# Fuel Supply Defaults

## Regional Fuels and the Fuel Wizard in MOVES4

EPA United States Environmental Protection Agency

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## Regional Fuels and the Fuel Wizard in MOVES4

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

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United States Environmental Protection Agency

EPA-420-R-23-025
August 2023

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# 1. Introduction

This document describes the background on the fuel supply components of MOVES and methodology used to develop them.

MOVES estimates emissions of onroad vehicles and nonroad equipment using the "fuel types" gasoline (E0 through E15), diesel (including biodiesel blends), compressed natural gas (CNG), and ethanol (E70-E85). MOVES also models nonroad equipment using liquified petroleum gas (LPG), and onroad vehicles powered by batteries or fuel cells using the electricity fuel type.[a] MOVES does not currently model use of liquified natural gas (LNG) due to its small market share and lack of related data. MOVES also does not currently model emission impacts of renewable diesel, as it is chemically identical to blendstocks found in petroleum diesel.

Within the gasoline and diesel fuel types, the model considers different fuel subtypes, as shown in Table 1-1. Each of these subtypes has a number of specific formulations that vary with region, season, and calendar year.

**Table 1-1. Fuel Subtypes in MOVES.**

| Subtype | Description |
|---|---|
| 10 | Conventional Gasoline |
| 11 | Reformulated Gasoline (RFG) |
| 12 | Gasohol (E10) |
| 13 | Gasohol (E8) |
| 14 | Gasohol (E5) |
| 15 | Gasohol (E15) |
| 20 | Conventional Diesel Fuel |
| 21 | Biodiesel (BD20) |
| 22 | Fischer-Tropsch Diesel (FTD100) |
| 23 | Nonroad Diesel Fuel |
| 24 | Marine Diesel Fuel |
| 30 | Compressed Natural Gas (CNG) |
| 40 | Liquefied Petroleum Gas (LPG) |
| 50 | Ethanol |
| 51 | Ethanol (E85) |
| 52 | Ethanol (E70) |
| 90 | Electricity |

The MOVES fuel supply is primarily comprised of three tables that reference each other. The regionCounty table assigns a fuel region to each county for each calendar year. This allows a given county to change fuel regions over time, which may occur if a local area adopts a volatility control program, for example. The fuelFormulation table assigns specific properties, such as

[a] While hydrogen may be used in fuel cells, it is not considered a fuel type in MOVES and the model doesn't quantify any emissions from its combustion, refueling, or leakage.

ethanol, aromatics, and sulfur level, to each fuelFormulationID. The fuelSupply table designates a fuelFormulationID and marketShare for each fuel region by month and year, which allows formulations to change by season as well as over the years as federal regulations or market blending practices change.

The default fuel supply in MOVES4 uses the same regional fuel structure and data sources as in MOVES3. Significant updates were made for 2018 and later gasoline fuel supply to incorporate the latest available data, as well as to carbon content, energy content, and density of diesel fuels.

The report is organized into the following sections plus three appendices.

- Sections 2 and 3 describe development of the geographical areas used in the fuel supply.
- Sections 4 through 6 describe updates to data sources and analysis of fuel properties as well as changes to ethanol market shares.
- Sections 7 and 8 describe the onroad diesel and nonroad components of the fuel supply.
- Section 9 describes the Fuel Wizard tool used to estimate secondary fuel property changes for gasoline blending.
- Appendix A provides color-coded maps showing which counties correspond with which regionIDs for years 1990-2020.
- Appendix B presents average gasoline formulation trends over years 1990-2020.
- Appendix C describes the refinery modeling work used to update the Fuel Wizard.

The fuel supply report has undergone two peer-reviews since the release of MOVES2014, consistent with EPA's peer review guidance.[1] In 2017, we peer-reviewed an internal version referred to as "MOVES201X" that included initial updates made from MOVES2014.[2] In 2020, we conducted another peer-review to review further updates made for MOVES3.[3] Updates to the MOVES3 fuel supply were made in response to peer-review comments from both reviews. Materials from each peer review, including peer-review comments and EPA responses are located on the EPA's science inventory webpage.

# 2. Development of Base Fuel Regions

The base fuel regions in MOVES were developed starting from Petroleum Area for Defense District boundaries (a historic division of fuel supply areas developed in the 1950s) along with locations of fuel terminals and pipelines using data from Oil Price Information Service (OPIS) and Energy Information Administration (EIA), which allowed grouping of areas sharing connections to similar refined product delivery networks.[4,5] A dividing line between base regions 1 and 2 can be seen along the Appalachians, with the Colonial pipeline forming a major distribution corridor running from Houston, Texas, to the east side of the mountain range and up into New England. Meanwhile, the Magellan pipeline network runs north from the Houston area into the midwest and plains states that comprise base regions 2 and 3. A high-level depiction of these pipelines overlaid onto state boundaries is shown in Figure 2-1. This analysis led to the base fuel regions described in Table 2-1 and shown in Figure 3-1.

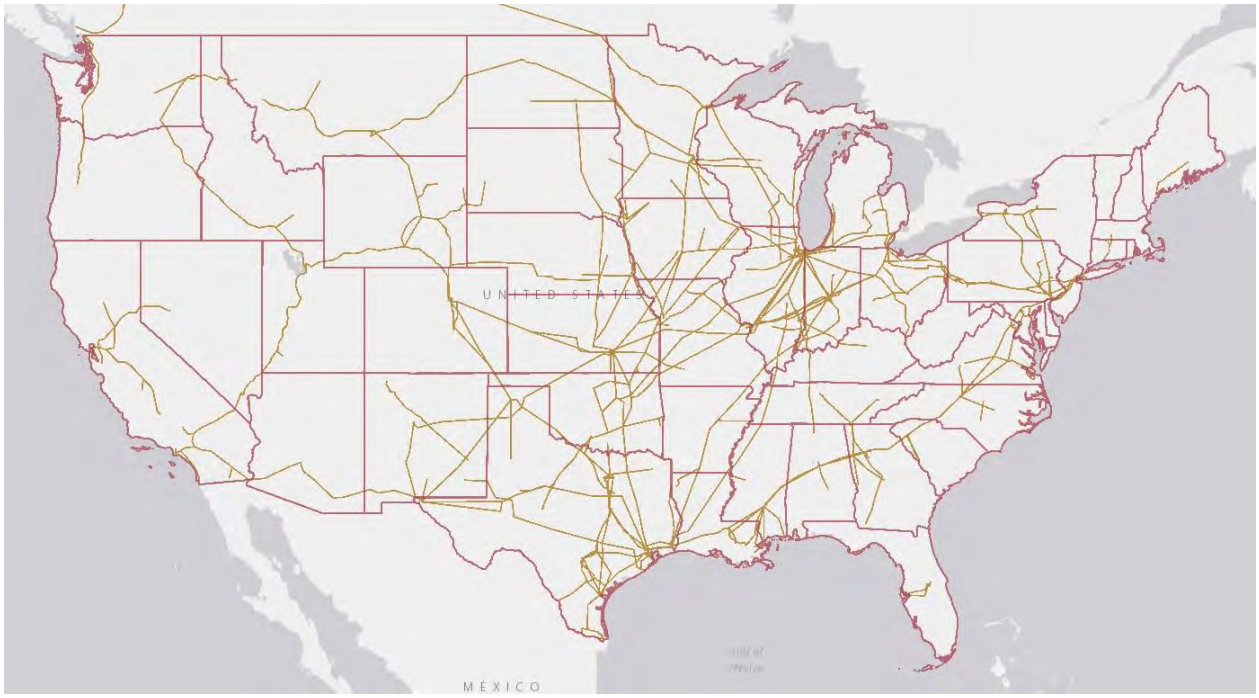


**Figure 2-1 Illustration of petroleum product pipelines in the continental United States[5]**

**Table 2-1. Base fuel region ID numbers and general descriptions.**

| Base Region ID# | Base Region Name | General Description |
|---|---|---|
| **1** | **East Coast, Caribbean** | East coast states, west to Appalachians; Florida; and Gulf Coast region; Puerto Rico and U.S. Virgin Islands |
| **2** | **Midwest** | Midwest states, east to Appalachians; Tennessee; Kentucky |
| **3** | **South** | Iowa to Texas (North to South); Alabama to New Mexico (East to West); does not include counties along the Gulf Coast |
| **4** | **North** | North and South Dakota, Minnesota, Wisconsin |
| **5** | **Rocky Mtns.** | Pacific Northwest, Rocky Mountain states |
| **6** | **AZ/NV/HI** | Arizona besides Phoenix area; Nevada; Hawaii |
| **7** | **Alaska** | All Alaska counties |
| **11** | **East Coast RFG** | East Coast states and regions using reformulated gasoline (RFG) |
| **12** | **MD/VA RFG** | Maryland and Virginia regions using RFG |
| **13** | **Texas RFG** | Texas regions using RFG |
| **14** | **Midwest RFG** | Midwest regions using RFG |
| **15** | **California RFG** | California and Phoenix-area counties using fuel produced by California refineries |

# 3. Incorporation of Local Fuel Programs

After developing the base fuel regions, areas of local fuel controls were added. The regionCounty table assigns a region [*regionID*] to each county [*countyID*] in a given year [*fuelYearID*], including regions with state or local fuel control programs. Each county also has an identifier [*regionCodeID*] which allows separate fuel regions for onroad and nonroad applications (though this is not exercised in the default supply).

The *regionID* field contains formatted information regarding key parameters in the fuel region and can be decoded as *AABBCCDDXX* where:

*AA = base region ID*
*BB = maximum summer region RVP value (pre-2021)*[b]*, or 00 for ASTM*
*CC = absence of RVP waiver, where 01 indicates no waiver*
*DD = minimum ethanol level in vol%*
*XX = reserved for future use*

[b] The RFG program was modified in 2021 to change the RFG limit from 7.0 to 7.4. This is reflected in the fuel properties, but the regionID values were not modified.

The full set of the 21 regionID values used in MOVES are shown in Table 3-1. The maximum summer RVP refers to the maximum Reid Vapor Pressure, which is a measure of the volatility of the fuel. Local air agencies may set a limit on vapor pressure of the gasoline fuel to reduce evaporative emissions of volatile organic compounds. A value of "00" indicates that the region is using the federal RVP limit.

The RVP waiver refers to the "1.0 psi RVP allowance for gasoline containing ethanol at 9 to 10 volume percent."[6] For example, for a region with an RVP waiver and a summer RVP limit of 7.8 psi, the RVP of an E10 fuel in the market is assumed to be 8.8 psi. Not all fuel regions allow for the 1.0 psi fuel waiver; for example, a State Implementation Plan (SIP) may withhold the 1.0 psi waiver to help meet air quality goals. Thus, the presence or absence of an RVP waiver is part of each region definition.

The minimum ethanol content indicates the minimum ethanol level required either by RFG or a local fuel program. While the RFG oxygenate requirement was lifted by the Energy Policy Act of 2005, the regionIDs for RFG areas continue to show the minimum ethanol flag for all years, something that has no impact on the emission computations.[7]

**Table 3-1. RegionID values in MOVES.**

| Region ID | Base Region ID# | Base Region Name | Maximum Summer RVP (psi) or 0.0 for ASTM | E10 RVP Waiver Status (01=No 1-psi Waiver) | Minimum Ethanol Volume, % |
|---|---|---|---|---|---|
| 0 | 0 | Nationwide region [a] | 0.0 | 01 | 51 |
| 100000000 | 1 | East Coast, Caribbean | 0.0 | 00 | 0 |
| 100010000 | | | 0.0 | 01 | 0 |
| 170000000 | | | 7.0 | 00 | 0 |
| 178000000 | | | 7.8 | 00 | 0 |
| 178010000 | | | 7.8 | 01 | 0 |
| 200000000 | 2 | Midwest | 0.0 | 00 | 0 |
| 270000000 | | | 7.0 | 00 | 0 |
| 278000000 | | | 7.8 | 00 | 0 |
| 278010000 | | | 7.8 | 01 | 0 |
| 300000000 | 3 | South | 0.0 | 00 | 0 |
| 370000000 | | | 7.0 | 00 | 0 |
| 370010000 | | | 7.0 | 01 | 0 |
| 400000000 | 4 | North | 0.0 | 00 | 0 |
| 500000000 | 5 | Rocky Mtns | 0.0 | 00 | 0 |
| 578000000 | | | 7.8 | 00 | 0 |
| 600000000 | 6 | AZ, NV, HI | 0.0 | 00 | 0 |
| 678000000 | | | 7.8 | 00 | 0 |
| 700000000 | 7 | Alaska | 11.5 | 00 | 0 |
| 1170011000 | 11 | East Coast RFG | 7.4 [b] | 01 | 10 |
| 1270011000 | 12 | MD/VA RFG | 7.4 [b] | 01 | 10 |
| 1370011000 | 13 | Texas RFG | 7.4 [b] | 01 | 10 |
| 1470011000 | 14 | Midwest RFG | 7.4 [b] | 01 | 10 |
| 1570011000 | 15 | California RFG | 7.4 [b] | 01 | 10 |

[a] Region 0 is only used in estimating the emissions from vehicles running on high-level ethanol blends (e.g., E85). For additional details, see MOVES fuel effects report.[8]

[b] The value of 7.4 psi more accurately reflects the RVP limit after the RFG program was modified in 2021, though regionID values were not modified.

Figure 3-1 shows the mapping of all fuel regions at a county level for the continental U.S. in July, 2024.[c] These region assignments are carried forward through 2060. Additional maps are available in Appendix A.

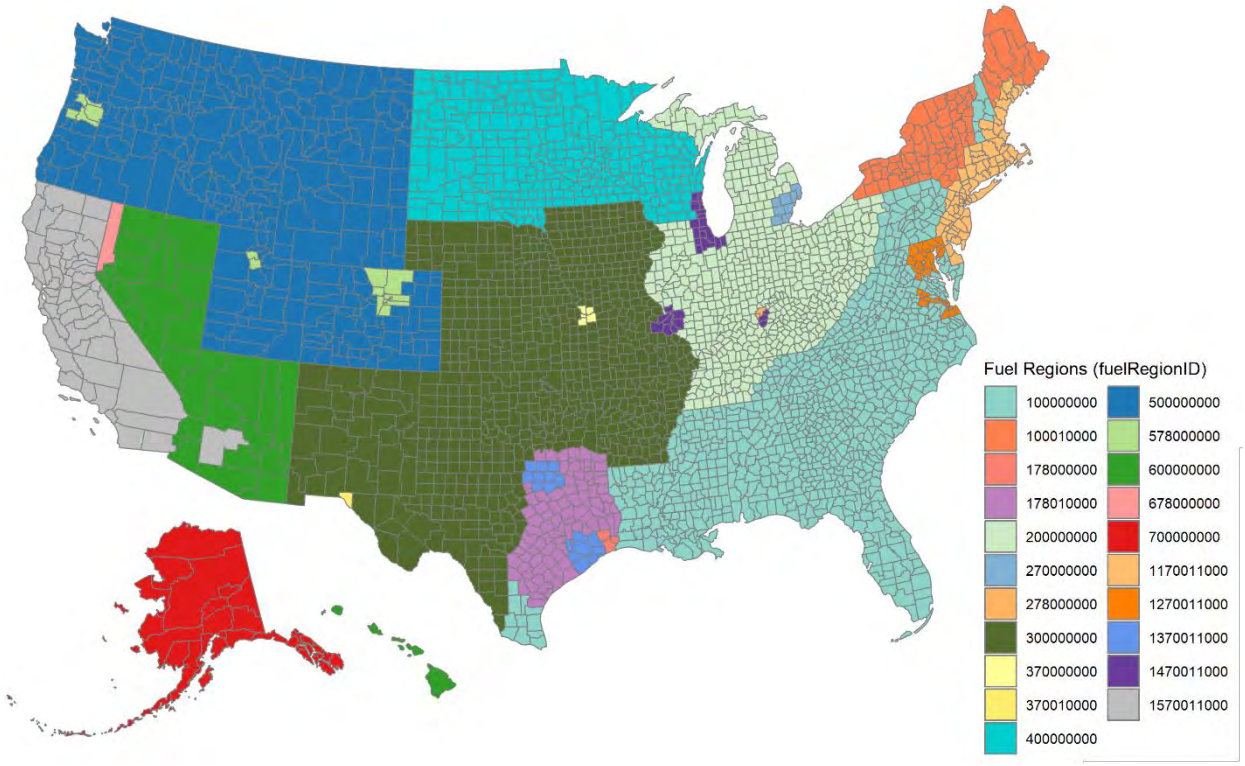


**Figure 3-1. Map of MOVES fuel regions in the continental U.S. for fuelYearID 2024.**

As mentioned above, the regionCounty table includes a fuelYearID dimension, spanning 1990 through 2060. This allows the model to account for changes over time in the region to which a county is assigned, for example when local volatility programs start or end. With MOVES3, this table was updated to include year-by-year changes in volatility designations from 1990 to 2020 based on information available in the Federal Register and other sources.[d] Table 3-2 summarizes the updates and information sources that were included.

[c] New RFG counties in the Denver area will be added to the default fuel supply when there is more information available about the fuel properties.

[d] For calendar year 1990, RVP values in the MOVES gasoline fuel supply are based on ASTM volatility class limits. Historical retail survey data suggests actual 1990 RVP values were lower.

**Table 3-2. Local fuel programs in the MOVES regionCounty table.[a]**

| Year[b] | State | Change and Data Source |
|---|---|---|
| 2002 | GA | Georgia marketing rule requires 7 psi fuel in 45 Atlanta metro and northern Georgia counties: Banks, Barrow, Bartow, Butts, Carroll, Chattooga, Cherokee, Clarke, Clayton, Cobb, Coweta, Dawson, DeKalb, Douglas, Fayette, Floyd, Forsyth, Fulton, Gordon, Gwinnett, Hall, Haralson, Heard, Henry, Jackson, Jasper, Jones, Lamar, Lumpkin, Madison, Meriwether, Monroe, Morgan, Newton, Oconee, Paulding, Pickens, Pike, Polk, Putnam, Rockdale, Spalding, Troup, Upson, Walton. |
| 2004 | CO | Adoption of a 7.8 psi control program in the Denver-Boulder nonattainment area (enforcement was waived from 1992 to 2003). This area includes parts of Adams, Arapahoe, Boulder counties and all of Denver, Douglas, and Jefferson counties. (In MOVES, fuel programs in partial counties are assumed to cover the full county). https://www.govinfo.gov/content/pkg/FR-2009-08-24/pdf/E9-20290.pdf |
| 2006 | IL | End of 7.2 psi state control program for Metro-East St. Louis Illinois nonattainment area (Madison, Monroe and St. Clair counties) implemented from 1995-2006, and replaced with RFG in 2007. This was modeled in MOVES with 7.0 psi / 1 psi E10 waiver. This program was effectively superseded by the adoption of RFG for these counties in 2007, and officially ended in 2014. https://www.govinfo.gov/content/pkg/FR-2014-10-06/pdf/2014-23767.pdf |
| 2007 | IL | Adoption of RFG in Jersey, Madison, Monroe, St. Clair counties (St. Louis-Illinois nonattainment area) in July 2007 to replace the 7.2 psi state program. Includes Jersey County, which was not part of the previous control area. https://www.govinfo.gov/content/pkg/FR-2007-04-24/pdf/E7-7777.pdf |
| 2008 | LA | End of Grant Parish control program, a 7.8 psi control program implemented from 1992-2007. https://www.govinfo.gov/content/pkg/FR-2008-02-13/pdf/E8-2705.pdf |
| 2010 | CO | Adoption of 7.8 psi fuel from the 2004 Denver-Boulder control area (Broomfield, Larimer, and Weld counties). https://www.govinfo.gov/content/pkg/FR-2009-08-24/pdf/E9-20290.pdf |
| 2014 | NC | Davidson, Forsyth, Guilford, Davie, Durham, Wake, and Granville counties move to 9 psi. https://www.govinfo.gov/content/pkg/FR-2014-05-22/pdf/2014-11911.pdf |
| 2014 | FL | All areas now at 9 psi. https://www.govinfo.gov/content/pkg/FR-2014-05-22/pdf/2014-11911.pdf |
| 2015 | AL | All areas now at 9 psi. https://www.govinfo.gov/content/pkg/FR-2015-07-02/pdf/2015-16392.pdf |
| 2015 | ME | York, Cumberland, Sagadahoc, Androscoggin, Kennebec, Knox, and Lincoln counties move to RFG. https://www.govinfo.gov/content/pkg/FR-2014-08-28/pdf/2014-20177.pdf |
| 2016 | GA | 13 Atlanta metro counties move to 7.8 psi Federal gasoline from 7.0 psi "Georgia Gasoline" (Cherokee, Clayton, Cobb, Coweta, DeKalb, Douglas, Fayette, Forsyth, Fulton, Gwinnett, Henry, Paulding, and Rockdale). Remaining 32 Georgia Gasoline counties move to 9 psi. https://www.govinfo.gov/content/pkg/FR-2014-03-14/pdf/2014-05697.pdf |
| 2016 | NC | All areas now at 9 psi. https://www.govinfo.gov/content/pkg/FR-2015-08-17/pdf/2015-20243.pdf |
| 2017 | OH | All areas now at 9 psi. https://www.govinfo.gov/content/pkg/FR-2017-04-07/pdf/2017-06889.pdf and https://www.govinfo.gov/content/pkg/FR-2017-02-15/pdf/2017-03082.pdf |
| 2017 | TN | Nashville area (Davidson, Rutherford, Sumner, Williamson, and Wilson) moves to 9 psi. https://www.govinfo.gov/content/pkg/FR-2017-06-07/pdf/2017-11700.pdf |
| 2018 | LA | Louisiana parishes (Beauregard, Calcasieu, Jefferson, Lafayette, Lafourche, Orleans, Pointe Coupee, St. Bernard, St. Charles, St. James, and St. Mary) move to 9 psi. https://www.gpo.gov/fdsys/pkg/FR-2017-12-26/pdf/2017-27628.pdf |
| 2018 | KY | Cincinnati area (Boone, Campbell, and Kenton) moves to 9 psi, effective July 1, 2018. https://www.govinfo.gov/content/pkg/FR-2018-04-02/pdf/2018-06538.pdf |
| 2018 | TN | Shelby county moves to 9 psi. https://www.govinfo.gov/content/pkg/FR-2017-12-22/pdf/2017-27630.pdf |
| 2019 | PA | Allegheny, Armstrong, Beaver, Butler, Fayette, Washington and Westmoreland move to 9.0 psi. https://www.epa.gov/gasoline-standards/gasoline-reid-vapor-pressure |
| 2019 | LA | All areas now at 9 psi. https://www.govinfo.gov/content/pkg/FR-2018-10-24/pdf/2018-23247.pdf |
| 2020 | GA | All areas now at 9 psi. https://www.govinfo.gov/content/pkg/FR-2019-05-14/pdf/2019-09929.pdf |
| 2024 | TX | Expansion of RFG in the Dallas-Fort Worth area to include Ellis, Johnson, Kaufman, Parker, Rockwall and Wise counties. https://www.epa.gov/gasoline-standards/reformulated-gasoline |

[a] Pressure values are Reid Vapor Pressure (RVP). Ethanol blending waiver of 1 psi should be added to all RVP values shown here unless otherwise specified. RFG is federal reformulated gasoline.

[b] Changes shown were effective at the start of the calendar year (for RFG) or the summer volatility control season unless otherwise specified.

# 4. Background on Fuel Property Data

For gasoline, fuelSupply and fuelFormulation tables are based on the nationwide refinery gate compliance data collected by EPA on all batches of gasoline entering the distribution system from refiners, blenders, and importers. This includes several fuel properties that can be used to predict emissions. For diesel, MOVES fuel adjustments are simpler than for gasoline, only using inputs of sulfur level and, for engines 2006 and older, biodiesel content.[8]

The rest of this discussion of fuel properties pertains to gasoline, unless otherwise noted. The data reported for each gasoline batch includes the properties and other values required to determine compliance with EPA requirements. These are summarized in Table 4-1. These properties are reported for approximately thirty-thousand batches per year, a database which forms the basis for the fuel properties used in the regional fuel methodology. These compliance reports are considered Confidential Business Information (CBI) and cannot be provided to the public in its raw form. The data analysis and aggregation are discussed in more detail in the next section.

**Table 4-1. Fuel data used in MOVES regional fuel property methodology.**

| |
|---|
| **Batch descriptors:** Product Type, Grade, Volume (gallons), Production Date. |
| **Property data in vol%:** Aromatics, Benzene, E200, E300, ETBE, Ethanol, MTBE, Olefins, TAME. |
| **Other property data:** Oxygen (wt%), RVP (psi), Sulfur (ppm wt), T50 (°F), T90 (°F). |

The Product Type value specifies whether the fuel is designed by the producer as conventional gasoline (CG), reformulated gasoline (RFG), or blendstock for oxygenate blending (BOB). Fuel property data reported for RFG accounts for the downstream blending of ethanol, while the other types generally do not, and therefore, we made the required adjustments mathematically when producing the fuel supply. More detail is given on this in the next section.

While we have access to some retail survey data, for example hundreds of samples per year from the Alliance of Automobile Manufacturers,[17] review of the compliance data reveals a large batch-to-batch variation. Figure 4-1 provides an example of the variation in gasoline aromatics level occurring over the course of a year for each refinery. This suggests that trying to rely on seasonal retail samples in a couple dozen key markets may provide results unrepresentative of the mean. Further plots and analysis for other fuel properties are available in EPA's Fuel Trends Reports.[9,10] These documents also compare retail survey data to refinery production data, generally validating the approach of using compliance data on a regional basis.

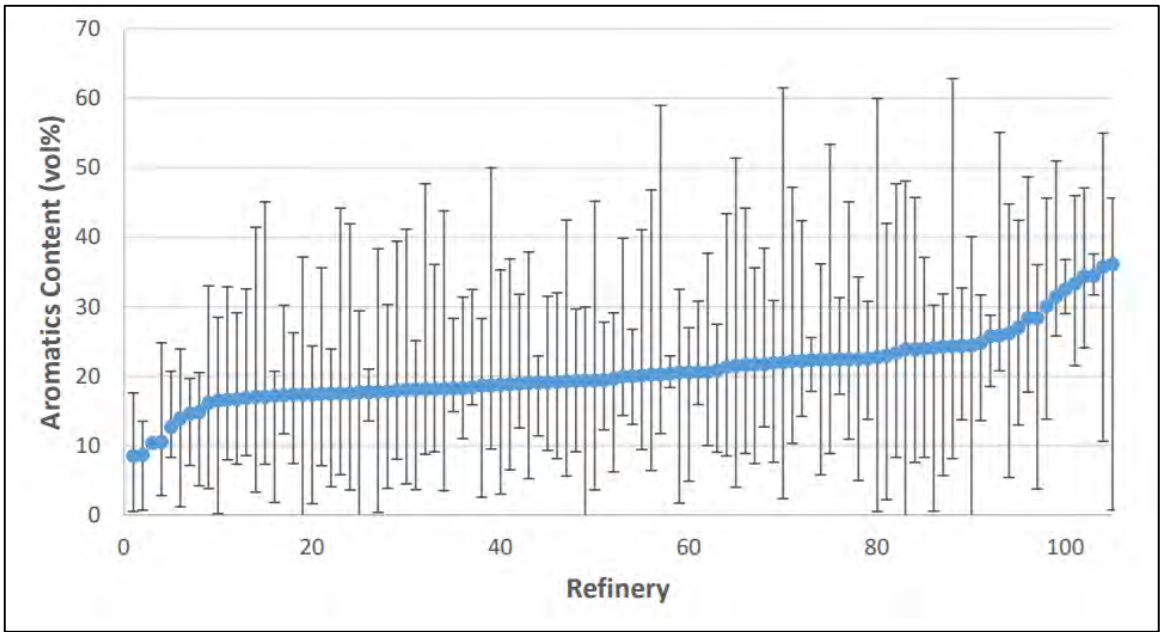


**Figure 4-1. Aromatics maximum, minimum, and mean by U.S. refinery in 2016 for RFG (includes ethanol blending) and CG (not adjusted for ethanol blending).[9]**

# 5. Regional Gasolines for 2013 and Earlier

Starting with MOVES3, updates focused on the years 2014 and later, where we expect most model runs to occur. For years 2013 and earlier, the fuelSupply and fuelFormulation tables were imported directly from MOVES2014b except for adjustments described in Section 5.2.

## 5.1 Information Carried Over from MOVES2014

For calendar years 1990-2006, refinery batch data was unavailable for use in MOVES2014 development. Thus, the MOVES2014 fuel supply for these years was produced by aggregating the county-level fuel properties in MOVES2010 into the new fuel regions using county VMT weightings. For years 2007 and later, a large amount of gasoline batch data was available. Before aggregating this data into fuel regions, we processed the dataset to exclude duplicate reporting (i.e., a refinery and independent results may both report the same fuel). We also repaired or excluded batches with missing or inappropriate data. For example, in many cases the T-number distillation values were missing, since compliance reports require E-number values. This was repaired using correlations in Equation 5-1 and Equation 5-2 (derived from E0 gasoline data).

$$T50 = 2.0408 \times (147.91 - E200) \quad \textbf{Equation 5-1}$$

$$T90 = 4.5454 \times (155.47 - E300) \quad \textbf{Equation 5-2}$$

Finally, we separated differing types of fuel batches for further processing. In these steps, non-ethanol and pre-blended gasolines were included in the dataset without adjustment, blendstocks

for oxygenate blending (BOBs) were adjusted to account for ethanol added downstream from the refinery gate. This was generally done by a dilution calculation because the properties reported were for the sub-grade hydrocarbon, which would simply be "splash blended" with ethanol at the destination terminal prior to local distribution. This adjustment is described in more detail in the introduction section of EPA's Fuel Trends Report.[9]

After these steps, we had between twenty and thirty-five thousand usable batch records, depending on year, with no fuel region being represented by less than one thousand batches. The fuel property data were then aggregated by fuel region (see Section 2), using fuel batch size as a weighting factor. Initially, fuels were aggregated into four seasonal categories, including summer, winter, and two transitionary 'shoulder' seasons. After reviewing the results of these categories, we determined that there was not adequate data (<100 batches for some regions) on fuel properties other than RVP and distillation to determine specific shoulder season values. Thus, two aggregation seasons were used for this dataset: summer (May through September) and winter (January, February, March, April, October, November, and December). The RVP values for shoulder season (April and October) were set to intermediate values between summer and winter, and distillation values adjusted using the factors described in Section 9, Table 9-2. Other fuel properties were set to winter values for the shoulder months for calendar years 2013 and earlier.

To determine ethanol content of fuels in years prior to 2014, we used information from the Annual Energy Outlook report (AEO2014) generated by the U.S. Energy Information Administration (EIA).[11, 12] The AEO report provides year-by-year projections for biofuel energy consumption by fuel type for ethanol-gasoline blends, flexible- fuel vehicle (FFV) blends (E70-E85), and biodiesel blends far into the future. We used these projections in conjunction with the overall fuel energy requirements computed by the model to calculate the E10 market share for years 2013 and earlier.

Gasoline compliance data suggests that over 80 percent of batches in the 2011 database consist of blendstock (CBOB/RBOB) for downstream ethanol blending. Therefore, for calendar years beyond 2011, when making adjustments to include the addition of ethanol, we did not include dilution effects on sulfur or benzene, which are controlled to specific levels in finished gasoline by federal or state regulations. For sulfur in calendar years prior to 2011, we used the batch fuel data as the source of the fuel sulfur content. In MOVES2014, 2011 and later gasoline had sulfur set to 30 ppm consistent with full phase-in of Tier 2 sulfur program. With MOVES3, the updates were made starting in 2014 so the sulfur content of 30 ppm remains in place for 2011-2013, and sulfur then begins to follow the declining batch data trend as the Tier 3 sulfur requirement is phased in.[13]

The EPAct model implemented in MOVES2014 for fuel adjustments in 2001 and newer vehicles, was built specifically around ethanol blends and cannot be used to compute emission impacts of MTBE. Thus, in MOVES2014, MTBE was replaced with ethanol in oxygenate blends in order to provide an approximation of fuel effects across the range of model years (no other fuel properties were adjusted besides the oxygenate). More details on the EPAct models are available in the MOVES2014 Fuel Effects report.[14]

As a final step, the production-based fuel properties were weighted together with incoming

regional transfers of gasoline produced elsewhere, using data from EIA's Petroleum Supply Annual reports, in an effort to make them more representative of fuel being consumed in a particular area.[15] This technique was developed for benzene in the MSAT2 rulemaking analysis and is described in more detail in Chapter 6.10.1.3 of the regulatory impact analysis.[16]

## 5.2 Revision of Volatility Parameters

The underlying gasoline batch data used in generating the fuel supply contains E200/E300 values for the vast majority of batches, consistent with reporting requirements, and T50/T90 for only a subset. Since MOVES fuel adjustments rely on T50/T90, the missing data were estimated from the E200/E300 values using correlations developed during a period when there was little ethanol in the fuel supply. A review of recent market survey data suggested that the correlation between E and T values should be updated for E10 fuels. Figure 5-1 shows a correlation analysis developed from 2017 and 2018 Alliance of Automobile Manufacturers (AAM) surveys for E10 regular grade gasoline for both conventional and reformulated gasolines.[17]

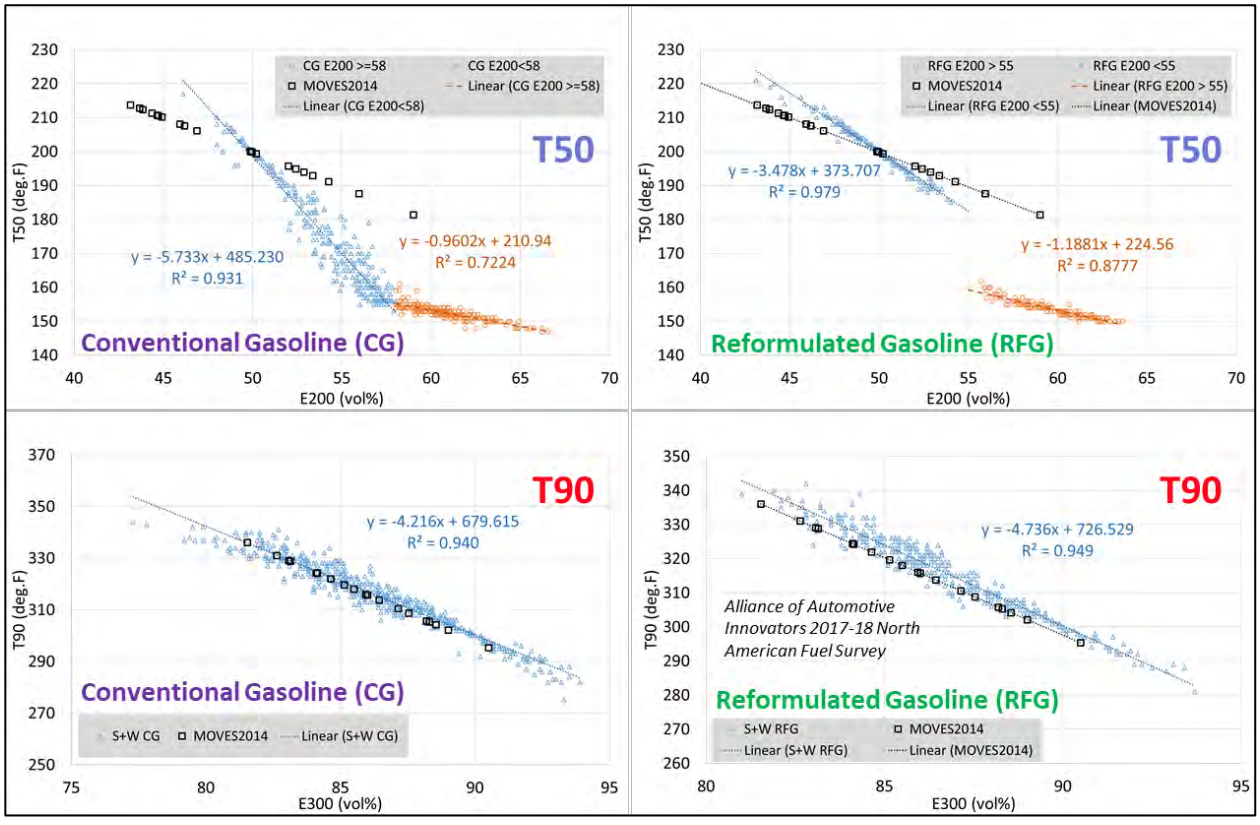


**Figure 5-1. Derivation of updated T50 and T90 correlations for regular grade E10 gasoline. Conventional gasoline are the left plots and reformulated are on the right.**

Visible in the plots is a clear seasonal difference in the correlation for T50/E200 but none for T90/E300. Thus, two correlations (orange and blue points) were fit around an E200 cutpoint of

58% for conventional gasoline and 55% for reformulated. While there was little change in the T90/E300 correlation from the historical E0-based relationship, new values were computed for MOVES3 regardless. These updated correlations were used to generate new T-numbers for all E10 formulations in the fuel supply, including historical fuels. The updated correlations for E10 are shown in Equation 5-3 through Equation 5-8.

$$CG\ T50 = 485.230 - 5.733 \times E200 \quad (where\ E200 < 58) \qquad \textbf{Equation 5-3}$$

$$CG\ T50 = 210.94 - 0.9602 \times E200 \quad (where\ E200 \geq 58) \qquad \textbf{Equation 5-4}$$

$$CG\ T90 = 679.615 - 4.216 \times E300 \qquad \textbf{Equation 5-5}$$

$$RFG\ T50 = 373.707 - 3.478 \times E200 \quad (where\ E200 < 55) \qquad \textbf{Equation 5-6}$$

$$RFG\ T50 = 224.56 - 1.1881 \times E200 \quad (where\ E200 \geq 55) \qquad \textbf{Equation 5-7}$$

$$RFG\ T90 = 726.529 - 4.736 \times E300 \qquad \textbf{Equation 5-8}$$

## 5.3 Revision of California Fuel Properties

Another change to the 2013 and earlier fuel supply in MOVES3 was to replace the MOVES2014b California fuel properties with a set derived from AAM surveys collected in Los Angeles and San Francisco annually between 2000 and 2016.[17] This applies to all years, where 1990 and 1999 values duplicated the 2000 properties, and 2017 and later duplicated the 2016 properties. After review of available data sources, we felt this would produce the most accurate and consistent results.

## 5.4 Revision of Ethanol Blend Market Shares

Beginning with MOVES3, market shares of ethanol blends were simplified to reflect 100% E10 in all regions for 2012 and later. This required replacing very small market shares of E15 in year 2013 with E10 (this was the earliest year E15 had been included in the MOVES2014b supply). Given the difficulty of estimating the sales volumes and locations of E0 (non-ethanol fuel) and E15 ethanol blends, both of which are very small relative to E10, their market shares have been set to zero. However, the MOVES default fuel supply provides E0 and E15 properties in 2014 and later for all regions to allow users to model these fuels by adding market share for these fuels as needed. Note that summer E15 was assumed to be made with sub-RVP blendstocks prior to 2019 when the 1 psi waiver was extended to this blend level.

## 5.5 Removal of Duplicate Fuel Formulations

Finally, we removed several near-duplicate fuel formulations. Fuel formulations in MOVES2014 were generated algorithmically from the compliance batch data, which resulted in a number of formulations that differed in very small ways that were unlikely to represent real-world differences in market fuel.

Specifically, a series of sorting operations were carried out on the properties ETOHVolume,

aromaticContent, RVP, E200, and sulfurContent and then neighboring fuels were compared for differences smaller than a margin deemed insignificant (0.5 ppm for sulfur and 0.05 vol% or psi for the others). Where all five properties were a match within the margin, the lowest fuelformulationID of the group was recorded as the representative fuel for the others. The sort was repeated for each property until a robust list of representative fuels had been assigned throughout the fuelFormulation table. Though some properties were ignored in the process (e.g., benzeneContent and E300), a review of the results found the five properties to be sufficiently precise.

Similarly, a number of fuel regions that were not referenced in any year or county were removed from the model, along with their associated formulations if those were not used elsewhere, to reduce the size of the fuel supply database.

# 6. Regional Gasolines for 2014 and Later

With MOVES3, we replaced the MOVES2014b gasoline fuel supply entirely for calendar years 2014 and later, where we expect most model runs to occur. For years 2013 and earlier, the fuelSupply and fuelFormulation values were imported directly from MOVES2014b except for the adjustments described in Section 5.2.

## 6.1 Updates to Calendar Years 2014 and Later

Table 6-2 depicts the overall scheme for producing the gasoline fuel supply in the current release of MOVES.[e] For years 2014 and later (non-California) fuels, the fuelSupply and fuelFormulation tables were updated based on batch data from 2015 and 2016, using the MOVES2014 methodology described above. It also assumed 100 percent E10 because the data indicated that usage of other ethanol blend levels (including E0) was too small to account for on a national or regional basis. One notable difference was that shoulder season gasoline properties were set to values intermediate between summer and winter in each region.

To produce 2014, 2015 and 2017-2020 fuel supplies from the 2015-16 dataset, adjustments were made by applying year-by-year relative difference factors computed from publicly-available refinery batch data summaries on EPA's website.[18] This analysis computed national-scale adjustments by season, year, CG/RFG, and fuel property, and did not attempt to adjust for the ethanol level of the batch data. These adjustment factors were generally small (i.e., a few percent) and the ratio of BOB to finished gasoline was not changing greatly from year to year.

During this process, we observed that applying the batch data factors for the year 2020 produced unrealistic results for sulfur for some fuel regions, likely related to the fact that some refiners' sulfur levels were declining rapidly to meet the final phase-in requirements of the Tier 3

[e] The MOVES4 fuel supply included updates to 2018, 2019, and 2020 fuel formulations. For 2018, aromatic and olefin levels were adjusted to remove default value data submitted to EPA during a prolonged chemical reagent shortage. For 2019-2020, the fuel properties were updated to include refinery batch data made available since MOVES3.

program. To mitigate this issue, we set the sulfur level in each region to match the national average batch data value for the corresponding season and RFG/CG (Table 6-1). Other 2020 fuel property values were computed from 2019 values by applying the Fuel Wizard factors (described in Section 9) for the sulfur changes occuring from 2019 to 2020. Fuel formulations in 2020 were duplicated for 2021-2060 as no further data was available at the time of this analysis.

**Table 6-1. Gasoline sulfur levels for 2020 and later for all regions except California.**

| | Summer | Winter |
|---|---|---|
| Conventional | 7.15 ppm | 8.12 ppm |
| Reformulated | 7.36 ppm | 8.70 ppm |

Finally, E0 and E15 formulations were produced for calendar years 2014 and later (E15 summer blends begin in 2019). While their market share was set to zero in the fuelSupply table, the formulations were computed to give users a simple and consistent way to model these fuels if desired.

**Table 6-2. Scheme for building the default gasoline fuel supply.**

| Calendar year ---> | 1990-2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020+ |
|---|---|---|---|---|---|---|---|---|---|---|
| E0 formulations | MOVES2014 | | | Computed E0 properties from local E10 formulation using fuel wizard factors (i.e., reverse match blending) | | | | | | |
| E10 formulations | MOVES2014 with updated distillation correlation | | | Adjusted 2016 values using batch data and any local RVP changes | | Refinery batch data | Adjusted 2016 values using batch data and any local RVP changes | | | Sulfur set to 2020 batch levels and other properties derived from 2019 using Fuel Wizard factors |
| E15 formulations | None | | | Computed splash-blends from local E10 for winter and shoulder seasons only | | | | | Computed splash-blends from local E10 year-round | |
| Market share | MOVES2014 | 100% E10 | | | | | | | | |

E15 properties were computed assuming splash blending from the local E10, consistent with the extension of the 1 psi waiver to E15. This is the most likely scenario until E15 volumes are large enough to warrant their own regional sub-grade blendstocks. Thus, the aromatics, sulfur, benzene, and olefin values for E15 were computed as 0.95 times the E10 property value based on mathematical dilution. Effects on distillation were estimated by comparing regular grade E10 and E15 values from Appendix A of the 2010 API blending study[19] (presented in Figure 6-1 and Figure 6-2).

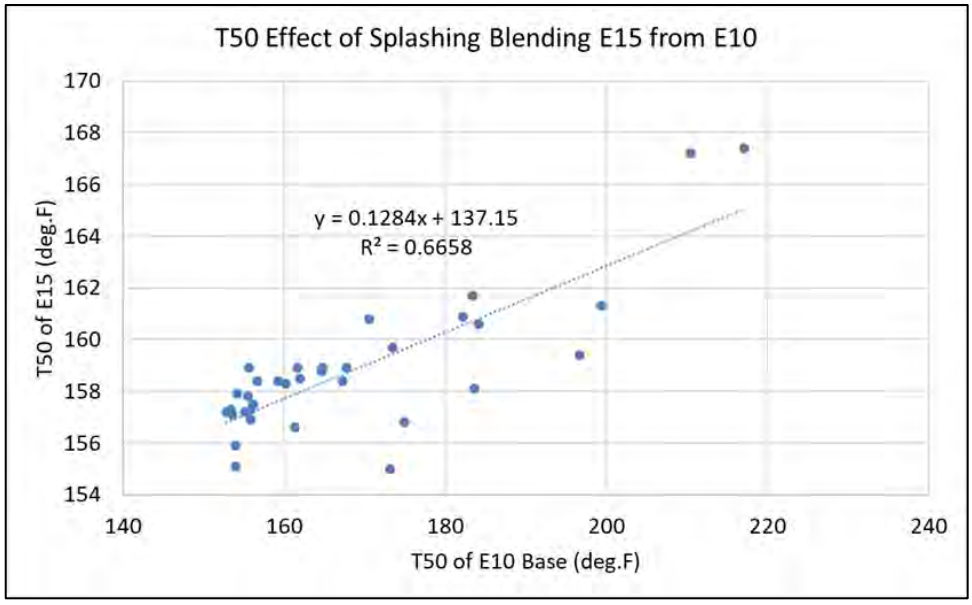


**Figure 6-1. T50 effect of splash blending E15 from E10 in 2010 API blending study.**

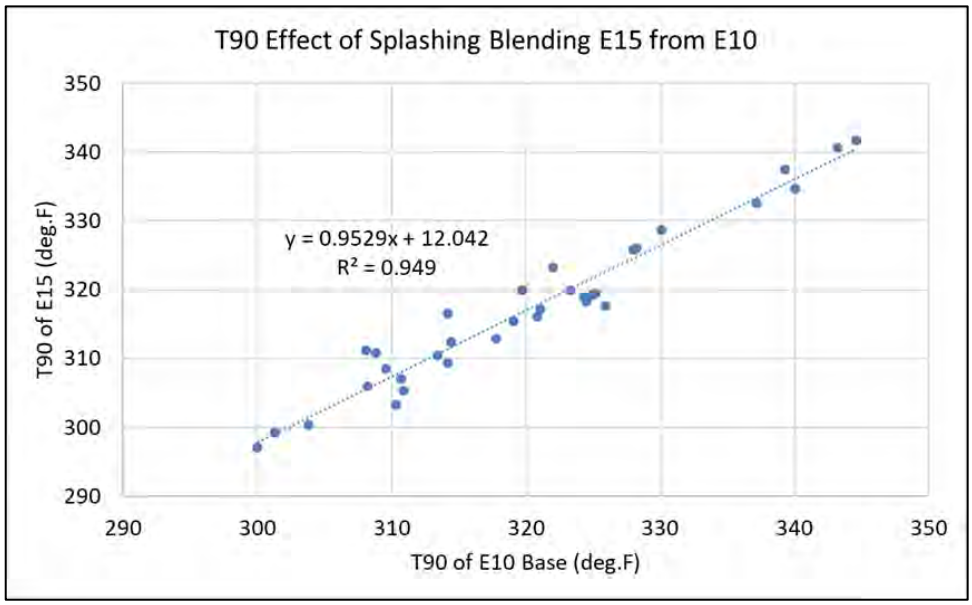


**Figure 6-2. T90 effect of splash blending E15 from E10 in 2010 API blending study.**

The correlations shown in Equation 6-1 and Equation 6-2 suggest that adding 5% ethanol to an E10 blend reduces and compresses the T50 temperature into a narrow range between 150-162°F. The effect on T90 is much more moderate, reducing the E10 value by a few degrees. RVP was reduced by 0.15 psi for the E15 blend based on results of the same study.

$$T50_{E15} = 137.15 + 0.1284 \times T50_{E10} \quad \textbf{Equation 6-1}$$

$$T90_{E15} = 12.042 + 0.9529 \times T90_{E10} \quad \textbf{Equation 6-2}$$

Populating the fuelFormulation table with the E15 splash blends requires E200 and E300 values, so the reverse of the earlier conversions on the batch data was required here. Since there is no large survey of market E15 fuels to draw upon, the same AAM survey dataset used for the E10 correlations was used (Figure 6-3).

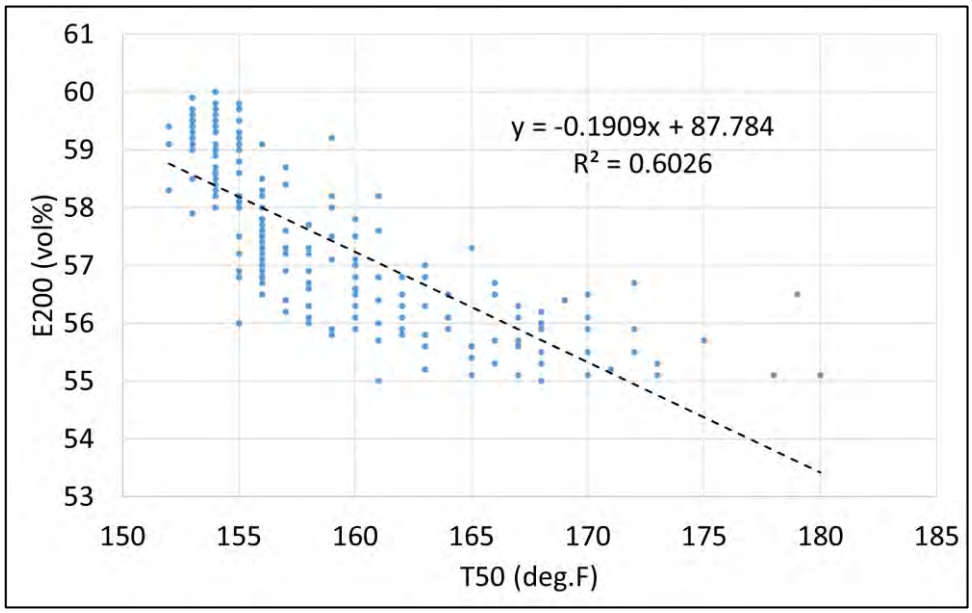


**Figure 6-3. E200 to T50 correlation for E15 fuels based on AAM 2017-18 market surveys.**

The earlier E300/T90 relationship was simply inverted, but for E200/T50 the correlation was refit to a limited T50 range of 55-60 vol% expected to be most applicable to E15 fuels. Results of this analysis are shown in Equation 6-3 and Equation 6-4 and Figure 7-3.

$$E200 = 87.784 - 0.1909 \times T50 \qquad \textbf{Equation 6-3}$$

$$E300 = 156.69 + 0.2229 \times T90 \qquad \textbf{Equation 6-4}$$

Producing E0 properties for each region based on the local E10 required a reverse match-blending computation to make up for ethanol's octane. The updated Fuel Wizard factors (discussed in more detail in Section 9) were applied for all properties except RVP and T50/T90. RVP was adjusted downward by 1 psi except in areas without the 1-psi waiver. The distilation values of T50/T90 were computed using the E0 correlations to E200/E300 shown in Equation 5-1 and Equation 5-2.

Table 6-3 summarizes the assignment of fuelFormulationID (FFID) values after these updates. The fuels for years 2014 and later were assigned FFIDs in bands of 122 values according to their calendar year and ethanol blend level. For example, E15 formulations in year 2019 fall between 8600 and 8722. This scheme leaves gaps for user-created fuels to follow the same scheme. Calendar year 2013 and earlier gasolines imported from MOVES2014b span the FFID range 1000-2801 after elimination of historical E15 formulations and near-duplicates as described in Section 5.2.

**Table 6-3. FuelFormulationID numbering scheme.**

| | Starting FuelFormulationID | | |
|---|---|---|---|
| Calendar Year | E10 | E0 | E15 |
| 1990-2013 | 1000, 2000 | | |
| 2014 | 3000 | 3300 | 3600 |
| 2015 | 4000 | 4300 | 4600 |
| 2016 | 5000 | 5300 | 5600 |
| 2017 | 6000 | 6300 | 6600 |
| 2018 | 7000 | 7300 | 7600 |
| 2019 | 8000 | 8300 | 8600 |
| 2020+ | 9000 | 9300 | 9600 |

# 7. Diesel, CNG, and E85

For these fuels, we do not use regulatory compliance data as the source of the fuel properties. Data sources for each fuel are discussed in the subsections below.

## 7.1 Diesel

MOVES uses two fuel properties when computing emissions from diesel: sulfur and biodiesel (methyl ester) content. These values are summarized by calendar year in Table 7-1. The model applies the same formulation across all regions for a given fuel type and calendar year.

**Table 7-1. Onroad diesel sulfur and biodiesel contents in MOVES across all fuel regions.**

| Year | Sulfur level, ppm | Biodiesel, vol% |
|---|---|---|
| 1990 | 1000 | 0 |
| 1999-2006 | 130 | 0 |
| 2007-2010 | 6 | 0 |
| 2011+ | 6 | 3.4 |

National average diesel sulfur levels in survey data collected by the Alliance for Automotive Innovation[17] indicate that an average level of 6 ppm is representative of years 2007 and later (Figure 7-1). A review of individual locations suggests there is very little regional variation, with $10^{th}$-$90^{th}$ percentile ranges spanning 4-10 ppm during the same period.

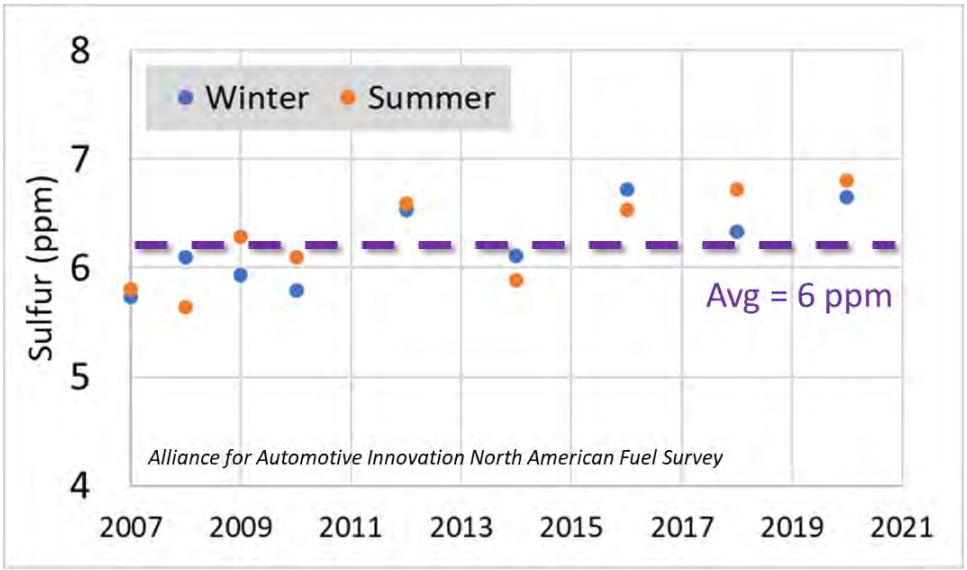


**Figure 7-1. National average diesel sulfur level from market survey data.**

For onroad diesel, we assume that conventional non-ester diesel (fuelSubtypeID 20) constitutes 100 percent of the market share in all fuel regions for 1990 through 2010 calendar years. Beginning in 2011, MOVES3 assumes B3.4 (3.4 vol% biodiesel; fuelSubtypeID 21) constitutes 100 percent market share for the nation. The national average biodiesel blend levels were computed using EIA data for biodiesel and transportation distillate consumption.[20] Figure 7-2 shows the national blend level trend over the past decade, where blend levels have varied according to blending mandates and market forces.

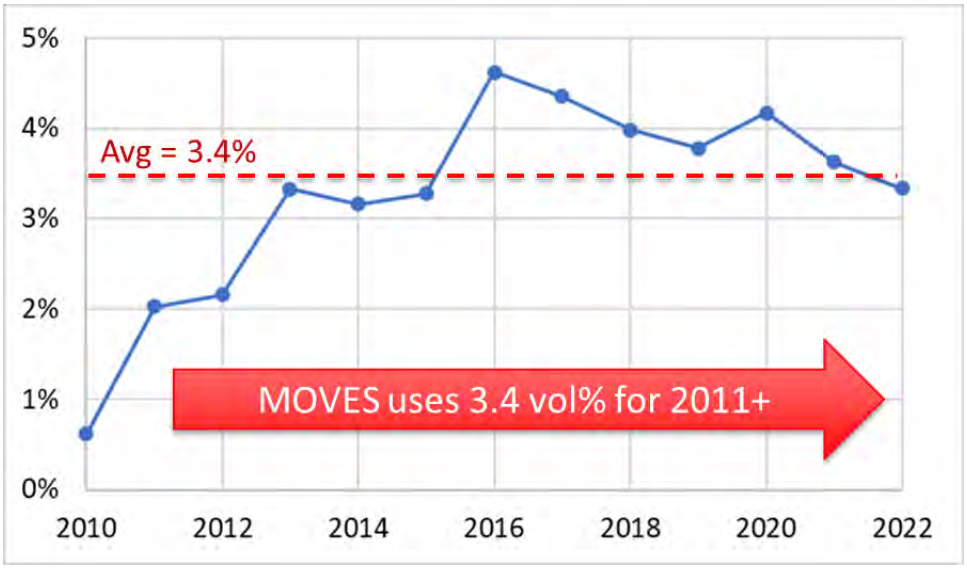


**Figure 7-2. National average biodiesel blend level computed from EIA Monthly Energy Review data, showing MOVES blend level of 3.4% for 2011 and later.**

The year 2011 was selected as this was when the national average blend level first surpassed 1 vol%. As we lack consistent and reliable data on biodiesel across the country, using a national average blend level is a reasonable simplifying assumption that is consistent with aggregate usage figures from EIA and other sources. The fuelFormulation table also contains biodiesel blend levels of 0, 5, and 20 vol%, which users may specify as alternatives.

The energy content of biodiesel is set at 43.061 (KJ/g) to represent B5 fuel. The density, energy and carbon content of the fuels are based on aggregate values that are constant across fuel types and fuel subtypes as documented in the MOVES GHG and energy report.[21]

## 7.2 Compressed Natural Gas (CNG)

MOVES assumes that CNG (fuelSubtypeID 30) used in onroad vehicles has a sulfur content of 7.6 ppm based on a CNG transit bus study documented in the MOVES fuel effects report.[8]

## 7.3 High-Level Ethanol Blends (E85)

As described in the Population and Activity technical report, MOVES models a subset of the vehicle fleet as "flexible fueled vehicles" (FFVs).[22] These vehicles may operate on gasoline or E85 fuel as indicated in the FuelUsageFraction table. Starting with MOVES3, we set the E85 usage fraction to 1.78% for all regions in calendar years 2010 and later. This value was derived from AEO2014 during the analysis described above in Section 5.1, and represents the fraction of total fuel used by FFVs that is E85.

The MOVES algorithms used to model the emissions from FFVs when they are operating on E85

are described in the Fuel Effects technical report.[8] The E85 algorithm uses the sulfur, benzene, and RVP values stored in the fuelFormulation table, which do not vary by region as they are not expected to vary regionally. The other property values come from the E10FuelProperties table, which includes representative E10 fuel formulations for every fuel region, calendar year, and month. The table also stores a national average E10 formulation as RegionID 0, which is used for national scale runs using pre-aggregation in the advanced features. The national E10 formulation was calculated as a weighted average of the E10 fuel formulations assigned to different regions using their respective share of light-duty vehicle VMT (stored in the zoneRoadType table) and E10 fuel marketshare (in the fuelSupply table).

The sulfur and benzene values for E85 represent blending market gasoline with denatured ethanol. Denaturants are petroleum blendstocks that are expected to have sulfur and benzene content similar to market gasoline. The RVP values represent typical summer and winter seasonal targets and are usually achieved by addition of butanes or pentanes. These values are summarized in Table 7-2.

**Table 7-2. E85 fuel properties used in emission calculations for all regions.**

| E85 Fuel Formulation ID | Months Applied | RVP (psi) | Sulfur Level (ppm) | Benzene Content (% volume) |
|---|---|---|---|---|
| 27001 | October…April | 10.5 | 8 | 0.16 |
| 27002 | May…September | 7.7 | | |

# 8. Nonroad Fuel Supply

The nonroad gasoline fuel supply is identical to the onroad fuel supply except that it contains no fuels with ethanol content over 10.5 vol%.

For nonroad diesel, MOVES includes two types of diesel: nonroad (fuelTypeID 23) and marine diesel (fuelTypeID 24). The only difference between them is sulfur content, as shown in Table 8-1. These values represent a walk-down in sulfur to meet regulatory requirements based on what was known about refining, consumption, and credit trading patterns.[23] The final sulfur level of 6 ppm in nonroad reflects the end of the phase-in period and merger of onroad and nonroad refinery products, thus nonroad fuel attains the sulfur level observed in onroad fuel. Survey data suggests there is little variation in diesel sulfur levels across the continental US, so the 6 ppm level is applied nationwide to nonroad as in onroad fuel. The locomotive/marine fuel type is assumed to remain separate from onroad/nonroad, and thus, the final sulfur level is left at the 15 ppm regulatory level, though the other properties have been harmonized with nonroad diesel. Note that MOVES does not model locomotives or commercial marine vessels, so these fuels apply to railroad support equipment and recreational marine.

Nonroad CNG and liquified petroleum gas (LPG, fuelSubtypeID 40) sulfur levels are 7.6 ppm for all years, consistent with the onroad CNG sulfur level. Other properties of nonroad fuels are shown in Table 8-2. Note that fuel density is set at the fuelTypeID level, thus it is fixed across subtypes (e.g., conventional diesel and biodiesel blend).

**Table 8-1. Nonroad diesel sulfur content in MOVES (ppm wt).**

| Calendar Year | Nonroad | Marine |
|---|---|---|
| 1999 and earlier | 2284 | 2640 |
| 2000 | 2284 | 2640 |
| 2001 | 2284 | 2635 |
| 2002 | 2284 | 2637 |
| 2003 | 2284 | 2637 |
| 2004 | 2284 | 2637 |
| 2005 | 2284 | 2637 |
| 2006 | 2242 | 2588 |
| 2007 | 1139 | 1332 |
| 2008 | 351 | 435 |
| 2009 | 351 | 435 |
| 2010 | 165 | 319 |
| 2011 | 32 | 236 |
| 2012 | 6 | 124 |
| 2013 | 6 | 44 |
| 2014 and later | 6 | 15 |

**Table 8-2. Onroad and Nonroad fuel properties by SubtypeID in MOVES.**

| SubtypeID | TypeID | SubtypeDesc | Petroleum Fraction | Fossil Fraction | Carbon Content (g/kJ) | Energy Content (MJ/kg) | Fuel Density (g/gal) |
|---|---|---|---|---|---|---|---|
| 10 | 1 | Conventional Gasoline | 0.95 | 1 | 0.0196 | 43.488 | 2829 |
| 11 | 1 | Reformulated Gasoline (RFG) | 0.95 | 1 | 0.0196 | 42.358 | 2829 |
| 12 | 1 | Gasohol (E10) | 0.94 | 0.94 | 0.01982 | 41.696 | 2829 |
| 13 | 1 | Gasohol (E8) | 0.945 | 1 | 0.01982 | 42.027 | 2829 |
| 14 | 1 | Gasohol (E5) | 0.945 | 1 | 0.01984 | 42.523 | 2829 |
| 15 | 1 | Gasohol (E15) | 0.94 | 0.94 | 0.01980 | 40.877 | 2829 |
| 20 | 2 | Conventional Diesel Fuel | 1 | 1 | 0.02022 | 42.869 | 3203 |
| 21 | 2 | Biodiesel Blend | 0.81 | 0.81 | 0.02022 | 42.700 | 3203 |
| 22 | 2 | Fischer-Tropsch Diesel (FTD100) | 0 | 1 | 0.0205 | 43.247 | 3203 |
| 23 | 23 | Nonroad Diesel Fuel | 1 | 1 | 0.02022 | 42.869 | 3198 |
| 24 | 24 | Marine Diesel Fuel | 1 | 1 | 0.02022 | 42.869 | 3198 |
| 30 | 3 | Compressed Natural Gas (CNG) | 0 | 1 | 0.0161 | 48.632 | 500 |
| 40 | 4 | Liquefied Petroleum Gas (LPG) | 0 | 1 | 0.0161 | 46.607 | 1923 |
| 50 | 5 | Ethanol | 0.26 | 0.26 | 0.0194 | 26.592 | NULL |
| 51 | 5 | Ethanol (E85) | 0.26 | 0.26 | 0.0194 | 29.12 | NULL |
| 52 | 5 | Ethanol (E70) | 0.46 | 0.46 | 0.0194 | 31.649 | NULL |
| 90 | 9 | Electricity | 0.02 | 0.87 | 0 | NULL | NULL |

The fuel density values in Table 8-2, above, are stored in the MOVES default database, but they are not actually used in MOVES nonroad module calculations. Instead, the equivalent values in pounds/gallon are hard-coded in the nonroad model. Similarly, the nonroad model uses a hard-coded carbon mass fraction for diesel and gasoline of 0.87.[24,25]

# 9. Updates to Fuel Wizard Factors for Ethanol Blending

Since MOVES2014a, the model software has included a "Fuel Wizard" tool to help users create realistic gasoline blends that are not present in the default fuel supply. In the real world, specifying a limit or range for one fuel property can produce collateral changes in other properties as a result of impacts on refining and blending processes. For example, reducing sulfur may affect aromatics and olefins, or allowing higher RVP may affect distillation points.

The Fuel Wizard allows a user to input a change in one of three gasoline properties (RVP, ethanol level, or sulfur level) and the tool estimates secondary fuel property changes using data from refinery modeling runs. This allows for the full emissions impact of proposed fuel changes (as part of state or local programs) to be estimated properly, including the subsequent effects of non-regulated fuel property changes. The Fuel Wizard is currently capable of creating fuels with ethanol variations between E0 and E15, sulfur from 5-80 ppm, and RVP from 5-14 psi.

The Fuel Wizard is used in conjunction with the county data manager in the MOVES graphical user interface (GUI). More information on when users should use the Fuel Wizard is provided in our technical guidance.[26]

The Fuel Wizard adjustments are stored in the fuelWizardFactors table and are applied in an additive way (not multiplicative factors). In MOVES2014 (a and b), the adjustments used in the Fuel Wizard were derived from refinery modeling done as part of the Tier 3 rulemaking analysis, and are the same as those used in developing a portion of the default fuel supply (see Section 5.1).

However, in MOVES3, we updated the factors for ethanol blending using the results of recent refinery modeling work conducted by MathPro, Inc. Data on petroleum and biofuels markets from EIA and other sources was used to develop assumptions and market inputs to the model. The refinery modeling analysis was conducted at the PADD level for summer and winter seasons after developing and validating a calibration case to ensure key outputs aligned with actual observed performance of the refining sector. A business-as-usual scenario was run for calendar year 2016 as a reference case, followed by two "low-biofuel" scenarios where the only ethanol use was in E10 in RFG areas. The two low-biofuel scenarios differed in the price and availability of alkylation feedstocks, which affected the relative proportions of aromatics and iso-paraffins used to make up octane if a large volume of ethanol were removed from the gasoline supply.

The updated Fuel Wizard factors in MOVES for ethanol blends, shown in Table 9-1, were derived from the "Low-Biofuel #2" case based on the favorable economics of that scenario as described by MathPro. The increase in refinery demand for isobutane and butane in this scenario can easily be met by the large increases in U.S. isobutane and butane production associated with increasing U.S. light crude oil production.[27] The MathPro report is available in Appendix B, and additional details on the refinery model development and calibration are available in the docket of the 2020 Renewable Volumes rule.[28] The specific factors shown in Table 9-1 were computed by taking the difference between the "Low-Biofuel #2" and "Reference" cases in Table 1 of Appendix B, except for RVP, which were derived from the API blending study as discussed in Section 6.1.[19]

An alternative method suggested by some stakeholders for estimating the effect of ethanol blending on gasoline properties involves looking back over a period when ethanol use was

increasing steeply, for example comparing 2006 to 2016. While this approach may seem to have the advantage of utilizing direct observations, the problem is that other market changes were also at play and their impacts are overlaid upon and confound the effects of increasing ethanol use. Such changes include: phase-in of Tier 2 sulfur and MSAT2 benzene control regulations; the phase-out of MTBE; rising crude oil prices and the associated expansion of domestic oil and gas production, including light hydrocarbons, which favored the use of alkylation as an octane source over reforming; and reduced demand for gasoline hydrocarbons relative to diesel, which caused many refiners to swing a portion of the heavier end of gasoline into distillate products. Given these complexities, we chose to utilize a well-established refinery model where the impacts of ethanol blending could be isolated from several other changes in petroleum markets.

**Table 9-1. Updated Fuel Wizard factors for ethanol blends (additive changes for ETOH Change shown).**

| ETOH Change | RVP | SULF | AROM | OLEF | BENZ | E200 | E300 | T50 | T90 |
|---|---|---|---|---|---|---|---|---|---|
| Vol% to Vol% | psi | ppm | Vol% | Vol% | Vol% | Vol% | Vol% | Deg.F | Deg.F |
| E0 to E10 Winter | 0.80 | | -1.7 | 1.7 | -0.01 | 6.4 | 0.2 | -23.8 | -0.63 |
| E0 to E10 Summer | 0.90 | | -2.2 | 1.6 | | 7.0 | -0.2 | -26.0 | 0.63 |
| E10 to E15 Winter | -0.15 | | -0.85 | 0.85 | -0.01 | 3.2 | 0.1 | -11.9 | -0.32 |
| E10 to E15 Summer | -0.15 | | -1.1 | 0.80 | | 3.5 | -0.1 | -13.0 | 0.32 |

Table 9-2 and Table 9-3 show the Fuel Wizard factors for changes resulting from adjusting RVP and sulfur level, respectively. These values have remained unchanged since MOVES2014b.

**Table 9-2. Adjustment factors for lower RVP blends (additive adjustments per psi).**

| DESCRIPTION | RVP | SULF | AROM | OLEF | BENZ | E200 | E300 | T50 | T90 |
|---|---|---|---|---|---|---|---|---|---|
| | psi | ppm | Vol% | Vol% | Vol% | Vol% | Vol% | Deg.F | Deg.F |
| Volatility adj. | -1.00 | 0 | 0 | 0 | 0 | -1.26 | -0.50 | 2.57 | 2.27 |

**Table 9-3. Adjustment factors for sulfur blends below 30 ppm (additive adjustments per ppm).**

| DESCRIPTION | RVP | SULF | AROM | OLEF | BENZ | E200 | E300 | T50 | T90 |
|---|---|---|---|---|---|---|---|---|---|
| | psi | ppm | Vol% | Vol% | Vol% | Vol% | Vol% | Deg.F | Deg.F |
| Sulfur fuel adj | 0 | -1.00 | -0.032 | 0 | 0 | 0 | 0 | 0 | 0 |

As with the compliance batch data, the distillation values in the refinery modeling output are in terms of E200 and E300 and need conversion to T-values. Since the Fuel Wizard uses a single entry for each parameter, the multi-region T50 correlations described in Section 5.2 for conventional gasoline (CG) were simplified as shown in Figure 9-1, resulting in Equation 9-1. For the E300 to T90 conversion, Equation 5-5 was used directly.

For simplicity, the E10 to E15 factors in Fuel Wizard were made by taking 50 percent of the E0 to E10 change except for RVP, where the value was derived from the 2010 API ethanol blending study as described in Section 6.1. Note that the Fuel Wizard is not currently set up to perform splash blends. Users wanting to model emissions on E15 splash blends, a more likely scenario for the foreseeable future, should use the formulations available in the default supply, as explained in Section 6.1.

$$T50 = 377.34 - 3.7159 \times E200$$ **Equation 9-1**

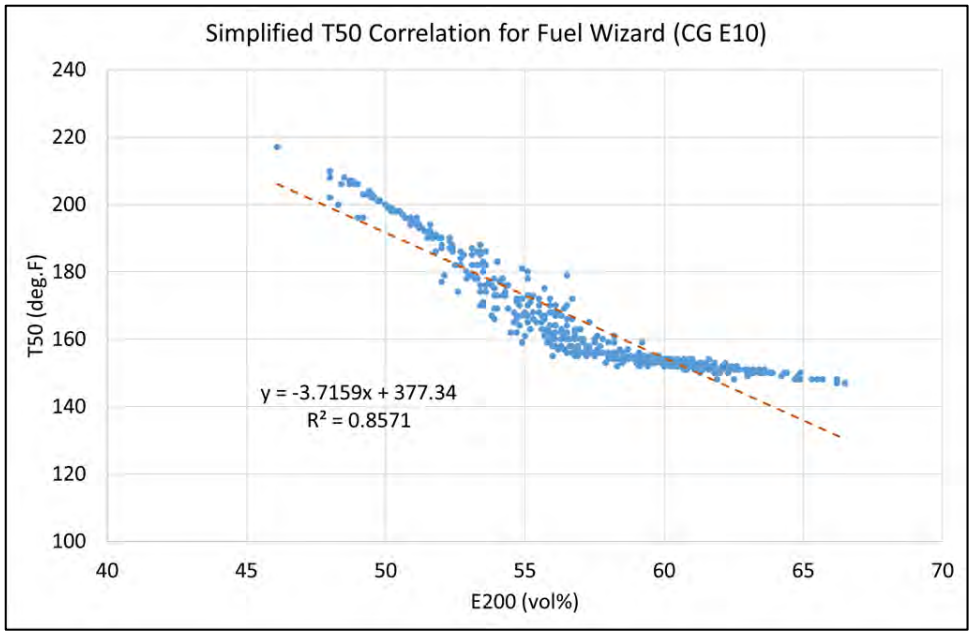


**Figure 9-1. Simplified T50 by E200 correlation for use in MOVES Fuel Wizard.**

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[19] American Petroleum Institute. *Determination of the Potential Property Ranges of Mid-Level Ethanol Blends, Final Report.* April 2010.

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[21] USEPA (2023). *Greenhouse Gas and Energy Consumption Rates for Onroad Vehicles in MOVES4*. EPA-420-R-23-026. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. August 2023.
https://www.epa.gov/moves/moves-onroad-technical-reports.

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https://www.epa.gov/moves/moves-onroad-technical-reports.

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https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100UXEN.pdf

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# APPENDIX A: MOVES FUEL REGION MAPS

The following 24 pages present 50-state maps of summertime MOVES fuel regions by county. Puerto Rico and U.S. Virgin Islands aren't shown but have the same formulation as base region 1 (regionID = 100000000) in all years. While RVPs are generally higher in winter than summer, the MOVES regionID values are identical for both seasons. Maps for 2021-2023 are identical to 2020, and thus are omitted. Maps for 2025 and later are identical to 2024.

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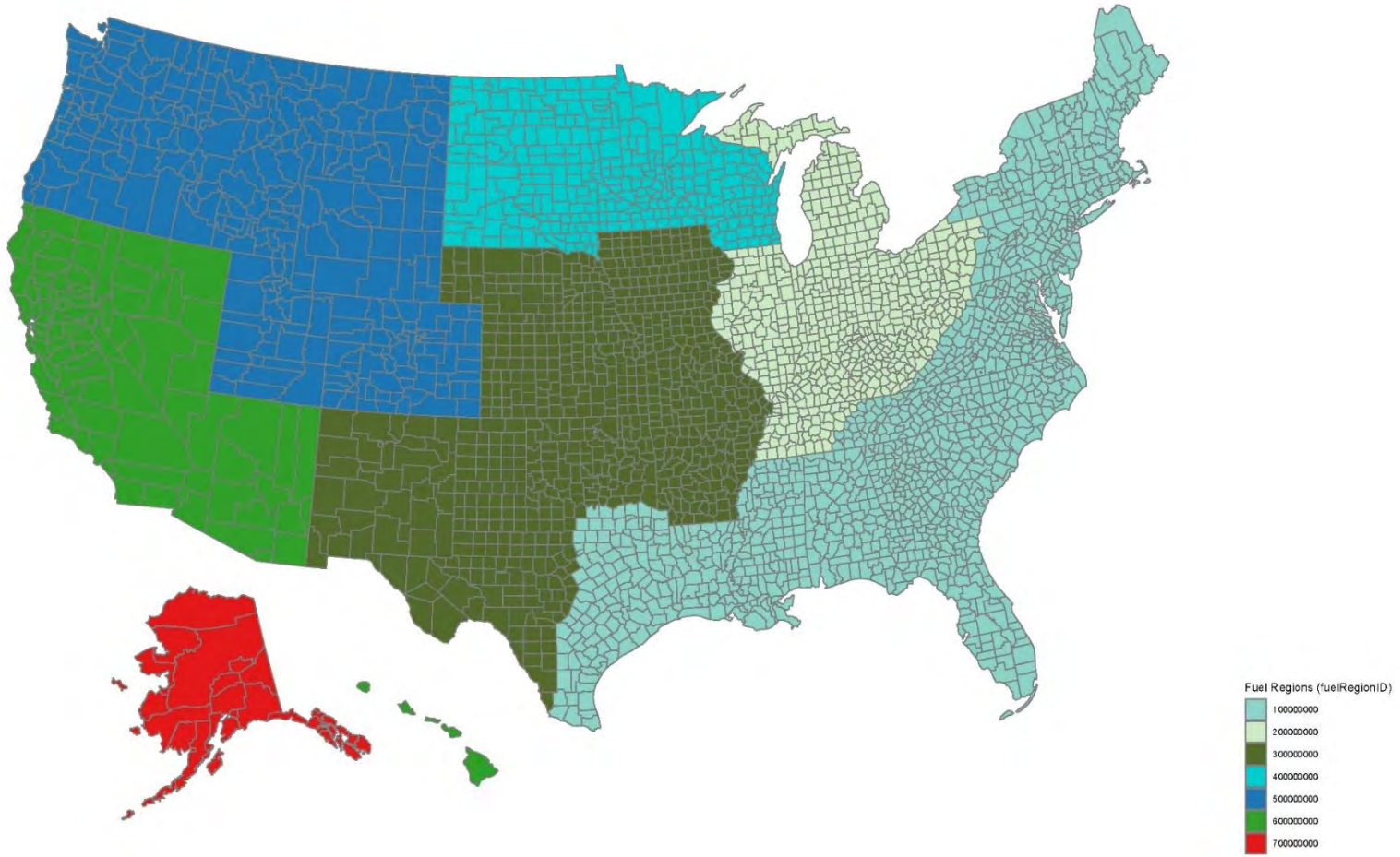
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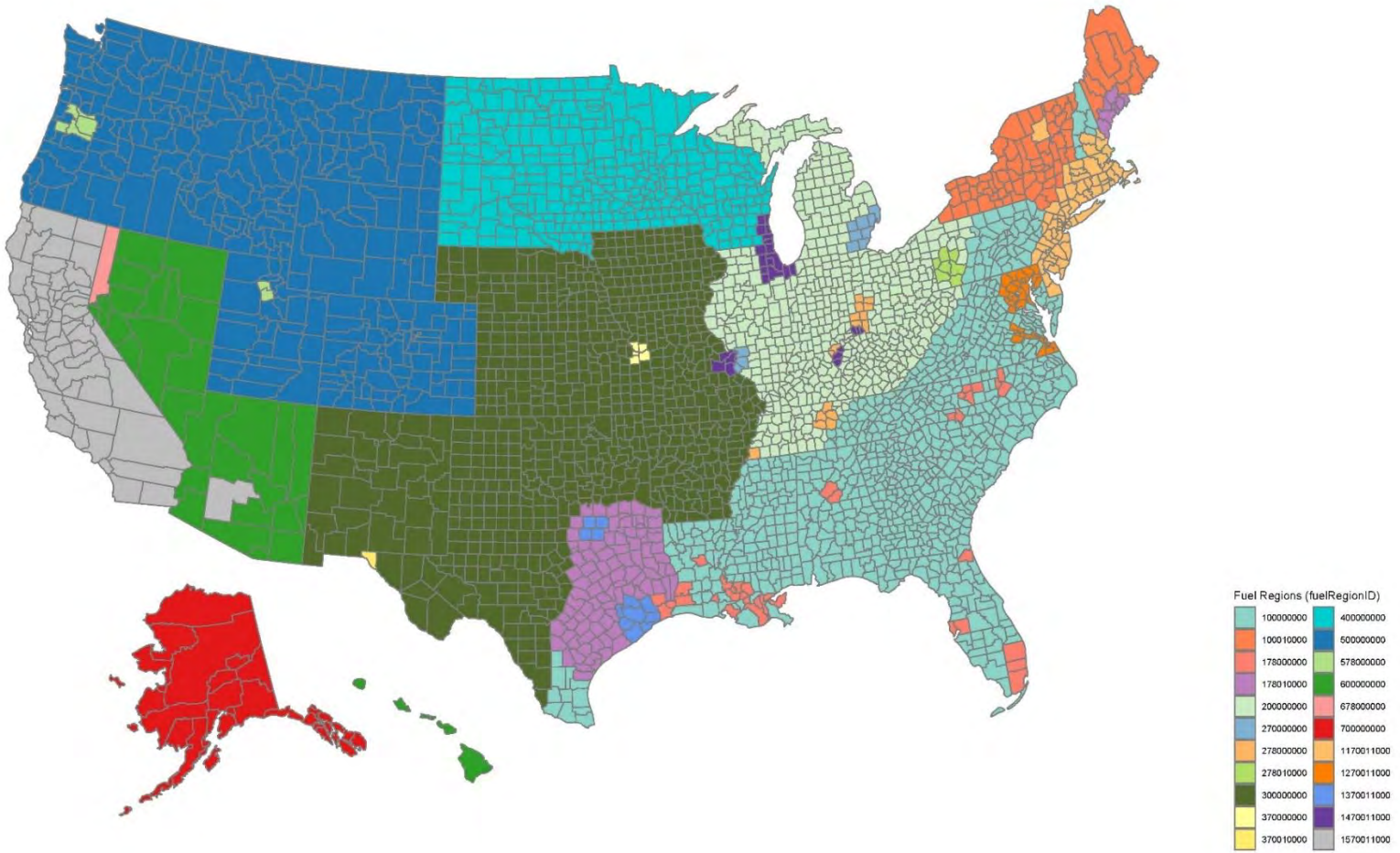
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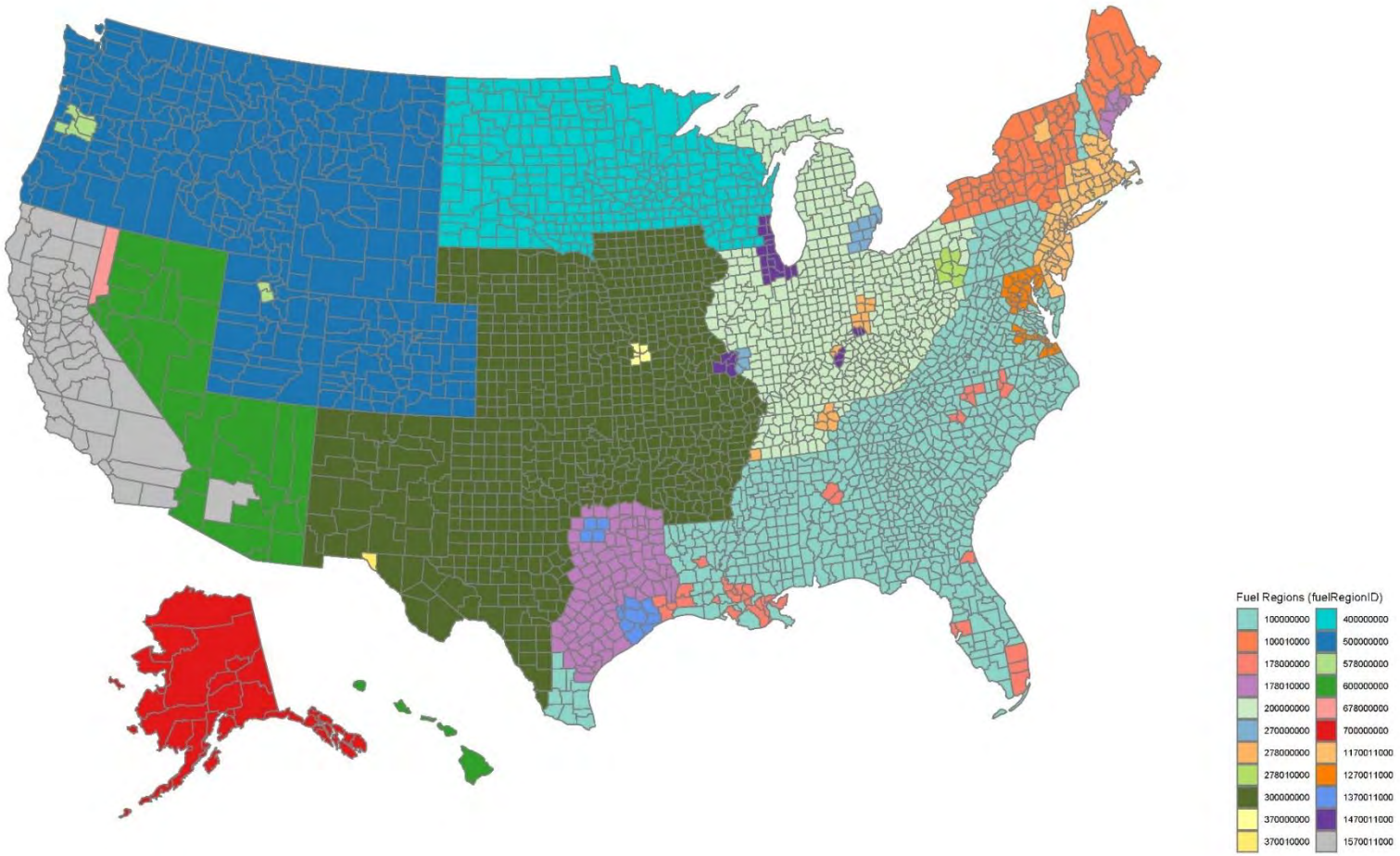
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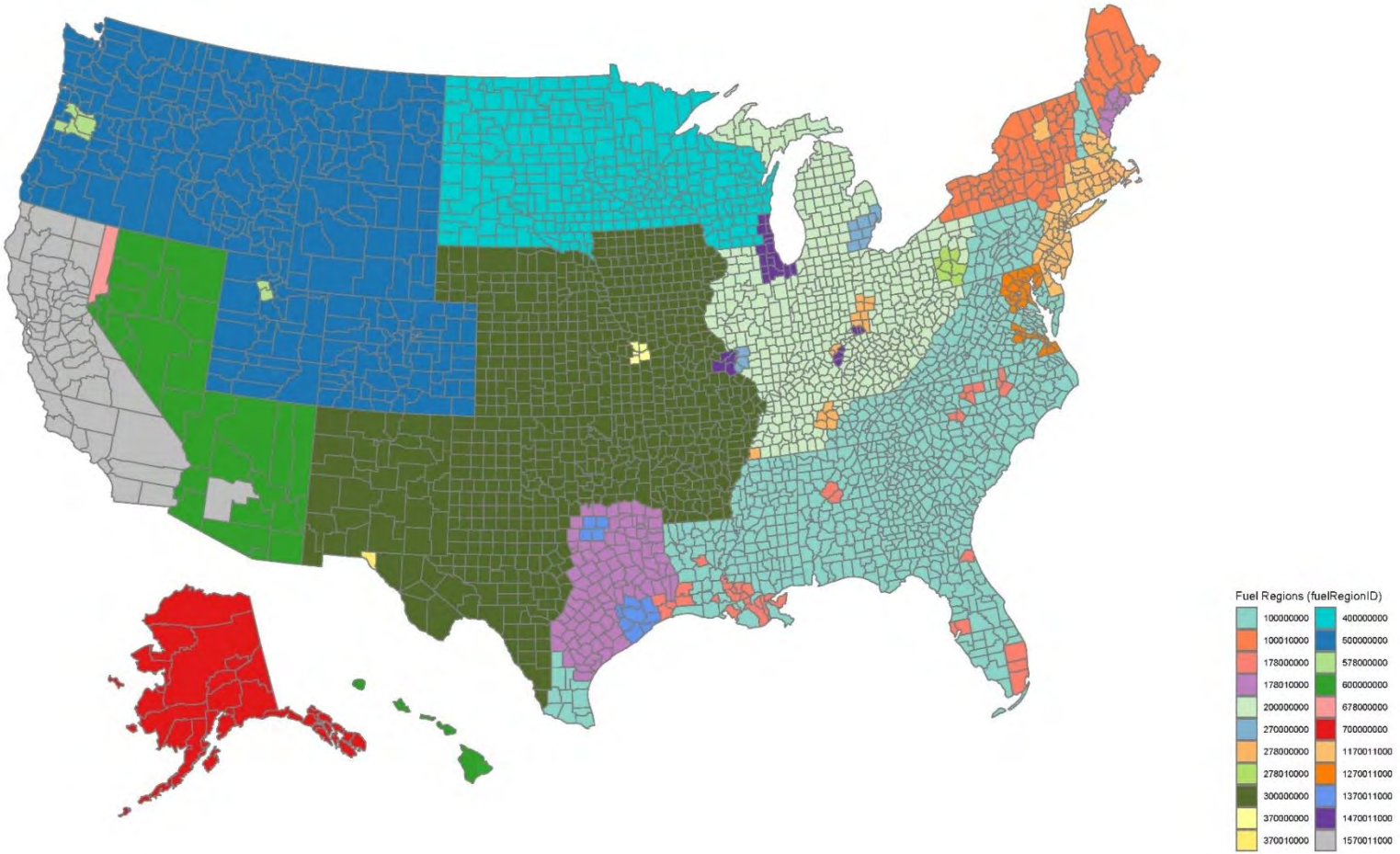
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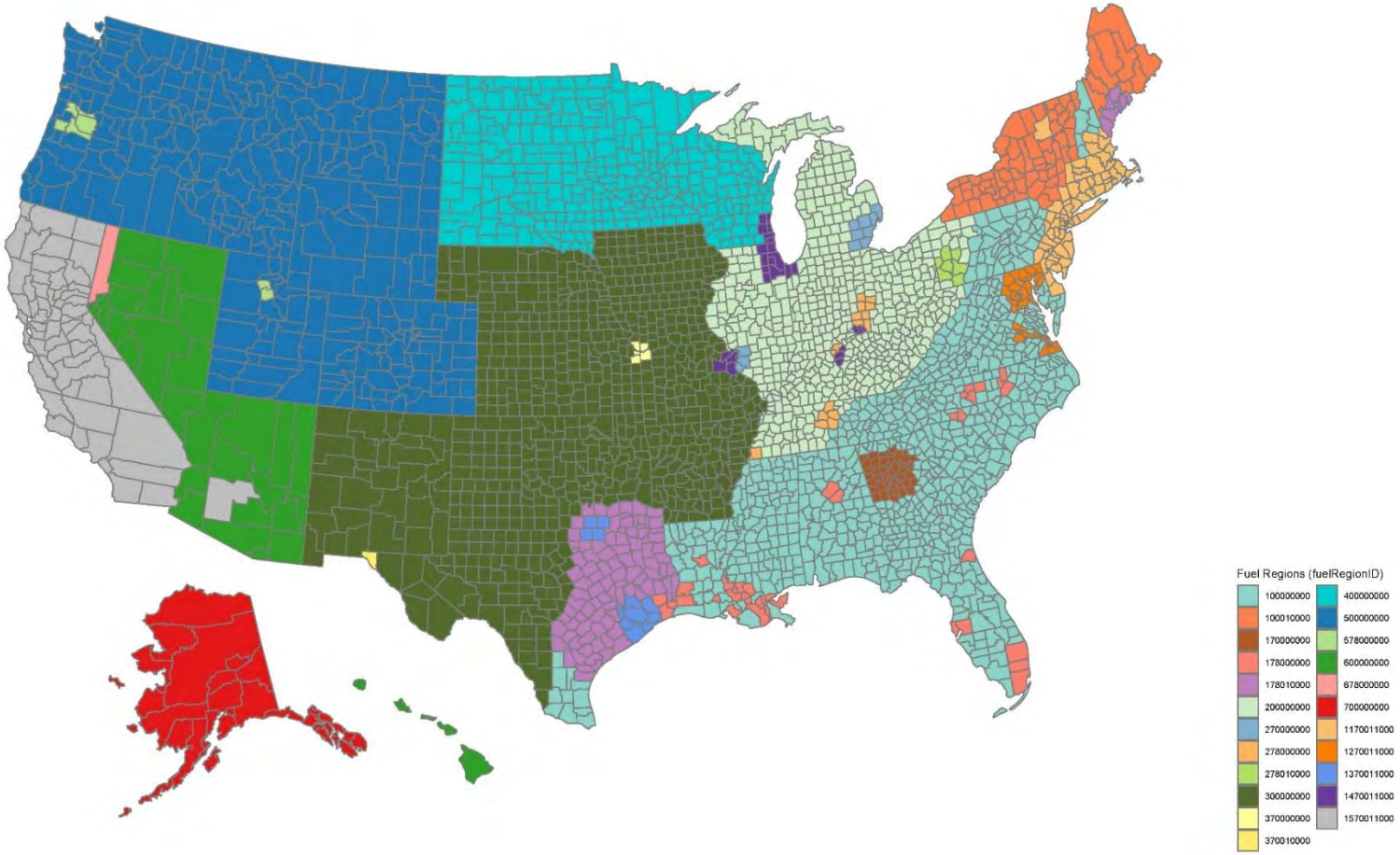
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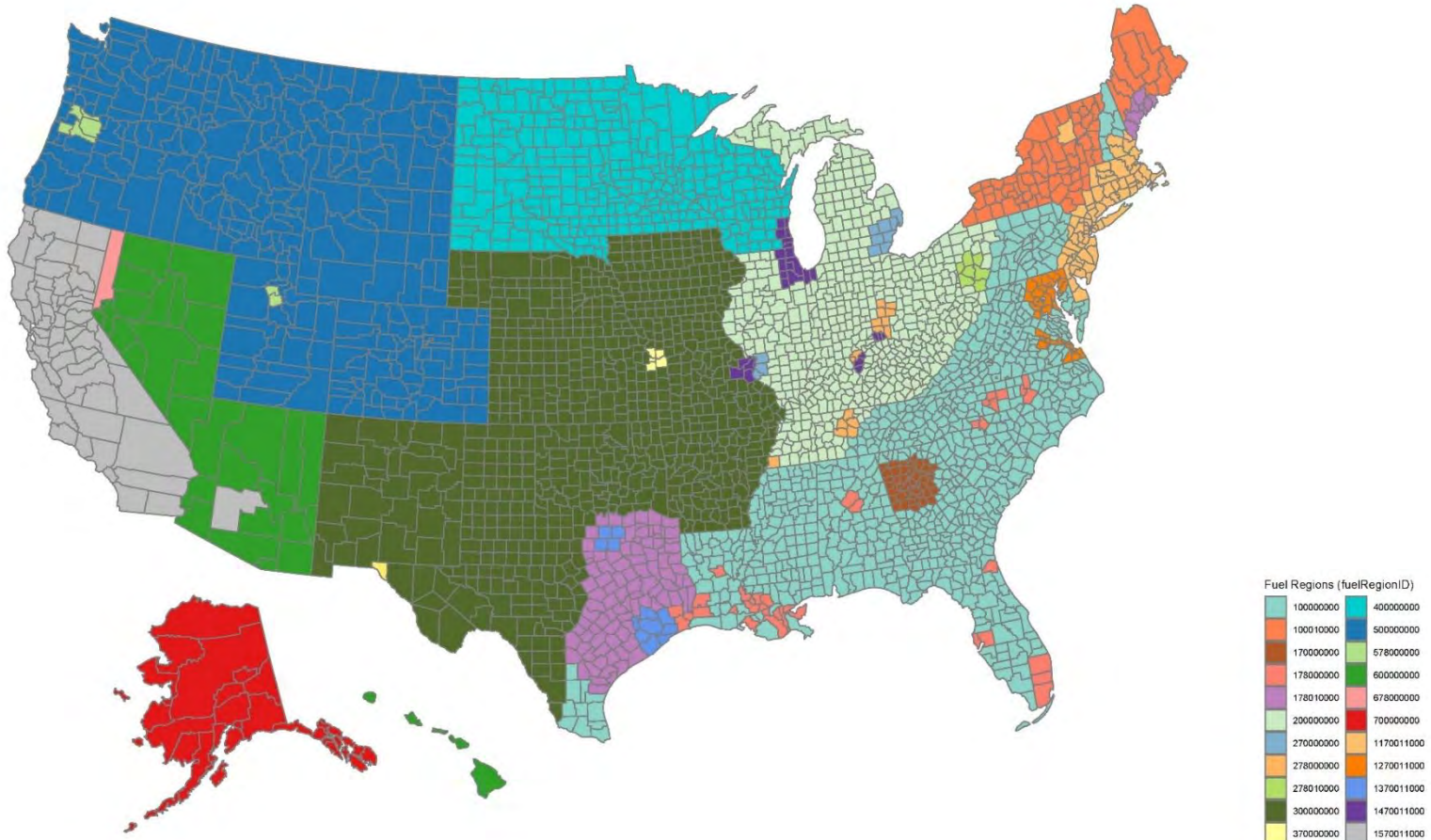
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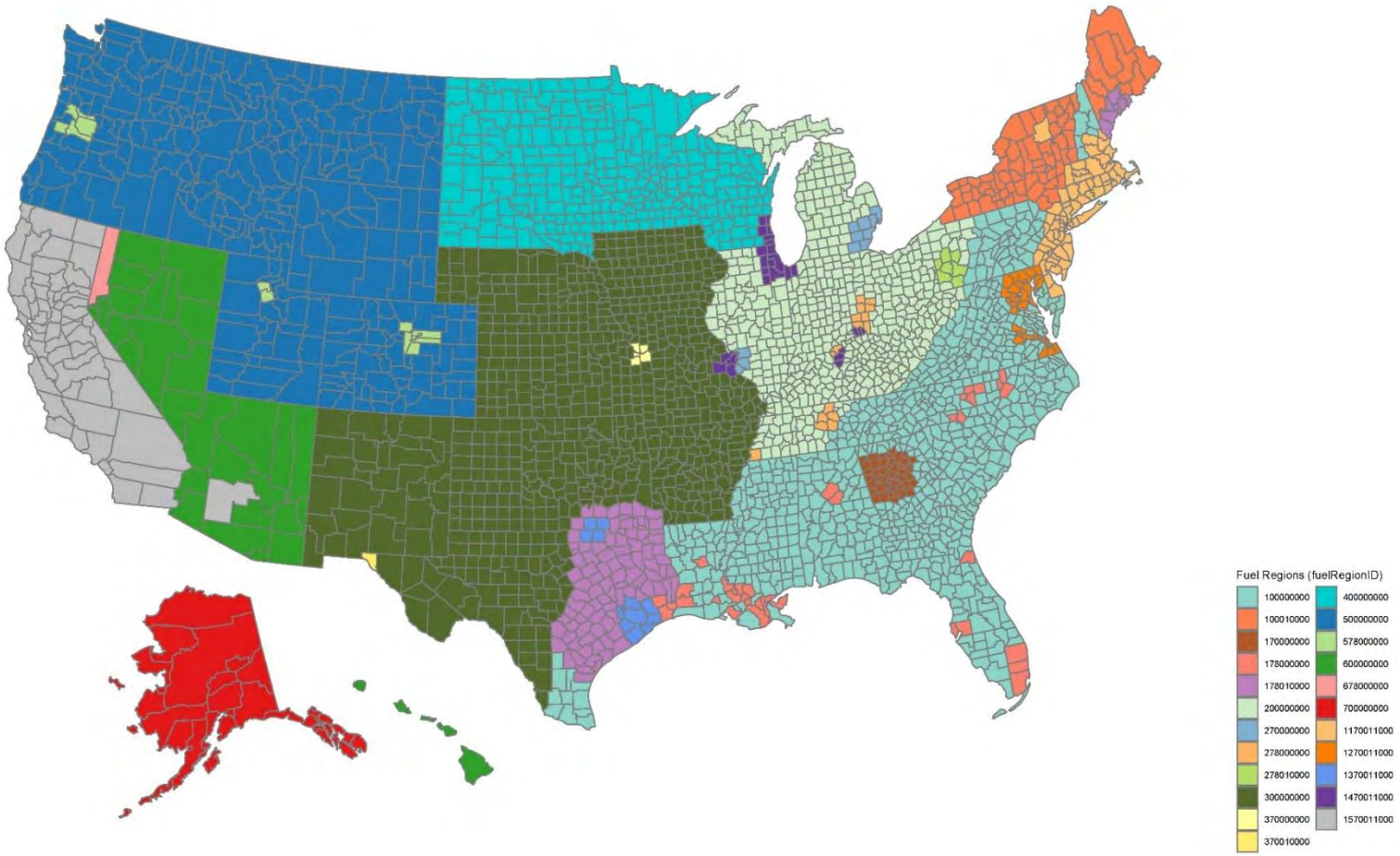
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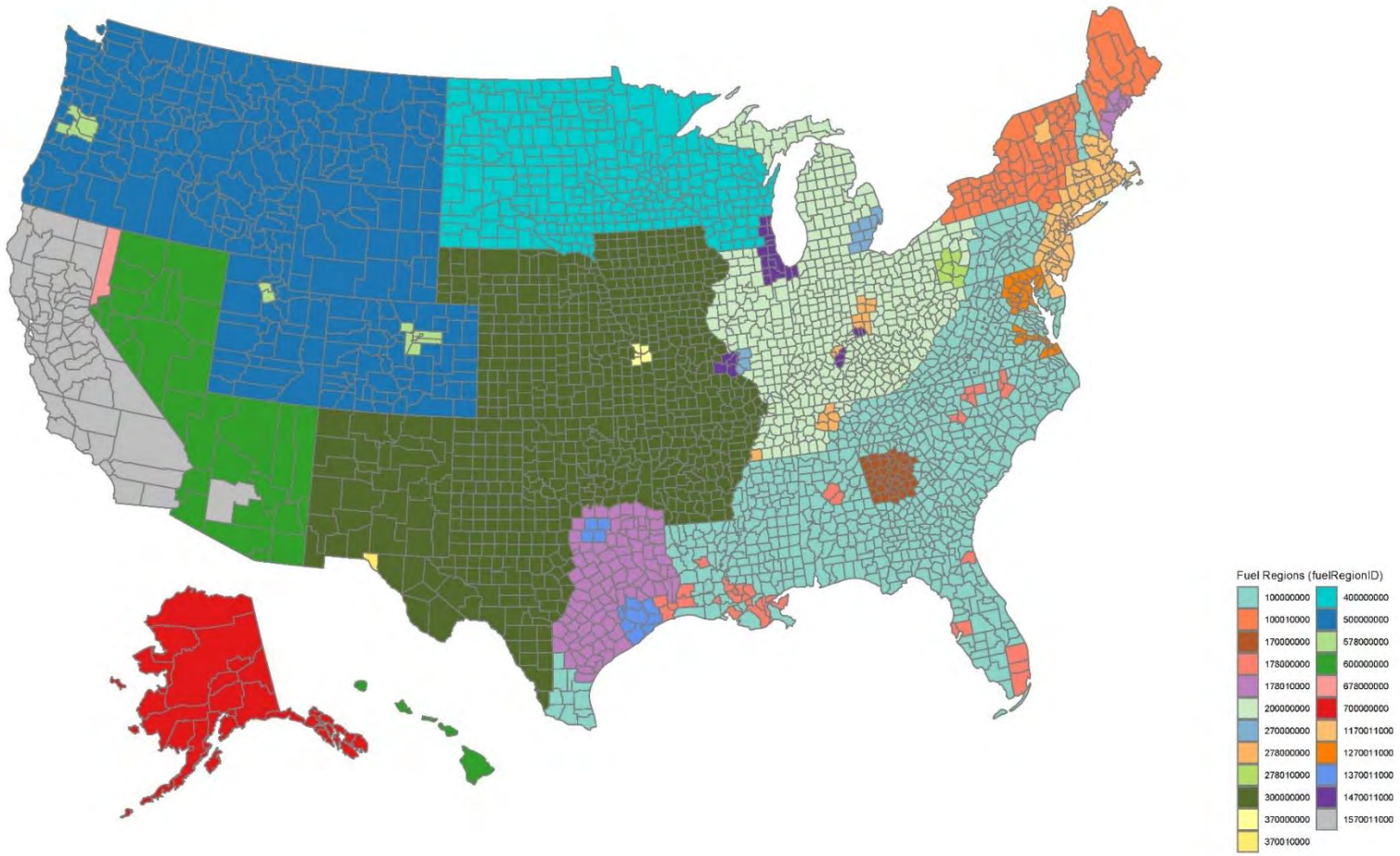
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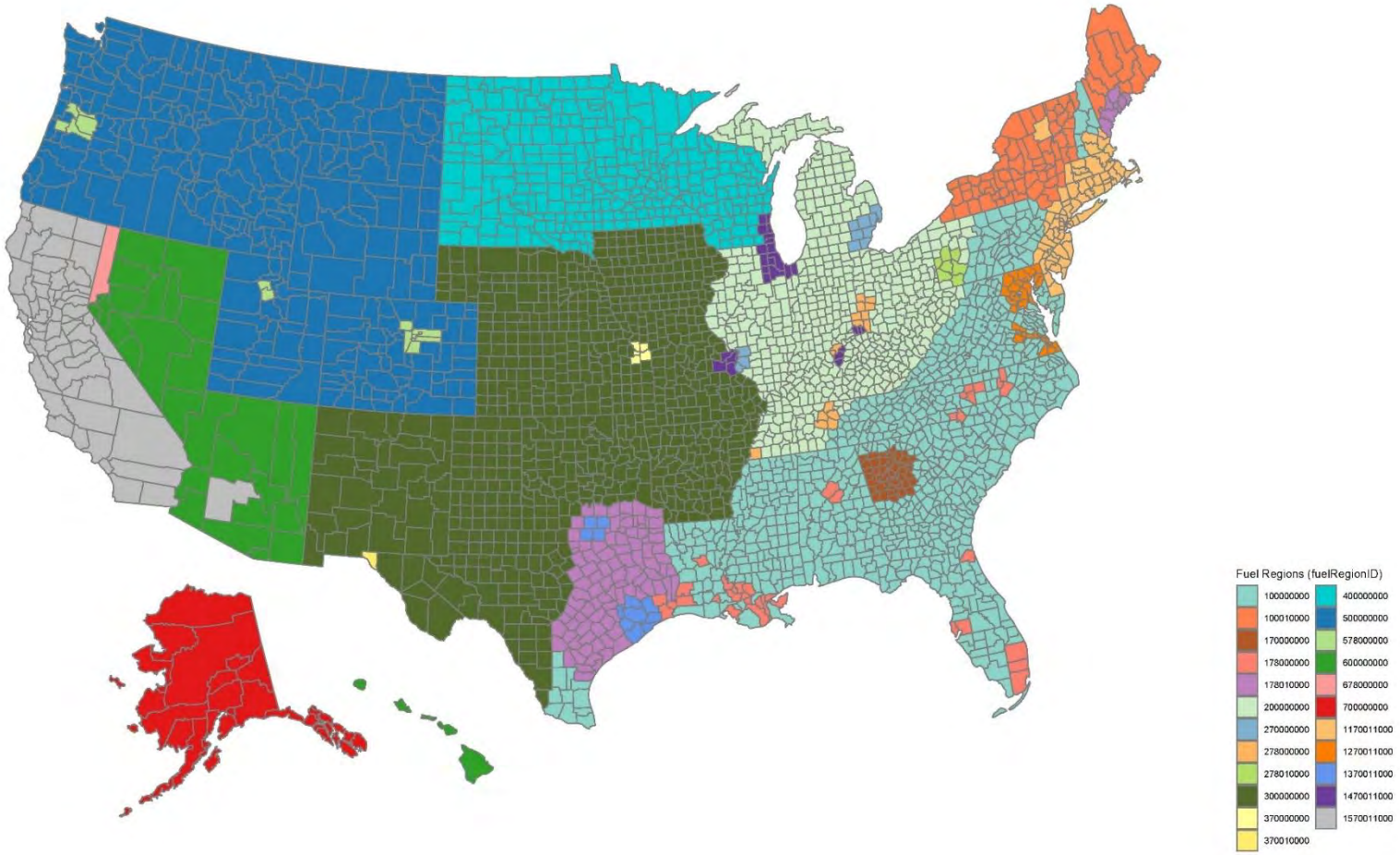
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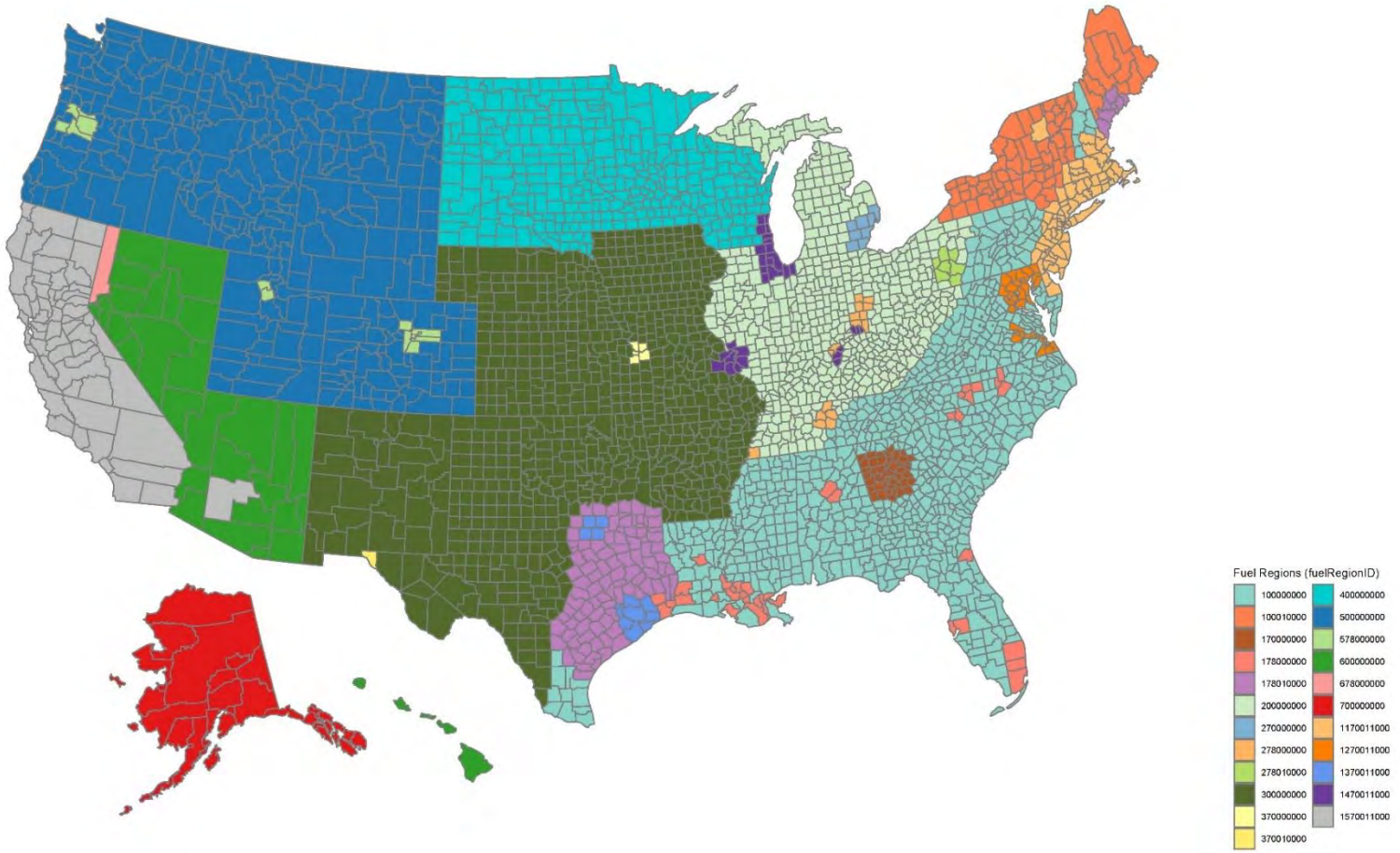
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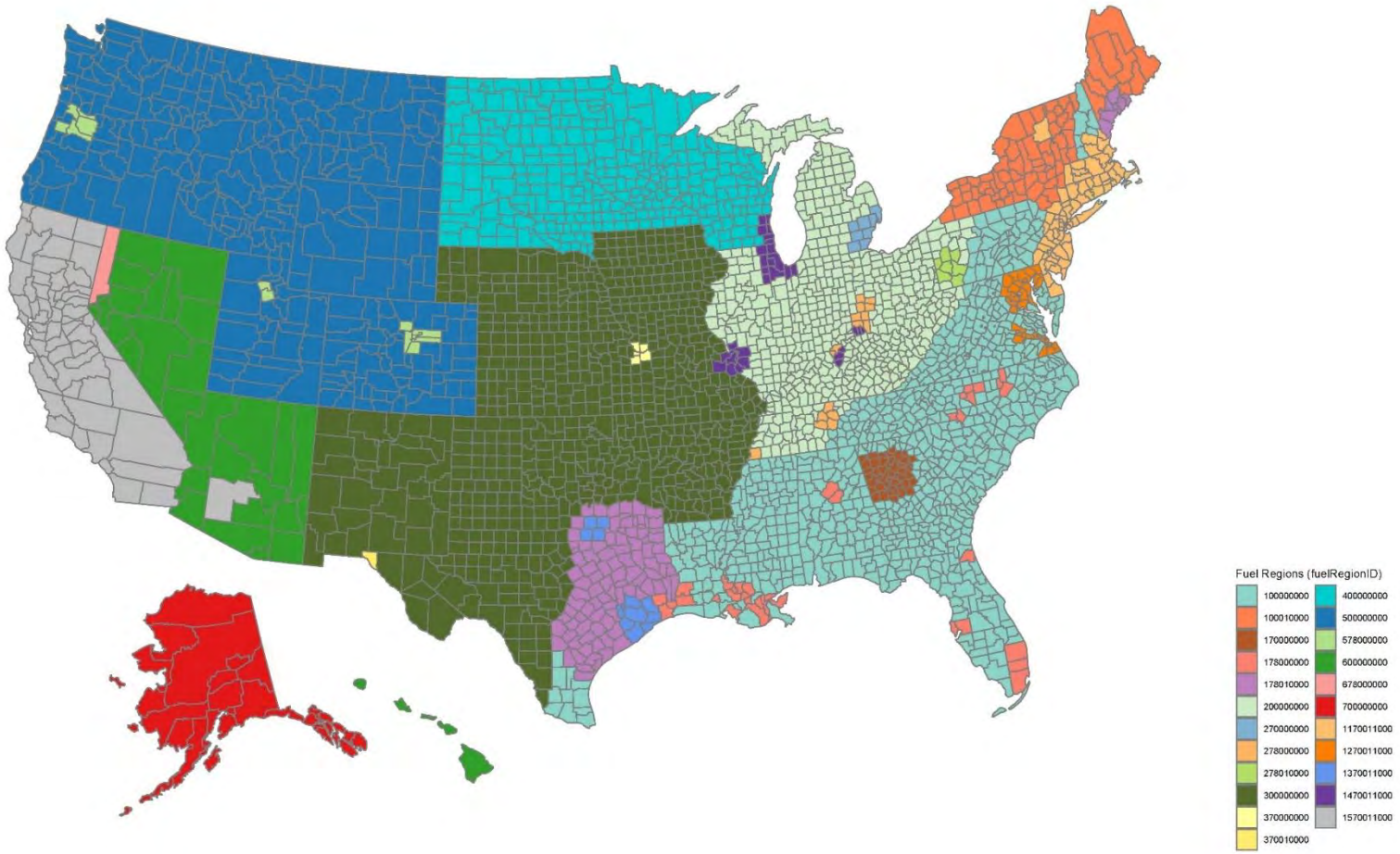
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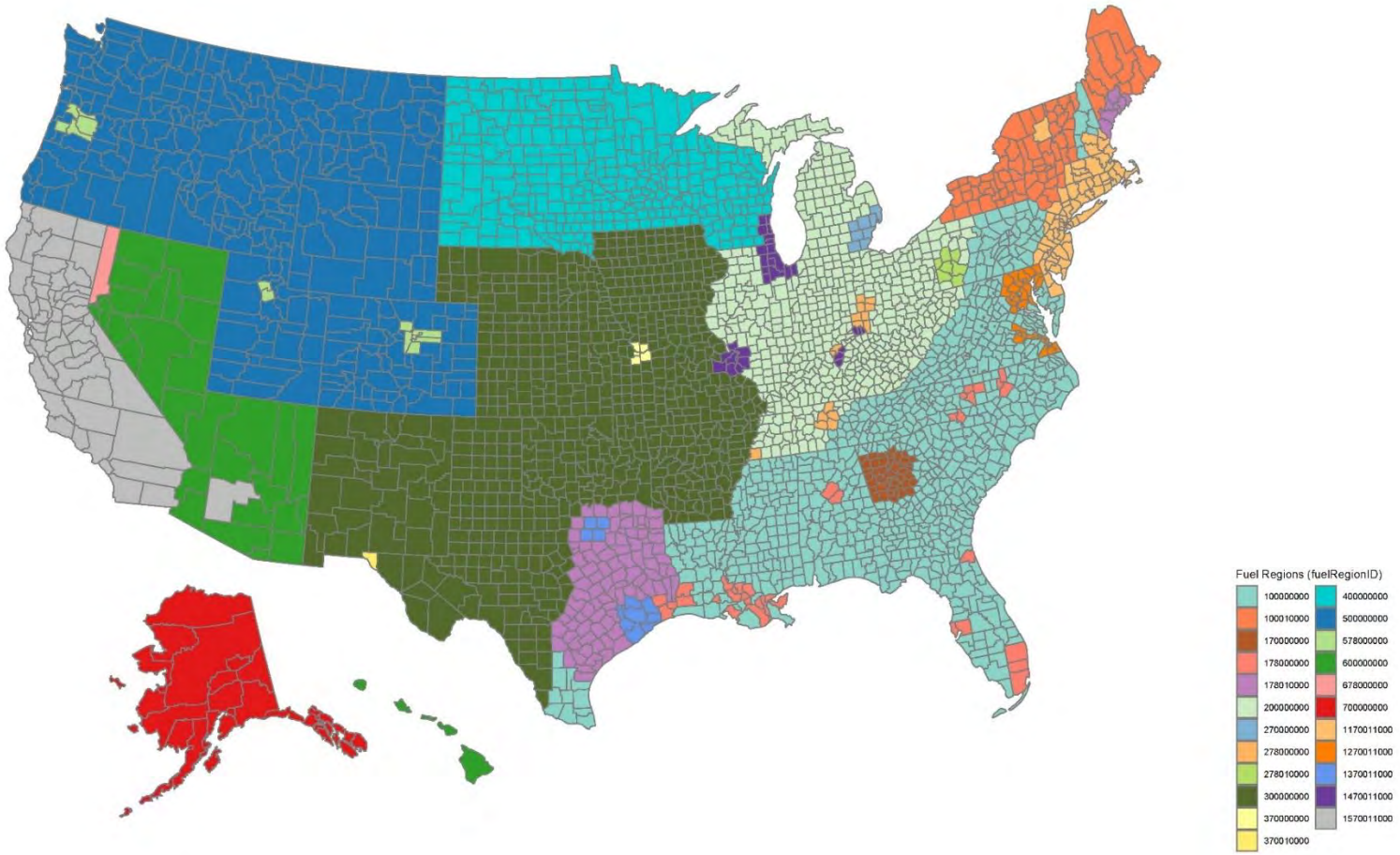
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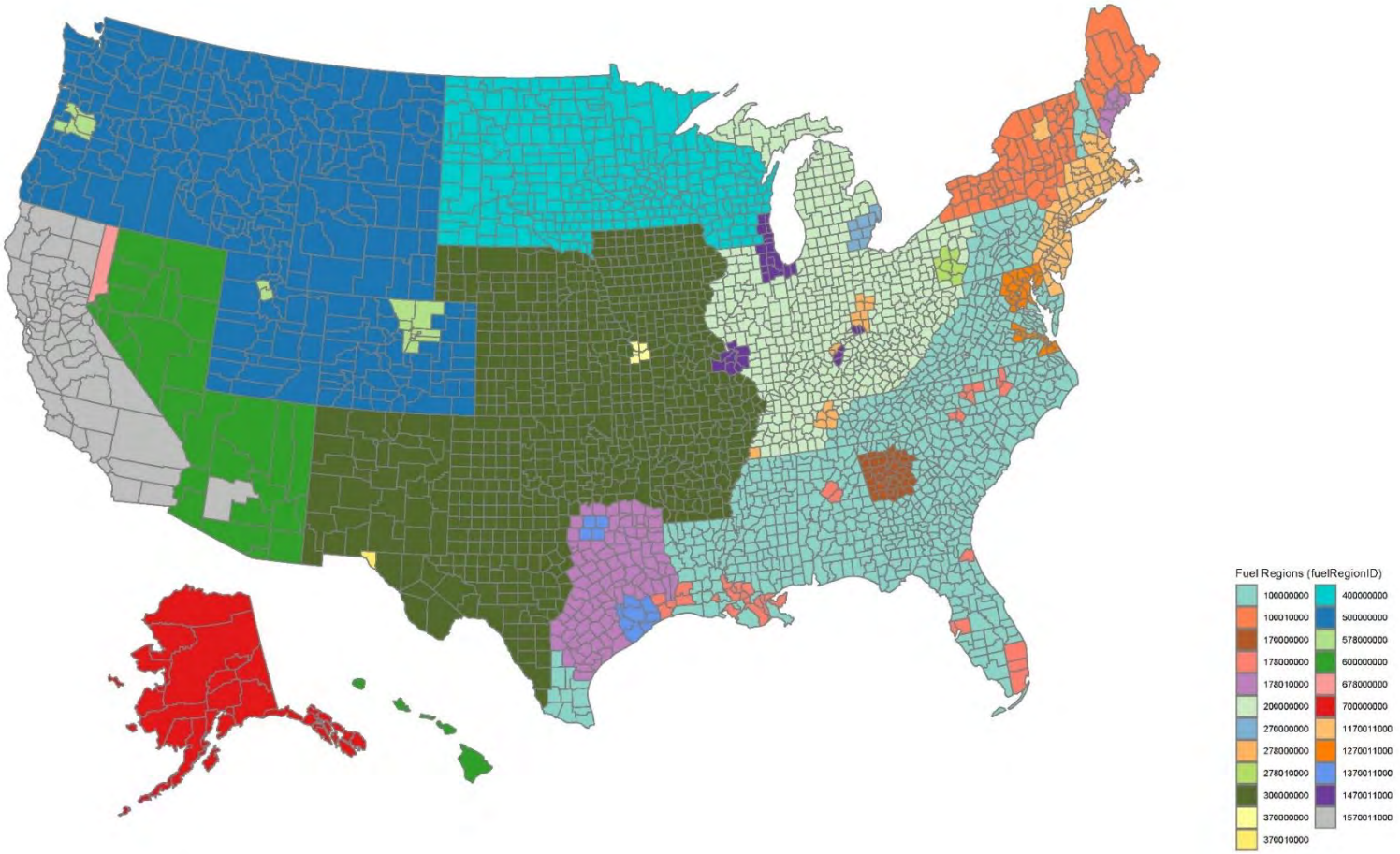
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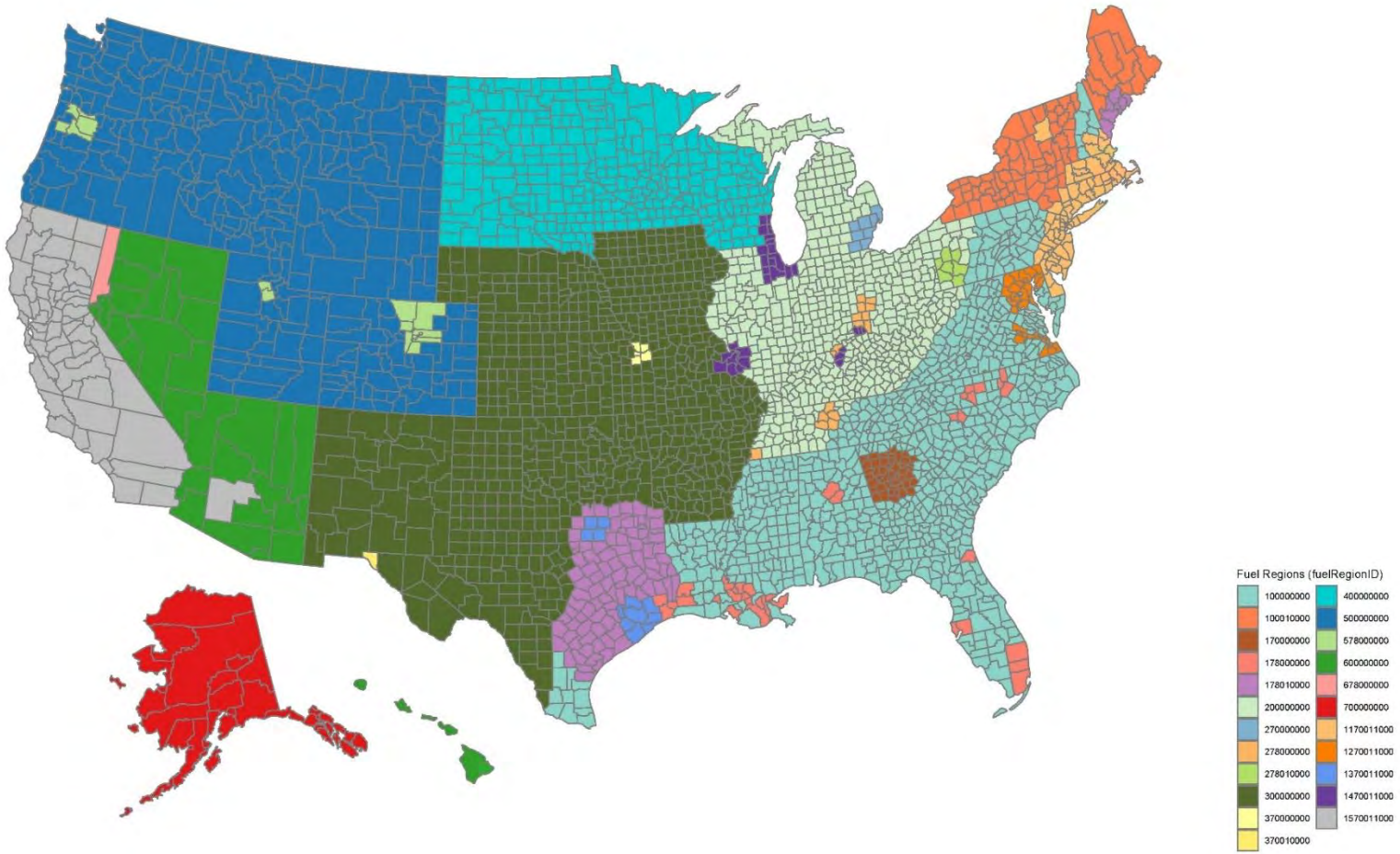
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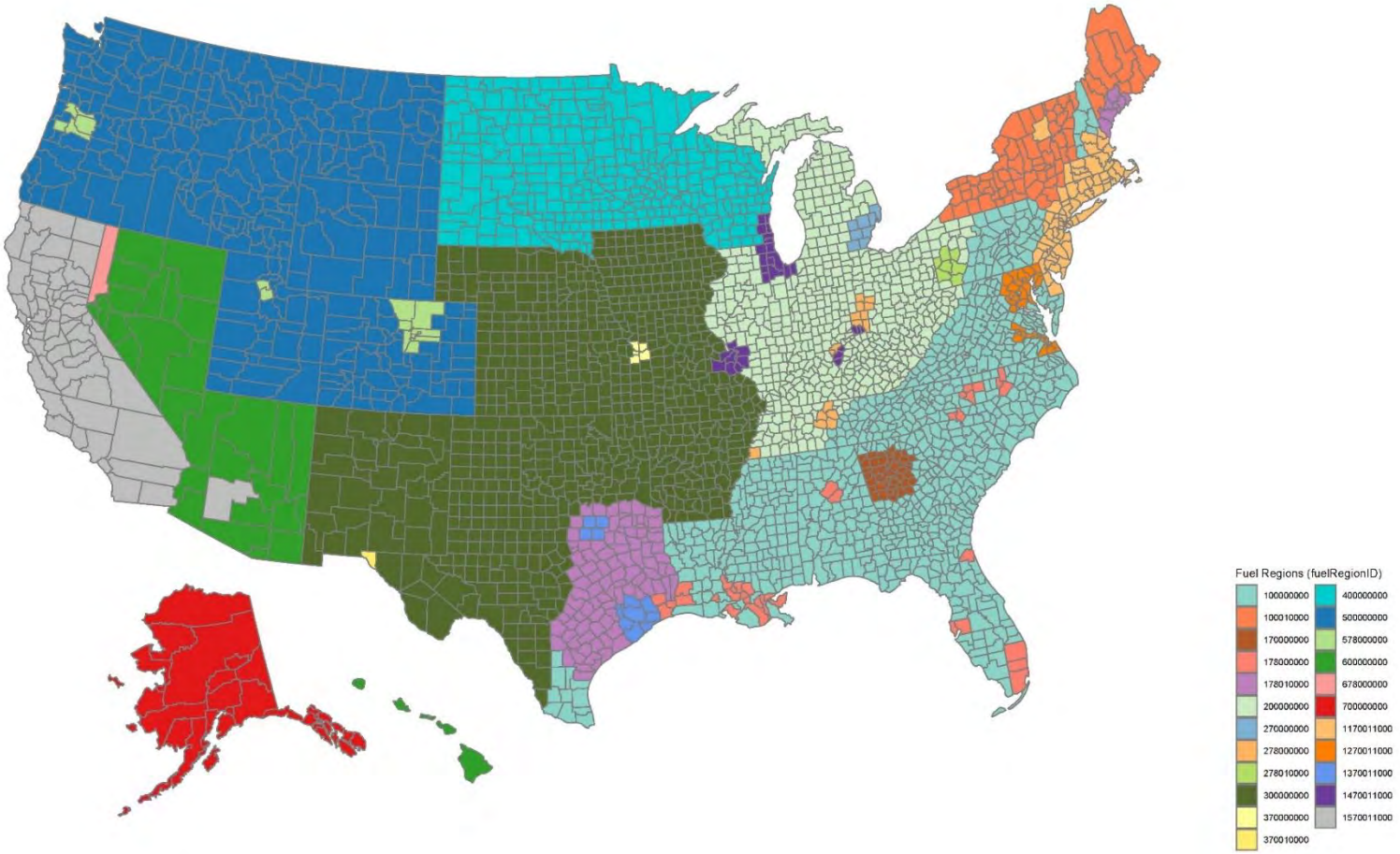
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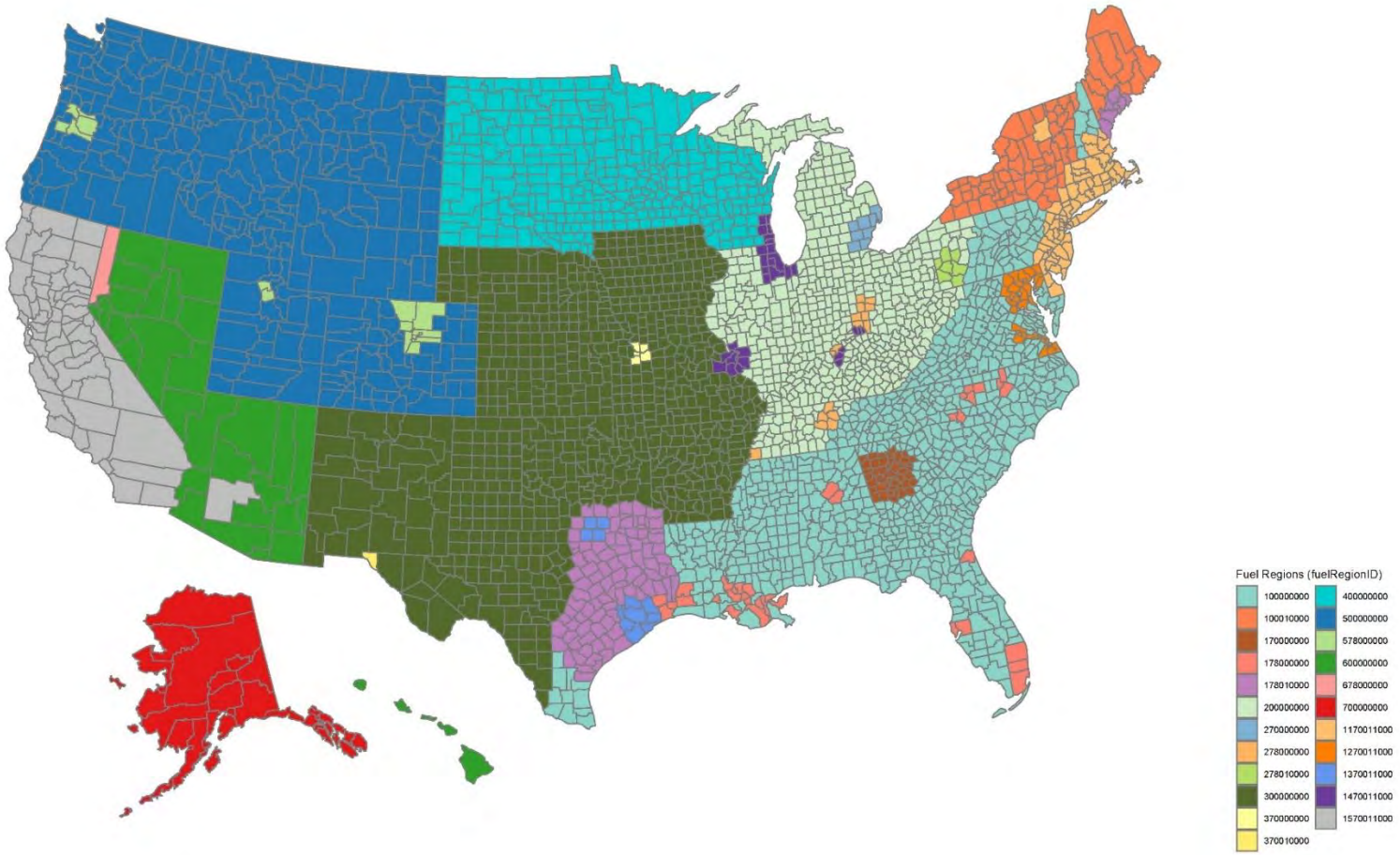
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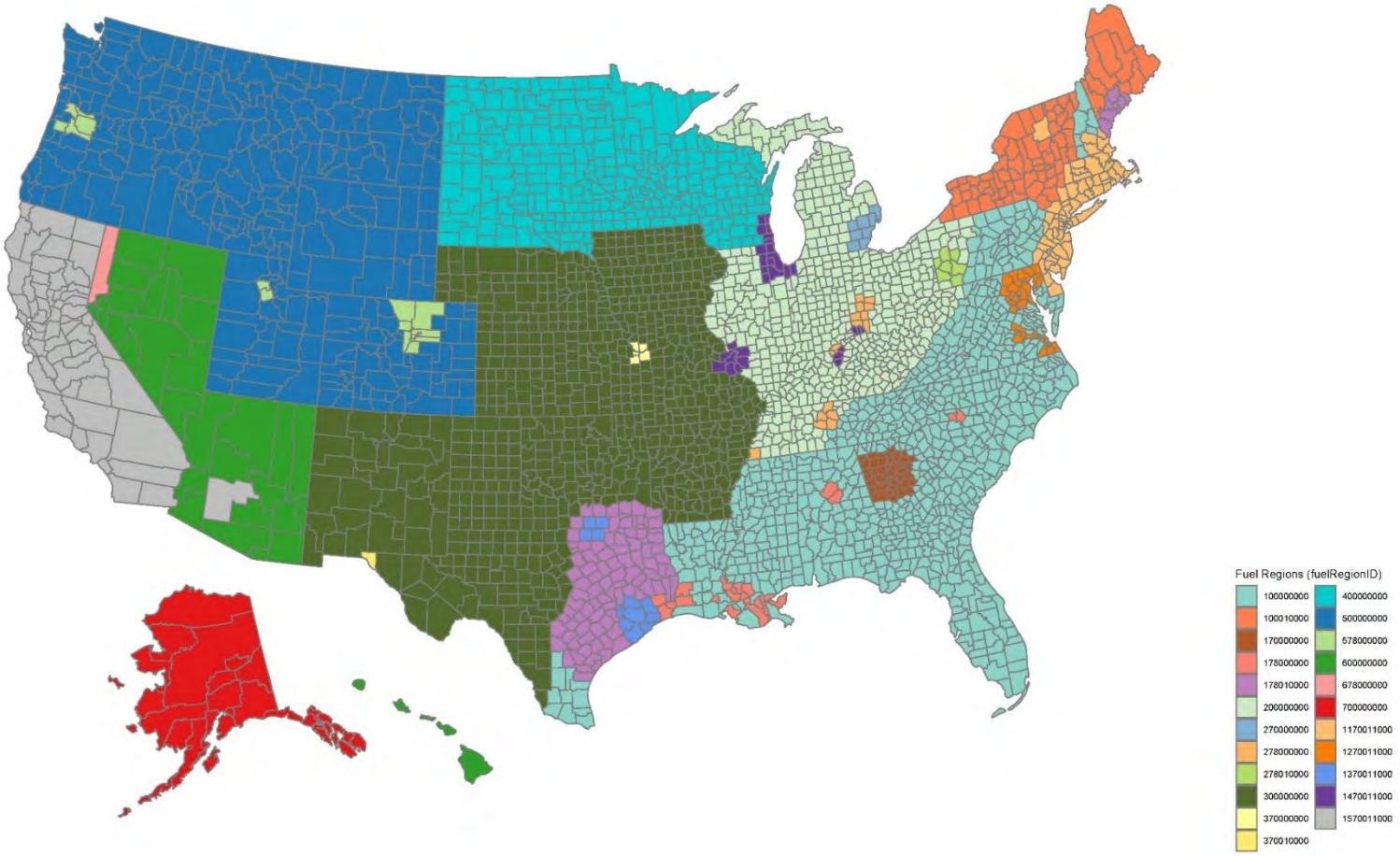
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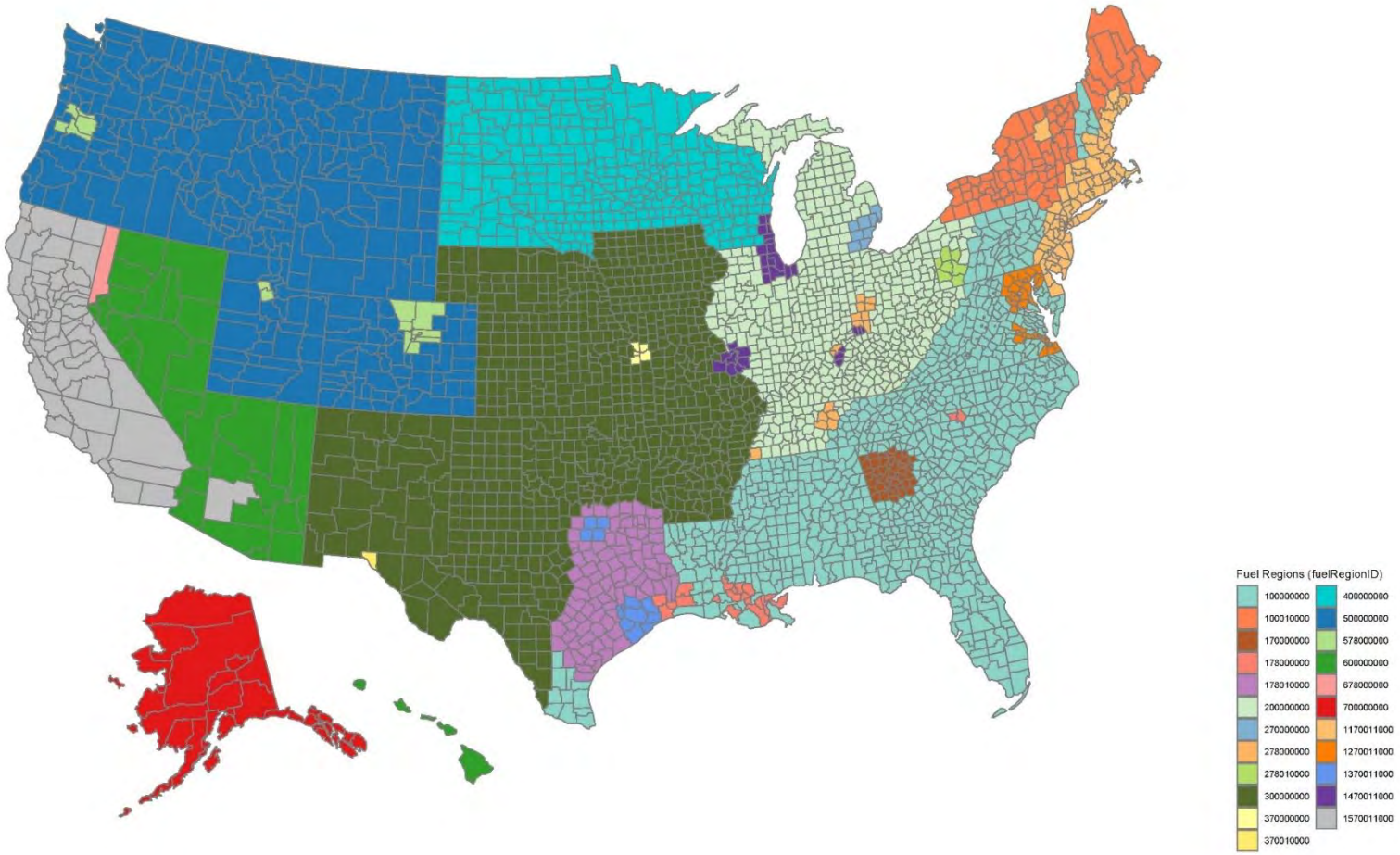
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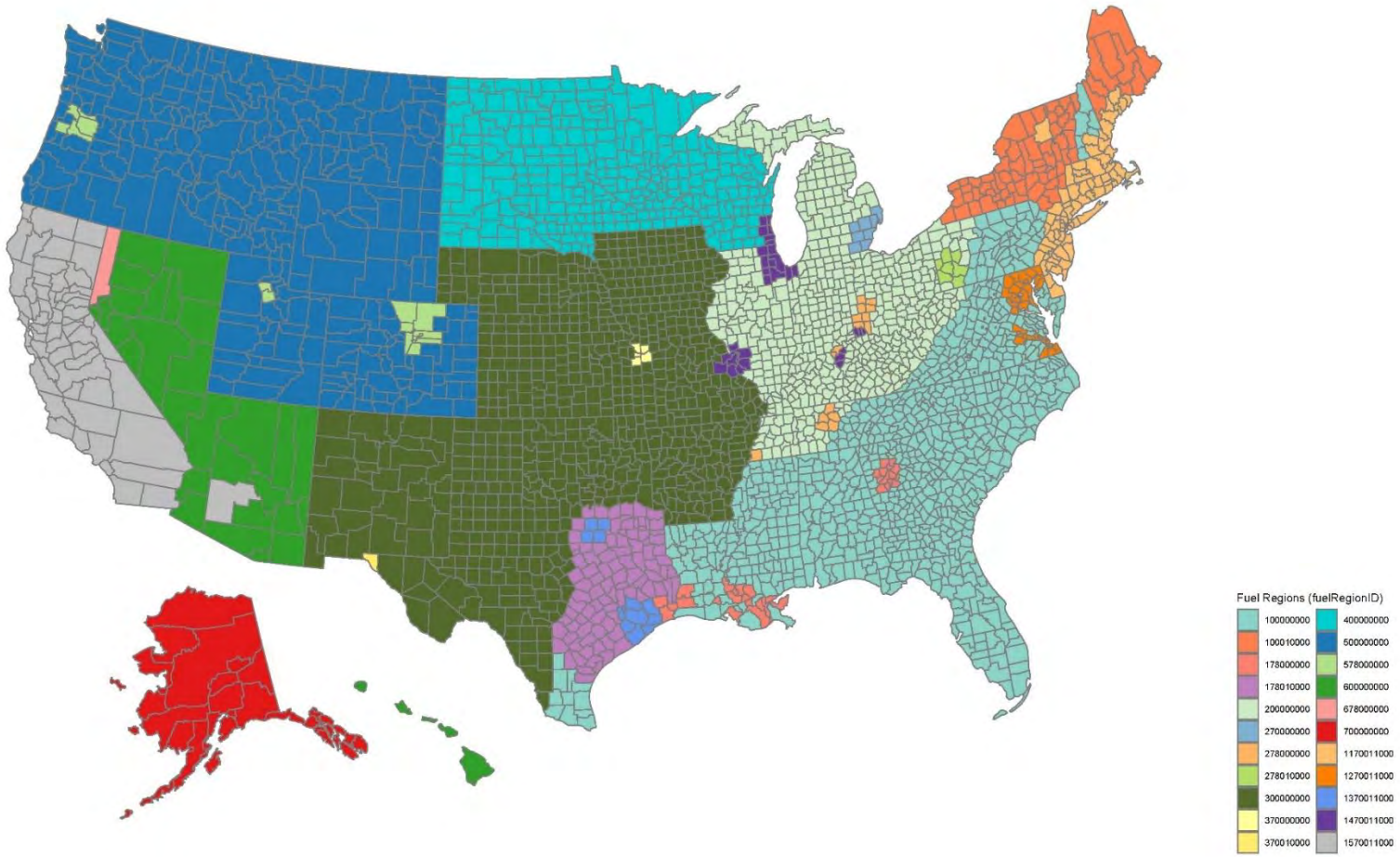
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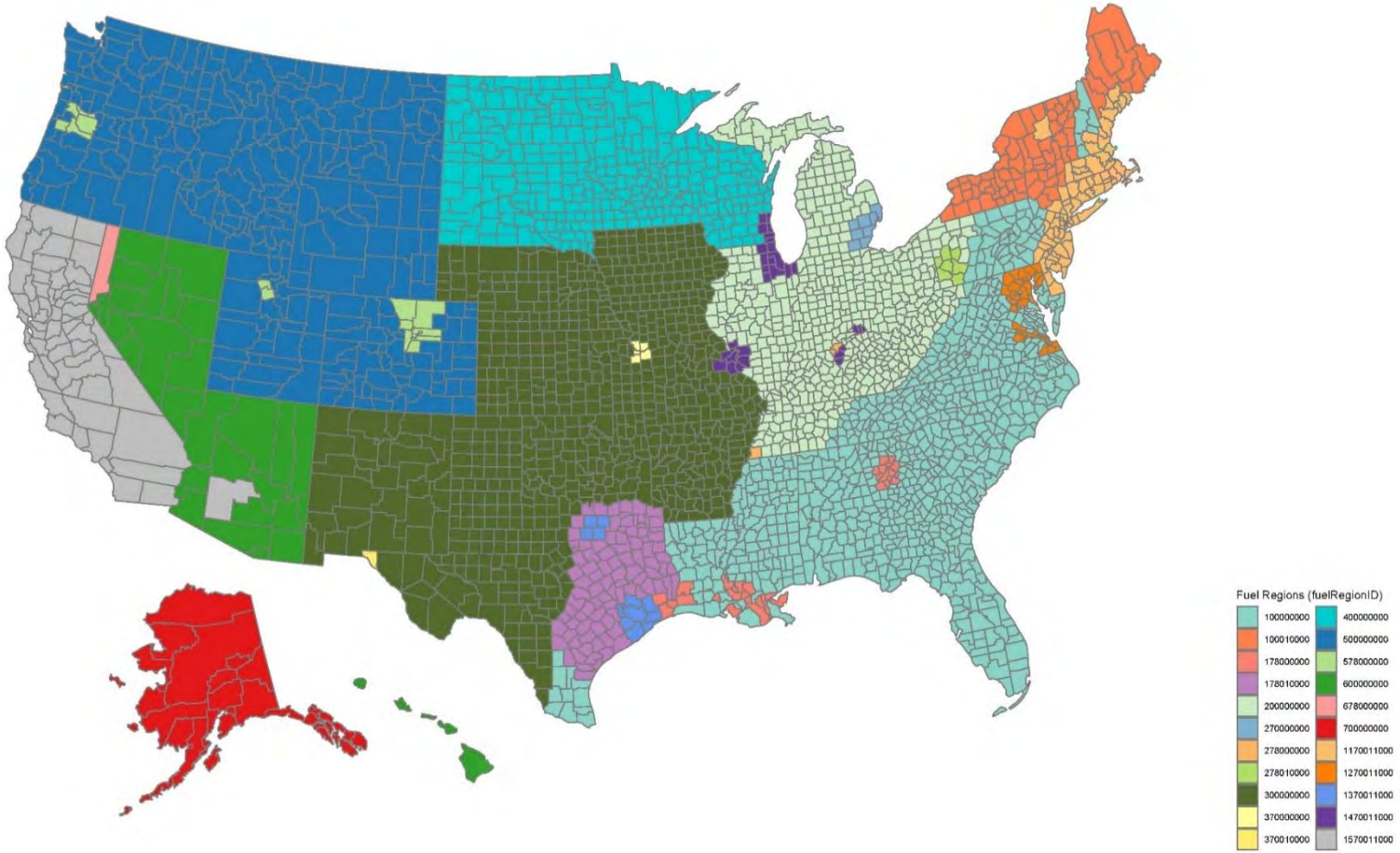
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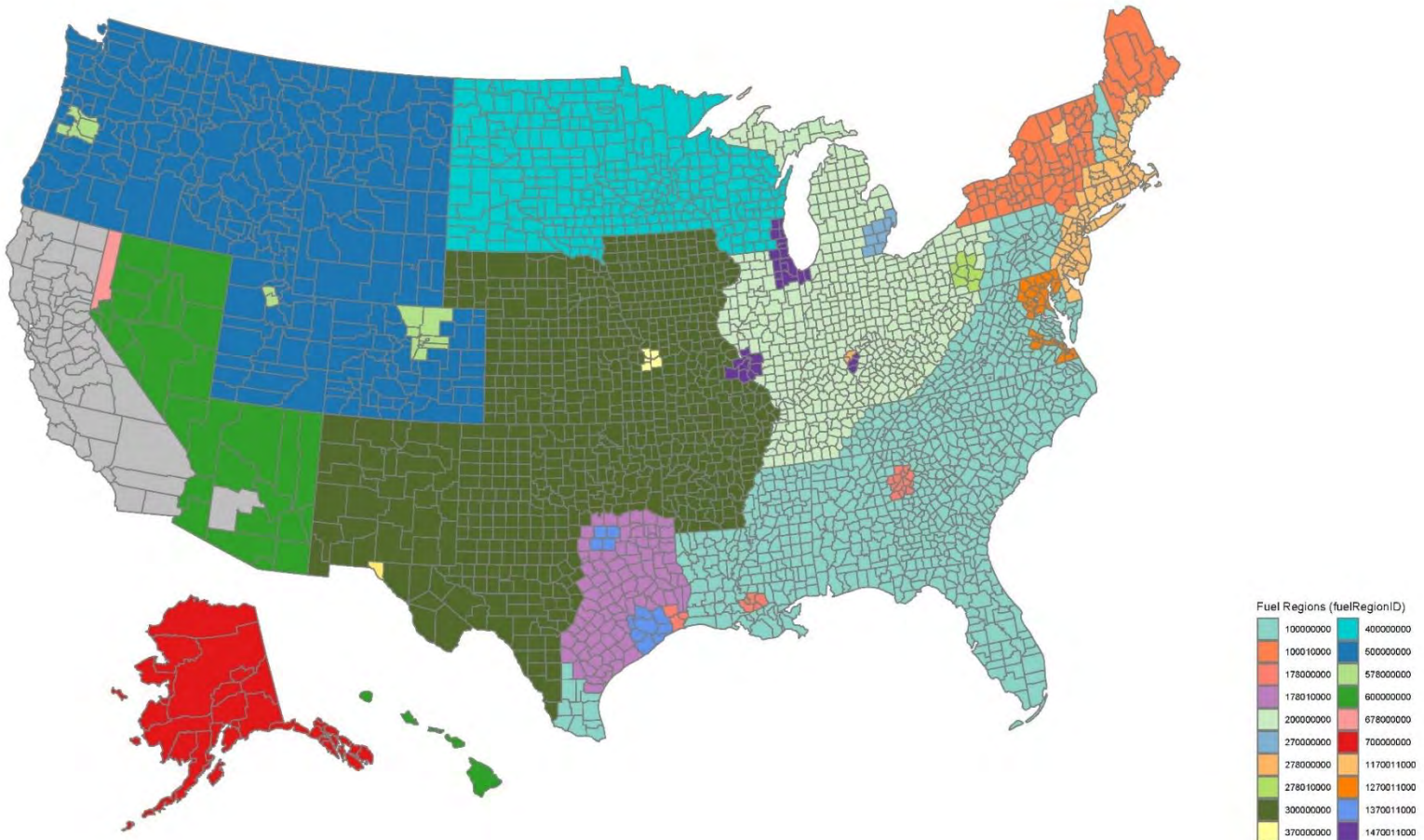
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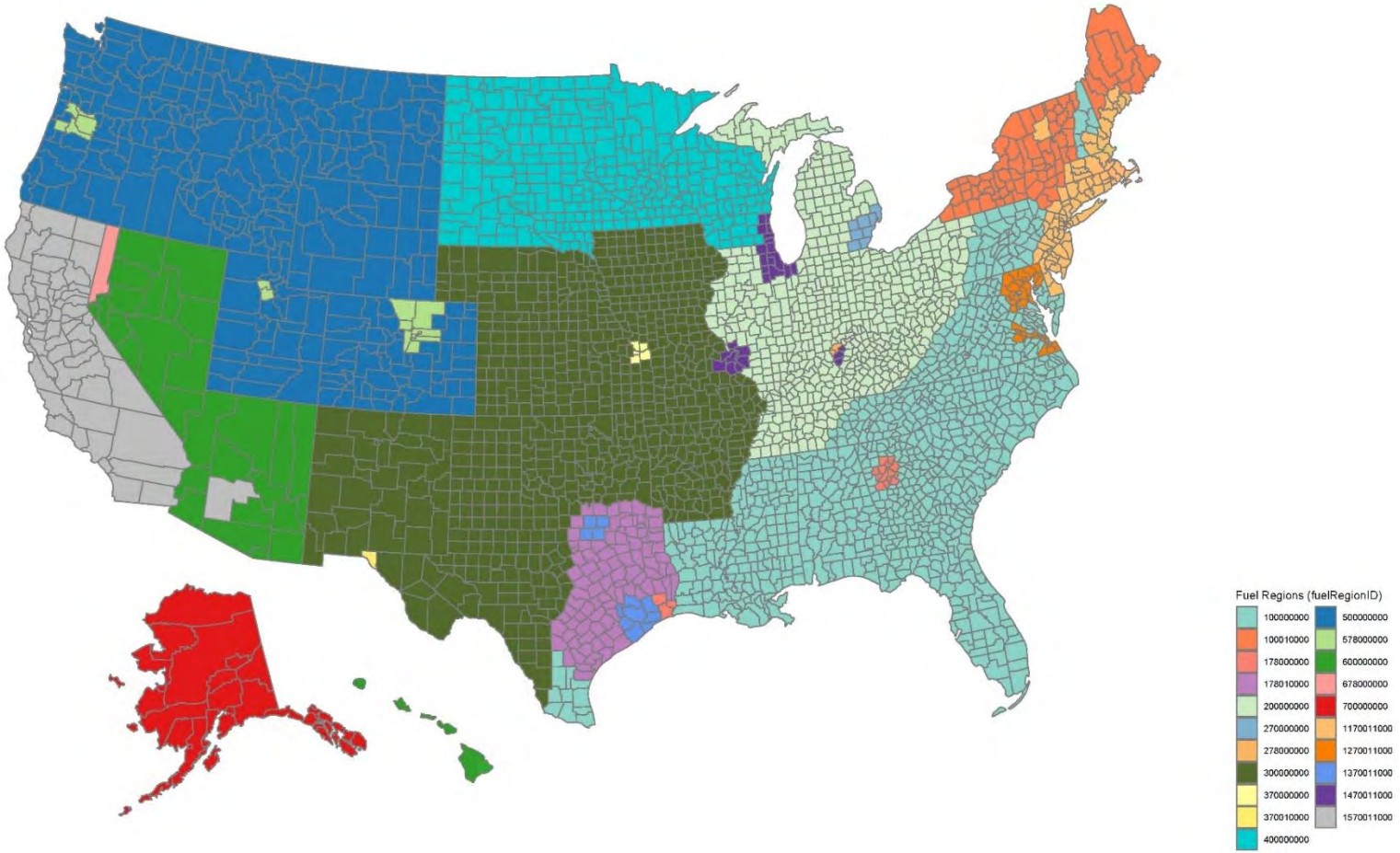
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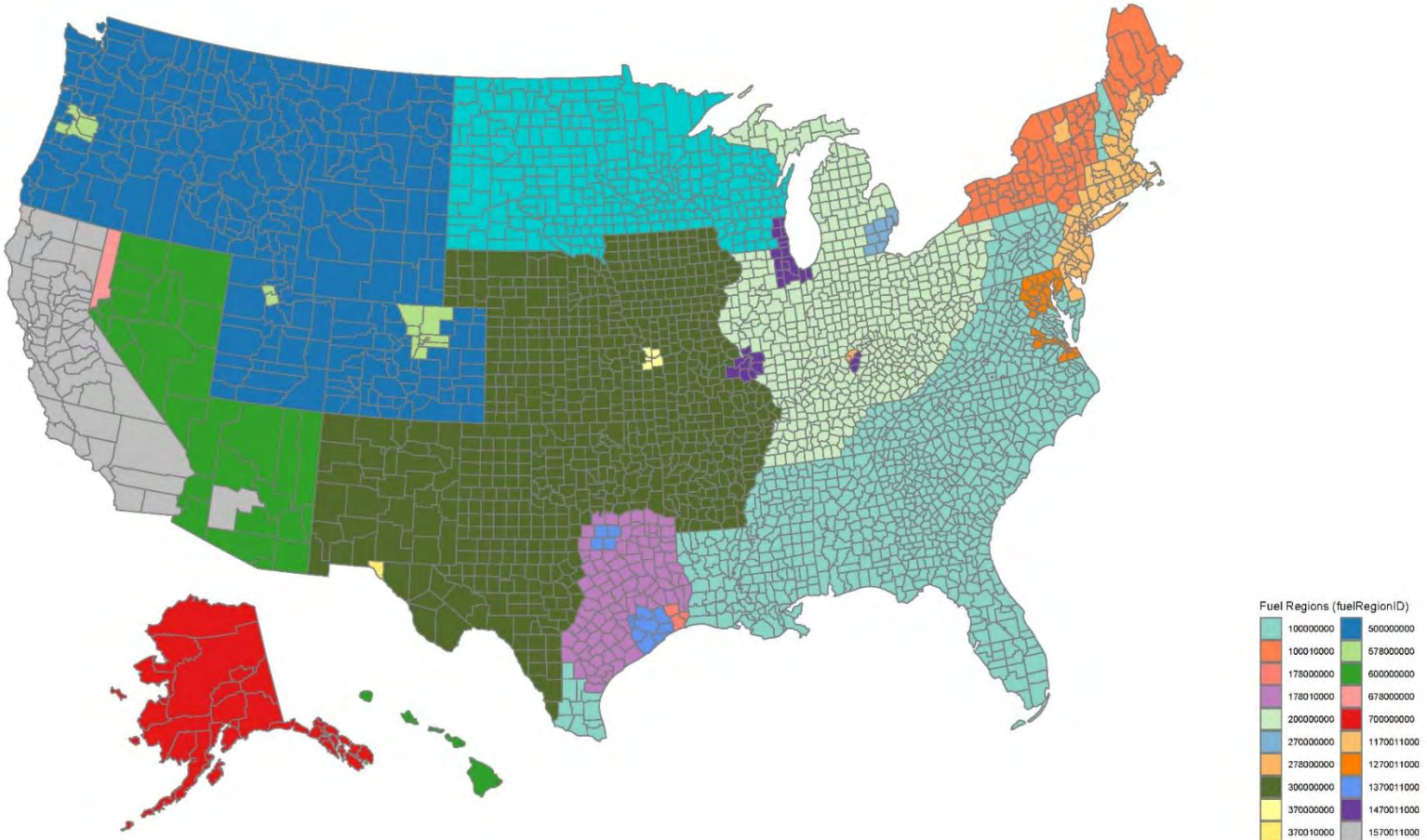
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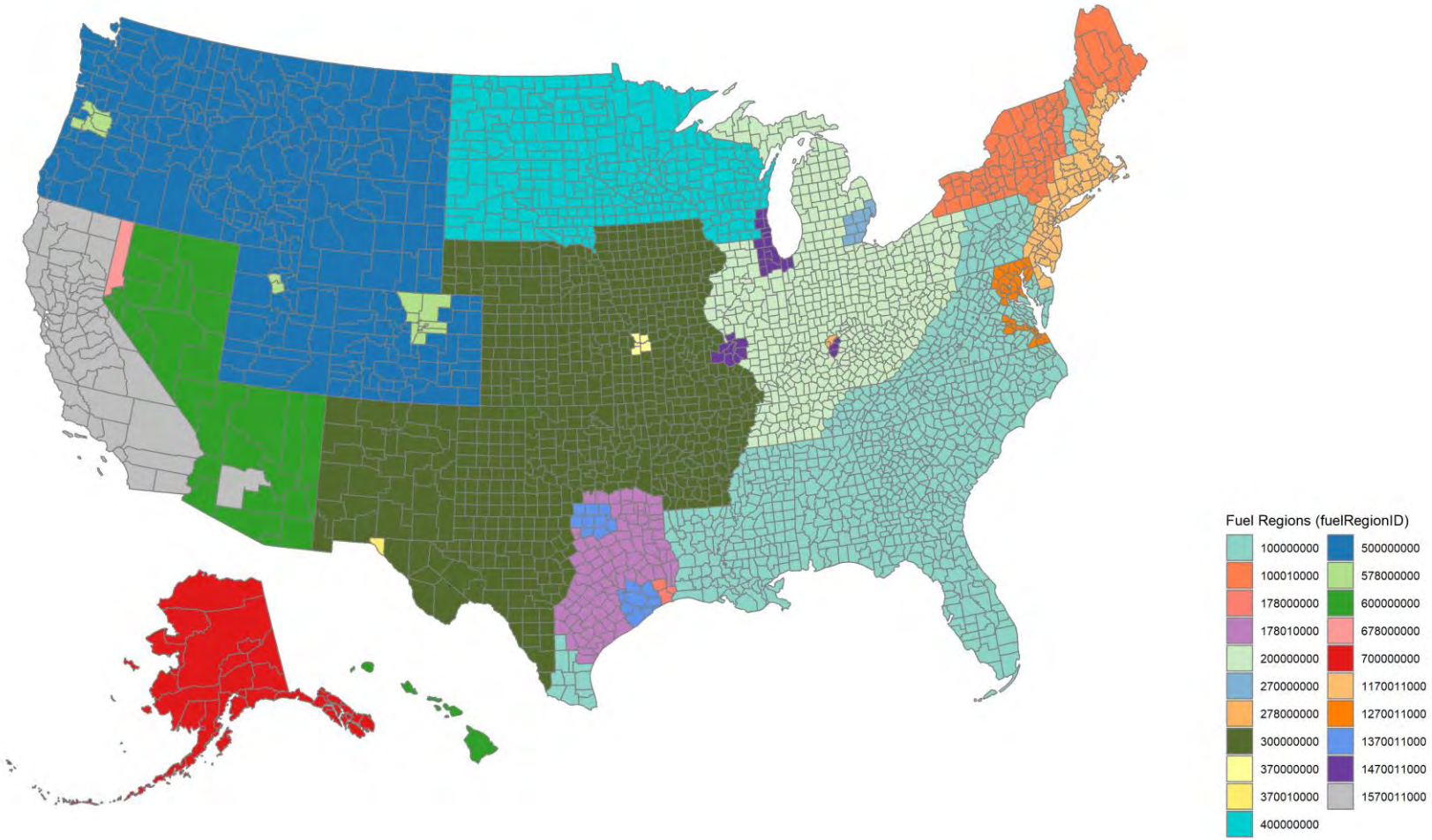
2024 - July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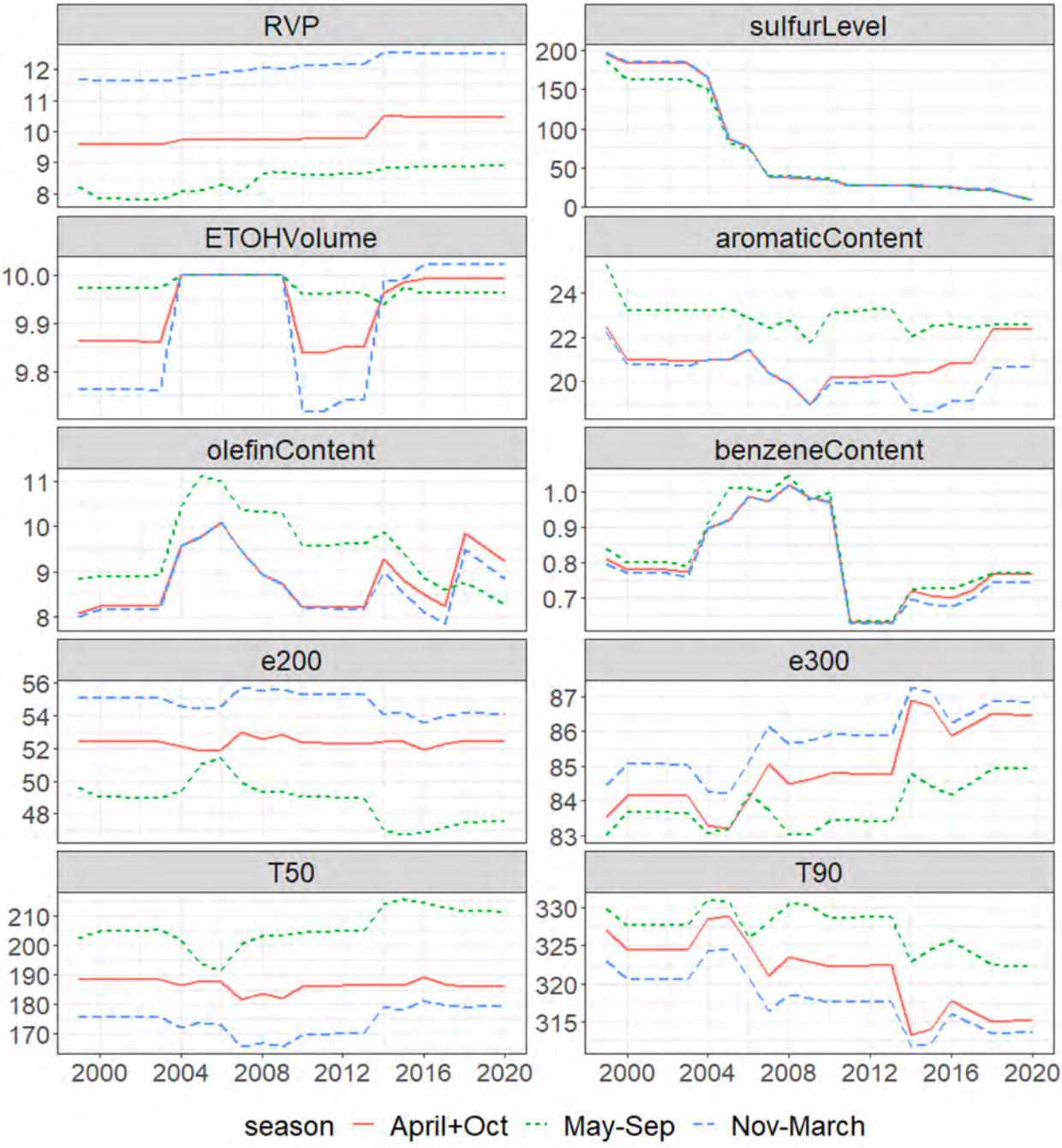
# APPENDIX B: AVERAGE GASOLINE FORMULATION TRENDS IN MOVES, 1990-2020

This plot series show average fuel property values across all E10 fuel formulations by calendar year.



# APPENDIX C: REFINERY MODELING RESULTS USED TO DEVELOP FUEL WIZARD FACTORS

# ANALYSIS OF THE EFFECTS OF LOW-BIOFUEL USE ON GASOLINE PROPERTIES

# AN ADDENDUM TO THE ICF "NO-RFS" STUDY

Prepared for
ICF Incorporated, LLC

Under

**EPA Contract No. EP-C-16-020**

By

**MathPro Inc.**

June 7, 2019

**MathPro Inc.**
P.O. Box 34404
West Bethesda, Maryland 20827-0404
301-951-9006

# 1. Study Objectives and Scope

The work discussed in the main body of this report -- the No-RFS Study -- was conducted to estimate the likely volumes of biofuels (primarily ethanol, but also bio-diesel and renewable diesel) that would be used if the RFS2 program were no longer in effect.

The analysis covered in this Addendum addresses a supplementary case – a "Low-Biofuels" case – in which ethanol is used only in RFG and there is no use of bio/renewable diesel in ULSD. This is similar to the situation in 2005/2006, when ethanol replaced MTBE in the RFG pool, essentially eliminating its use in the CG pool, and the use of biodiesel was minimal. The primary focus of the analysis is to assess the potential effects on finished gasoline properties (which would have consequent effects on particulate, VOC, NOx and toxics emissions) that could result from substantially reduced ethanol blending, by comparing a gasoline pool that is nearly all E10 to one that is predominantly E0.

The analysis involved developing a new Low-Biofuel case using the same refinery LP model as was used in the No-RFS study and comparing the results of the Low-Biofuel case to those of the Reference case developed in the No-RFS study. That Reference case represents PADD-level refinery operations modeled for 2020 based on projections reported in EIA's 2017 *Annual Energy Outlook* and the RFS remaining in force.

# 2. Technical Approach

Pursuant to the Work Assignment, the refining analysis conducted to assess the new Low-Biofuels case is an extension of the refinery modeling described in the main report. More specifically, the Low-Biofuels cases (for each PADD and season) are based on the corresponding 2020 Reference cases in the main study, but with the following modifications regarding the use of biofuels (ethanol and bio/renewable diesel):

- Conventional and low-RVP finished gasolines no longer would be blended with ethanol, i.e., they would be E0. Conventional and low-RVP gasolines together account for about 70% of gasoline production for the domestic market.
- Federal RFG and California RFG would continue to be blended with 10 vol% denatured ethanol and would continue to remain in compliance with applicable standards (including the requirements of California's Predictive Model). The Federal and California RFG programs, which are separate from and were promulgated before the RFS program, are assumed to remain in effect, along with their requirements for oxygenate blending.
- There would be no (1) post-refinery, splash-blending of ethanol into finished E0 gasoline; (2) spill-over of RFG into non-RFG areas (not already accounted for in the volumes specified in the Reference cases); or (3) use of higher ethanol blends, including E85. These assumptions simplify the modeling in terms of setting gasoline volumes and ethanol use.
- No biodiesel or renewable diesel would be blended in ULSD (or other distillate products). This is based on the assumption that, without the RFS mandates, such bio-fuels would be too expensive to be used as fuel extenders.

We also assume that the MSAT2 and Tier 3 gasoline sulfur standards, and the impending MARPOL sulfur standards, would have been implemented by 2020 in the absence of the RFS2 program.

The assumptions regarding reduced use of ethanol and no production of E85 required some adjustments be made to finished gasoline output in the Low-Biofuel cases. We assumed that volumes of conventional and low-RVP E0 in the Low-Biofuel cases would be roughly 3% lower than the corresponding volumes of E10 in the Reference cases to account for the lower energy density of the ethanol removed from the gasoline pool. We also adjusted the volume of conventional, regular-grade E0 in the Low-Biofuels cases to include small volumes of "clear" gasoline and E85 (energy-adjusted) produced for the domestic market in the Reference cases. These volume adjustments bring the total energy content (in BTU) of gasoline supplied in the Low-Biofuel cases in closer alignment with that supplied in the Reference cases.

Refinery production of ULSD was set at the same levels in the Low-Biofuel cases as in the corresponding Reference cases, because (1) the energy contents of hydrocarbon ULSD and bio/renewable diesel are similar; and (2) we assumed in the Reference cases that bio/renewable diesel was blended in ULSD at the refinery (rather than at terminals or large retail outlets). In practice, with "no bio/renewable diesel blending", refineries would produce greater volumes of hydrocarbon-only ULSD at the refinery, but end-use sales of ULSD would remain about the same.

These are the major structural changes incorporated in the refinery modeling for all of the Low-Biofuel cases. However, a number of other modeling issues surfaced when conducting the refinery modeling. Some of the issues pertained to all regions (PADDs) modeled, while others were specific to particular regions.

The most important of these issues are:

- Setting RVP constraints on finished conventional gasoline and low-RVP gasoline.
- Response of gasoline exports to a large reduction in ethanol use in the domestic gasoline pool.
- Constraints on gasoline properties of RFG and export gasoline not "directly" affected by the removal of ethanol from conventional and low-RVP gasoline.
- "Harmonization" across seasons of new investments in refining processes needed to replace the gasoline volume and octane "lost" through displacement of ethanol.
- Setting the potential availability of butanes across regions to support investments in additional alkylation capacity, an alternative to reforming capacity, as a means of replacing the "lost" octane in the absence of ethanol.

The following sections discuss the resolution of these issues in the Low-Biofuel case.

## 2.1 RVP Constraints on Finished Conventional and Low-RVP Gasoline

The posited shift of E10 conventional gasoline and low-RVP gasoline to E0 would affect the RVP of finished gasoline in a number of ways.

In the summer, most conventional E10 gasoline (about 4.5 MM b/d) now and in the Reference cases qualifies for the ethanol 1 psi RVP waiver. When this gasoline pool shifts to E0, the RVP of finished gasoline would decline by about 1 psi – from about 9.7 psi to 8.7 psi. However, a small volume of conventional gasoline sold in upstate New York and Maine (about 180 K b/d) that does not qualify for the RVP waiver would continue to meet the 8.7 psi RVP standard. Low-RVP gasoline now sold in parts of Pennsylvania, Eastern Texas, and El Paso (about 470 K b/d) does not qualify for the ethanol RVP waiver and, therefore, would continue to meet RVP standards of 7.8, 7.8, and 7.0 psi, respectively. The remaining low-RVP gasoline (about 720 K

b/d or a little over 50% of all low-RVP gasoline sales) qualifies for the ethanol RVP waiver and so, when converted from E10 to E0, would see a reduction in RVP of about 1 psi – from a weighted average of about 8.6 psi to about 7.6 psi.

In the winter, the average finished RVP of conventional gasoline of about 13.9 psi was estimated using data from the Alliance gasoline surveys. This includes the uplift in RVP associated with E10 ethanol blending at terminals. Backing out the estimated RVP uplift of about 0.8 psi (based on the estimated relationship between finished gasoline RVP and ethanol's RVP uplift), indicates that E10 BOBs produced by refineries had an average RVP of about 13.1 psi. Our understanding is that refineries currently produce winter BOBs with RVPs that are compliant with ASTM winter RVP standards (before being blended with ethanol at terminals). Hence, we assume that the "calculated" average BOB RVP of 13.1 psi (with ethanol "backed out") is compliant with ASTM winter RVP standards and would be maintained for finished E0 in the Low-Biofuel cases.

## 2.2 Volume of Gasoline Exports

A shift in conventional gasoline produced by U.S. refineries for the domestic market from E10 to E0 would: (1) reduce ethanol use by about 600 K b/d (equivalent to about 400 K b/d of hydrocarbon gasoline on an energy-adjusted basis); and (2) remove ethanol's octane (AKI) contribution to the finished conventional gasoline pool (the octane of E10 hydrocarbon BOBs averages about 3½ octane numbers less than the octane of finished gasoline).

The U.S. refining sector potentially could make up the volume and octane loss by: (1) investing in new, gasoline-related refining process capacity and increasing crude oil throughput; (2) shifting some gasoline exports (which are forecast to average almost 800 K b/d annually in 2020) to the domestic market to offset the volume loss (but not the loss in octane); or (3) pursuing some combination of the two. However, we elected to hold gasoline export volumes constant in this analysis for a number of reasons.

First, PADD 3 is the primary source of gasoline exports -- accounting for almost 90% of gasoline exports forecast for the Reference case – with most of the remainder from PADD 5. This indicates that shifting export gasoline into the domestic pool is an option available mostly to refineries only in PADD 3 (and within that region to refineries situated along the Gulf Coast). Second, positing certain volume reductions in gasoline exports, without pursuing supporting refinery modeling, could be viewed as arbitrary. Third, conducting an extensive series of supporting modeling runs to attempt to identify some sort of conceptual global and inter-PADD "equilibrium" regarding gasoline production and supply is beyond the scope of the study and the capabilities of the modeling tool used for the analysis.

Thus, in this analysis, the changes estimated in gasoline properties reflect the investments in new refining process capacity and changes in refining operations undertaken in each PADD to replace the volume and octane loss from reduced ethanol use -- without recourse to shifting export gasoline into the domestic market.

## 2.3 Constraints on Gasoline Properties of RFG and Export Gasoline

RFG (about 2.6 MM b/d) and export gasolines (almost 800 K b/d) are not *directly* affected by the posited shift from E10 to E0 for conventional and low-RVP gasolines. Their properties could be affected indirectly as refineries that produce a mix of these gasoline types adjust their operations and make investments in new process capacity to offset the loss in volume and octane associated with reductions in the use of ethanol. However, the extent to which their properties might change is difficult to ascertain for a number of reasons.

Aggregate refinery models can easily move gasoline blendstocks between different types and grades of gasoline in ways that are not necessarily consistent with refinery blending practices. This can result in gasoline properties returned by refinery models differing from reported properties for specific grades or types of gasoline, even though properties for the "aggregate" gasoline pool are reasonably close to reported properties. Thus, the "allocation" of gasoline properties across gasoline types returned by refinery models can be misleading.

Most refineries in PADD 2 and refineries in the Pacific Northwest (which are included in the aggregate refinery model representing PADD 5) do not produce RFG or export gasoline and do not have the option of shifting gasoline blendstocks (and properties) across different types of gasolines. (Only a handful of refineries in PADD 2, predominantly in Illinois and Indiana, produce RFG, and California refineries produce relatively small volumes of conventional gasoline.) About half of the refineries in PADD 3 do not produce RFG, but these tend to be the smaller refineries, many of which are located inland. The remainder, mostly larger refineries along the Gulf Coast, produce a mix of conventional gasoline and RFG. Refineries in PADD 1 also produce a mix of conventional gasoline and RFG. (No refineries in PADD 4 produce RFG or export gasoline.) Thus, for PADD 2 and PADD 5, and partially for PADD 3, the options for moving blendstocks between gasoline types are more constrained, in practice, than as represented in aggregate refinery models.

Gasoline is exported primarily by refineries in PADD 3. Data are not available regarding which refineries are active in the export market. It may well be that shifting blendstocks between export gasoline and conventional gasoline is not an option available to many PADD 3 refineries, particularly the smaller inland refineries.

In view of the inherent problems associated with "allocating" the effects on gasoline properties and composition of a posited large reduction in ethanol use, we concluded that the most appropriate analytic technique was to concentrate such effects in the combined conventional and low-RVP gasoline pools – the gasoline types directly affected by the posited shift from E10 to E0. We did so by (1) constraining the aromatics and olefins content of RFG and export gasoline in the Low-Biofuels cases to be the same as in the Reference cases[6]; and (2) "reassigning" gasoline blendstocks and properties returned by the refinery modeling such that changes in the gasoline composition and properties were completely concentrated in the E0 pool.[7]

## 2.4 Harmonization of Investments in Refining Process Capacity across Seasons

[6] The RVP, benzene content, and sulfur content of RFG and export gasoline already were specified. The refinery models returned either no, or very low, "shadow values" for the constraints on aromatics and olefin content, which implies that such constraints affected the "allocation" of properties among gasoline pools, but not materially the response (cost and investments in process capacity) of the refinery models in moving from E10 to E0 for conventional gasoline. On the other hand, constraining all gasoline properties of RFG and export gasoline to their Reference case values, specifically E200 and E300 (the percent of gasoline distilled off at 200°F and 300°F, respectively), generally resulted in the refining models returning small shadow values for those properties, with associated minor increases in the cost of supplying gasoline. Hence, we allowed E200 and E300 to vary in Low-Biofuel cases, which they did, to provide the refinery models with limited flexibility in producing multiple gasoline types and grades.

[7] Under this procedure, the E0 pool meets the applicable standards (constraints) for octane, RVP, benzene content, and sulfur content. However, changes in aromatics content, olefins content, E200, and E300 are concentrated in the E0 pool, as are changes in refinery production of gasoline blendstocks.

The refinery modeling for the Low-Biofuel case was conducted for the summer and winter seasons, as in the main report, rather than annually, to account for seasonal differences in gasoline RVP and ethanol's effects on gasoline RVP. The seasonal refinery models are "stand-alone" models, in the sense that refinery process capacity added in one season in response to reductions in ethanol blending (say for the summer) are not formally "linked" via computer code to refinery operations in the other season (the winter). Thus, the initial profiles of investment in new refining process capacity returned by the refinery models can differ substantially by season. In most cases, initial investments in process capacity made for the summer season were only partially adopted in the winter season. This implies that the models' investment profiles would not be "optimal," as the required rate of return on investments in new process capacity would not be met on an *annual* basis.

To address this issue, we conducted a series of modeling iterations in which we adjusted the capital charges associated with the major gasoline upgrading processes (alkylation, pen/hex isomerization, and reforming), generally up for the summer and down for the winter, until the seasonal investment profiles were roughly consistent with the investments meeting the required annual rate of return. This generally resulted in "final" investments in process capacity returned by the models being (1) lower than "initial" investments for the summer and higher for the winter and (2) fairly similar (with exceptions) across seasons. The procedure is imprecise, but it moves the modeling results closer to what might result from a planning process that considers a refinery's year round operations.[8]

## 2.5 Availability of Butanes to Support Alkylation Capacity

The projected growth in natural gas production and associated natural gas liquids production forecast by EIA suggests that the supply of butanes (a feedstock in the production of alkylate) could increase significantly for favorably situated refining centers, particularly those in PADDs 2 and 3, and possibly in PADD 4. This led us to consider two alternative modeling scenarios regarding the potential response of the refining sector to a large scale reduction in the use of ethanol.

In the ***Low-Biofuel #1*** case, we: (1) limited the volume of purchased butanes to that forecast for the Reference cases for each PADD; and (2) constrained FCC operations such that catalyst use, which affects light olefin production (another feedstock to alkylation), was the same as in the corresponding Reference case.[9] With these constraints on refining operations, the volume and octane deficit arising from the large reduction in ethanol use called out a mix of additional refining capacity for alkylation, pen/hex isomerization, and reforming.

In the ***Low-Biofuel #2*** case, for PADDs 2, 3, and 4 only, we: (1) priced iso-butane at $50/b[10], both in the summer and winter, and allowed unlimited purchases; and (2) allowed FCC

[8] Initial modeling results for PADD 1 (for the summer only) indicated that moving from E10 to E0 for conventional gasoline would increase the incremental cost of producing gasoline beyond the likely delivered cost of gasoline from Europe or PADD 3. Consequently, we reduced PADD 1's production of premium gasoline for the summer, which reduced its incremental cost of gasoline production, bringing it more in line with estimated delivered costs from PADD 3 (to which we assigned an additional production volume of premium E0).

[9] The refinery model is structured so that catalyst use can vary depending on internal refinery demand for light olefins (propylene and butylenes that are inputs to alkylation).

[10] This iso-butane price is roughly equal to the average of the spot prices reported by OPIS for PADDs 2 and 3 for iso-butane in 2016 times the ratio of the crude oil acquisition costs projected for 2020 to those reported for 2016. This likely overstates future spot prices for iso-butane, because the recent increase in natural gas and LPG production appears to have reduced the prices of LPGs relative to crude oil acquisition costs.

operations to modify catalyst use and produce additional light olefins as needed by alkylation operations. This resulted in significant increases in iso-butane purchases and new alkylation process capacity. On the other hand, process capacity additions of pen/hex isomerization declined somewhat and almost no new reforming capacity was added. This suggests there could be an alternative, "less-reforming-heavy," path to replacing ethanol, at least in regions situated to take advantage of forecast future increases in butane availability.

We did not pursue the second option (the Low-Biofuel #2 case) in: (1) PADD 1, because of the lack of investment incentives to replace lost volume and octane in that region due to the availability of low-cost gasoline supplies from Europe and the Gulf Coast; and (2) PADD 5, because it is not clear that the region would benefit from increased natural gas production and butane availability east of the Rockies.

# 3. Results of the Analysis

The results of primary interest are the potential effects of reducing ethanol's use as a gasoline blendstock on the properties of finished gasoline and the consequent effects on vehicle emissions. Other analytical results, such as potential investments in new refining process capacity, changes in refining operations, and changes in the composition of finished gasoline indicate how the refining sector is likely to respond to large-scale changes in ethanol use. Finally, effects on the incremental production cost of refined products and on the blending value of ethanol indicate potential market effects stemming from reduced ethanol use.

**Table 1**, below, shows the estimated average properties of the U.S. conventional gasoline pool (including low-RVP gasoline) for the Reference case and the two Low-Biofuel cases in which ethanol no longer is blended in conventional gasoline. As discussed above, we held the properties of RFG and export gasoline constant, so that the effects on gasoline properties of moving from E10 to E0 for conventional gasoline were concentrated in the conventional gasoline pool. The most significant changes in gasoline properties occur for aromatics and E200. In the Low-Biofuel #1 case (which features additional reforming), aromatics increased by about six percent points in both the summer and winter, and E200 declined by about seven to eight percent points. In the Low-Biofuel #2 case (which features more alkylation), aromatics increased, but only by about two percent points, and E200 declined by about seven percent points.[11] More detailed, PADD-level estimates, of the effects on gasoline properties of large scale removal of ethanol from the U.S. gasoline are shown in Table A-5 in the accompanying Appendix.

**Table 1: Properties of Finished Conventional Gasoline, U.S Average**

| Properties | Reference | | Low-Biofuel #1 | | Low-Biofuel #2 | |
|---|---|---|---|---|---|---|
| | Summer | Winter | Summer | Winter | Summer | Winter |
| RVP (psi) | 9.4 | 13.9 | 8.5 | 13.1 | 8.5 | 13.1 |
| Fuel Ethanol (vol%) | 9.9 | 9.9 | | | | |
| Aromatics (vol%) | 19.0 | 15.6 | 25.1 | 22.3 | 21.2 | 17.3 |
| Benzene (vol%) | 0.57 | 0.55 | 0.57 | 0.59 | 0.57 | 0.56 |
| Olefins (vol%) | 6.4 | 6.5 | 5.7 | 7.0 | 4.8 | 4.8 |
| Sulfur (ppm) | 9 | 9 | 9 | 9 | 9 | 9 |
| E200 (vol% off) | 55.3 | 57.3 | 47.0 | 50.4 | 48.3 | 50.9 |
| E300 (vol% off) | 83.7 | 85.6 | 81.7 | 82.8 | 83.9 | 85.4 |
| Energy Density[1] | 4.663 | 4.600 | 4.854 | 4.780 | 4.821 | 4.750 |
| Octane | | | | | | |
| (R+M)/2 | 87.9 | 88.0 | 87.9 | 88.0 | 87.9 | 88.0 |
| MON | 83.4 | 83.7 | 84.6 | 84.4 | 85.0 | 85.0 |
| RON | 92.5 | 92.3 | 91.3 | 91.6 | 90.9 | 90.9 |
| Sensitivity | 9.0 | 8.6 | 6.8 | 7.2 | 6.0 | 5.9 |

Note: Includes conventional and low-RVP gasoline; excludes RFG, exports, and imports.

1 Lower heating value (MM btu/b).

[11] Octane Sensitivity (the difference between RON and MON) declined by about one and a half to two numbers for the Low-Biofuel # 1 case and about three numbers for the Low-Biofuel #2 case, because alkylate has much lower Octane Sensitivity than reformate, and both have lower Octane Sensitivity than ethanol.

**Table 2**, below, shows refining capacity for gasoline upgrading processes present in the Reference case and added in the Low-Biofuel cases. For the Low-Biofuel #1 case a mix of alkylation, isomerization, and reforming capacity is added. As discussed above, the addition of alkylation capacity was limited by constraints on purchases of iso-butane. In this case, relative to the Reference case, reformer *throughput* increases by about 500 K b/d and reformer severity increases by about two and a half numbers, averaged across seasons. Such increases are consistent with the increase in the aromatics content of gasoline shown in Table 1.

In the Low-Biofuel #2 case, the loss in gasoline volume and octane from the removal of ethanol is made up primarily by a large increase in alkylation process capacity (about a 75% increase relative to existing capacity), along with additional isomerization capacity. The increase in alkylation capacity was facilitated in the refinery modeling by setting a $50/b price for purchased iso-butane and allowing unlimited purchases.

**Table 2: Gasoline Upgrading Process Capacity and Reformer Operations, U.S.**

| Processes & Operations | Reference | | Low-Biofuel #1 | | Low-Biofuel #2 | |
|---|---|---|---|---|---|---|
| | Summer | Winter | Summer | Winter | Summer | Winter |
| **Capacity (K b/cd)** | | | | | | |
| **Existing** | | | | | | |
| Alkylation | 1,214 | | | | | |
| Pen/hex Isomerization | 530 | | | | | |
| Reforming | 3,438 | | | | | |
| **New**[1] | | | | | | |
| Alkylation | | | 333 | 133 | 925 | 932 |
| Pen/hex Isomerization | | | 384 | 345 | 273 | 229 |
| Reforming | | | 316 | 280 | 10 | 10 |
| **Reformer Operations** | | | | | | |
| Throughput (K b/d) | 2,864 | 2,697 | 3,264 | 3,349 | 2,969 | 2,900 |
| Severity (RON) | 96.3 | 93.8 | 99.2 | 95.6 | 98.9 | 95.2 |
| Feed (%) | | | | | | |
| Straight Run Naphtha | 77% | 72% | 78% | 77% | 78% | 77% |
| 160-250° F | 23% | 20% | 26% | 32% | 28% | 33% |
| 250-325° F | 54% | 52% | 51% | 45% | 50% | 44% |
| Hydrocrk. (200-325° F) | 12% | 16% | 12% | 13% | 11% | 12% |
| Coker Nap. (160-375° F) | 12% | 12% | 11% | 10% | 11% | 11% |

1 Adjusted from K b/sd to K b/cd using a specified 90% utilization rate.

As indicated in Table 3, the Low Biofuel #2 case virtually eliminates investment in additional reforming process capacity. However, existing reforming capacity is used more extensively than in the Reference case – both reformer throughput and severity increase. This is consistent with the aromatics content of the gasoline pool increasing, but not by as much as in the Low-Biodiesel #1 case.

The extent to which alkylation, rather than reforming, would be the preferred approach for replacing the lost volume and octane when moving from E10 to E0 would depend on the price and availability of iso-butane in the various refining regions relative to the price of crude oil and practical constraints that might limit expansion of alkylation capacity. If we had priced iso-

butane higher than $50/b, the refinery models would have invested more heavily in additional reforming capacity in the Low-Biofuel # 2 case, rather than alkylation capacity. However, recent increases in natural gas and LPG production and observed prices suggest that iso-butane likely would be priced lower, relative to crude oil acquisition costs, than is assumed in our analysis.

**Table 3**, below, shows how the composition of gasoline (the relative use of gasoline blendstocks) changes in the Low-Biofuels cases. As indicated in the Table, ethanol's blending volume declines from about 10% in the Reference case to zero in the Low-Biofuel cases. This loss in volume (and octane) is made up by increases in higher-octane blendstocks (C5s and isomerate, alkylates, and reformate), with some corresponding declines in lower octane blendstocks (mostly raffinate, naphthas, and hydrocrackate). The use of FCC naphtha blendstocks also declined in the Low-Biofuel #2 case. This results from a relative reduction in FCC naphtha production and expansion in FCC olefin production to support the large increase in alkylate production (olefins are a feedstock for alkylation). In effect, the Model indicates refiners would increase alkylation capacity and alkylate production by modifying the FCC operation to produce more butylenes (olefins) at the expense of FCC naphtha to increase the octane of the pool.

**Table 3: Composition of Finished Conventional Gasoline, U.S. Average**

| Gasoline Blendstock | Reference | | Low-Biofuel #1 | | Low-Biofuel #2 | |
|---|---|---|---|---|---|---|
| | Summer | Winter | Summer | Winter | Summer | Winter |
| C4s | 2.0% | 10.1% | 2.6% | 10.9% | 3.4% | 12.4% |
| Natural Gas Liquids | 2.0% | 1.7% | 0.6% | 0.3% | 1.7% | 0.8% |
| C5s & Isomerate | 5.9% | 5.3% | 11.5% | 11.7% | 9.3% | 7.0% |
| Raffinate | 2.8% | 3.0% | 2.2% | 1.7% | 1.4% | 2.3% |
| Naphthas (C5-250°) | 12.6% | 13.3% | 5.8% | 4.1% | 9.1% | 7.5% |
| Hydrocrackate | 7.2% | 4.7% | 8.0% | 3.9% | 4.1% | 2.6% |
| Alkylate | 8.8% | 9.2% | 17.0% | 12.4% | 27.4% | 26.5% |
| Poly Gas | 0.1% | | 0.1% | 0.1% | 0.0% | |
| FCC Naphtha | 27.2% | 25.3% | 23.4% | 28.1% | 18.4% | 20.0% |
| Reformate & Aromatics | 21.5% | 17.6% | 28.8% | 26.8% | 25.1% | 20.9% |
| Ethanol | 9.9% | 9.9% | | | | |

**Table 4**, below, shows the effects of large-scale removal of ethanol from the gasoline pool on the incremental production costs of major refined products and on the blending value of ethanol. The Table indicates that removing ethanol as a blendstock from conventional gasoline would increase the incremental refining cost of producing all gasoline – both RFG and conventional gasoline. Increases in incremental production costs for gasoline are highest: (1) in the Low-Biofuels #1 case (the refining models are more constrained regarding investment options in this case because investment in alkylation is constrained via limits imposed on butane purchases); (2) in the summer; and (3) for conventional gasoline. On an annual basis, the increase in incremental production costs averages about $3/b for RFG and $11/b for conventional gasoline in the Low-Biofuel #1 case, and about $1/b for RFG and $5/b for conventional gasoline in the Low-Biofuel #2 case. However, if the prices for purchased iso-butane in the Low-Biofuel #2 case were set at a higher level, incremental gasoline production costs also would be higher.

Ethanol's implicit blending values increased in both Low-Biofuel cases, with more substantial increases in the summer (about $34/b), the season in which octane is more constrained. Prices for jet fuel and ULSD were relatively unaffected in both Low-Biofuel cases.

**Table 4: Incremental Production Cost of Major Refined Products and Refinery Blending Values of Ethanol, U.S. Average ($/b)**

| | Reference | | Low-Biofuel #1 | | Low-Biofuel #2 | |
|---|---|---|---|---|---|---|
| | Summer | Winter | Summer | Winter | Summer | Winter |
| **Refined Product** | | | | | | |
| Finished Gasoline | | | | | | |
| RFG | 88.2 | 80.2 | 93.8 | 81.2 | 91.5 | 78.7 |
| Conventional | 80.9 | 78.2 | 97.2 | 84.0 | 92.0 | 77.8 |
| Jet Fuel | 86.8 | 84.6 | 86.7 | 85.4 | 87.5 | 85.5 |
| ULSD | 84.4 | 83.9 | 83.7 | 85.2 | 85.0 | 85.0 |
| **Ethanol** | **100.0** | **93.0** | **135.0** | **105.0** | **133.0** | **99.0** |