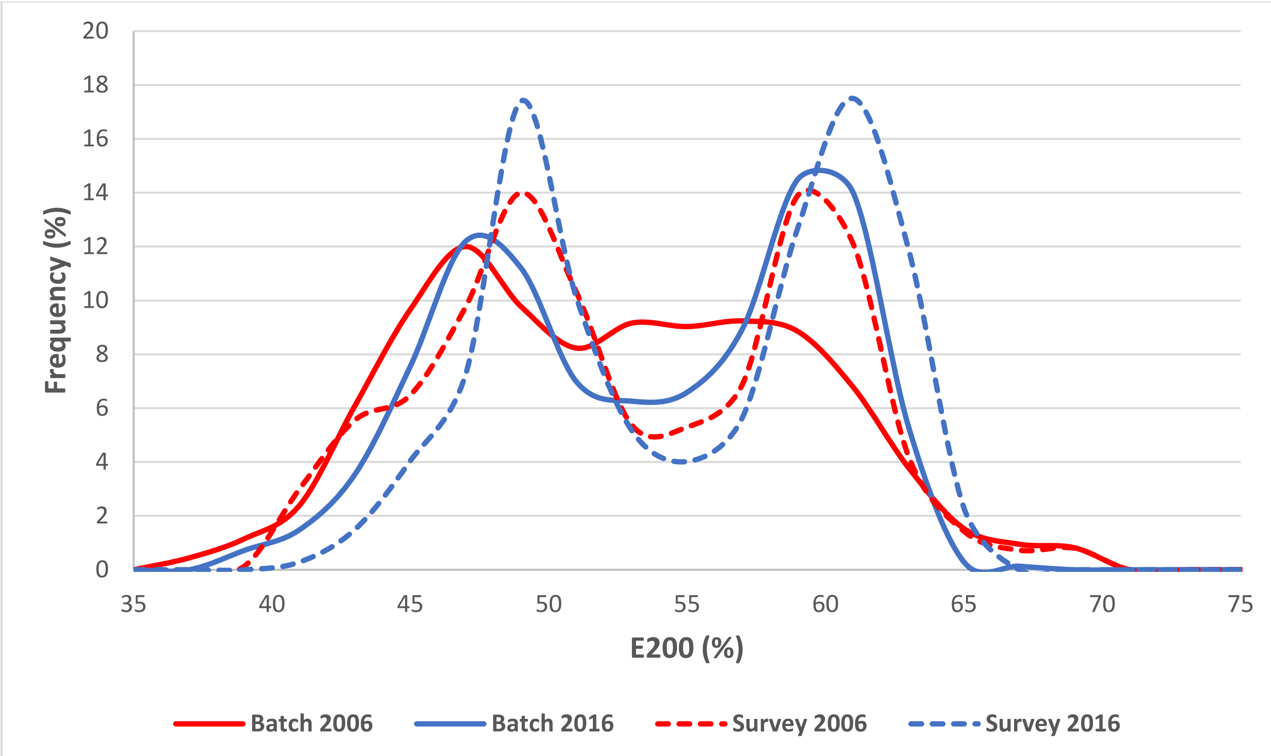

Figure 132 E200 RFG 2006 vs 2016 Histogram (bucket size = 2 %)

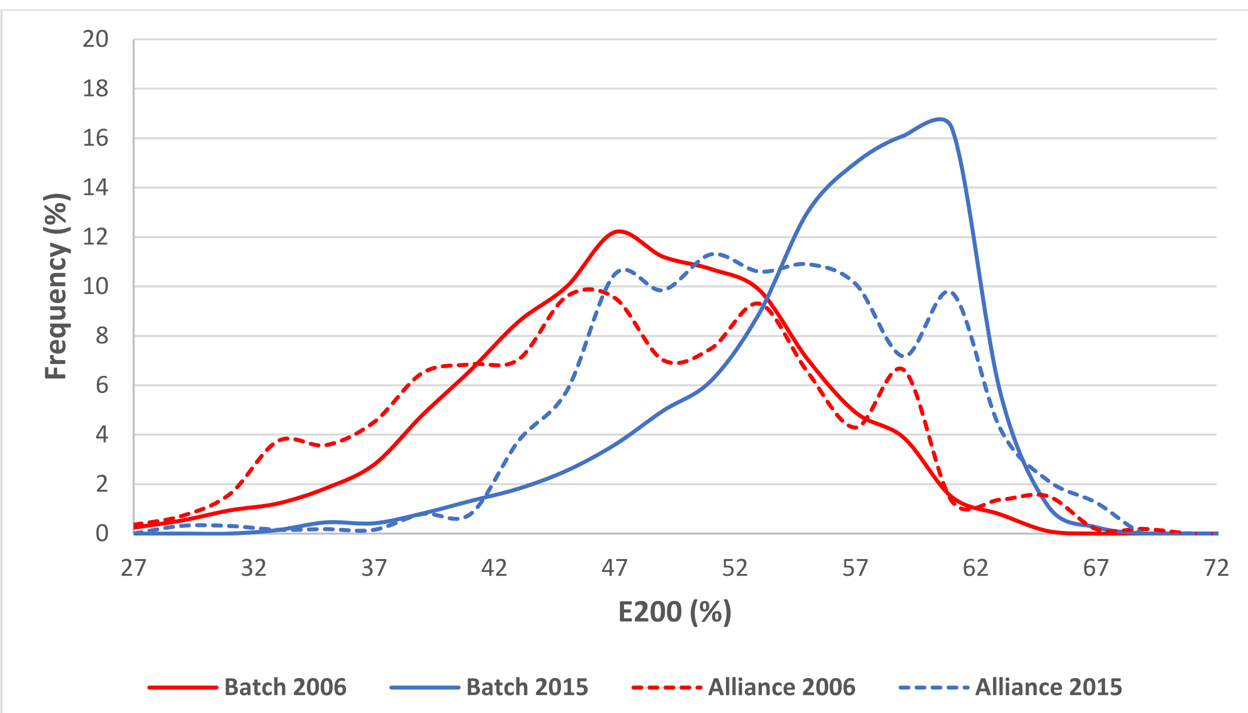

Figure 133 E200 CG 2006 vs 2015 Histogram (bucket size = 2 %; ethanol-adjusted)

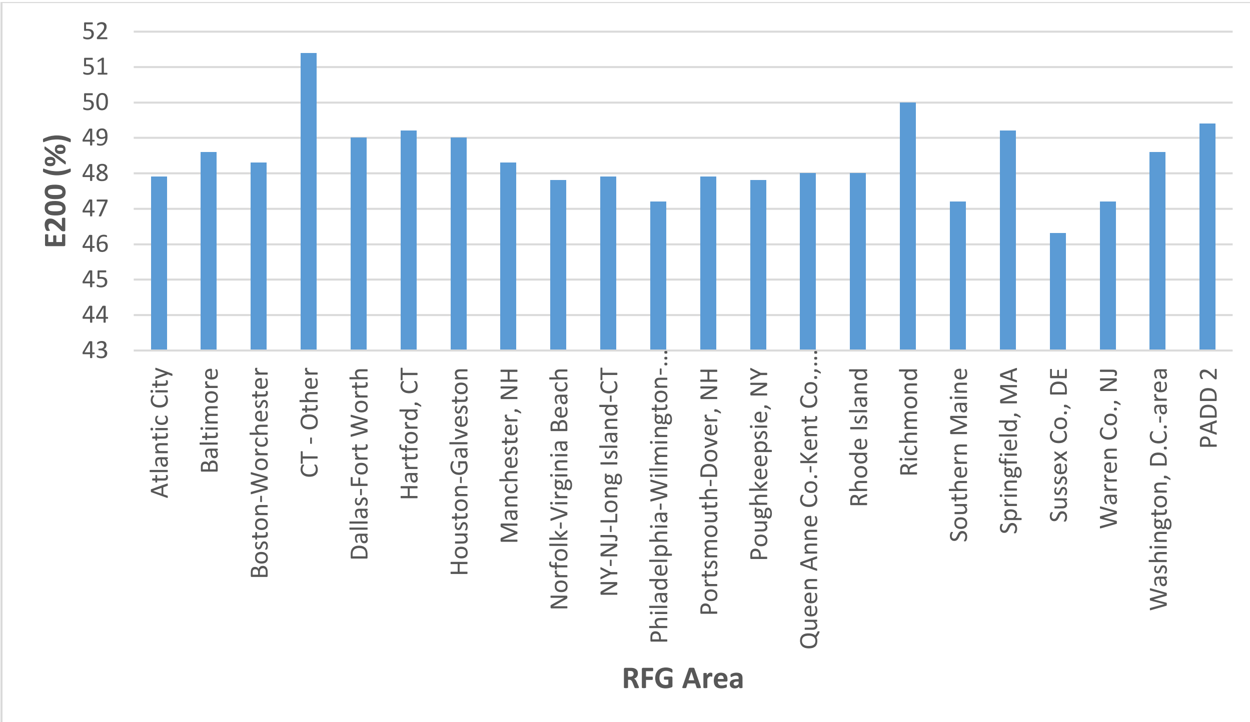

Figure 134 Summertime E200 Levels by RFG Area in 2016 from RFG Survey Data

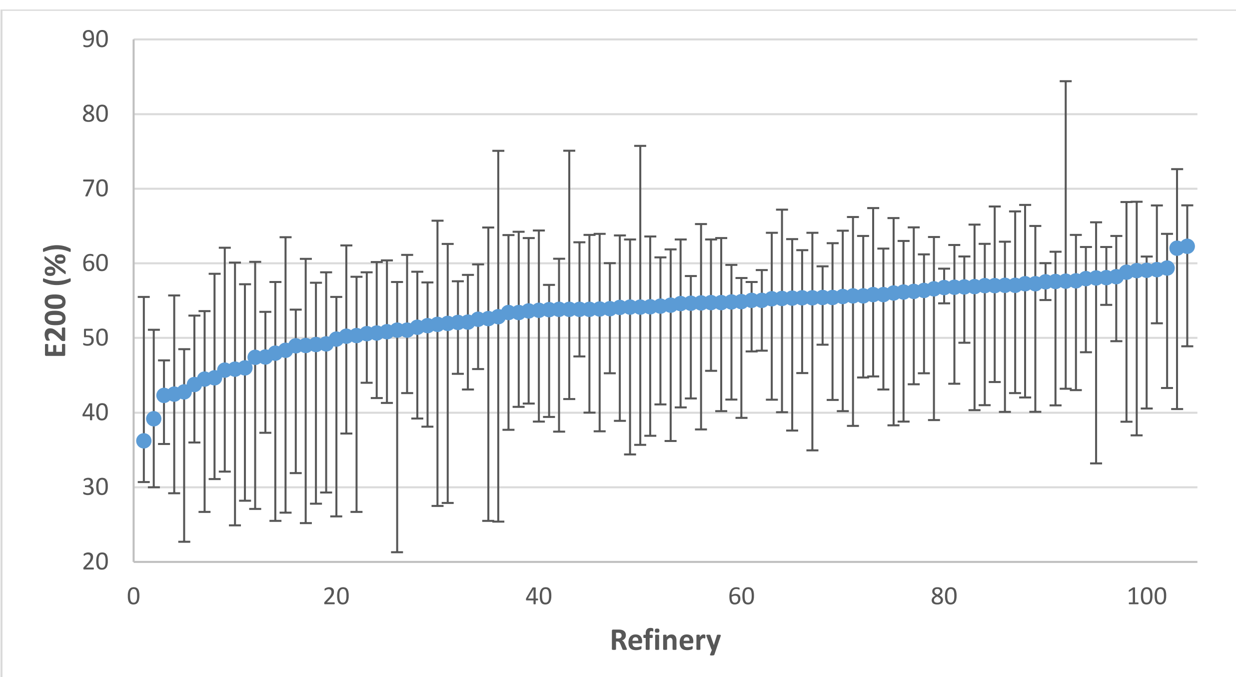

Figure 135 E200 by individual refinery from lowest to highest average (average, minimum and maximum for CG and RFG in 2016; not ethanol-adjusted)

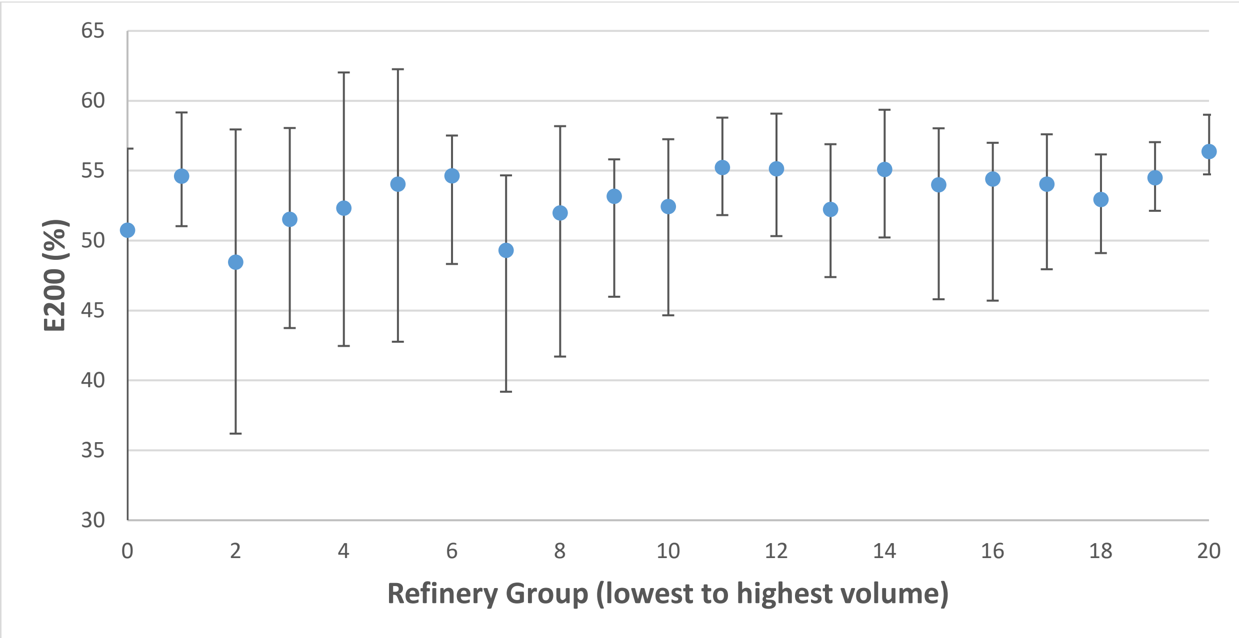

Figure 136 E200 for refineries grouped by volume output (groups of five refineries; average of the average, minimum and maximum values for CG and RFG 2016; not ethanol-adjusted)

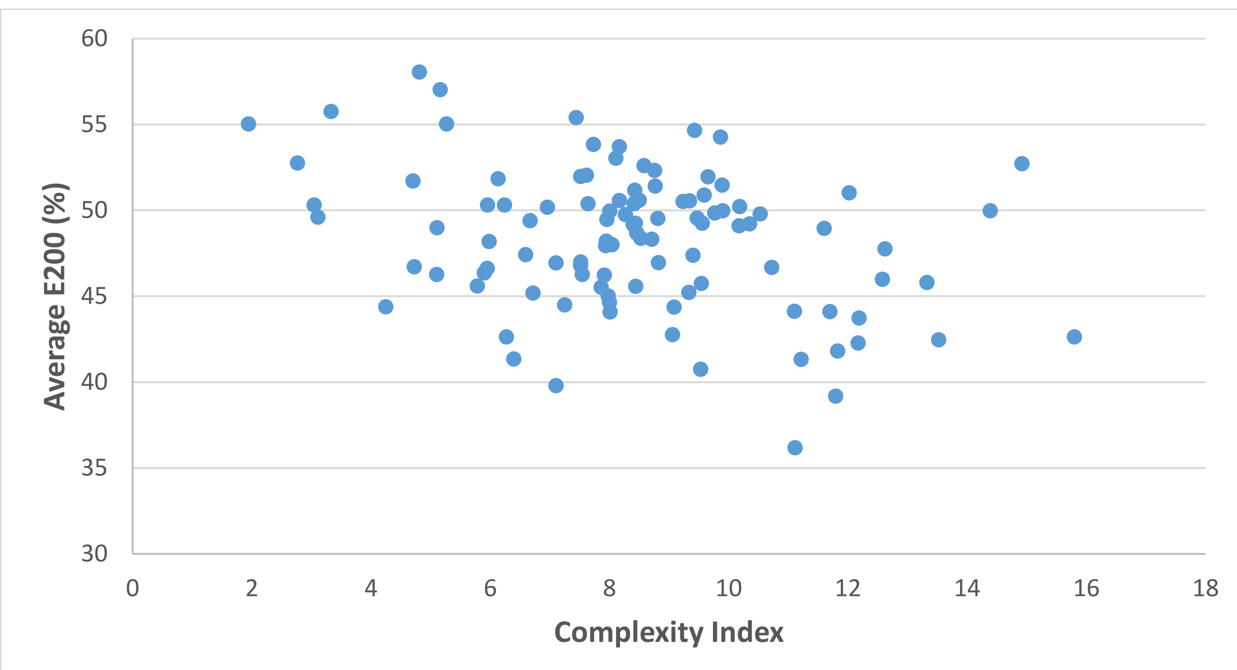

Figure 137 Average Gasoline E200 Content by Refinery Complexity Index in 2016 (not ethanol-adjusted)

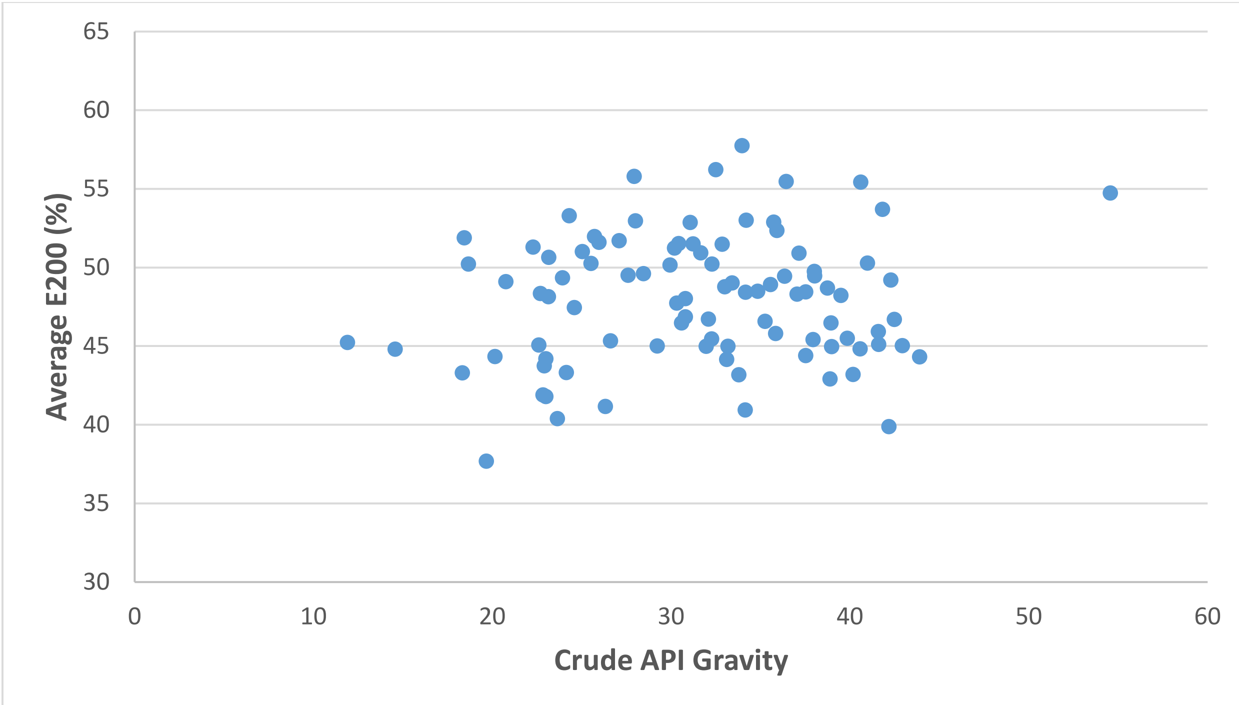

Figure 138 Gasoline E200 Content by Crude Oil API Gravity in 2011 (not ethanol-adjusted)

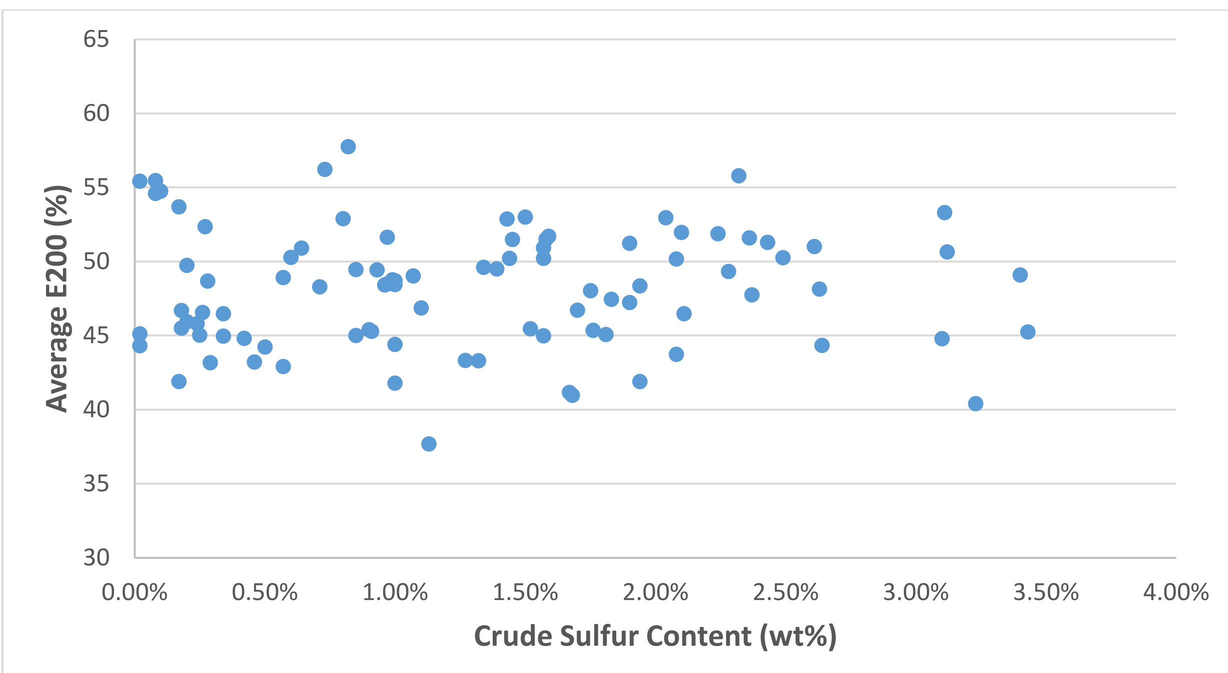

Figure 139 Gasoline E200 Content by Crude Oil Sulfur Content in 2011 (not ethanol-adjusted)

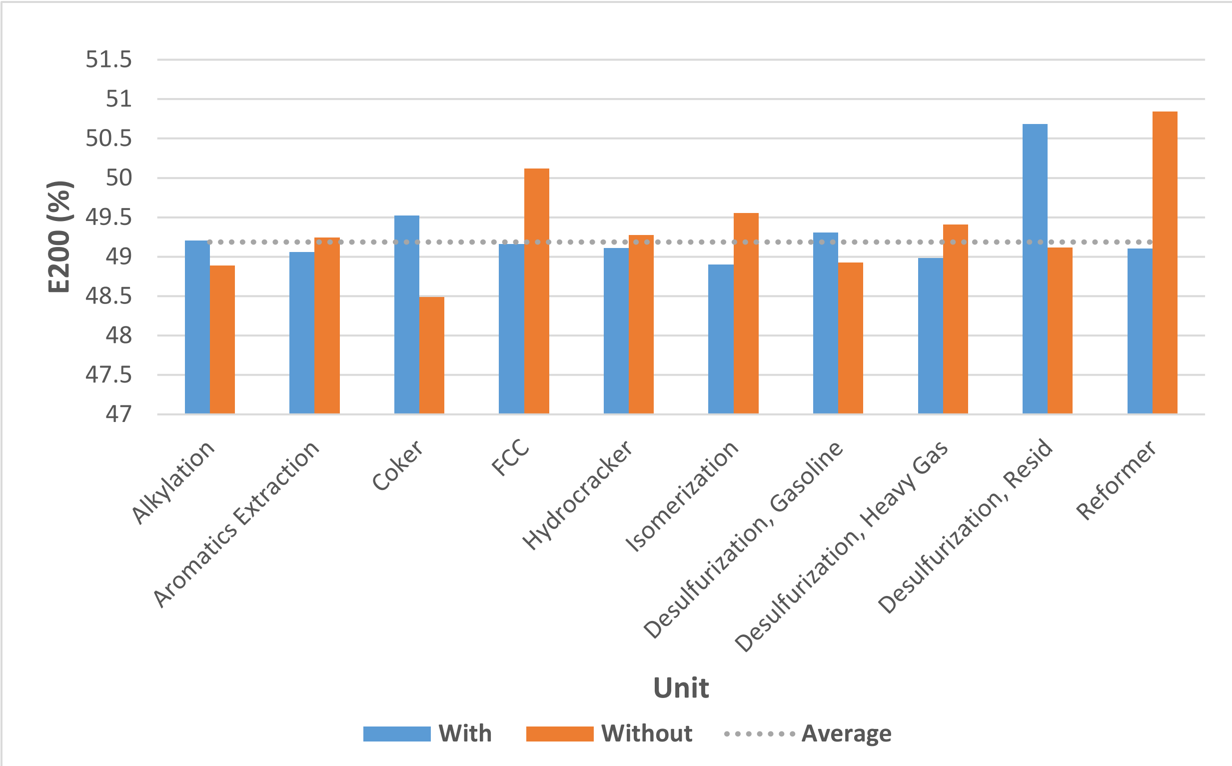

Figure 140 Average E200 Content by Refinery Unit Type in 2016 (not ethanol-adjusted)

g. E300

Highlights for the following E300 figures:

- Figure 141 shows that over the period of 2006 to 2014, E300 levels increased in both the CG and RFG pools likely due to market forces which increasingly favored greater diesel fuel production over gasoline production – also additional ethanol blending is a factor.
    - The large E300 spike in 2008 shown in both the batch and survey data corresponds to a spike in diesel fuel prices that year, which reflects the overall trend from 2006 to 2014.
- The decrease in E300 levels after 2013 is likely due to the market forces described in Section 5 which favored a reversed trend for increased gasoline production over diesel fuel production from U.S. refineries.
- Figures 151 through 157 show that, although refinery gasoline E300 averages have shifted lower, the variance in batch E300 levels has continued.
- Premium grade gasoline E300 levels remain consistently higher than those of regular grade gasoline, likely due to the blending of higher octane gasoline blendstocks, such as alkylate and reformate, which tend to have a lower temperature endpoint and contribute to a higher E300.
- Both the RFG survey data and the Alliance data show less gasoline with low E300 compared to the batch data.
    - The mixing of batches in the distribution system could contribute to this difference.
- Figures 159 to 162 show that, refinery size, complexity index, crude oil API gravity or crude oil sulfur content have no discernable impact on gasoline E300 levels.

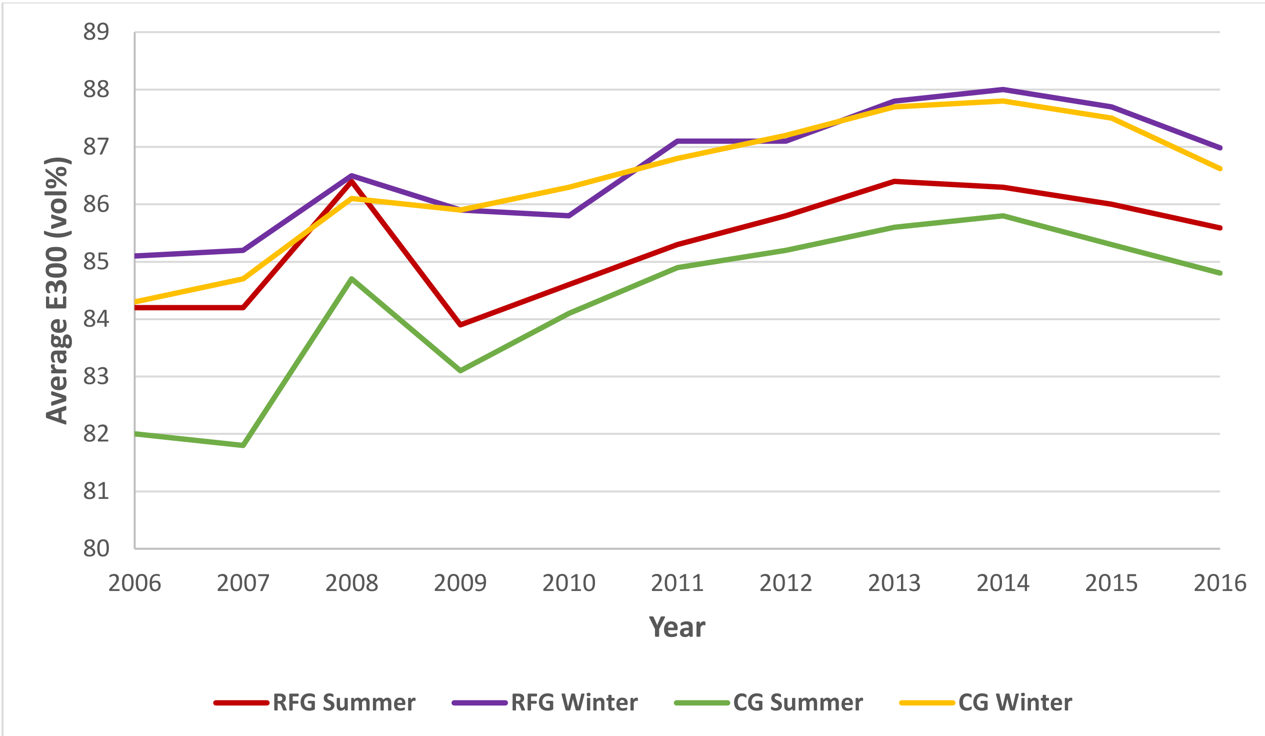

Figure 141 E300 Trends Summer versus Winter (ethanol-adjusted)

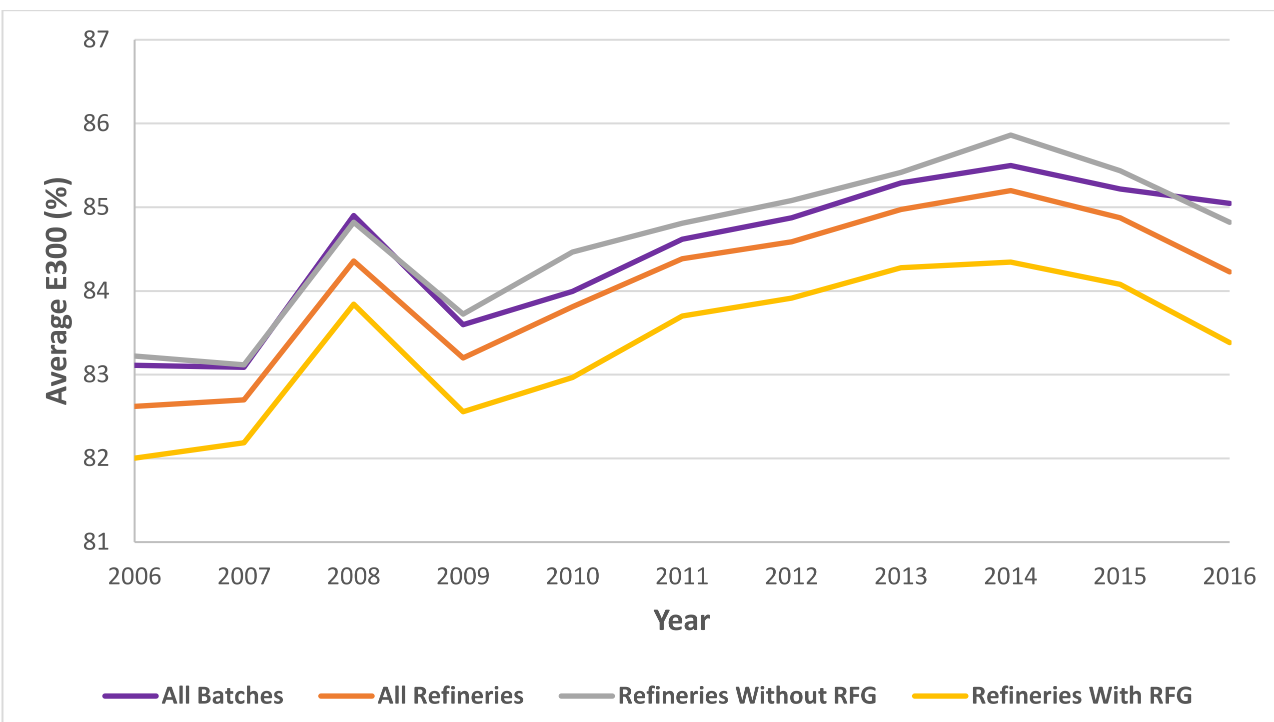

Figure 142 Average CG E300 by Refinery Type (not ethanol-adjusted)

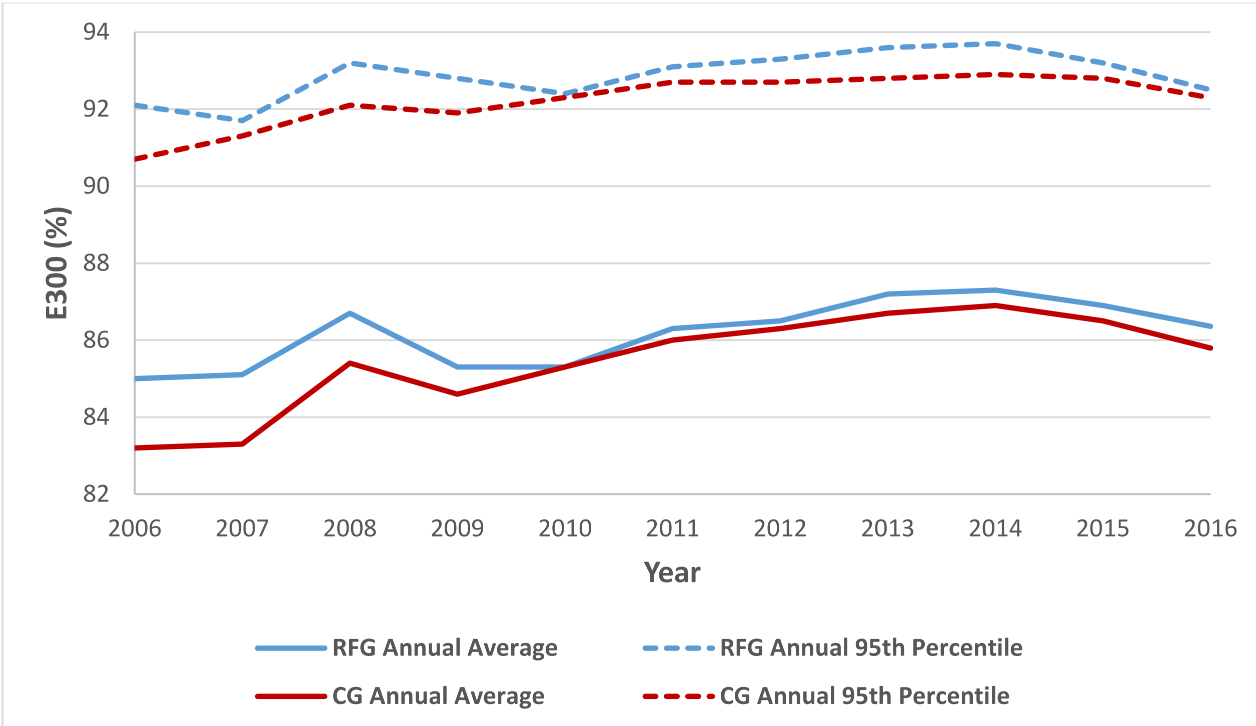

Figure 143 E300 Trends 95th Percentile versus Average (ethanol-adjusted)

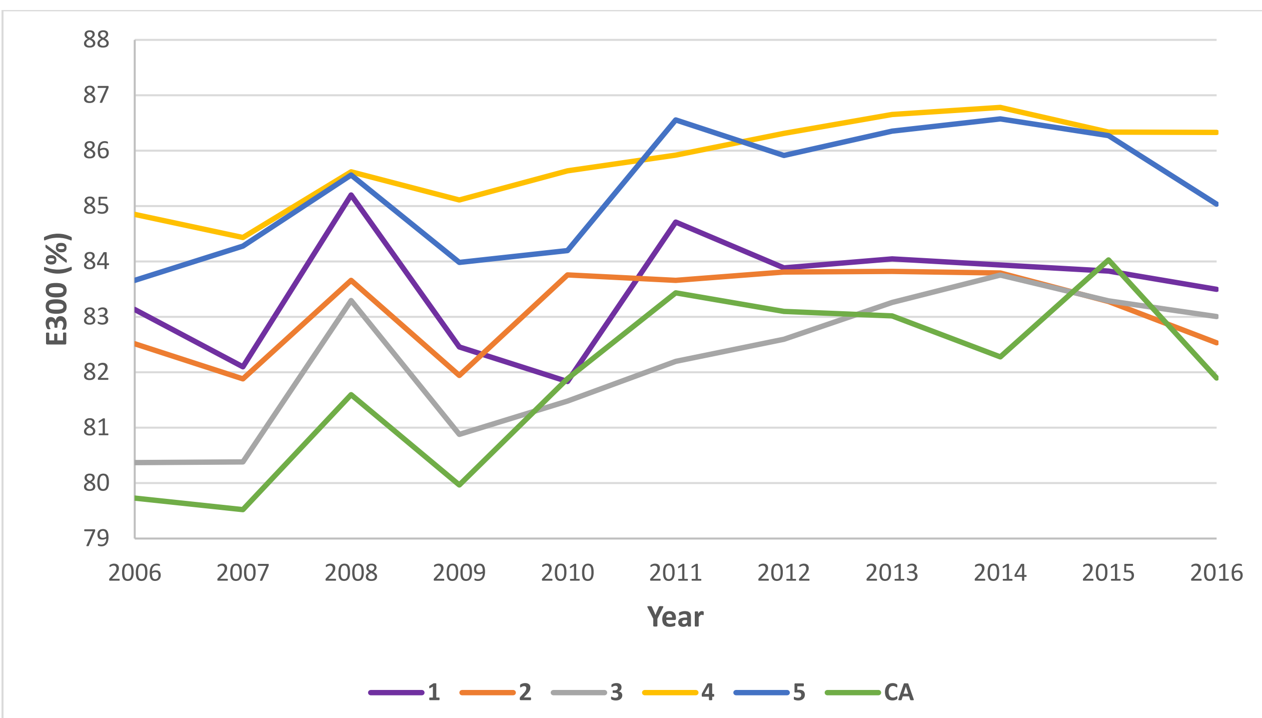

Figure 144 CG Summer E300 by PADD (not ethanol-adjusted)

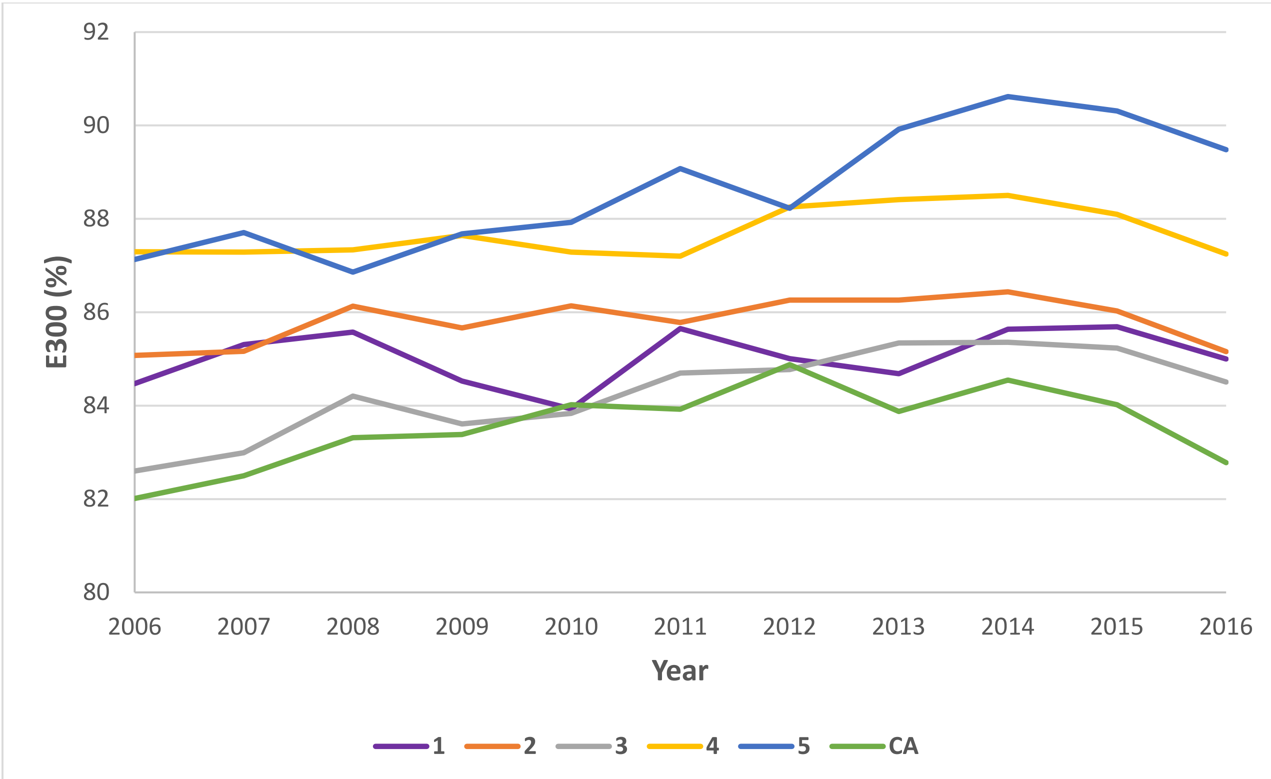

Figure 145 CG Winter E300 by PADD (not ethanol-adjusted)

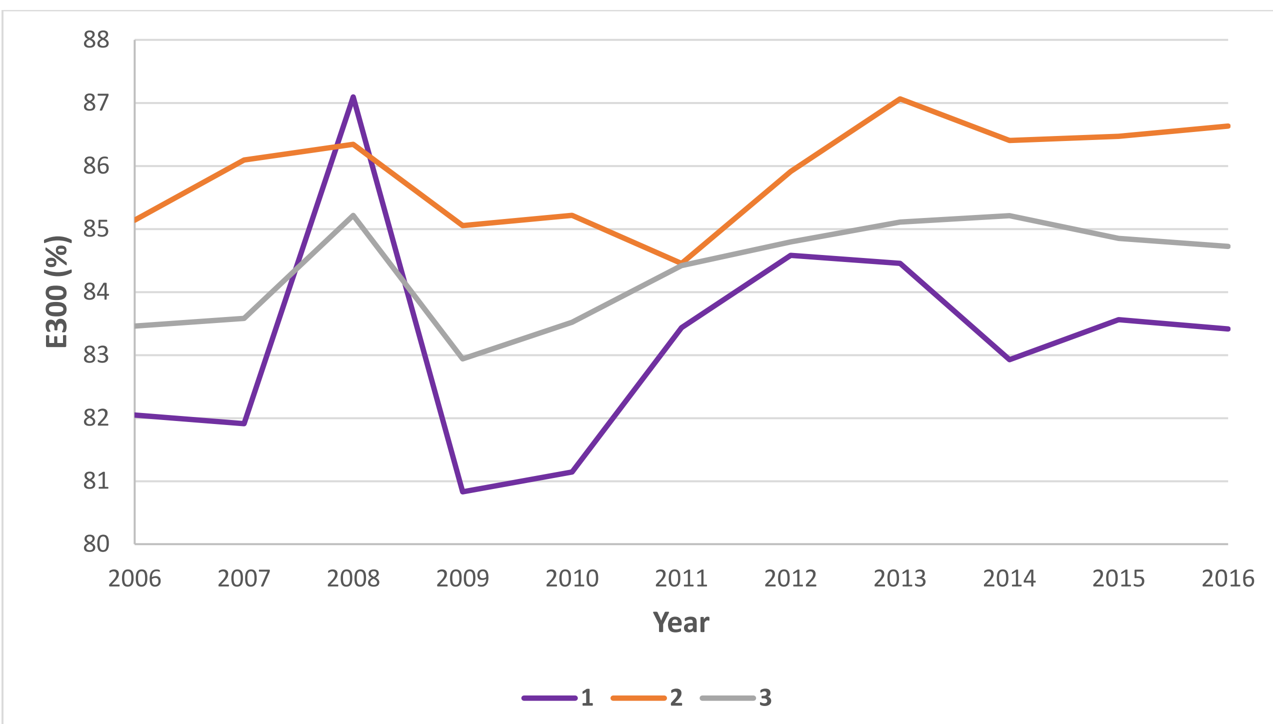

Figure 146 RFG Summer E300 by PADD Produced from Batch Data

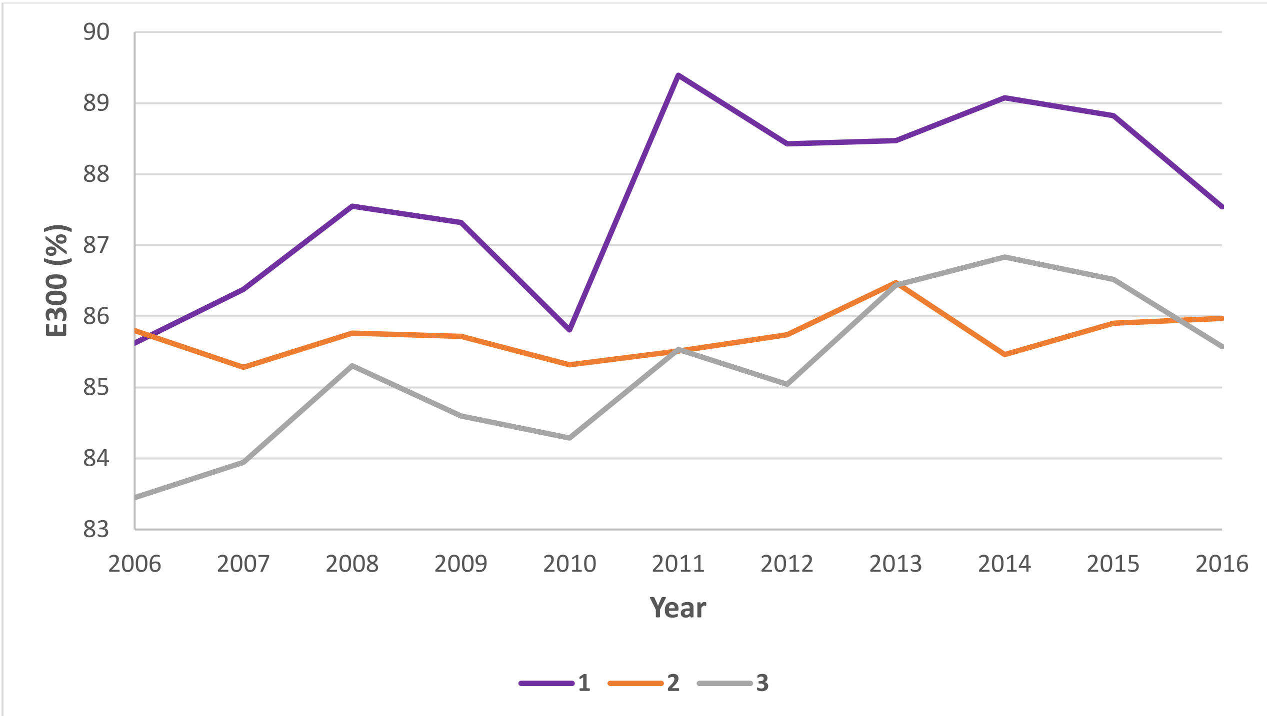

Figure 147 RFG Winter E300 by PADD Produced from Batch Data

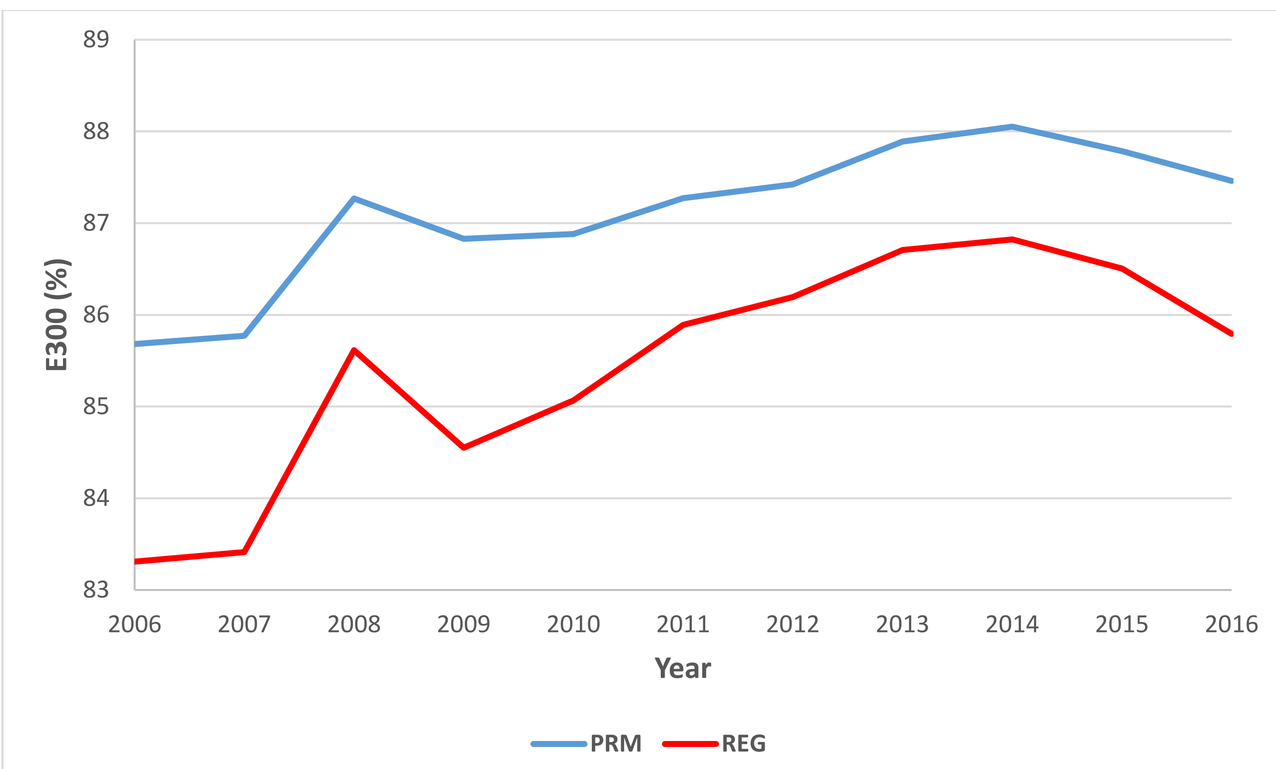

Figure 148 Regular vs Premium CG and RFG E300 (ethanol-adjusted)

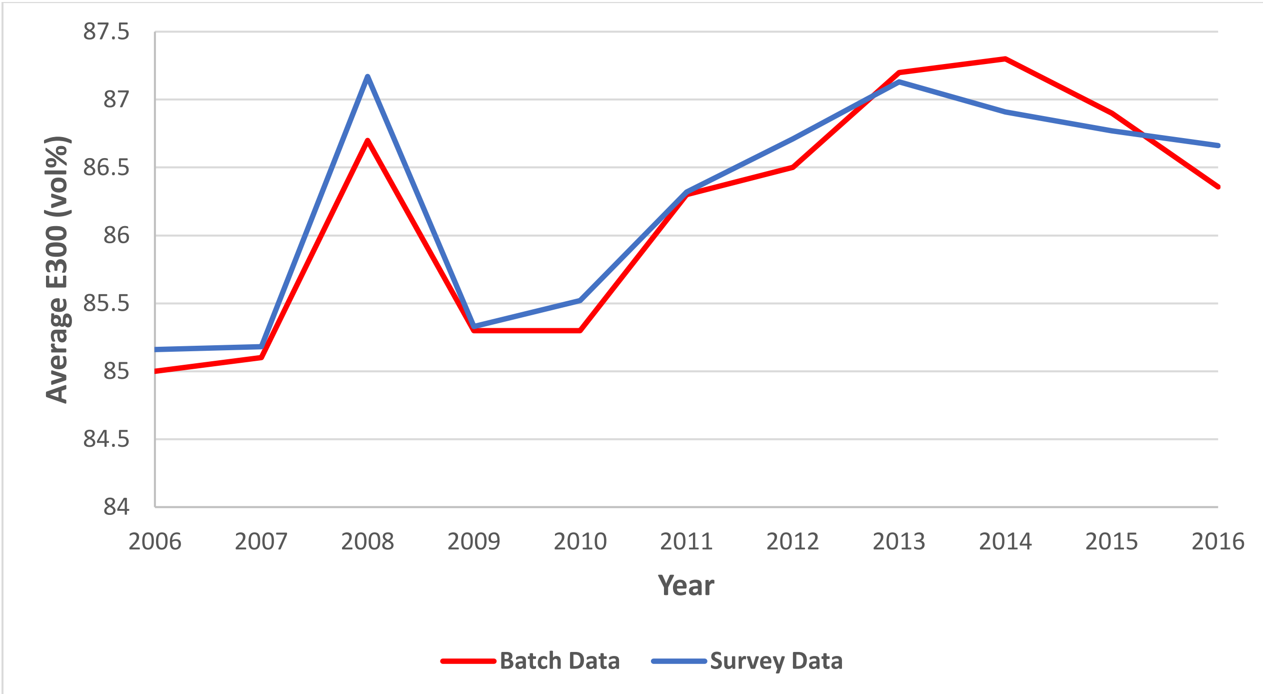

Figure 149 E300 RFG Batch versus Survey

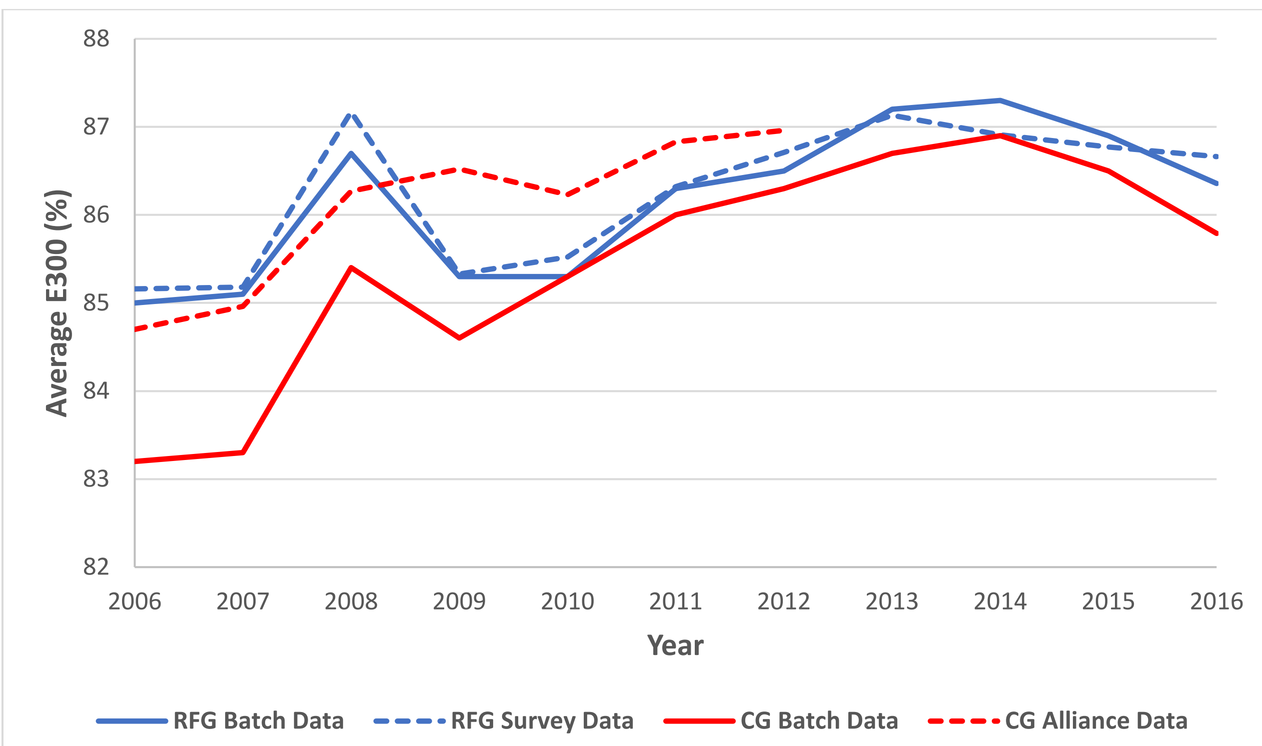

Figure 150 Comparing Batch, Survey, and Alliance Data (ethanol-adjusted)

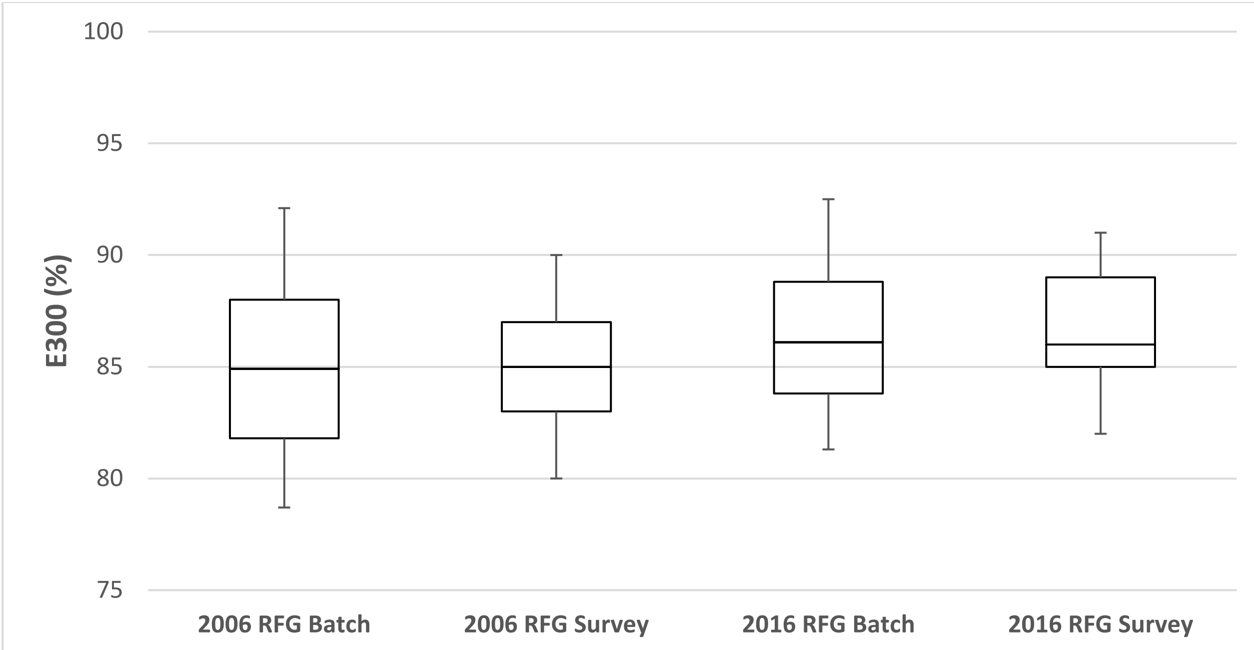

Figure 151 E300 RFG Box and Whiskers (5%, 25%, median, 75%, 95%)

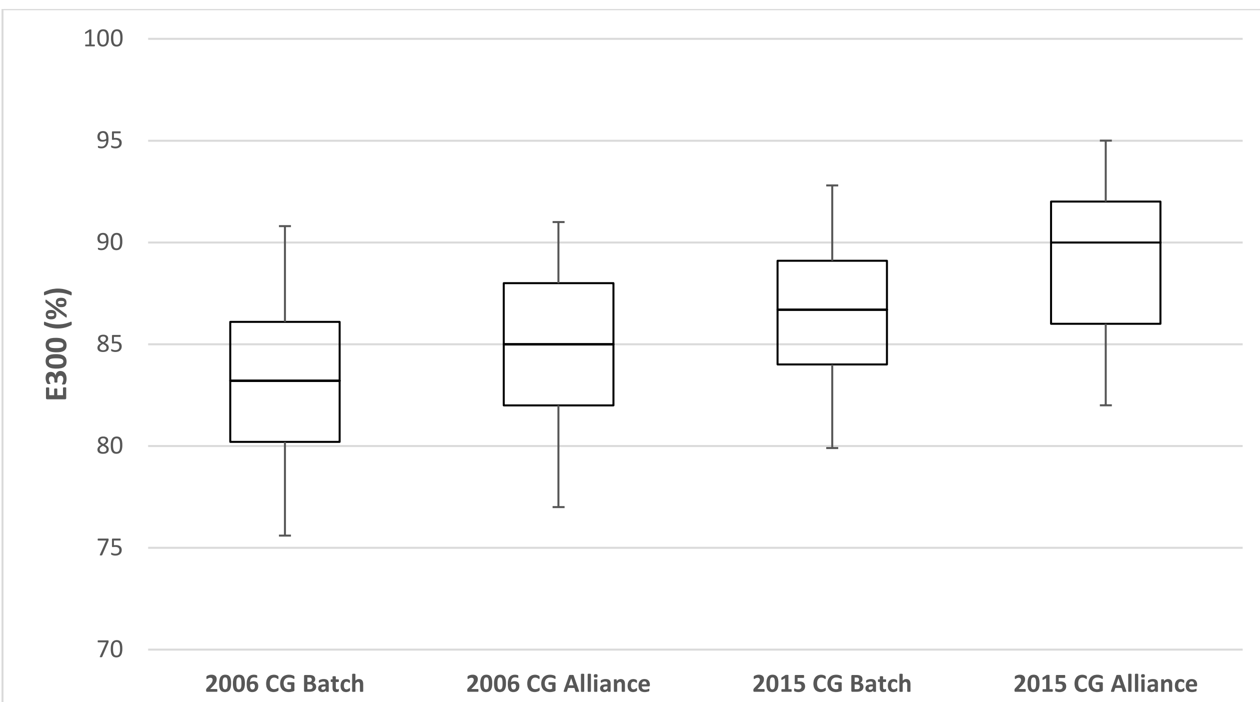

Figure 152 E300 CG Box and Whiskers (5%, 25%, median, 75%, 95%; (ethanol-adjusted))

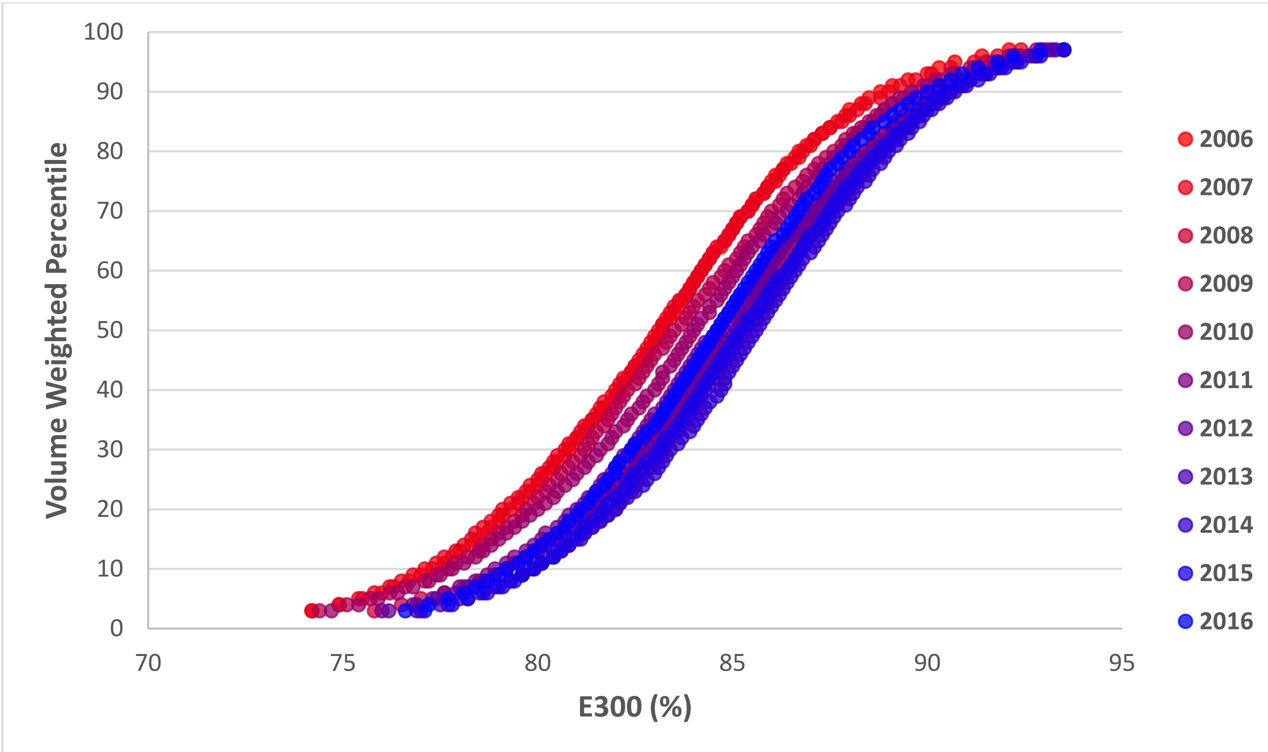

Figure 153 E300 Layered Percentile CG (not ethanol-adjusted)

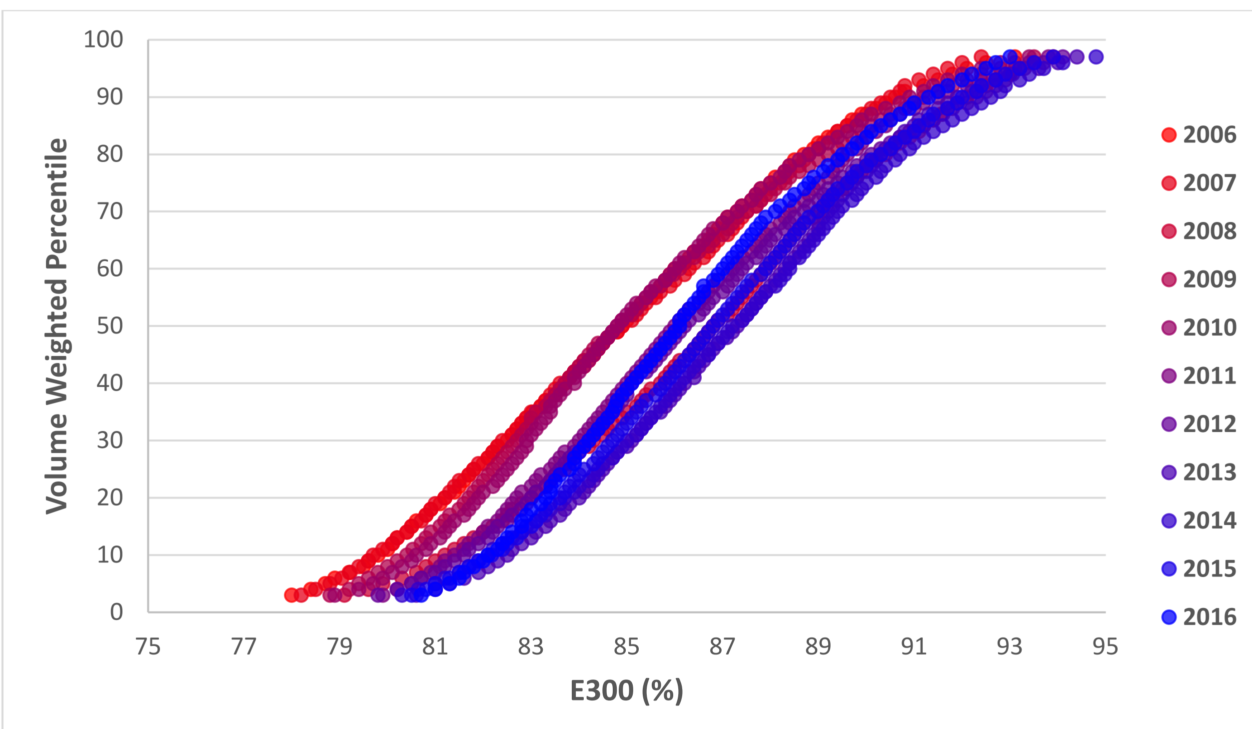

Figure 154 E300 Layered Percentile RFG

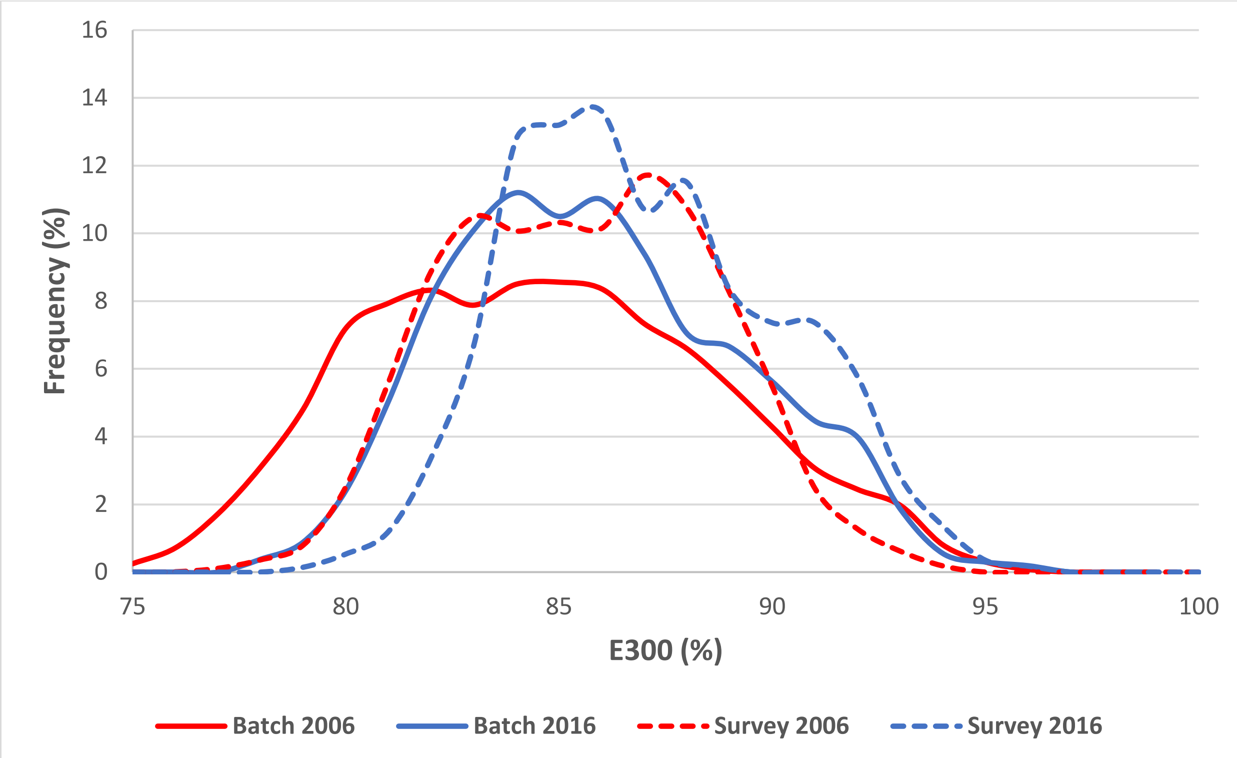

Figure 155 E300 RFG 2006 versus 2016 Histogram (bucket size = 1 %)

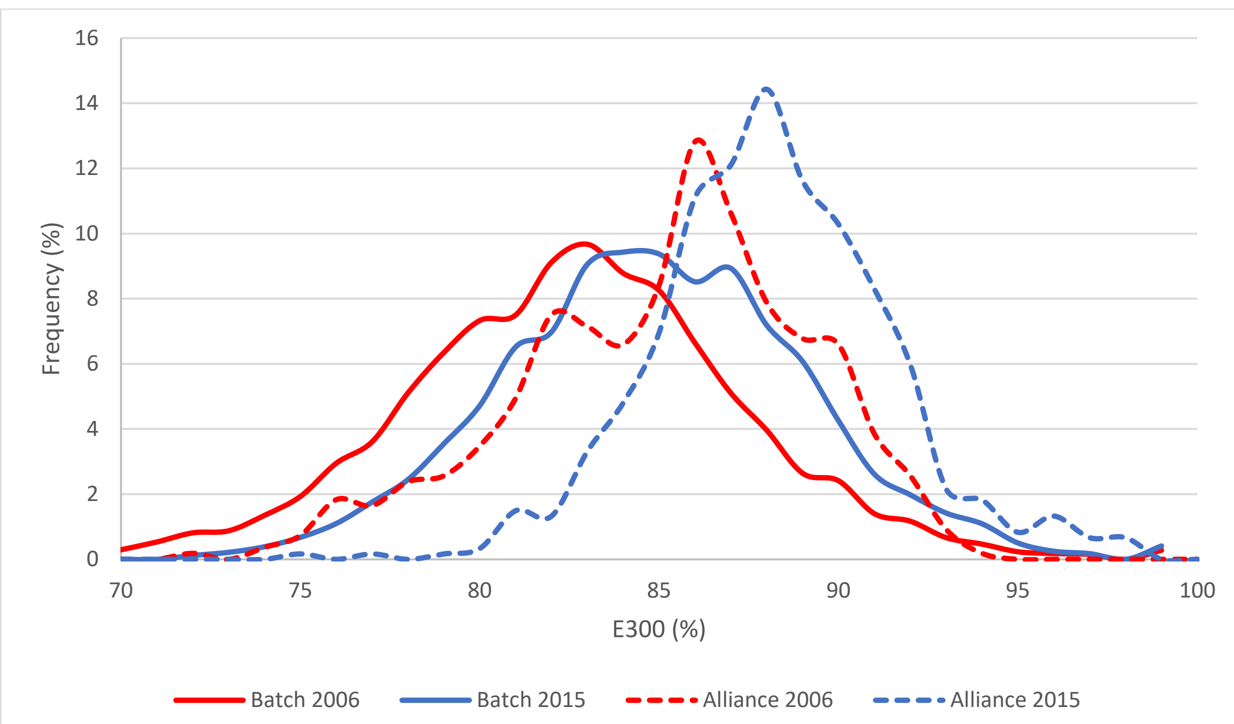

Figure 156 E300 CG 2006 versus 2015 Histogram (bucket size = 1 %; ethanol-adjusted)

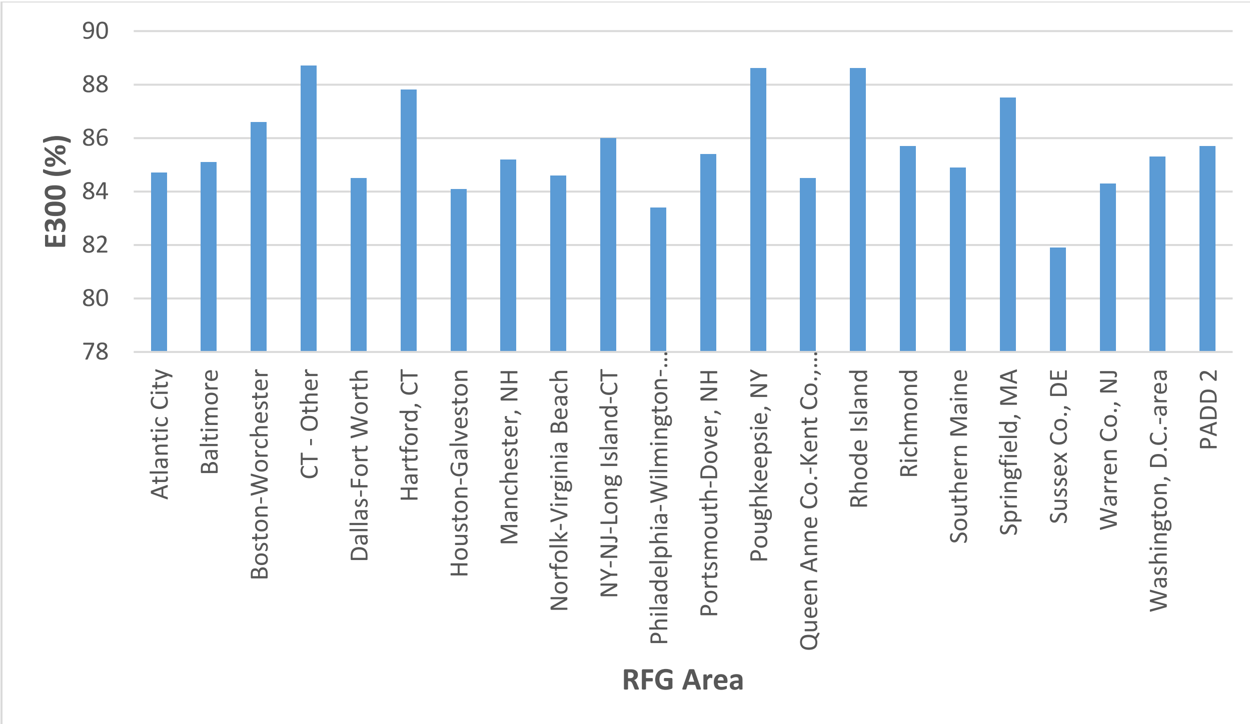

Figure 157 Summertime E300 Levels by RFG Area in 2016 from RFG Survey Data

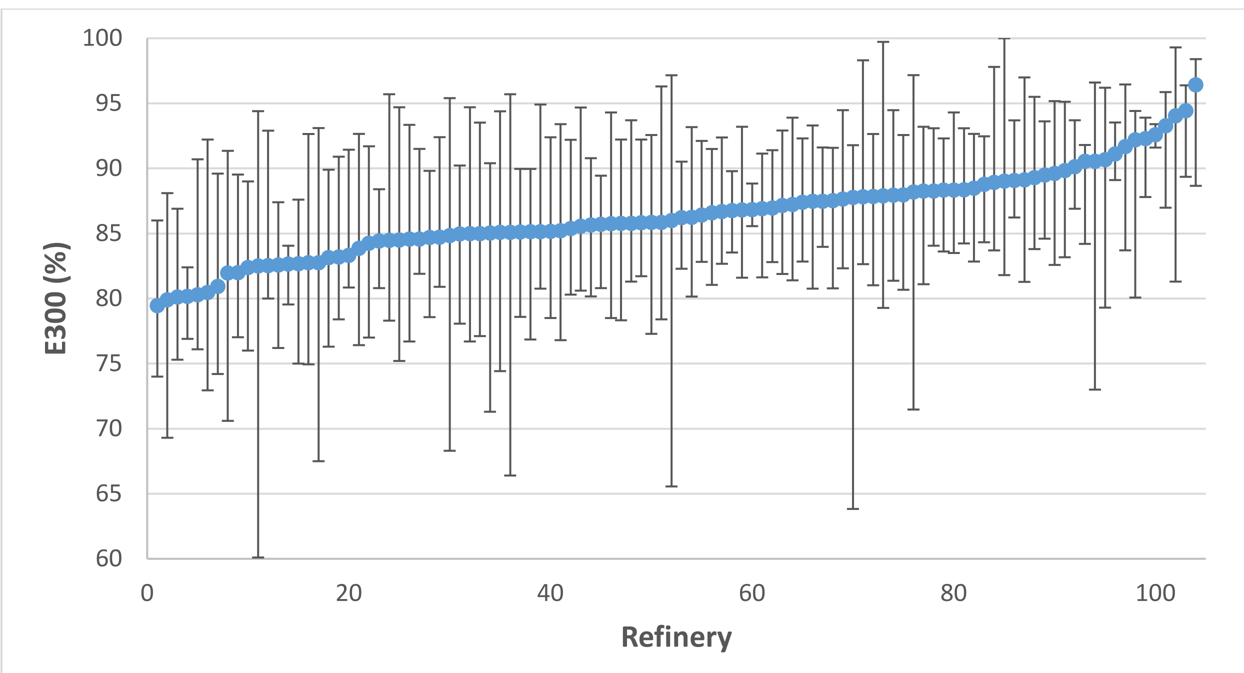

Figure 158 E300 by individual refinery from lowest to highest average (average, minimum and maximum for CG and RFG in 2016; not ethanol-adjusted)

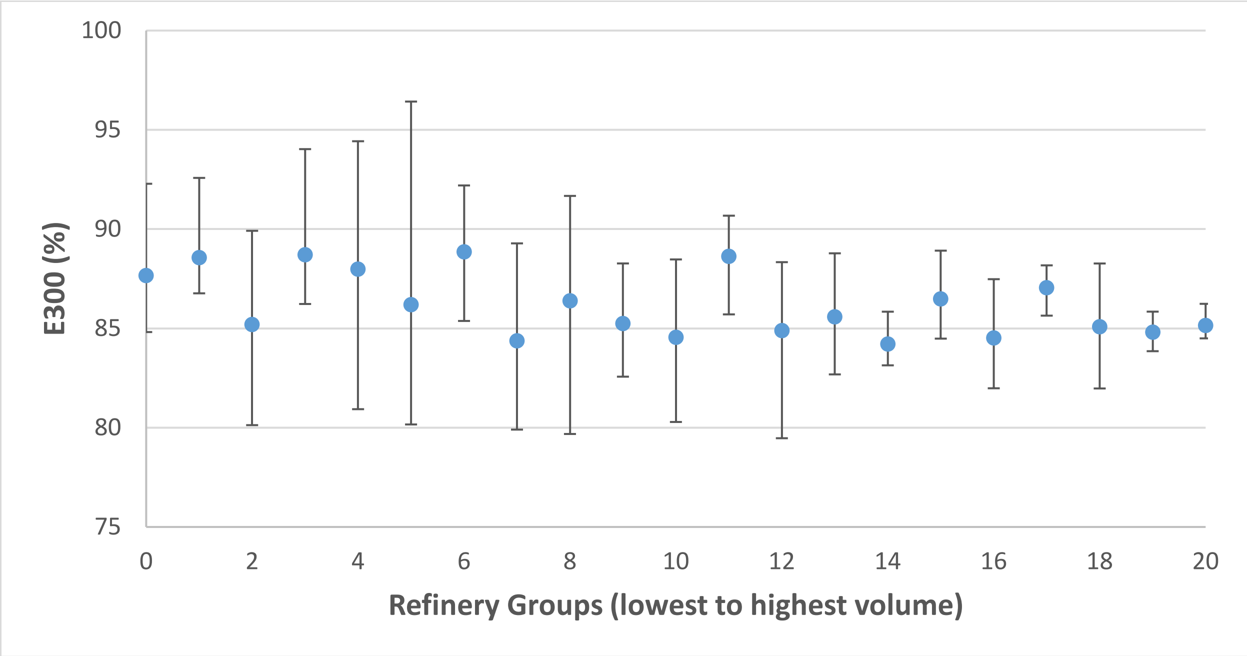

Figure 159 E300 for refineries grouped by volume output (groups of five refineries; average of the average, minimum and maximum value for CG and RFG 2016; not ethanol-adjusted)

Figure 160 Average Gasoline E300 Content by Refinery Complexity Index in 2016 (not ethanol-adjusted)

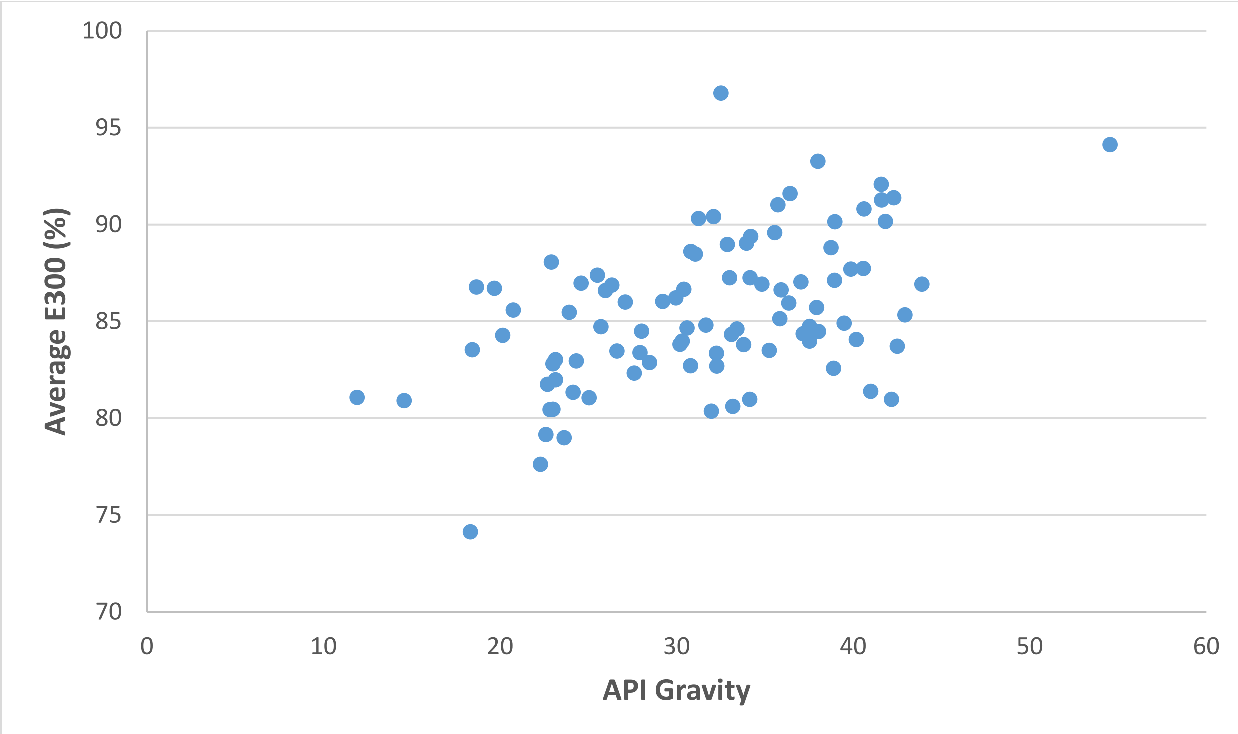

Figure 161 Gasoline E300 Content by Crude Oil API Gravity in 2011 (not ethanol-adjusted)

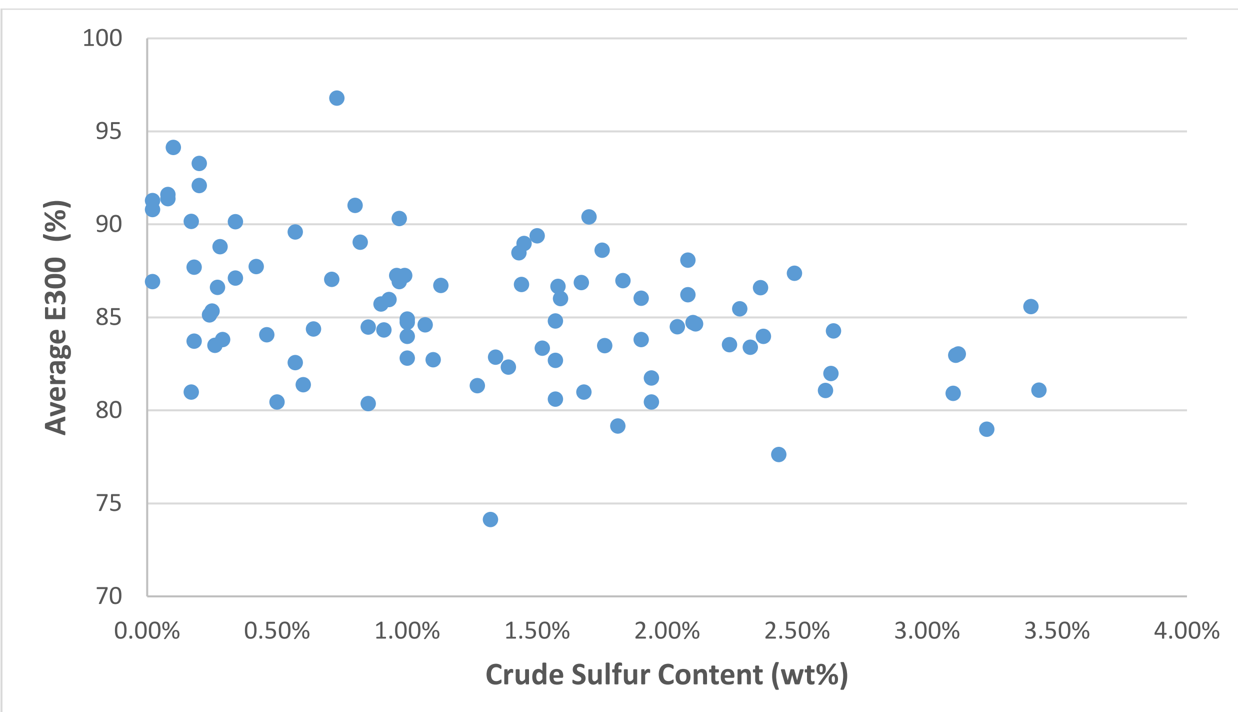

Figure 162 Gasoline E300 Content by Crude Oil Sulfur Content in 2011 (not ethanol-adjusted)

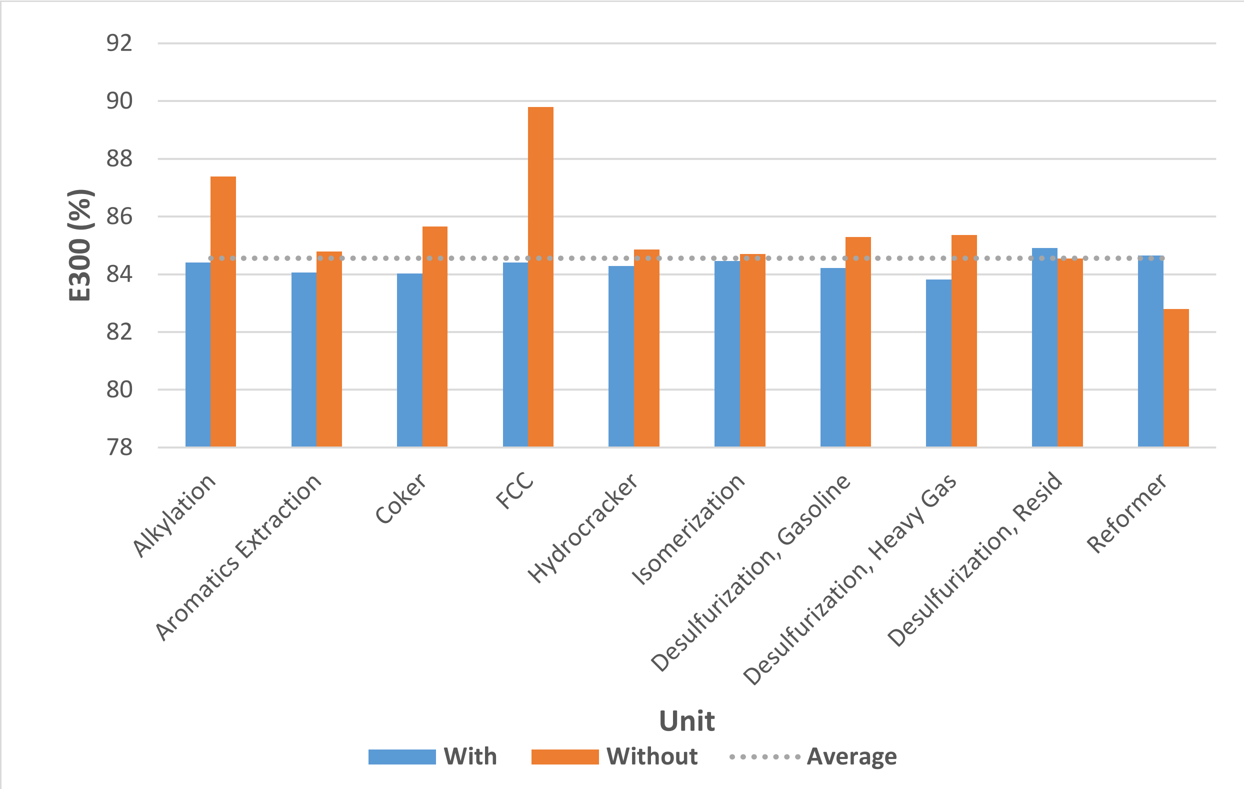

Figure 163 Average E300 Content by Refinery Unit Type in 2016 (not ethanol-adjusted)