Evaluation of Ethanol Fuel Blends in EPA MOVES2014 Model

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EXECUTIVE SUMMARY

Ethanol has become a major consideration for use as an alternative fuel for motor vehicles in the United States and other nations. Since its commercial introduction in the late 1970s, the use of ethanol has grown significantly and represented approximately 10% of the U.S. gasoline fuel supply in 2011 and usage has continued at this rate (RFA, 2012; RFA, 2014). In the U.S., ethanol is most commonly consumed as E10 (10% ethanol, 90% gasoline). However, mixtures of E85 (85% ethanol, 15% gasoline) are also commonly used in the U.S. and Europe for flexible-fuel vehicles. Other "mid-level" ethanol blends, such as E25, are in use in countries such as Brazil, and there is interest in more broadly adopting similar blends in the United States Air quality is an important consideration for the use of any fuel used in motor vehicles, with accurate prediction of emissions necessary for decision-making by regulators, manufacturers, and other stakeholders. The U.S. Environmental Protection Agency (USEPA) has been gathering information on the air quality impact of ethanol for some time with specific reporting back to 1980.

To assist with the development of air quality regulatory actions, USEPA has created the Motor Vehicle Emission Simulator (MOVES) modeling system. The development of MOVES actually began in 2000 based on recommendations made by the National Research Council, with EPA reporting initial considerations in 2002 and 2003. Ethanol was not formally addressed until the development of MOVES2004 and EPA has continued work to integrate ethanol in subsequent MOVES versions. The current version is MOVES2014 (EPA, 2014).

In this report, the methodology and prediction effects of the MOVES model development are reviewed and evaluated in relation to the use of ethanol fuel blends. Particular attention is placed on "mid-level" ethanol fuel blends (containing between 10 and 30% ethanol). The report includes a review of relevant information from the literature, discussion of MOVES input requirements, algorithms, and output. General findings were derived from an evaluation of the predicted emissions by evaluating the sensitivity to adjustments of individual fuel property parameters within MOVES2014. . Finally, a comparison of the differences in emissions predictions resulting from the use of "splash-blended" ethanol fuel blends versus "match-blended" fuels is reported.

Overall, it was found that the predictive emissions results generated by MOVES2014 for mid-level ethanol blends were sometimes inconsistent with other emissions results from the scientific literature for both exhaust emissions and evaporative emissions. This variance is by trends and/or magnitude of results. This reflects the authors findings that

the use of the default fuels listed in MOVES2014 may need further adaptation to accurately approximate the fuels being blended in the real world via splash blending. In use "splash blends" likely do not have the same attributes as the default "match blends" used in the MOVES2014 default database. It was determined that the model (and the Fuel Wizard module in particular) could benefit by increased capability to examine the emissions of "splash-blended" mid-level ethanol blends. The use of the fuel properties and the Fuel Wizard in MOVES must be considered carefully when determining changes due to ethanol blends to prevent inaccurate use of models. In addition, the trends used to determine constants in the model's equations may need to consider many more variables than are now being considered.

Since MOVES2014 depends upon a series of adjustment factors based on fuel properties, it is important for the user to be aware of this concern and check the fuel properties by using the Fuel Wizard during input if ethanol blends are to be used. However, for blends above E20, manual input is required in the Fuel Formulation and Fuel Supply tables because the Fuel Wizard does not allow all adjustments to individual parameters for fuels containing more than 20% ethanol.

Evaluation of absolute emission rates from mid-level ethanol blends was not possible because a rigid and robust data set with known fuel properties would be required. Evaluation of the predicted exhaust emissions from MOVES, compared to other models and on-road measurements, have shown reasonable agreement in many cases. However, without the fuel properties being known, the error created by fuel parameter input cannot be evaluated. There is a need for more research in this area, and additional vehicle exhaust testing from mid-level ethanol blends with well-defined fuel properties is recommended.

The MOVES2014 evaluation conducted for this reporting included reviewing inputs and a sensitivity study of fuels available in MOVES. This required separate runs and analysis to allow changes in emissions to be observed based on input of customized fuel properties. Evaporative emission prediction changes were also reviewed. This required four separate test scenarios:

1. Fuel Wizard Ethanol Sensitivity Analysis
2. Splash Blend Analysis
3. Fuel Formulation Parameter Sensitivity Analysis
4. Evaporative Fuel Leak Ethanol Sensitivity Analysis

Input in the MOVES2014 Run Specification and Project Data Manager (PDM) were kept the same for all four components of the analysis, with the exception being the fuel supply and fuel formulation input data (which was varied by test scenario). This

permitted a review of how the changes in fuel properties affected the model output. Fuel properties that were varied included RVP, aromatic content, olefin content, e200, e300, T50, and T90 parameters, as well as the "fuelsubtypeID."

The Project Scale runs for each analysis component consisted of running a single hour for two distinct roadway links where the links represented two highway facility types; urban restricted and unrestricted access. The two facility types allowed two different drive cycles to be evaluated. The urban restricted access drive cycle had an average speed of 35 miles per hour while the urban restricted access facility type had an average speed of 50 miles per hour. Each drive cycle includes all vehicle modes; idle, acceleration, deceleration, and cruise. All runs were for the year 2015.

A total of 68,400 fuels make up the MOVES2014 master fuel list. Reducing for only gasoline-based fuels, 25,421 fuel combinations from MOVES2014 were originally identified that could be used in this analysis. Based on available resources, a reduction was required. By choosing low, mid, and high values of Reid Vapor Pressure (RVP) and aromatics content, it was possible to reduce the analysis to a base of four fuel formulations from the lists of summer gasoline fuel formulations to be evaluated. Even with this large reduction, during analysis of various fuel properties, the number of unique variations of fuel used in the analysis increased to 18,923 for the Fuel Wizard analysis scenario and 38,874 for the Fuel Formulation analysis scenario. These numbers were reduced to manageable limits based on available resources by reviewing the properties in the literature and in MOVES2014 and selecting key fuel mixes.

When the ethanol content is changed using the Fuel Wizard in MOVES2014, the program automatically adjusts the RVP, aromatic content, olefin content, e200, e300, T50, and T90 parameters, as well as the fuelsubtypeID, to match blends built into MOVES2014. However, when applying a 20% or greater ethanol content in the MOVES Fuel Wizard, the MOVES subtypeID does not adjust the other fuel properties. Manual changes to the Fuel Formulation table and Fuel Supply table are required for blends above E20. This is a very important point of which modelers should be aware.

The following trends in MOVES2014 were noted as a result of the Fuel Wizard ethanol sensitivity analysis, which was based in this work on the fuel changes that occur internally within MOVES2014:

- Carbon monoxide (CO) decreases with increasing ethanol content;
- Nitrogen components increase with increasing ethanol content;
- Total hydrocarbons (THC) decrease from E0 gasoline to E5, then increases;
- Volatile organic compounds (VOC) increases from E0 to E10, decreases at E15, and increases for E20 to E30;

- Ethanol emissions increase from E0 to E10, plateau to E15, and then increase for E20 and above;
- Particulate matter (PM) species increase with increasing ethanol content;
- Sulfur dioxide (SO_2) increases with increasing ethanol content until E20, then becomes a constant (this could be due to the fact the Fuel Wizard could not be used above E20 and manual input was required);
- Carbon dioxide (CO_2) is a step function, with values above E20 having lower values;
- Changes in ethanol content also affected some emission rates for pollutants that are not understood, such as SO_2, and,
- The urban unrestricted access facility type, with the higher speeds and fuel consumption results in greater emission rates indicating that other parameters such as drive cycle are crucial in all analysis.

As noted in this paper, the results and trends from MOVES2014 for certain pollutants are often contrary to the findings of other studies and reports in the literature.

Unfortunately, during the splash blend analysis, for the two cases supplied (E15 splash and E15 match blend) the fuel properties with the exception of T50 are very similar. Thus, as would be expected, the predicted emission rates are also similar, with the exception being that CO is slightly less for the splash blend. Differences for one geographic location, Saint Louis, did show some differences from other geographic locations for predicted emission rates. In some cases, unexpected results occurred. For example, the emission rates were similar for the reference fuel (E10) as compared to the Saint Louis E10 fuel, even though fuel multiple fuel properties were quite different. This points out that the adjustment factor approach may need to be more robust and consider the changes to emissions as a function of all properties, not independently.

Also of importance in real world analyses is the variance that occurs for predicted emission rates based on changes to fuel parameters. Large changes in predicted emissions from varying fuel parameters would result in a greater concern than only minimal changes. A review of the changes using real blend fuel properties for E10 and E15 indicate predicted VOCs varying the most, between 11 and 13%. PM, both 2.5 and 10, varied between 10 to 11%. CO varied between 8 to 10%. Ethanol emissions and NOx varied the least, between 5 to 6%. The differences in CO, PM, and VOC emissions, with the greater variance, would seem to be the most important. Based on project level analysis for highway projects, the most important could be PM where compliance with standards may be more difficult.

In the Fuel Formulation Parameter Sensitivity Analysis, fuel properties including RVP, sulfur level, ethanol volume, aromatic content, olefin content, T50, and T90 were all varied individually while holding all other parameters constant. To show the results effectively, E10 was used as the base fuel. As in the other analysis, the urban unrestricted access, with the higher speeds and fuel consumption resulted in greater emission rates. Trends indicated by this analysis were similar in many ways to the trends from the Fuel Wizard analysis. Of interest, however, is that THC emission rates did not decrease at E5 for Fuel Formulation 3202 as for other formulations, but did continue to increase with increasing ethanol content. Also the effects for E10 and E15 were slightly different. Overall emissions rates were also slightly higher in this analysis compared to the Fuel Wizard analysis, showing that the Fuel Wizard changes do not exactly match results when the fuel parameters are individually selected.

The USEPA states that ethanol has a unique effect and increases permeation of specific compounds. This was reflected in the results of the Evaporative Fuel Leak ethanol sensitivity analysis, although not for all hydrocarbon species. The analysis included a total of 770 evaluations, including variations on 45 parameters. Important take-aways from this analysis were that for some hydrocarbon species, the use of ethanol does not affect predicted emissions from MOVES2014 and are the same as pure gasoline (E0). For other hydrocarbon species, increasing the content of ethanol resulted in increasing emissions as predicted by MOVES2014. Some conflicting results occur in the literature on evaporative emissions where decreases were sometimes shown. Urban unrestricted access facilities showed a slight increase in emissions over urban restricted access facilities.

The Department of Energy's GREET model was also evaluated, to determine whether differences exist between GREET and MOVES with respect to ethanol fuel blend emissions. While the GREET model was designed for more overall greenhouse gas estimates than project-level evaluation, the model is easy to use, has few inputs for the user to choose, and no control over fuel properties without making manual changes. Even so, it provides somewhat acceptable estimates for CO and PM, but a greater error for VOCs and CO_2. NOx estimates were found to be much different.

1 BACKGROUND

In the quest for alternative fuels, ethanol has become a major consideration. Ethanol (CH_3CH_2OH), also known as ethyl alcohol or grain alcohol, is a colorless, flammable, clear liquid, with a boiling point of 78°C (173°F) and freezes at -112°C (-170°F). Ethanol is used to increase our nation's fuel supply and is a way to boost octane since lead and MTBE (Methyl Tertiary Butyl Ether) have been removed due to health concerns. A comparison of the fuel parameters of gasoline and ethanol are shown in Table 1.

Table 1. Gasoline and Fuel Grade Ethanol Comparison (Source: NIOSH)

	Gasoline	**Fuel Ethanol**
Flash Point	*-45°F*	*-5°F*
Ignition Temperature	*530–853°F*	*793°F*
Specific Gravity	*0.72–0.76*	*0.79*
Vapor Density	*3–4*	*1.49*
Vapor Pressure	*38–300 mmHg*	*44 mmHg*
Boiling Point	*100–400°F*	*173°F*
Flammable Range (LEL–UEL)	*1.4%–7.6%*	*3.3%–19%*
Conductivity	*None*	*Yes*
Smoke Character	*Black*	*Slight to none*
Toxicity		*Lower than gasoline*
Water Solubility	*None*	*Completely*

Fuel ethanol is not a pure compound and contains different and varying components. Table 2 shows the analysis of two samples of fuel ethanol, prior to denaturing.

Table 2. Compounds Identified by GC-MS in Two Samples of Fuel Ethanol (Weaver, 2009)

Name	Formula	CAS. Number	Retention Time (min)	Concentration (wt. %) Wet Mill Sample	Dry Mill Sample
Water[1]	H_2O	7732-18-15	n.a.	0.65	0.08
Methanol	CH_4O	67-55-1	2.191	0.07	0.06
Ethanol[2]	C_2H_6O	64-17-5	2.324	97.3	96.60
1-Propanol	C_3H_8O	71-23-8	2.673	0.03	0.08
Isobutyl Alcohol	$C_4H_{10}O$	78-83-1	3.186	0.10	0.08
2-Methyl 1-Butanol	$C_5H_{12}O$	137-32-6	5.147	0.06	0.01
3-Methyl 1-Butanol	$C_5H_{12}O$	123-51-3	5.033	0.21	0.02
Ethyl Acetate	$C_4H_8O_2$	141-78-6	3.077	0.02	--
1,1-Diethoxyethane	$C_6H_{14}O_2$	105-57-7	4.958	0.28	--

[1] Determined by Karl Fischer titration
[2] Determined by remainder of other compounds

As previously pointed out, anhydrous ethanol blended with gasoline for use in gasoline engines are in use around the world. Special internal combustion engine (ICE) modifications are required for higher blends of pure hydrous or anhydrous ethanol. Lower percentage blends can be used in ICEs designed for use with gasoline. Ethanol fuel mixtures are designated as "E" numbers according to the percentage of ethanol in the mixture by volume. A fuel designated as E10 is 10% anhydrous ethanol and 90% gasoline.

Blends of E10 or less are the more frequently used blends. Ethanol represented approximately 10% of the U.S. gasoline fuel supply in 2011 and this trend is continuing, which represents gasoline in use in the country today as E10. (RFA, 2011; RFA, 2014) Mixtures of E85 are becoming more common in the U.S. and Europe for flexible-fuel vehicles. Higher ratio blends, like E25, are in use in countries such as Brazil. Figure 1 shows a sampling of the ethanol fuels used around the world.

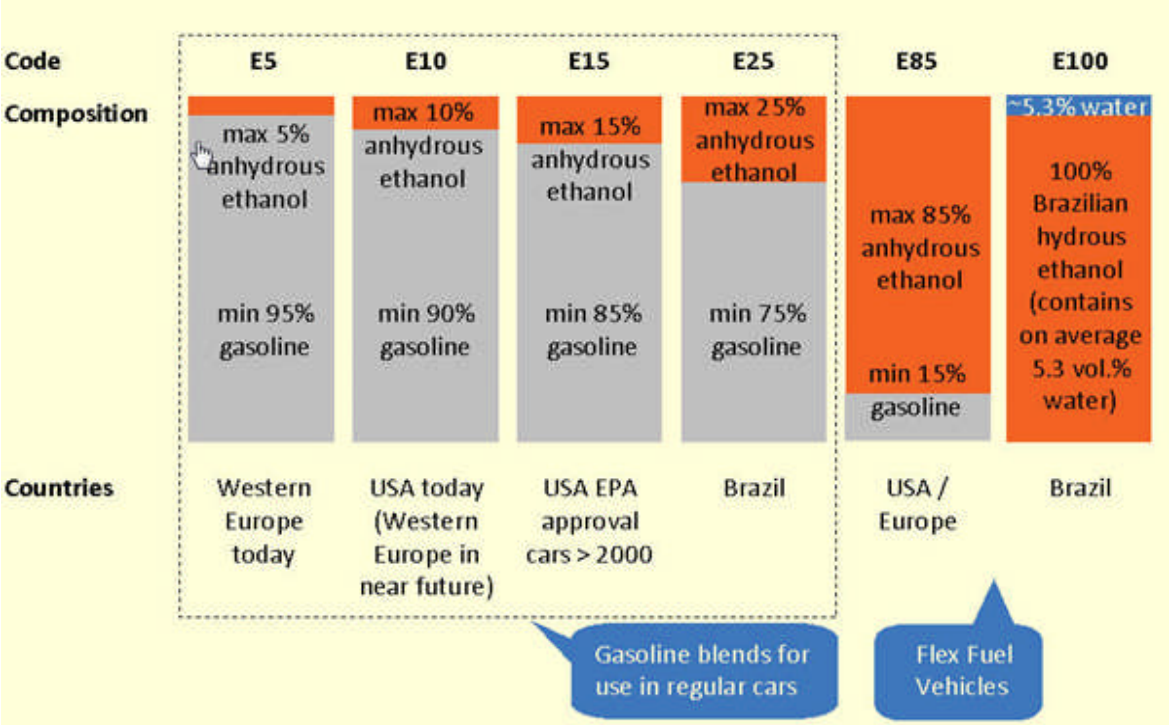


Figure 1. Common Ethanol Fuel Mixtures in Use (From Hanskeuken, retrieved 2015)

Air quality is an important consideration for the use of any fuels; and with the large and increasing usage of ethanol in motor vehicles, accurate prediction of emissions is necessary. The U.S. Environmental Protection Agency (USEPA) has been gathering information on ethanol impacts for some time. One of the first reports was published in 1980 (Darlington, 1980). In this report, the effects of ethanol on carbon monoxide (CO) and hydrocarbon (HC) emissions were investigated at idle from Inspection/Maintenance testing. Based on testing of only three vehicles, all passenger cars, it was reported that CO emissions were reduced about 1.1% while HC emissions were more variable ranging from no reduction to a complete reduction (zero).

The USEPA has promulgated vehicle emission factors and later introduced predictive models to estimate motor vehicle emissions since the 1970's. The latest in the series of required models is the Motor Vehicle Emission Simulator or MOVES. The development of MOVES actually began around 2000 with recommendations made by the National Research Council. In 2002 and 2003 official reports on the design (USEPA, 2002) (Koupal, 2002) and proof of concept (USEPA[a], 2003) were released. While fuel was considered, ethanol was not formally addressed until MOVES2004 (Koupal, 2005). Measurement studies have been accomplished to compare MOVES to measured

values. MOVES2010 was compared to other emissions models as well as measured on-road tunnel emissions and remote sensing (Fujita, 2012). CO and NOx were reported in reasonable agreement (± 25%) while other pollutant results were mixed and variables such as temperature made significant differences. EPA has continued work on MOVES. The current version is MOVES2014 (EPA, 2014).

This document explores the methodology of the MOVES model in relation to the use of ethanol fuels and reports information on the literature, input requirements, algorithms, output, and general findings. Results of a review of the inputs and a sensitivity analysis of MOVES2014 are also included as a primary goal of this work. Particular attention is placed on mid-level ethanol fuel blends (up to E30).

2 BACKGROUND LITERATURE SPECIFIC TO MOVES

As expected, much of the information relating to the explicit inclusion of ethanol in MOVES has been released by USEPA. In order to provide a sequential view of MOVES as reported by the USEPA and then to show independent reporting, this section is divided into two subsections. The first includes pertinent EPA documentation on MOVES development, with an emphasis on ethanol fuel blends, is discussed first and then related information by other researchers is presented.

2.1 USEPA Documentation

As stated on the MOVES website, USEPA releases documents as they become available. Many of the references available are from older versions of MOVES documenting the development as it occurred. Accordingly, these documents contain pertinent information on how the methodology for ethanol has developed over time, leading to the current modeling approach. In some cases, very recent documents, although referenced in other documents, have not been made available at the time of this writing.

2.1.1 "Composition and Behavior of Fuel Ethanol"

In this document, two samples (wet and dry mill) were reviewed following a comprehensive analysis (Weaver, 2009). Information pertinent to this report was previously discussed (see Table 2). The determination of these properties as well as other components of ethanol fuel use were then used as considerations in later EPA work.

2.1.2 "Development of Gasoline Fuel Effects in the Motor Vehicle Emissions Simulator (MOVES2009)"

Adjustment to estimated emissions for ethanol fuel use has been incorporated into MOVES since MOVES2009 (USEPA, 2009). Primary fuel formulations were obtained from the USEPA National Mobile Inventory Model (NMIM) model and the National Emission Inventory (NEI) process. A database was created (NMIMRFS2Fuels2005Base) for the calendar year 2005 from then in-use fuel surveys for use in MOBILE2009. Other more specific databases were also created and information is reported in multiple reports including a National Science and Technology Council Report (NST, 1997) where the fuel properties were examined. Of interest is a footnote that occurs about ethanol use at the end of the Database Name Table. This is:

> *"E10 and E85 are for the EISA control case, but they will be run separately in MOVES and weighted together. In NMIM, which will be used for motorcycles, diesel, and nonroad, the E10 case will be run. The E85 database will be prepared in NMIM, because that is the basis for creating MOVES fuels tables."*

Input for the fuel information in MOVES2009 consisted of four primary, self-descriptive, data tables: FuelFormulation, FuelSupply, FuelAdjustment, and HCSpeciation. Several hundred fuel formulations were contained in the model and included a range of fuel properties to account for such variables as geographic location. Fuels are given unique IDs and those containing ethanol were given the IDs of 12, 13, 14, 51, 52, and 53. The fuel properties included:

- Defined fuel types with a subtype ID
- RVP (Reid Vapor Pressure)
- Sulfur level
- ETOH volume (Ethanol)
- MTBE volume
- ETBE volume (Ethyl Tertiary Butyl Ether)
- TAME volume (Tertiary-Amyl Methyl Ether)
- Aromatic content
- Olefin content
- Benzene content
- e200 (distillation temperature related to fuel properties; others such as e300)
- e300, and,
- Volume-to-weight percentage of oxygen.

Using these defined fuel properties and results of testing, an overall Fuel Adjustment Factor was developed to allow prediction of Fuel Corrected Emissions as shown in Equation 1.

*Fuel Corrected Emissions = Fuel Adjustment Factor * Base Emissions Factor*

Equation [1]

The Base Emission Factor was the base emission rates computed by MOVES primarily from Arizona IM240 lane data for pre-2001 vehicles and from USEPA in-use vehicle surveillance testing for model years 2001 to 2006. Later model years (≥ 2007) were computed using multiplicative adjustment factors.

Using this methodology, the Fuel Adjustment Factors were created by running the primary EPA Fuel Models for all combinations of in-use fuel formulations and then creating a ratio from emission factor of the fuel in question to a reference fuel emission result. Two reference fuels were used based on model year of the vehicle. Table 3 shows the reference fuel properties that were used for straight gasoline (E0). The fuels are the same except for the change in sulfur level as lower sulfur fuel was required and entered the market.

Table 3. Reference Fuel Properties for Gasoline (EPA, 2009)

Fuel Property	Pre-2001 Reference Fuel	2001+ Reference Fuel
Fuel Subtype	Conventional Gasoline	Conventional Gasoline
RVP (psi)	6.9	6.9
Sulfur Level (ppm)	90	30
Ethanol Volume (vol%)	0	0
MTBE Volume (vol%)	0	0
TAME Volume (vol%)	0	0
Aromatic Content (vol%)	26.1	26.1
Olefin Content (vol%)	5.6	5.6
Benzene Content (vol%)	1.0	1.0
E200 (F)	41.1	41.1
E300 (F)	83.1	83.1

Complexity then begins as speciated emissions are derived from equations that again relate these variables and emissions. Fuel adjustment in this emission process was possible by geographic location and vehicle type. Ethanol was grouped with other oxygenates (e.g., MBTE, ETBE, and TAME) as part of the overall fuel formulations affecting emissions. Based on a function of the oxygenate type, factors were derived to

determine speciation of the hydrocarbon emissions. Those pertaining to ethanol are shown by Equations 2 – 5.

$$NMHC = THC - Methane$$

$$VOC = NMHC * (speciationConstant + oxySpeciation * volToWtPercentOxy * ETOHVolume)$$

$$NMOG = NMHC * (speciationConstant + oxySpeciation * volToWtPercentOxy * ETOHVolume)$$

$$TOG = NMOG + Methane$$

Equations [2 – 5]

where VOC = Volatile Organic Compound, NMHC = Non-Methane Hydrocarbons, NMOG = Non-Methane Organic Gases, and variables are self-explanatory.

Development of a model that could incorporate each effect of the fuel properties listed in Table 3 would be desirable. EPA noted this fact as well as plans to pursue development of the predictive/complex model components. However, in MOVES2009 a compromise was sought to streamline the process and specific fuels bins using Bin IDs were created based on the average and limit values determined for each property. Ethanol content for E0, E5, E8 and E10 was included. The binning process reduced the listing of fuel formulations from over 10,000 to less than 500, a more manageable number. The use of these bins made properties simpler to use and access in the model by number designation as shown in Figure 2, an excerpt of the source code.

```
UPDATE fuelformulation1 SET Etohbin = 1          WHERE ETOHVolume <=
0.00001;
UPDATE fuelformulation1 SET Etohbin = 2          WHERE ETOHVolume >
0.00001 and ETOHVolume <= 6.0000;
UPDATE fuelformulation1 SET Etohbin = 3          WHERE ETOHVolume >=
6.00001 and ETOHVolume <= 8.0000;
UPDATE fuelformulation1 SET Etohbin = 4          WHERE ETOHVolume >=
8.00001;
```

Figure 2. Excerpt of MOVES2009 Source Code Showing the Use of Bins

To effectively summarize the overall fuel adjustment process, Figure 3 was derived.

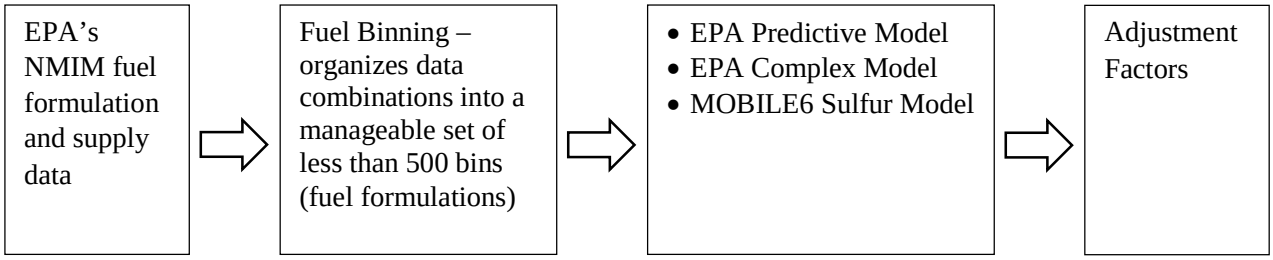


Figure 3. Data Processing to Derive Fuel Adjustment Factors

MOVES2009 also included algorithms for air toxic adjustments. Air toxics that were included were Benzene, Ethanol, MTBE, 1,3 Butadiene, Formaldehyde, Acetaldehyde, Naphthalene, and Acrolein. Again, corrections were made using a common factor approach where as shown in Equation 6. Table 4 shows the typical gasoline / ethanol air toxic ratios that were used in Equation 6

*Air Toxic Pollutant Emission Rate = Hydrocarbon Emission Rate * Air Toxic Factor*

Equation [6]

Table 4. Typical Gasoline / Ethanol Air Toxic Ratios for Calendar Year 2005

	Gasoline Vehicles				Ethanol Vehicles
	Min AT Ratio	Avg AT Ratio	Max AT Ratio	Std Dev	E-85 Ratios
Benzene	0.032	0.050	0.086	0.0082	0.0041
MTBE	0.00	0.0017	0.018	0.0048	0.00
Naphthalene	0.088	0.088	0.088	0.00	0.086
1,3 Butadiene	0.0038	0.0055	0.0066	0.00063	0.00062
Formaldehyde	0.0097	0.013	0.016	0.0012	0.010
Acetaldehyde	0.0036	0.0070	0.013	0.0032	0.075
Acrolein	0.00061	0.00061	0.00061	0.00	0.00027
Ethanol - E0		0.00			
Ethanol - E10		0.024			
Ethanol - E85		0.484			

2.1.3 "MOVES2010 Fuel Adjustment and Air Toxic Emission Calculation Algorithm – Development and Results"

For MOVES2010, the idea of using a fuel adjustment factor was still included for HC speciation adjustments. Ethanol blends were as before (E0, E5, E8, E10). Based on the result of a base fuel, total emissions are calculated and a specific fuel adjustment is applied as in the general process previously described. Air toxics are then calculated as a ratio to other pollutants, primarily hydrocarbons. Many different algorithms were used based on the air toxic. As described by EPA these were:

- For Benzene, 1,3 Butadiene, Formaldehyde, and Acetaldehyde: The Complex Model Algorithms for Gasoline Vehicle Air Toxic Fuel Effects
- MTBE: MTBE Complex Model
- CO: Complex Model Algorithms for Carbon Monoxide
- THC, NOx: Predictive Model for Total Hydrocarbons (THC) and Oxides of Nitrogen (NOx) Fuel Effects, and
- Ethanol, Acrolein and Naphthalene.

Fuel sulfur was also modeled with special predictive procedures, as was diesel. Each of these models are described in the MOVES2010 EPA report.

EPA did note that a more comprehensive fuels update was being completed as part of the analysis mandated by the 2005 Energy Policy Act (EPAct) and this is discussed later in Section 2.1.4.

Three base fuels were provided, as opposed to the two reference fuels noted in the 2009 Report. Table 5 shows these base fuel properties. Base Fuel A (lower sulfur level) is used for modeling 2001 and later vehicles. Base Fuel B is for 2000 and earlier vehicles. Base Fuel C is used only in the air toxic ratio calculations. Note that ethanol was not included in the base fuels (E0).

Table 5. MOVES2010 BaseFuel Properties

Fuel Property Name	Base Fuel A	Base Fuel B	Base Fuel C
Fuel Sub-Type	Conventional Gas	Conventional Gas	Conventional Gas
RVP	6.9 psi	6.9 psi	8.7 psi
Sulfur Level	**30.0 ppm**	**90.0 ppm**	338.0 ppm *
ETOH Volume	0.0 %	0.0 %	0.0 %
MTBE Volume	0.0 %	0.0 %	0.0 %
ETBE Volume	0.0 %	0.0 %	0.0 %
TAME Volume	0.0 %	0.0 %	0.0 %
Aromatic Content	26.1 %	26.1 %	26.4 %
Olefin Content	5.6 %	5.6 %	11.9 %
Benzene Content	1.0 %	1.0 %	1.64 %
E200	41.1 %	41.1 %	50.0 %
E300	83.1 %	83.1 %	82.0 %
Volume to percent Oxygen	0.0 %	0.0 %	0.0 %
• Air toxic computation is not a function of sulfur level			

From this methodology, ethanol emissions were predicted as shown in Equation 7.

*Ethanol = Ethanol/VOC Ratio * VOC*

Equation [7]

where the Ethanol/VOC ratio for E0 is 0.00000, for E5 the value is 0.01195, for E8 the ratio is 0.001912 and for E10, 0.02390. Values for E70 and E80 were also determined but were not used in the MOVES evaluation and not discussed here.

Fuel formations use adjustments to the basic emission factors as well. The factors were based on local area parameters such as vehicle mode. Again, based on a multiplicative adjustment factor, the emissions were corrected as shown in Equations 8 and 9.

Fuel Corrected Emissions = (Fuel Adjustment Factor of Target Fuel) x (Base Emissions Factor)

Fuel Adjustment Factor of Target Fuel = (Emissions of Target Fuel) / (Emissions of Base Fuel)

Equations [8, 9]

For clarity, the reader is reminded the target fuel in Equations 8 and 9 is the fuel being modeled while the base fuel corresponds to a reference formulation based on year as shown in Table 3 and as expanded in Table 5. In any of the reference formulations, the ethanol content is zero.

Effects of ethanol fuel on the modeled emissions were evaluated within the USEPA report. Figures 4 and 5 show the reported trends. It can be seen that for blends up to E15, a general downward trend occurs for CO as ethanol content increases, and a general upward trend is noted for oxides of nitrogen (NOx), benzene, ethanol and acetaldehyde. Of importance is the flat line for particulate matter (PM) because adjustment factors were not included in this version of MOVES. Graphs showing trends for other fuel properties were also included in the USEPA document but not included here for brevity.

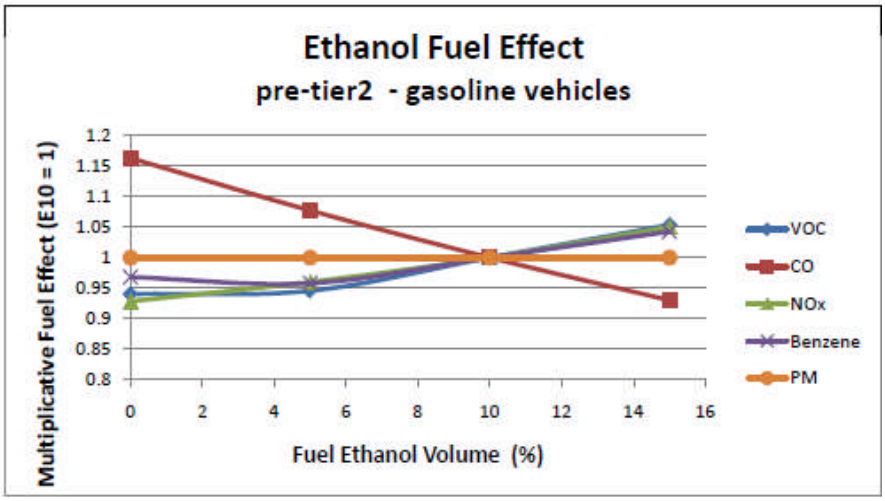


Figure 4. Relative Fuel Ethanol on Pre-2004 Model Year Gasoline Vehicles in MOVES (USEPA, 2011).

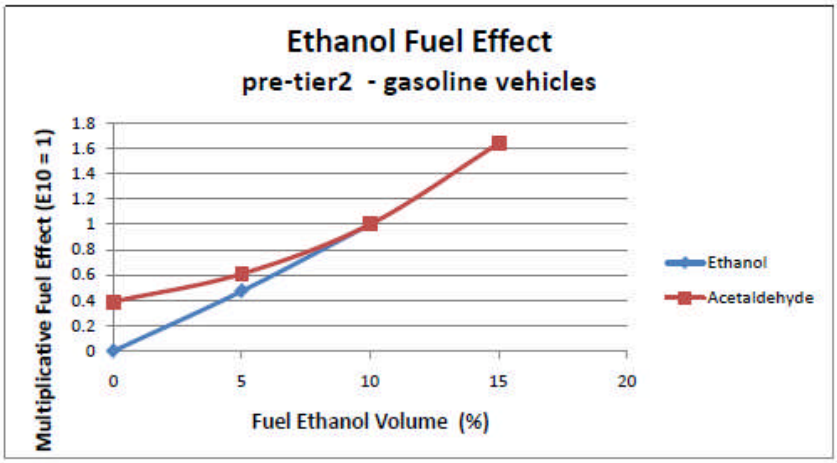


Figure 5. Relative Fuel Ethanol Effect on Pre-2004 Model Year Gasoline Vehicles in MOVES (USEPA, 2011)

2.1.4 "EPAct/V2/E-89: Assessing the Effect of Five Gasoline Properties on Exhaust Emissions from Light-Duty Vehicles Certified to Tier 2 Standards, Final Report on Program Design and Data Collection"

As mentioned in the last section, USEPA continued its fuel research as a requirement of the EPAct requirements (USEPA, 2013). While eleven fuel properties were initially considered, five fuel properties were included in the final review (ethanol, T50, T90, aromatics and RVP (but measured as Dry Vapor Pressure Equivalent, DVPE). Fifteen brand new 2008 model year vehicles were tested in 926 total tests with testing actually beginning in 2007; with only the later Phase 3 testing being discussed here. Four variations of ethanol content were reviewed: E0, E10, E15, and E20. Some testing also occurred for an E85 blend. A summary of all the primary ethanol blend test fuel set design is provided in Table 6.

Table 6. Summary of Initial Phase 3 Test Fuel Set Design (USEPA, 2013)

Fuel Parameter	Number of Levels	Values to Be Tested
Ethanol (vol%)	4	0, 10, 15, 20
T50 (°F)	5	150, 160 (E20 only), 190, 220, 240
T90 (°F)	3	300, 325, 340
Aromatics (vol%)	2	15, 40
RVP (psi)	2	7, 10

It was determined that 240 blends would be required for this matrix, so a partial factorial design was utilized. In this design, a subset of fuel blends were selected based on results from prior studies and "engineering judgement". This resulted in 27 fuels blends being tested and these are provided in Table 7. Other fuel properties were changed (e.g., olefin content, sulfur content, octane number, benzene) in a determined match blend. The California Unified Cycle (LA92) was used as the test drive cycle to include all vehicle modes in overall tests. This driving cycle is shown in Figure 6.

Table 7. Phase 3 Fuel Matrix Resulting from Partial Factorial Design (USEPA, 2013)

Test Fuel Number[a]	T50, °F	T90, °F	Ethanol, vol.%	DVPE, psi	Aromatics, vol.%
1	150	300	10	10	15
2	240	340	0	10	15
3	220	300	10	7	15
4	220	340	10	10	15
5	240	300	0	7	40
6	190	340	10	7	15
7	190	300	0	7	15
8	220	300	0	10	15
9	190	340	0	10	40
10	220	340	10	7	40
11	190	300	10	10	40
12	150	340	10	10	40
13	220	340	0	7	40
14	190	340	0	7	15
15	190	300	0	10	40
16	220	300	10	7	40
20	160	300	20	7	15
21	160	300	20	7	40
22	160	300	20	10	15
23	160	340	20	7	15
24	160	340	20	10	15
25	160	340	20	10	40
26	150	340	15	10	40
27	190	340	15	7	15
28	190	300	15	7	40
30	150	325	10	10	40
31	160	325	20	7	40

[a]Fuels 17-19 were tested in an earlier phase of the program. Fuel 29 is an E85 fuel not included in the statistical matrix design.

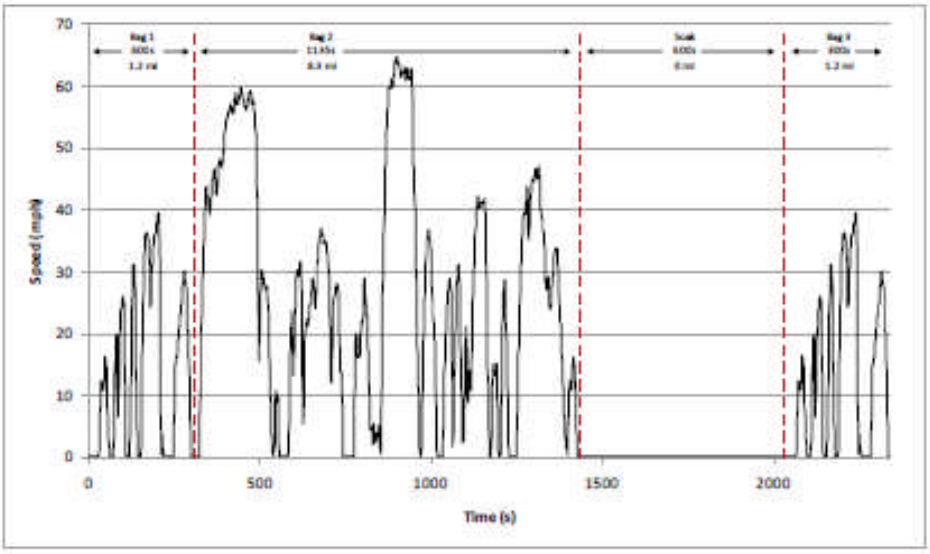


Figure 6. Speed Versus Time Schedule of California Unified Cycle, LA92 (USEPA, 2013)

Of note is that speciation testing was also part of the overall tests. The fuel properties used in the speication subset for testing are shown in Table 8.

Table 8. Summary of Fuel Properties For Speciation Subset (excluding E85 tests) (USEPA, 2013)

Fuel	Ethanol vol%	T50 °F	T90 °F	DVPE psi	Aromatics vol%
3	10.4	218	296	6.9	15.0
4	9.9	222	338	10.0	15.5
6	10.6	189	340	7.2	15.0
7	<0.10	193	298	7.2	17.0
10	9.8	217	340	7.1	34.0
13	<0.10	223	338	6.9	34.1
14	<0.10	193	339	7.1	16.9
21	20.1	168	305	7.1	35.5
23	20.3	163	338	6.8	15.9
27	14.9	222	340	7.0	14.9
28	15.0	217	299	6.9	34.5
31	20.1	167	325	7.0	35.5

Emissions were determined for these test fuels, but unfortunately not reported in this reviewed document.

2.1.5 "Speciation of Total Organic Gas and Particulate Matter Emissions from On-road Vehicles in MOVES2014"

The equations used in MOVES2010 for the VOC and NMOG were continued in MOVES2014. Updates were included in the adjustment factor complex method and documented in this USEPA report (USEPA[b], 2014). The complex method for emission rates for aggregates of individual chemical compounds (total hydrocarbons (THC), VOC, TOG, and PM) were described. Additionally, MOVES2014 included processes that were previously processed outside of MOVES (e.g., benzene, elemental carbon) and were incorporated into the MOVES2014 TOG (total organic gases) and $PM_{2.5}$ speciation. This expansion of the variable descriptions previously presented, with VOC and NMOG exhaust emissions calculated based on the use of several factors applied to NMHC emissions is indicated below.

$$NMHC = THC - (1\text{-}MethaneTHCRatio)$$

$$Methane = THC - (Methane\ Ratio)$$

$$NMOG = NMHC * [SpeciationConstant + \sum_{i=1}^{4}(oxySpeciation * volToWtPercentOxy_i * oxyVolume_i)$$

Equations [10 – 12]

In this case, *i* in the summation refers to one of four gasoline oxygenates: ethanol, MTBE, ETBE, or TAME. The speciation constant is determined based on the oxygenate volume and if the gasoline has no oxygenate volume, Equation 13 is applied.

$$SpeciationConstant = NMOG/NMHC$$

Equation [13]

In other cases, the remaining factors must be applied and are defined as:

oxySpeciation = an empirically derived value adjusted for NMOG/NMHC according to oxygen volume

volToWtPercentOxy = conversion of oxygenate percentage by volume (vol%) to the mass percentage of oxygen in the fuel (mass%) and determined by the mass fraction of oxygen and ratio of the density of the oxygenate to that of gasoline

oxyVolume = percent volume of each gasoline oxygenate in the respective fuel

Equations [14 – 16]

For ethanol, the mass fraction of oxygen is defined as 0.3473, density of 0.789 g/cm^3, the volToWtPercentOxy value of 0.3653 and the gasoline fuel density of 0.75 g/cm^3.

Extensive consideration for multiple components were considered for the NMOG/NMHC and VOC/NMHC ratios and not discussed here for brevity. The reader is directed to Appendix A of this USEPA document for detailed descriptions. Also, a TOG speciation map is included in Appendix B of that report which provides fuel IDs for the 19 fuels with ethanol specifics by blend (E0 to E15 and E85).

The equations for VOC and NMOG are similar in concept with the values for each factor different by pollutant, ethanol content, vehicle model year, and mode (process). This is exemplified in Table 9 for NMOG and Table 10 for VOCs. Of note is that pre-2001 factors, originally from MOBILE6.2 (USEPA[b], 2003) and used in MOVES2010, continued to be used in MOVES2014. More recent and extensive data were available for later model years to USEPA and later model year factors were updated.

Table 9. Parameters used to Calculate NMOG/NMHC Ratios for Gasoline Vehicle Emissions (USEPA[b] 2014)

Fuel Subtype	Model Year Group	Process	speciationConstant	oxySpeciation
E0 to E10	1960-1974	Start and Running Exhaust	1.0352	0.0062
	1975-1986		1.02113	0.0062
	1987-1989		1.0179	0.0062
	1990-1993		1.0167	0.0062
	1994-2000		1.0163	0.0062
	2001-2050	Start	1.0078	0.0082
		Running	1.0149	0.0028
E15	1960-2050	Start	1.0495	0
		Running	1.0318	0
E20	1960-2050	Start	1.0703	0
		Running	1.0367	0
E70 to E100	1960-2000	Start and Running Exhaust	1.4858	0

Table 10. Parameters used to Calculate VOC/NMHC Ratios for Gasoline Vehicle Emissions (USEPA[b] 2014)

Fuel Subtype	Model Year Group	Process	speciationConstant	oxySpeciation
E0 to E10	1960-1974	Start and Running Exhaust	1.0239	0.0133
	1975-1986		0.9799	0.0133
	1987-1989		0.976	0.0133
	1990-1993		0.9787	0.0133
	1994-2000		0.9797	0.0133
	2001-2050	Start	0.9787	0.0068
		Running	0.9148	-0.0013
E15	1960-2050	Start	1.0162	0
		Running	0.9049	0
E20	1960-2050	Start	0.9233	0
		Running	1.0436	0
E70 to E100	1960-2000[j]	Start and Running	1.3981	0

A discussion of evaporative emissions was also included in this document but is mirrored in Evaporative Emissions from On-road Vehicles in MOVES2014, discussed later in Section 2.1.9.

As noted, PM prediction and speciation changes were incorporated into MOVES2014 processing. Previous versions (MOVES2010b and earlier) produced only three species of $PM_{2.5}$: elemental carbon (EC), organic carbon (OC), and sulfates (SO_4). MOVES2014 was designed to produce all $PM_{2.5}$ species required by the Community Multiscale Air Quality CMAQv5.0 (Simon, 2012).

Under these previous versions of MOVES, ethanol content had no effect on PM emissions (USEPA 2011). This is no longer the case in MOVES2014, as the existing documentation (USEPA[b] 2014) as well as sensitivity runs indicate fuel effects on PM emissions. Figure 7 provides a visual synopsis of how fuel effects are determined for PM species emission rates.

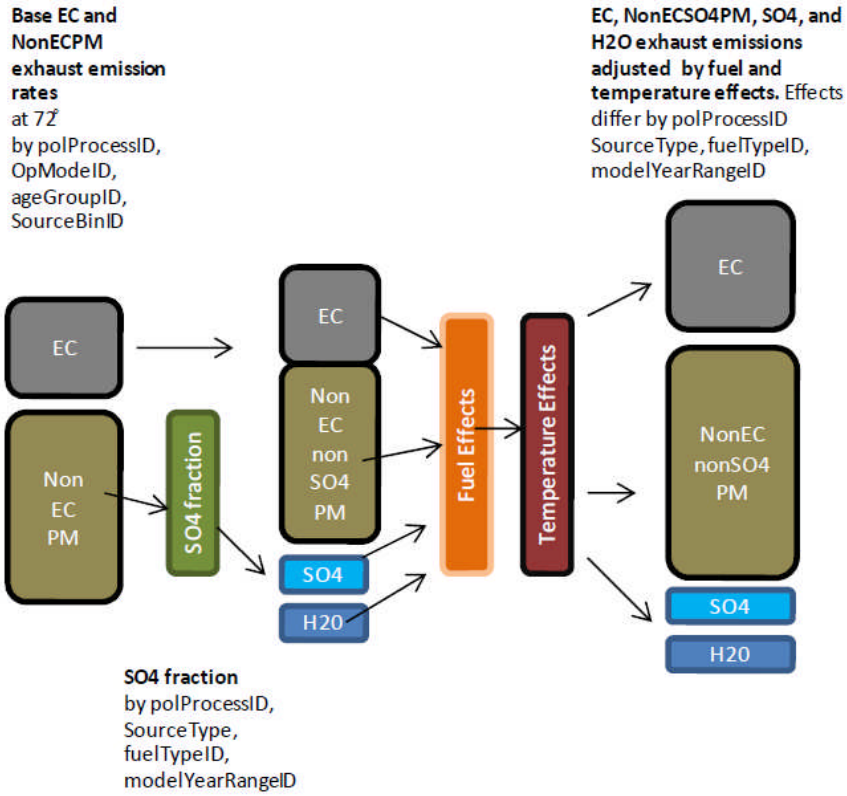


Figure 7. Flow Chart of Calculation of the Intermediate $PM_{2.5}$ Emission Rates (Source USEPA[a], 2014)

The documentation provides indications of fuel effects including ethanol-blend interdependencies with temperature in a USEPA document (USEPA[f] , 2014). However, although cited, the USEPA documentation for the MOVES2014 fuel effects on emissions is currently unavailable. It is indicated that for the other pollutants, fuel adjustments are still made to PM emissions using multiplicative factors developed empirically.

Unlike $PM_{2.5}$, no speciation is conducted in MOVES for PM_{10}. The $PM_{10}/PM_{2.5}$ ratios for primary exhaust and crankcase emissions in MOVES are constants by fuel type unaffected by oxygenate content and are 1.130 for gasoline and 1.087 for diesel.

2.1.6 "Air Toxic Emissions from On-Road Vehicles in MOVES2014"

Air toxics are predicted by MOVES2014 in four different categories: VOCs, Polycyclic Aromatic Hydrocarbons (PAHs), dioxin/furans, and metals (USEPA[c], 2014). These categories include 14 HC/VOC compounds, 16 PAH species, 17 dioxin/furan

compounds, and 5 different metals with mercury in three physical forms. Fuel properties remain as previously defined. Ethanol content in some cases has a direct effect on these emission rates and an indirect effect due to such parameters as RVP. A uniform approach was selected for estimation of toxics from E70 to E100 with data from E85 blends being the major driver.

Changes in emissions due to ethanol are implemented using the "complex" method or equation. This is:

$$lnY = \beta_0 + \beta_{oxy}(x_{oxyi} - x_{oxy}) + \cdots + \beta_{EtOH}(x_{EtOHi} - x_{aromEtOH}) + \cdots + \beta_{RVP}(x_{RVPi} - x_{RVP})$$

Equation [17]

In this equation, coefficients and mean property values occur for the included fuel properties. Mean property values for this formula are shown in Table 11 while the coefficients related to direct ethanol effects are shown in Table 12. Tables with coefficients related to indirect effects are not shown.

Table 11. Mean Fuel-Property Values Used for Centering Terms in the Complex Model

Property	Units	Mean Value
Aromatics	Vol. %	28.26110
Olefins	Vol. %	7.318716
Methyl-tertiary-butyl-ether (MTBE)[1]	Wt.%	0.947240
Ethyl-tertiary-butyl-ether (ETBE)[1]	Wt.%	0.023203
Ethanol (EtOH)[1]	Wt.%	0.314352
Tertiary-amyl-methyl-ether (TAME)[1]	Wt.%	0.016443
Oxygenate[2]	Wt.%	1.774834
RVP	Psi	8.611478
E200	%	46.72577
E300	%	85.89620
[1] Species-specific values used in the aldehyde models. [2] Aggregate value used for the butadiene and benzene models.		

Table 12. Complex Model Coefficients for Acetaldehyde by Technology Group

Technology Group	Fuel Property								
	Aromatics	Olefins	MTBE	ETBE	EtOH	TAME	RVP	E200	E300
1	-0.05548	-	-0.03646	0.316467	0.249326	-	-	-	-0.01216
2	-0.05548	-	-	0.316467	0.249326	-	-	-	-0.01216
3	-0.05548	-	-	0.316467	0.249326	-	-	-	-0.01216
4	-0.05548	-	-	0.316467	0.249326	-	0.24230	-	-0.01216
5	-0.05548	-	-	0.316467	0.249326	-	-	-	-0.01216
6	-0.05548	-	-	0.316467	0.249326	-	-	-	-0.01216
7	-0.05548	-	-	0.316467	0.249326	-	-	-	-0.01216
8	-0.05548	-	-	0.316467	0.249326	-	-	-	-0.01216
9	-0.05548	-	-	0.316467	0.249326	-	-	-	-0.01216
10	-0.05548	-	-0.05598	0.316467	0.249326	-	-	-	-0.01216

Following the same methodology as previously described, a fuel adjustment (f_{adj}) is derived by the ratio of the target fuel to the base fuel as defined in Equation 18.

$$f_{adj} = \frac{\exp(X\beta_{target})}{\exp(X\beta_{base})} - 1.0$$

Equation [18]

Also of note is that in this latest version of MOVES, the varying weights of corrections are not invariant but adjusted for each year, changes in fuel properties, and the mass of VOC emissions. This series of adjustment equations are shown in the EPA document as well as the weighting values. Blends from E5 to E8 are determined by interpolation between E0 and E10, while mass fractions of ethanol from E10 to E20 are constant. No data for E15 or E20 was available for 2000 or earlier model years.

Use of the fuel sub-type IDs continues with the different fuel types for ethanol built into MOVES2014 being 12 (E10), 13 (E8), 14 (E5), 15 (E15), 18 (E20), 51 (E85), and 52 (E70).

2.1.7 MOVES2014 User Interface Manual

This document provides an overview on the use of the latest version of MOVES (USEPA[d], 2014). In MOVES2014 the workings of the Data Manager and the fuel properties available in the Fuel Formulation importer remained the same. Again, a user could select an existing fuel from the MOVES database, change certain properties, or

create a new fuel with different properties. For new fuels, all fields except BioDiesel, Cetane, and PAHContent must be specified. Inputs for Cetane and PAHContent are inactive. In the Fuel Usage Importer, E85 could be specified as a fraction of fuels capable of using the fuel.

The Fuel Wizard is a new tool introduced in MOVES2014 for modifying interrelated properties which uses the Fuel Formulation Table. The wizard is capable of only changing one property at a time and then "…the Fuel Wizard will appropriately modify related fuel formulation properties, based on refinery modeling …." While not directly stated, it was concluded this meant match blending based on previous data sources. Use of the Fuel Wizard is highlighted in Section 2.1.10.

2.1.8 "MOVES2014 Technical Guidance: Using MOVES to Prepare Emission Inventories for State Implementation Plans and Transportation Conformity"

This document provides insight to the MOVES2014 default fuel listing (USEPA, 2015). While still based on four tables for changes due to fuels, the tables are not the same as were defined in MOVES2010. The four tables are now fuelsupply, fuelformulation, fuelusagefactor, and AVFT (fuel type and vehicle technology). The Fuel Supply and Fuel Formulation tables work in a similar manner as previously described. The Fuel Usage Fraction table allows definition of the frequency in which E85 capable vehicles use E85 versus conventional gasoline. The AVFT allows specification of the fraction of fuel types capable of being used by model year and source type.

Still contained in MOVES2014 is the large listing of fuels that can be selected within the model. As was previously mentioned, the default fuels defined within MOVES can be selected by geographic location from the default database. For MOVES2014, new values for fuel properties were developed by region. Figure 8 show graphically displays the fuel regions used in MOVES2014.

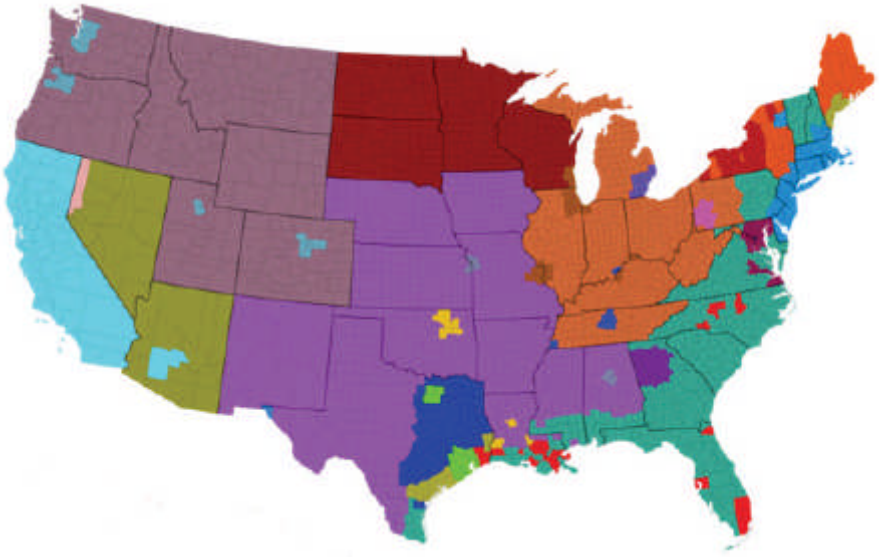


Figure 8. MOVES2014 Fuel Regions (EPA, 2015)

In terms of ethanol mixtures, beginning in the year 2013, MOVES2014 assumed fractions of E10, E15 and E85 blending based on projections from the Annual Energy Outlook 2014 Report.

2.1.9 Evaporative Emissions from On-road Vehicles in MOVES2014

For evaporation and permeation losses, emissions of methane, ethane, or acetone are considered insignificant. As such, MOVES treats THC emissions as equivalent to NMHC emissions and VOC emissions as equivalent to NMOG as well as TOG emissions. Evaporative emissions occur from multiple vehicle locations as shown in Figure 9. The MOVES processes associated with these multiple evaporation and permeation emissions are (USEPA[e], 2014):

- Evaporative permeation
- Evaporative vapor venting losses
- Evaporative liquid leaks
- Refueling displacement vapor losses
- Refueling fuel spillage

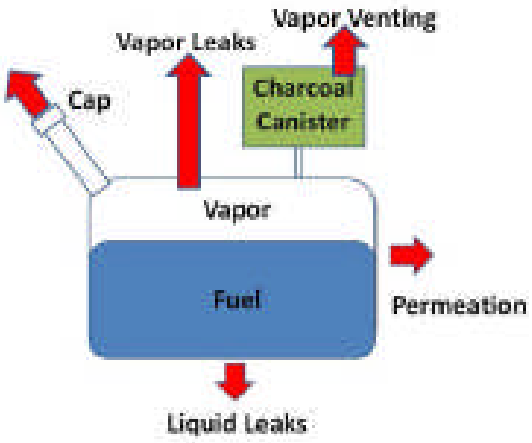


Figure 9. Fuel Losses (USEPA[e], 2014)

EPA states that ethanol has a unique effect and increases permeation of specific compounds. Permeation effects were based on 10 fuel systems that were filled with E0, E5.7, and E10 fuels with additional data from the CRC E-77-2 and E-772b programs. The effects were not large enough to support the three ethanol mixes and E5.7 and E10 were placed in the same data bin. The difference between E0 and the other fuel mixes is the fuel adjustment. Model years were adjusted due to changing evaporative standards. Tier 3 permeation includes E10. The VOC and NMOG evaporative and permeation parameters for ethanol fuels are presented in Tables 13 and 14.

Table 13. Gasoline Vehicle Evaporative THC to NMOG and VOC Speciation Factors (USEPA[e] 2014)

Engine Type	Fuel Subtype	Process	speciationConstant	oxySpeciation
Gasoline	<5% ethanol	Vapor Venting and Refueling Vapor Loss	1	0.0318
	E5 to E20		1	0.0318
	E70 to E100		1.511	0
Gasoline	<5% ethanol	Fuel Leaks and Refueling Spillage Loss	1	0.025
	E5 to E20		1	0.025
	E70 to E100		1.511	0

Table 14. Gasoline Vehicle Permeation Hydrocarbon THC to NMOG and VOC Speciation Factors (USEPA[e] 2014)

Engine Type	Fuel Subtype	Process	speciationConstant	oxySpeciation
Gasoline	E0 to E10	Permeation	1	0.036
Gasoline	E15	Permeation	1.1755	
Gasoline	E20	Permeation	1.2235	0
Gasoline	E70 to E100	Permeation	1.511	0

2.1.10 "Fuel Inputs in MOVES2014: User Document and Notes"

The MOVES2014 User Guide outlines the general input procedures, including input of ethanol fuel information. A discussion of specific inputs for ethanol fuels is addressed in this section. As shown in Figure 10, the fuel process begins when the user selects the on-road vehicle types and has a choice of fuels to select for the overall mixture of vehicles and fuels. Of note is that the only ethanol fuel blends that can be directly specified is E85.

As input continues, the user has a variety of basic and advanced options for fuel input. Although listed as an optional step and noted that "Most users will not populate this screen," there is an option to choose to execute a Fuels Effect Generator as shown in Figure 11.

More often, MOVES2014 will be executed using the County Data Manager input where specific counties in the U.S. may be selected, and data is input into individual panels, such as the Fuel Input Panel shown in Figure 12. This provides default values for fuel input parameters. Inputs from this panel include market share, composition of fuels, and fractions of vehicles using each fuel type. Defaults are available by county. The user may use Excel to modify the four MOVES tables previously discussed: FuelSupply, FuelFormulation, FuelUsageFraction, and AVFT for the various fuel properties and usage.

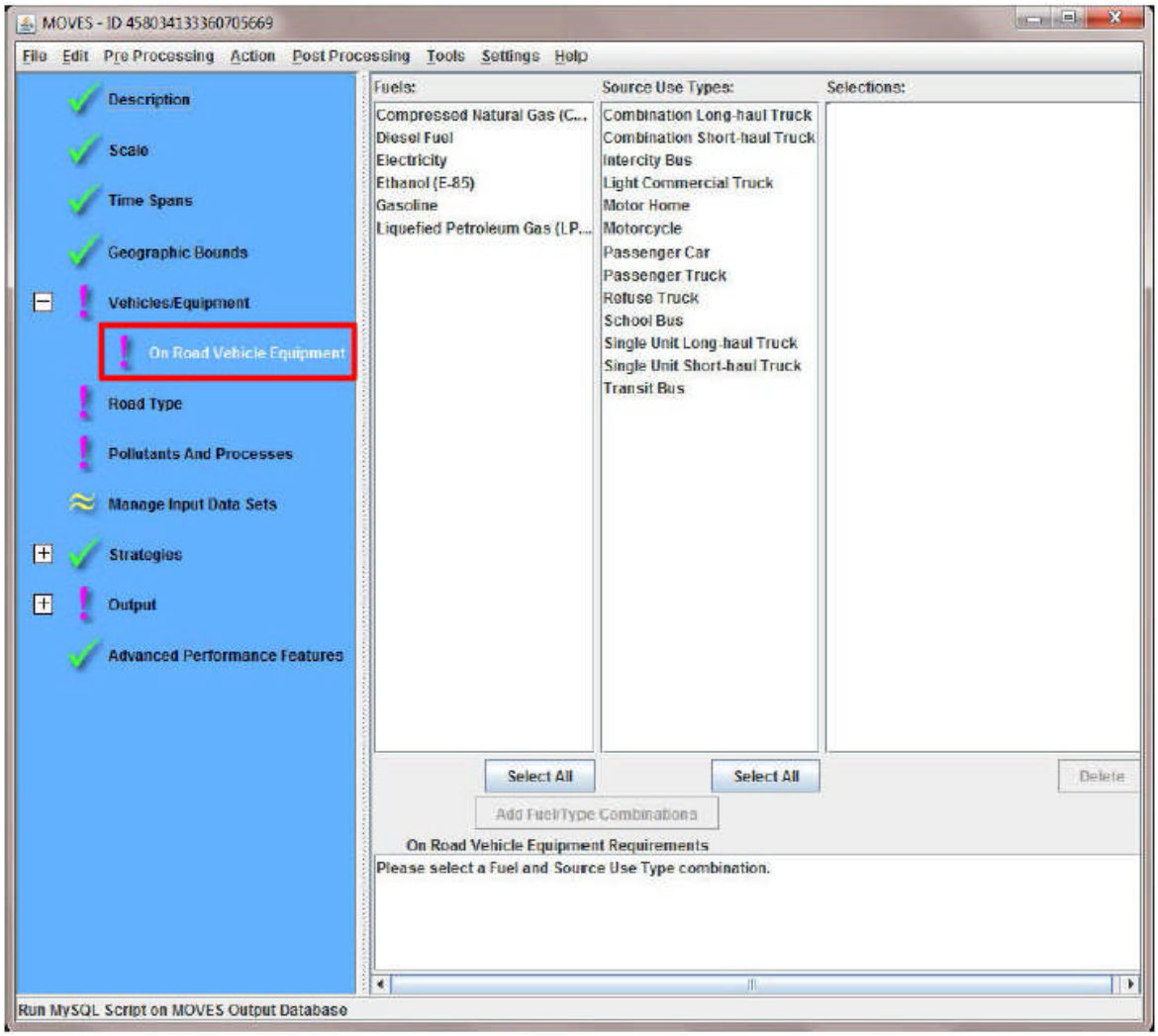


Figure 10. MOVES Selection Panel for On-Road Vehicles and Fuels

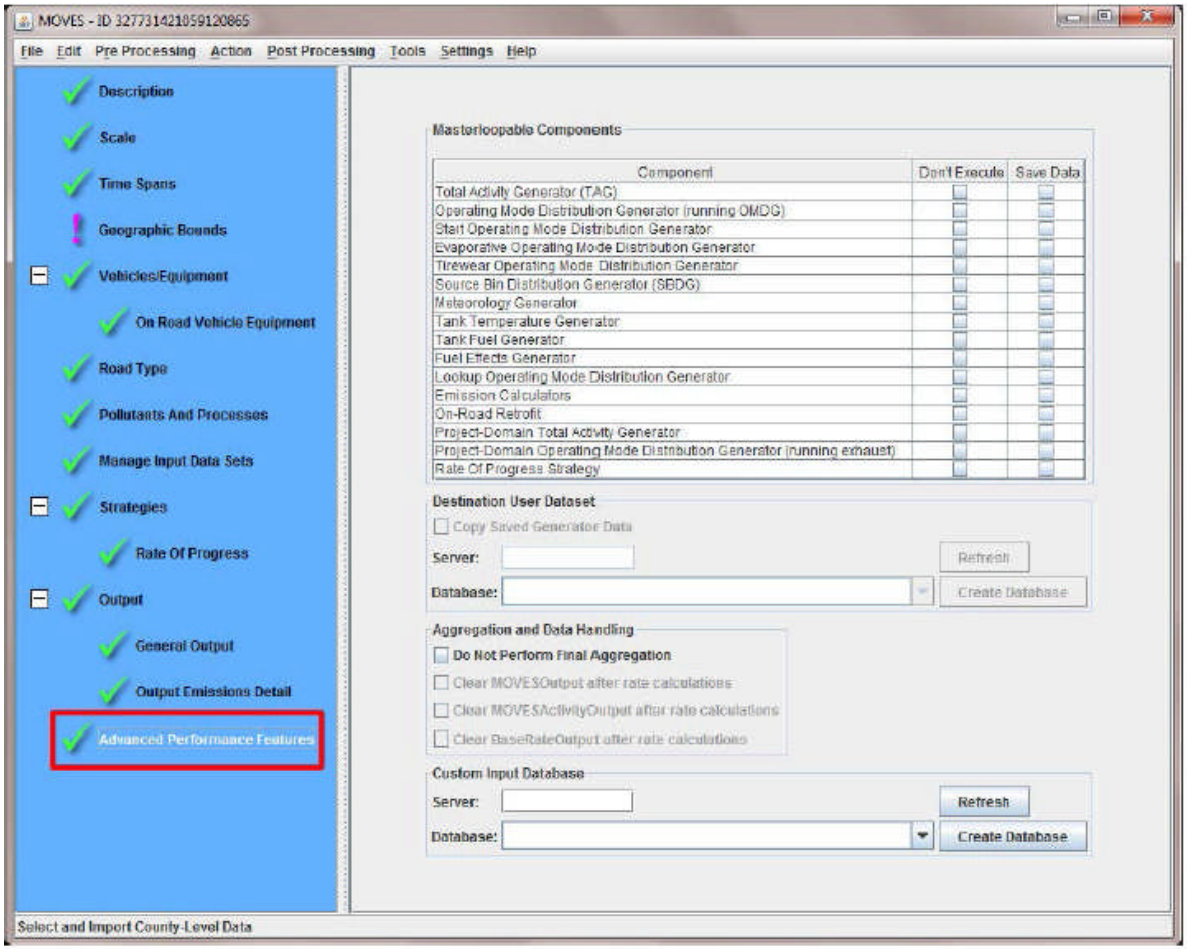


Figure 11. Advanced Performance Features Input Panel

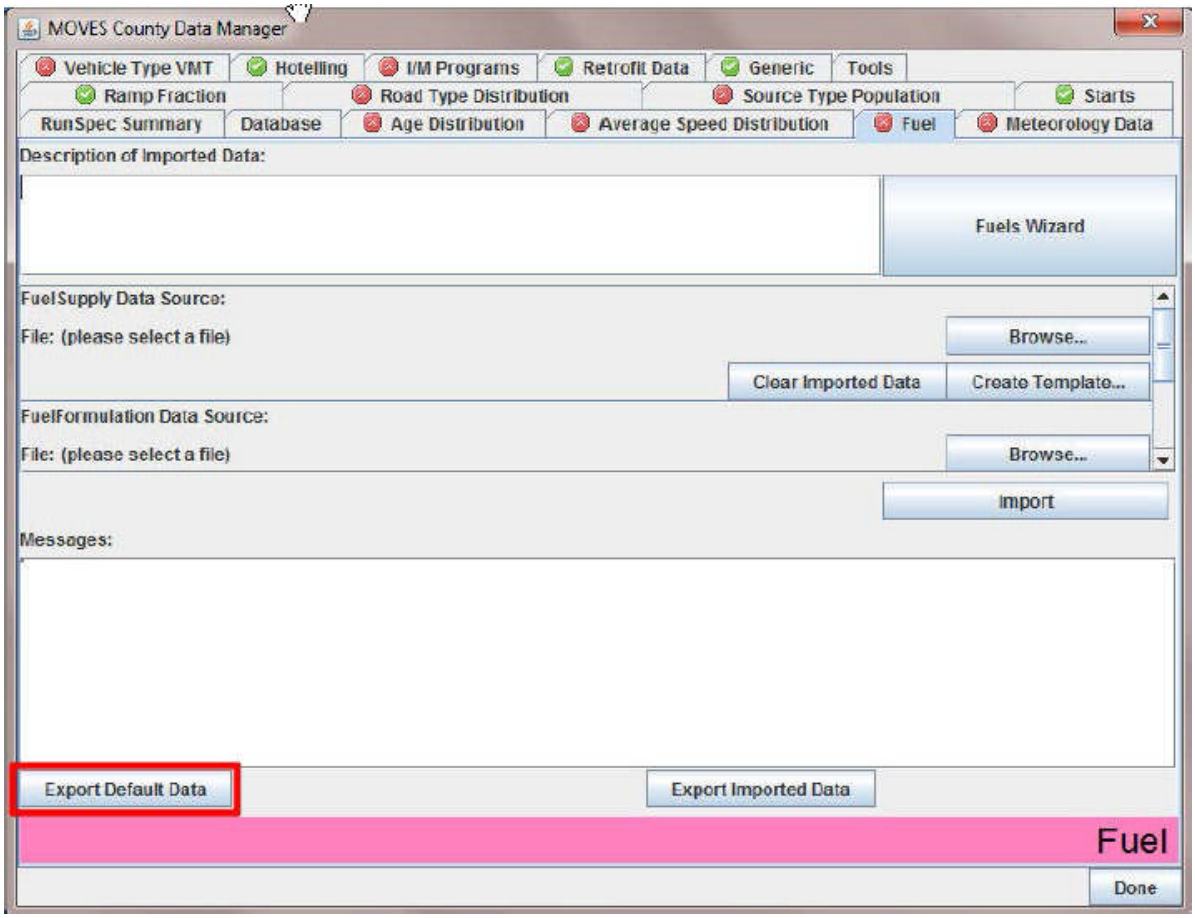


Figure 12. Fuels Input Panel

An interesting feature of MOVES2014 is the 'Fuel Wizard' button, which allows users to select changes to specific fuel properties. The pop-up input panel for use with the Fuel Wizard is shown in Figure 13. The user may manually include information and other inputs will change automatically according in matched fuel inputs. After input, the 'Calculate' button is pushed and the user may accept or reject the change as shown in Figure 14. After accepting the updated Fuel formulation the user must choose the 'Done' box for the fuel formulation to be updated in the input database as shown in Figure 15.

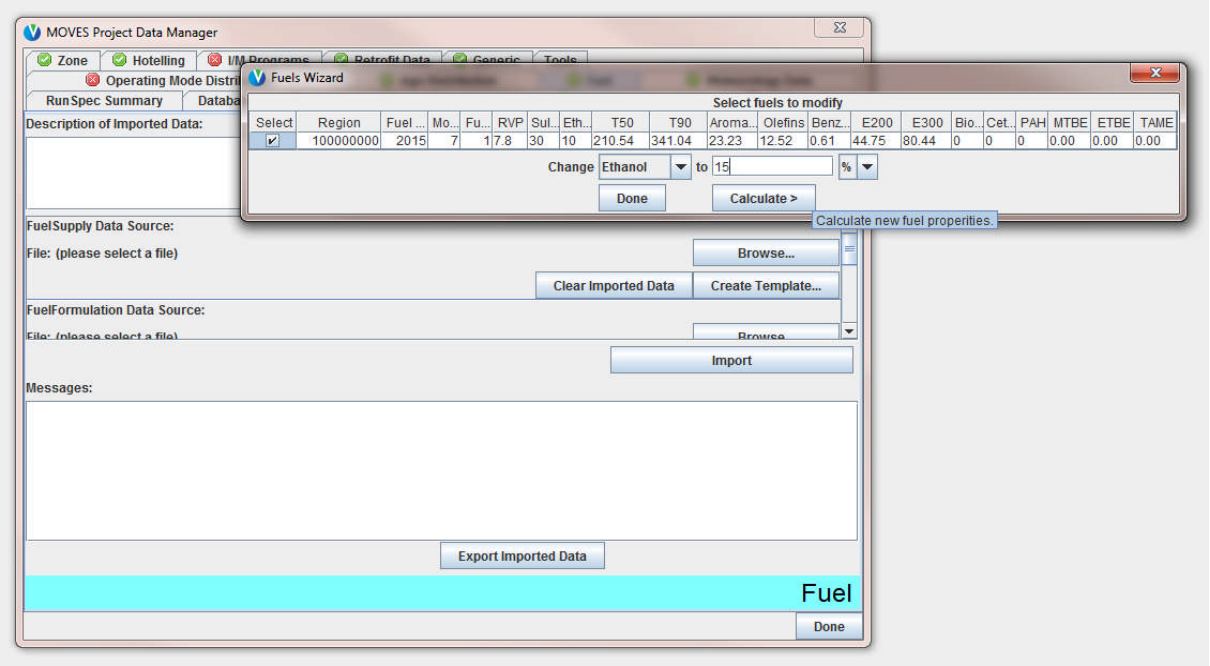


Figure 13. Fuel Wizard

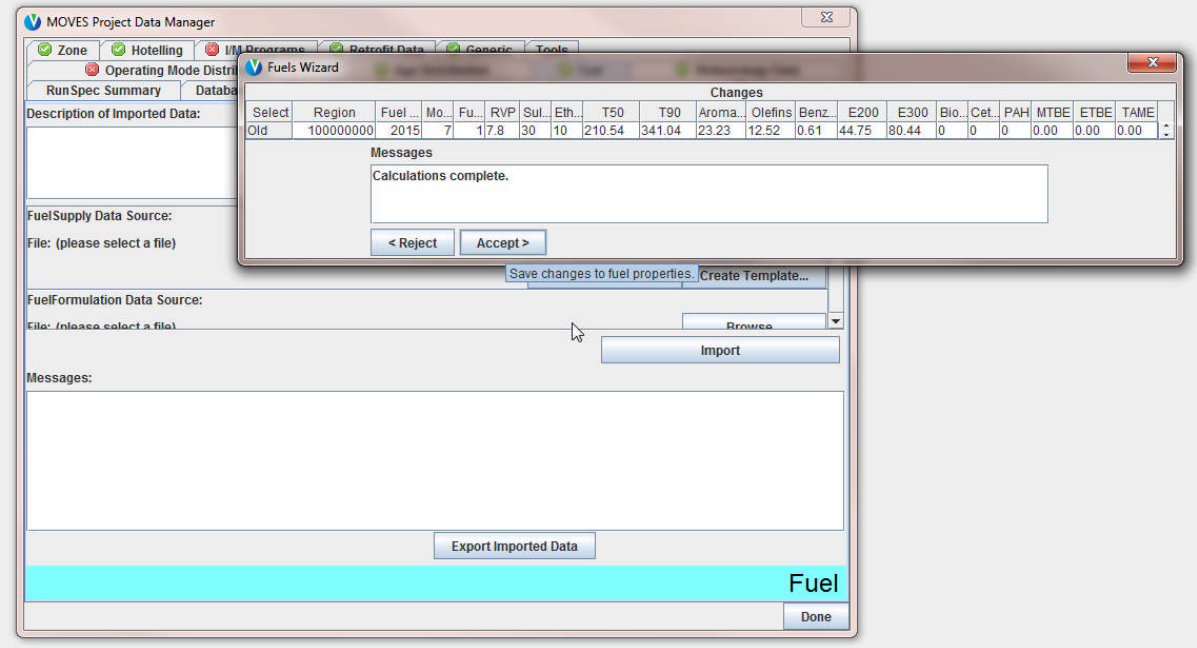


Figure 14. Fuel Wizard Beginning Input After Selecting Calculate

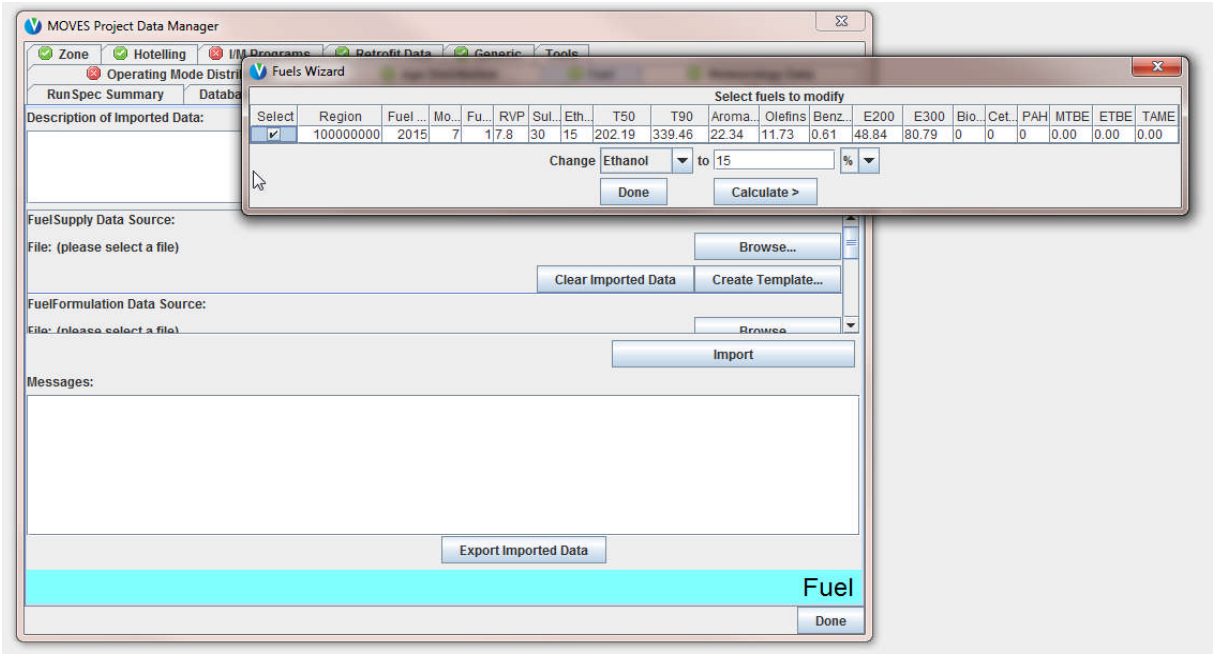


Figure 15. Saving Input for Fuel Wizard

The user may not wish to use the “match blending” approach underlying the Fuel Wizard operation. If so, the user must revert to the manual input tables, which is a more complex approach to using the model. This approach is discussed in more detail in Section 3.

Output can be selected for a variety of pollutants in multiple formats including rates per distance, vehicle type, profile, hour, or start emissions. Table 15 includes a listing of the types of emission rates associated with the MOVES defined processes. Table 16 is a list of pollutants that can be specified in the output.

Table 15. Types of Emission Rates Associated with Each MOVES Process (From EPA, 2014)

ID	Emission Process	Type of Emission Rate
1	Running Exhaust	Distance
2	Start Exhaust	Vehicle **or** Start
9	Brakewear	Distance
10	Tirewear	Distance
11	Evap Permeation	Distance **and** Vehicle
12	Evap Fuel Vapor Venting	Profile
13	Evap Fuel Leaks	Distance **and** Vehicle
15	Crankcase Running Exhaust	Distance
16	Crankcase Start Exhaust	Vehicle **or** Start
17	Crankcase Extended Idle Exhaust	Vehicle
18	Refueling Displacement Vapor Loss	Distance **and** Vehicle
19	Refueling Spillage Loss	Distance **and** Vehicle
90	Extended Idle Exhaust	Vehicle **or** Hour
91	Auxiliary Power Exhaust	Vehicle **or** Hour

Table 16. Output Possibilities for Pollutants

ID	pollutantname	ID	pollutantname	ID	pollutantname
1	Total Gaseous Hydrocarbons	83	Phenanthrene particle	1000	CB05 Mechanism
2	Carbon Monoxide (CO)	84	Pyrene particle	1001	CB05_ALD2
3	Oxides of Nitrogen (NOx)	86	Total Organic Gases	1002	CB05_ALDX
5	Methane (CH4)	87	Volatile Organic Compounds	1003	CB05_BENZENE
6	Nitrous Oxide (N2O)	88	NonHAPTOG	1004	CB05_CH4
20	Benzene	90	Atmospheric CO2	1005	CB05_ETH
21	Ethanol	91	Total Energy Consumption	1006	CB05_ETHA
22	MTBE	92	Petroleum Energy Consumption	1007	CB05_ETOH
23	Naphthalene particle	93	Fossil Fuel Energy Consumption	1008	CB05_FORM
24	1,3-Butadiene	98	CO2 Equivalent	1009	CB05_IOLE
25	Formaldehyde	99	Brake Specific Fuel Consumption (BSFC)	1010	CB05_ISOP
26	Acetaldehyde	100	Primary Exhaust PM10 - Total	1011	CB05_MEOH
27	Acrolein	106	Primary PM10 - Brakewear Particulate	1012	CB05_OLE
30	Ammonia (NH3)	107	Primary PM10 - Tirewear Particulate	1013	CB05_PAR
31	Sulfur Dioxide (SO2)	110	Primary Exhaust PM2.5 - Total	1014	CB05_TERP
32	Nitrogen Oxide (NO)	111	Organic Carbon	1015	CB05_TOL
33	Nitrogen Dioxide (NO2)	112	Elemental Carbon	1016	CB05_UNK
34	Nitrous Acid (HONO)	115	Sulfate Particulate	1017	CB05_UNR
35	Nitrate (NO3)	116	Primary PM2.5 - Brakewear Particulate	1018	CB05_XYL
36	Ammonium (NH4)	117	Primary PM2.5 - Tirewear Particulate		
40	2,2,4-Trimethylpentane	118	Composite - NonECPM		
41	Ethyl Benzene	119	H2O (aerosol)		
42	Hexane	120	Primary PM2.5 - NonECNonSO4PM		
43	Propionaldehyde	121	CMAQ5.0 Unspeciated (PMOTHR)		
44	Styrene	122	Non-carbon Organic Matter (NCOM)		
45	Toluene	130	1,2,3,7,8,9-Hexachlorodibenzo-p-Dioxin		
46	Xylene	131	Octachlorodibenzo-p-dioxin		
51	Chloride	132	1,2,3,4,6,7,8-Heptachlorodibenzo-p-Dioxin		
52	Sodium	133	Octachlorodibenzofuran		
53	Potassium	134	1,2,3,4,7,8-Hexachlorodibenzo-p-Dioxin		
54	Magnesium	135	1,2,3,7,8-Pentachlorodibenzo-p-Dioxin		
55	Calcium	136	2,3,7,8-Tetrachlorodibenzofuran		
56	Titanium	137	1,2,3,4,7,8,9-Heptachlorodibenzofuran		
57	Silicon	138	2,3,4,7,8-Pentachlorodibenzofuran		
58	Aluminum	139	1,2,3,7,8-Pentachlorodibenzofuran		
59	Iron	140	1,2,3,6,7,8-Hexachlorodibenzofuran		
60	Mercury Elemental Gaseous	141	1,2,3,6,7,8-Hexachlorodibenzo-p-Dioxin		
61	Mercury Divalent Gaseous	142	2,3,7,8-Tetrachlorodibenzo-p-Dioxin		
62	Mercury Particulate	143	2,3,4,6,7,8-Hexachlorodibenzofuran		
63	Arsenic Compounds	144	1,2,3,4,6,7,8-Heptachlorodibenzofuran		
65	Chromium 6+	145	1,2,3,4,7,8-Hexachlorodibenzofuran		
66	Manganese Compounds	146	1,2,3,7,8,9-Hexachlorodibenzofuran		
67	Nickel Compounds	168	Dibenzo(a,h)anthracene gas		
68	Dibenzo(a,h)anthracene particle	169	Fluoranthene gas		
69	Fluoranthene particle	170	Acenaphthene gas		
70	Acenaphthene particle	171	Acenaphthylene gas		
71	Acenaphthylene particle	172	Anthracene gas		
72	Anthracene particle	173	Benz(a)anthracene gas		
73	Benz(a)anthracene particle	174	Benzo(a)pyrene gas		
74	Benzo(a)pyrene particle	175	Benzo(b)fluoranthene gas		
75	Benzo(b)fluoranthene particle	176	Benzo(g,h,i)perylene gas		
76	Benzo(g,h,i)perylene particle	177	Benzo(k)fluoranthene gas		
77	Benzo(k)fluoranthene particle	178	Chrysene gas		
78	Chrysene particle	181	Fluorene gas		
79	Non-Methane Hydrocarbons	182	Indeno(1,2,3,c,d)pyrene gas		
80	Non-Methane Organic Gases	183	Phenanthrene gas		
81	Fluorene particle	184	Pyrene gas		
82	Indeno(1,2,3,c,d)pyrene particle	185	Naphthalene gas		

2.1.11 Summation of USEPA Documentation

The U.S. EPA has been modeling the effect of various fuels and fuel properties on motor vehicle emissions for some time. The greatest changes occurred in the MOVES2010 model where the overall methodology now in use was established. This methodology is based on the application of adjustment factors developed by using results from fuel and emissions databases. This method involves a direct comparison to a base fuel for the target (fuel of concern) with a large series of factors being developed. EPA noted that further advancements in emissions modeling would continue and this has been the case, as more detail becomes available on speciation, toxics, and fuel property impacts. In MOVES2014 both direct and indirect effects are modeled. Tools have been developed in the modeling process to assist in changing fuels properties, but the process becomes more difficult for the user if examining "splash-blended" ethanol fuels is preferable to the default match blending ethanol inputs.

2.2 Reports by others on Ethanol Effects on Emissions and Modeling

In this section, research papers conducted by others outside of EPA are included that were provide insight directly related to the topic. Readers who wish to explore more should use special report bibliographies of ethanol blend studies, such as the Oak Ridge National Laboratory report (Sluder, 2013).

2.2.1 "Preliminary Examination of Ethanol Fuel Effects on EPA's R-factor for Vehicle Fuel Economy"

This report (Sluder, 2013) includes information gathered during a Department of Energy (DOE) 5-year test program on impacts from intermediate blends of ethanol. While the primary emphasis of the study was about a key variable in calculations related to compliance with federal fuel economy standards (the R-factor), it must be noted that fuel blending is directly related. The R-factor is a value that describes the change in fuel economy and based on ratios of the test fuel to the reference fuel, similar to the idea implemented in MOVES for fuel properties. Miles traveled will vary by the fuel blend (see Figure 16). The trend shown in Figure 16 is a decrease in the R-factor for increasing ethanol content. This requires comparison to be made on a miles traveled basis instead of by fuel volume used to make accurate comparison of emissions. Unfortunately, this introduces another source of error in that the distance to fuel consumption rate must be accurately known.

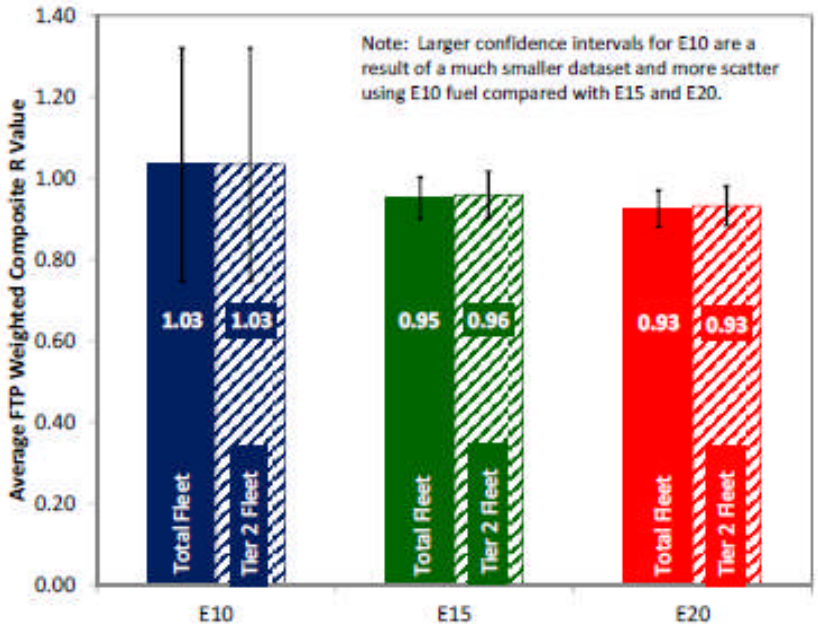


Figure 16. Fleet Average R-factor Values for Three Ethanol-Blended Fuels (2007 Honda Accord results omitted) (Sluder, 2013)

2.2.2 "National Renewable Energy Laboratory (NREL), Effect of Ethanol Blending on Gasoline RVP"

NREL supplied the RFA (Renewable Fuels Association) with a Discussion Document on the effects on fuel RVP due to blending ethanol (McCormick, 2012). Noted were the EPA summer waiver for the standard RVP restrictions where E10 (9 – 10 %vol) is permitted an additional 1 psi over E0 but higher blends are still limited to 9.0 psi. The major reported finding was that the RVP impact of E15 "is indistinguishable" from E10. For E20, the effects were reported to be indistinguishable from the summer RVP requirements. Of interest is that the RVP of the fuel blend effectively peaks at E10, then drops as the ethanol content increases due the strong molecular attractive forces. Figure 17 shows this trend. Based on eight studies, it was also reported that a range of RVP should be expected, even for the same blend percentages.

Also of note is that in Figure 17, DVPE is used instead of RVP. DVPE has been used in USEPA reporting for RVP requirements as previously discussed. NREL has reported a small difference does occur between the two methods (Gardiner, 2010).

The findings of the NREL paper are interesting because, as discussed later, the MOVES model shows a reduction in VOCs from E10 to E15, but then shows a steep

increase in VOCs as ethanol content is increased from 15% to 30%. Thus, the MOVES2014 model indicates that RVP and VOC emissions are not directly related.

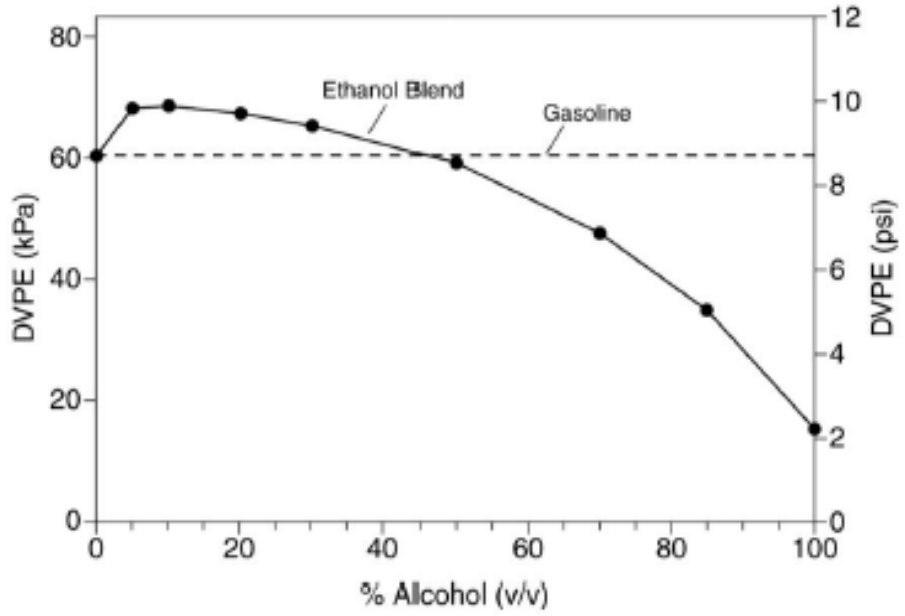


Figure 17. Effect of Ethanol Blending on Vapor Pressure of Gasoline (Gardiner, 2010)

2.2.3 "The Impact of Ethanol Fuel Blends on PM Emissions from a Light-Duty GDI Vehicle"

Multiple combustion effects influence emissions and although this paper (Maricq, 2012) reviews measured emissions from a gasoline direct injection (GDI) vehicle, the results are still valid in relation to ethanol fuel content. The reader is reminded that with MOVES2014, PM effects due to fuel changes were included. In this paper, as ethanol content increased from gasoline (E0) to E20, a small benefit for PM was shown. This is consistent with the MOVES2014 output as will be shown later in this paper. Above E30, a statistically significant reduction in PM mass was also measured. This is different than the MOVES2014 predictions. Table 17 shows the relevant fuel properties as related to MOVES2014 input while Figure 18 shows the emission measurement results. The continual downward trend is apparent until approximately E30 when results tend to

Table 17. Relevant Fuel Properties (Maricq, 2011)

Characteristic	E0	E10 cert	E10 pump	E100
Ethanol (%vol)	0	10.1	9.0	97.3
10% recovery dist. T (°C)	56.7	54.8	48.5	
50% recovery dist. T (°C)	105.6	98.4	69.8	
90% recovery dist. T (°C)	155.8	158.8	165.5	
Vapor pres. ASTM (kPa)	55.2	54.5	70.6	21.0
Sulfur (ppm)	19	5	58.8	3
Aromatics (%vol)	28.5	24.1	16.9	

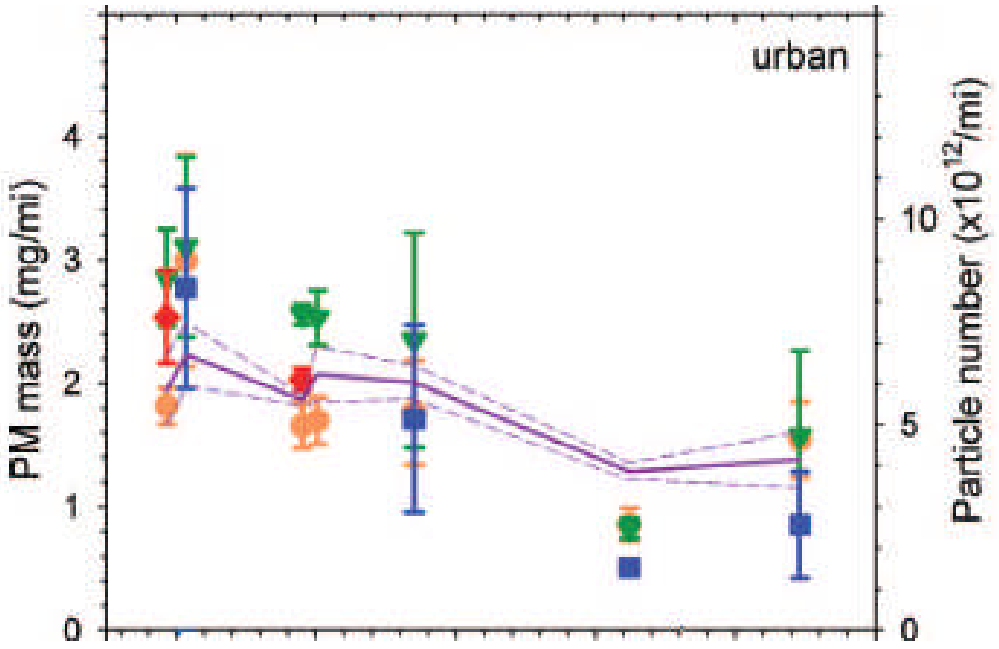


Figure 18. Measured PM Mass and Particle Number From a GDI Light-Duty Truck (Maricq, 2011)
Symbols = mass; Lines = Particle Number

become more constant. The results for elemental and organic carbon were similar until E30 and then increases, sometimes large, begin to occur. Elemental carbon dominates and this most likely masks changes in sulfates from the varying sulfur content of the fuel.

NOx and THC were also measured. A gradual reduction in emissions for these species were shown until approximately E30 and then became relatively constant, very similar to the PM results. This is very different from the MOVES2014 estimates where NOx increases.

2.2.4 "NMOG Emissions Characteirizations and Estimates for Vehicles Using Ethanol-Blended Fuels"

In this paper (Sluder, 2012) the primary reporting is on the effects of ethanol on NMOG emissions. The paper discusses hyrdrocarbon speciation, performed in a different manner than MOVES2014. Using measured emission data gathered over a several year period, statistical correlation was used to determine an estimation methodolgy for NMOG was derived based on ethanol content in the fuel and NMHC emissions. The derived equation is:

$$NMOG_{EST} = (\%ETOH * 0.0071 + 1.0302) * NMHC$$

Equation [19]

Where $NMOG_{EST}$ is the estimated composite NMOG emissions, %ETOH is the fuel ethanol content, and NMHC is from the composite mass emissions. Of note is that use of Equation 19 results in increased prediction of the NMOG fraction as the percent of ethanol increases, although measurements presented show NMOG and NMHC decrease for greater concentrations of ethanol in the fuel in mg/mile for 3 of 4 drive cycles. It is also interesting to compare this to Equations 12 and 13 presented earlier that are used in the MOVES formulation. Both depend on NMHC but come to the answers in different ways with more fuel properties involved in the MOVES modeling.

Sluder, et.al., noted that the study used splash blended fuels. This caused several fuel properties to be dependent upon the fraction of ethanol used. Unfortunately this prevented a direct determination of the impact on the NMOG emissions from each fuel property.

Another interesting finding was that ethanol, acetaldehyde, and formaldehyde dominate the oxygenated emissions. This is of interest since the oxygen volume is used for speciation in the MOVES2014 model.

2.2.5 "Determination of the Potential Property Ranges of Mid-Level Ethanol Blends, Final Report"

A report by the American Petroleum Institute echoes the result of the NREL findings (API, 2010). Based on a much larger set of samples (71 ethanol-free gasoline samples blended with E0, E10, E12.5, E15, E20 and E30) the reported findings were, "…with one exception, blending ethanol into gasoline at concentrations between 10% and 30% by volume should pose no additional challenge to meeting the volatility requirement in the current ASTM D4814-9b specifications." The one exception was meeting the T_{50} specifications for certain volatility classes.

2.2.6 "Issues with T50 and T90 as Match Criteria for Ethanol-Gasoline Blends"

This paper (Anderson, 2014) makes a very important contribution to the literature relevant to the MOVES model. As discussed by the EPA documentation, the gasoline blendstock composition has important consequences for the emissions of the finished fuel. However, gasoline can be "splash-" or "match-blended" with ethanol, and the blending method may have important implications for emissions. In splash blending, ethanol is simply added to market-available gasoline, meaning the compositions are more clearly defined and effects on emissions may be more accurately determined. On the other hand, match blending results in the blendstock composition being modified to match one or more specific fuel properties, and emissions are dependent upon which fuel properties are matched. This results in more complexity in determining exact emission trends, and match blending may not reflect actual blending practices in the marketplace. This report points out that match blending may have fundamental flaws that are very complex in nature. Major flaws include that all temperature effects may not be similarly blended, hydrocarbon mixtures can confound the observed emissions, misuse or misrepresentation may easily occur, and actual results may not be adequately reproduced by models.

One flaw is particularly of interest in this study: the improper use of emission models. As was previously pointed out in the EPA documentation, EPAct requirements were considered. In the EPAct/V2/E-89 study, match blending was used to statistically isolate the effects of fuel property effects on emissions. Modeling is based on the fuel properties as described in the USEPA reporting (USEPA[a], 2013) from blends containing different ethanol content, aromatic hydrocarbon content, T50, T90, and RVP. Matched

blends may not properly characterize what is actually being used in the marketplace as a result of splash blending. The changes in fuel properties that occur as a consequence of splash blending, and to what degree, need to be determined.

Results were compared for two scenarios: use of splash blending to make E15 from E10 and use of match blending to make E15 from E10. The results are shown in Figure 19. As can be seen, for multiple emissions, considerable differences occurred in the two scenarios. For example, the use of splash blending shows a reduction in NMHC, PM, and many HC species. Other testing tended to verify these results.

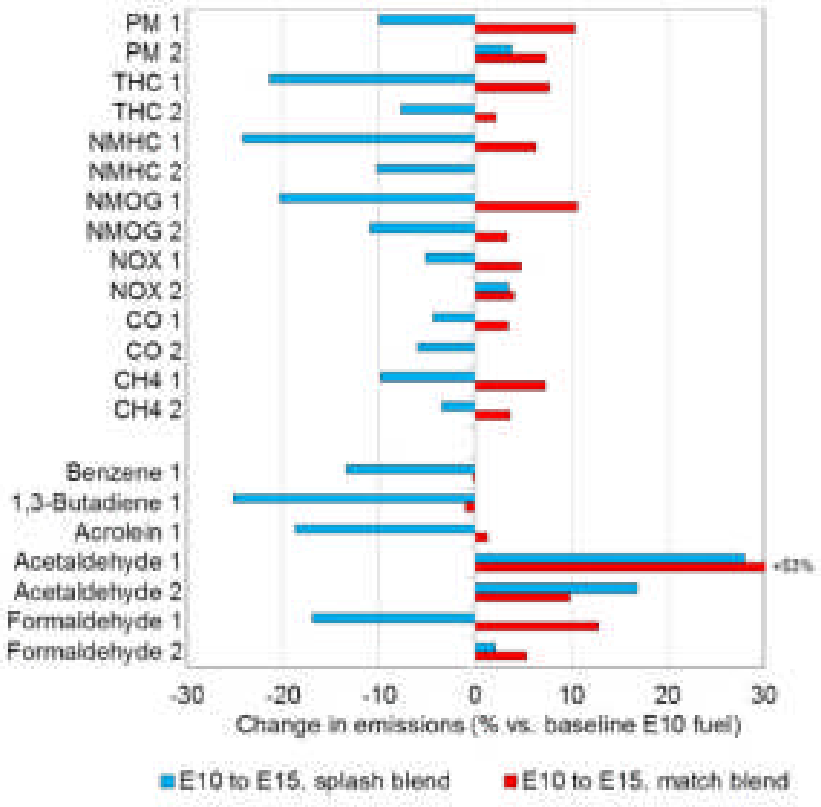


Figure 19. EPAct Model Results (match blend only increased ethanol content while T50, T90, RVP, and aromatic content were held constant).

In the Anderson study, the authors wished to show possible inappropriate use of models by different fuel blends. Table 18 provides the E10 base case used in EPAct, as well as a simulated E15 “splash blend” and an E15 blended to match E10 properties.

Table 18. Sample Fuel Property Combinations Used in EPAct Emission Model (bolded values are changed from the base case)(Anderson, 2014)

	Ethanol (%v)	Arom. (%v)	RVP (psi)	T50 (°F)	T90 (°F)
Fuel A – E10 (base)	9.95	23.3	7.20	217.1	308.2
Fuel B – E15 "splash"	**14.87**	**22.0**	**7.21**	**167.4**	**305.9**
Fuel C – E15 "match"	**14.87**	23.3	7.20	217.1	308.2

Multiple studies were referenced that show splash blended ethanol demonstrates reductions of some exhaust emissions including particulate matter, non-methane hydrocarbons, and two air toxics (1,3-butadiene and benzene).

2.2.7 "Impact of Ethanol Containing Gasoline Blends on Emissions From a Flex-Fuel Vehicle Tested Over the Worldwide Harmonized Light Duty Test Cycle (WLTC)"

While testing was accomplished in a slightly different fashion and both hydrous and anhydrous ethanol blends were tested, this study (Suarz-Betoa, 2014) does allow comparisons to emission factors derived using MOVES. Two driving cycles are tested: the Word-wide Harmonized Light Duty Test Cycle (WLTC) and the New European Driving Cycle (NEDC). These two cycles are shown in Figure 20 and when compared to Figure 6 show the WLTC to be closer to what was used in much of the USEPA development. A reference gasoline (E5) was testing along with four fuel blends for hydrous and anhydrous ethanol with mixtures of 10, 15, 75 and 85%.

Conclusions included that the emission factors were similar for E10 and E15 with no particular trend for CO_2 other than the higher blends (E85) resulted in less CO_2 than the E5-E15 blends. The high blends also resulted in reduced emissions of NOx (30 – 50% reductions) but increased emissions of CO, methane (CH_4), formaldehyde, acetaldehyde and ethanol. Low temperatures led to an increase in all studied compounds. Table 19 shows the results for all tests.

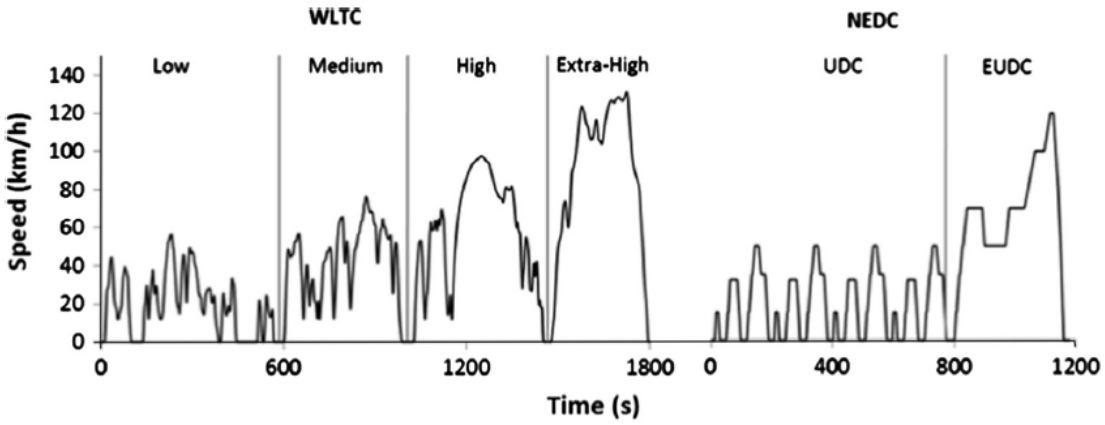


Figure 20. Drive Cycles Used In Emission Testing (Suarz-Betoa, 2014)

Table 19. Emission Factors Determined Over the NEDC and WLTC at -7 and/or 23ºC (mg/km with the exception of CO_2 which has the units g/km) (Suarz-Betoa, 2014)

	E5	AHE10	AHE15	HE10	HE15	AHE85	HE85	AHE75-7C	HE75-7C	E5-7C
NEDC mg/km										
THC	147	42	60	57	34	101	76	385	357	212
NMHC	126	34	48	49	25	72	40	229	208	197
CO	363	389	368	345	407	373	367	888	922	932
NO_x	10	13	10	9	10	6	8	23	19	25
CO_2*	169	172	170	171	171	156	163	187	188	164
Formaldehyde	1	1	1	1	1	2	2	4	4	2
Acetaldehyde	3	4	5	4	4	21	15	62	65	3
NH_3	4	11	9	8	10	13	15	19	14	5
N_2O	0.4	0.6	0.5	0.4	0.4	0.4	0.3	1.9	1.8	1.6
CH_4	5	6	7	5	7	18	19	46	54	20
EtOH	12	1	5	4	2	9	39	225	223	10
Ethane	2	1	1	1	1	1	1	4	5	3
Ethene	4	3	4	3	3	6	6	31	38	15
Propene	2	2	2	2	2	1	1	4	4	7
Acetylene	2	3	4	6	6	9	7	19	17	9
Isopentene	2	4	11	12	5	8	4	15	13	7
MeOH	0	2	2	1	1	3	1	5	2	0
Benzene	4	2	2	1	1	1	0	3	4	3
Toluene	17	5	5	4	2	3	1	9	11	15
OFP [mg O_3/km]	167	129	181	168	129	270	249	1099	1160	353
WLTC mg/km										
THC	93	42	39	40	43	71	69	202	198	139
NMHC	82	33	31	33	32	34	29	113	118	121
CO	394	469	400	363	423	735	606	1291	1248	932
NO_x	62	42	51	41	39	19	23	38	35	76
CO_2*	151	156	155	157	156	144	146	151	168	169
Formaldehyde	1	0	0	1	0	1	1	2	2	1
Acetaldehyde	1	3	3	3	3	10	11	31	35	2
NH_3	6	16	14	10	14	26	22	34	24	13
N2O	0.6	0.6	0.4	0.6	0.5	0.5	0.4	1.5	1.3	1.6
CH_4	7	7	7	6	6	26	24	56	60	17
EtOH	7	1	2	1	1	37	21	119	137	8
Ethane	1	1	0	0	0	1	1	3	3	3
Ethene	3	2	2	2	2	5	5	23	25	9
Propene	1	2	2	2	3	3	3	5	5	5
Acetylene	1	3	3	4	6	7	7	13	18	5
Isopentene	2	7	8	8	7	3	2	12	13	4
MeOH	0	2	2	1	1	1	2	1	1	0
Benzene	5	2	1	4	1	1	0	5	5	11
Toluene	15	5	4	11	2	2	1	14	14	22
OFP [mg O_3/km]	128	128	127	151	127	242	211	738	804	280

Euro 5a spark ignition emission limits (mg/km) at 22 °C: THC = 100; NMHC = 68; CO = 1000; NO_x = 60.

2.2.8 "Ethanol and Air Quality: Influence of Fuel Ethanol Content on Emissions and Fuel Economy of Flexible Fuel Vehicles"

This journal article from the Ford Motor Company (Hubbard, 2014) shows tailpipe emission trends for a vehicle operating on a chassis dynamometer. E0, E10, E20, E30, E40, E55, and E80 were evaluated. As ethanol content was increased, the tailpipe emissions of ethanol, acetaldehyde, formaldehyde, methane, and ammonia increased while NO_x and NMHC decreased. Emissions of CO, ethene, and N_2O were not discernibly affected. NMOG and THC emissions were at a minimum for mid-level blends (E20–E40) which was 25–35% lower than for E0 or E80. Emissions of NO_x decreased by approximately 50% as the ethanol content increased from E0 to E30–E40, with no further decrease seen with E55 or E80. Figure 21 shows some of the trends. NOx seems to primarily decrease with increasing ethanol fuel content but when hydrocarbons are included (in this case NMOG) the trend is to first decrease and then at about a blend of E40 start to increase.

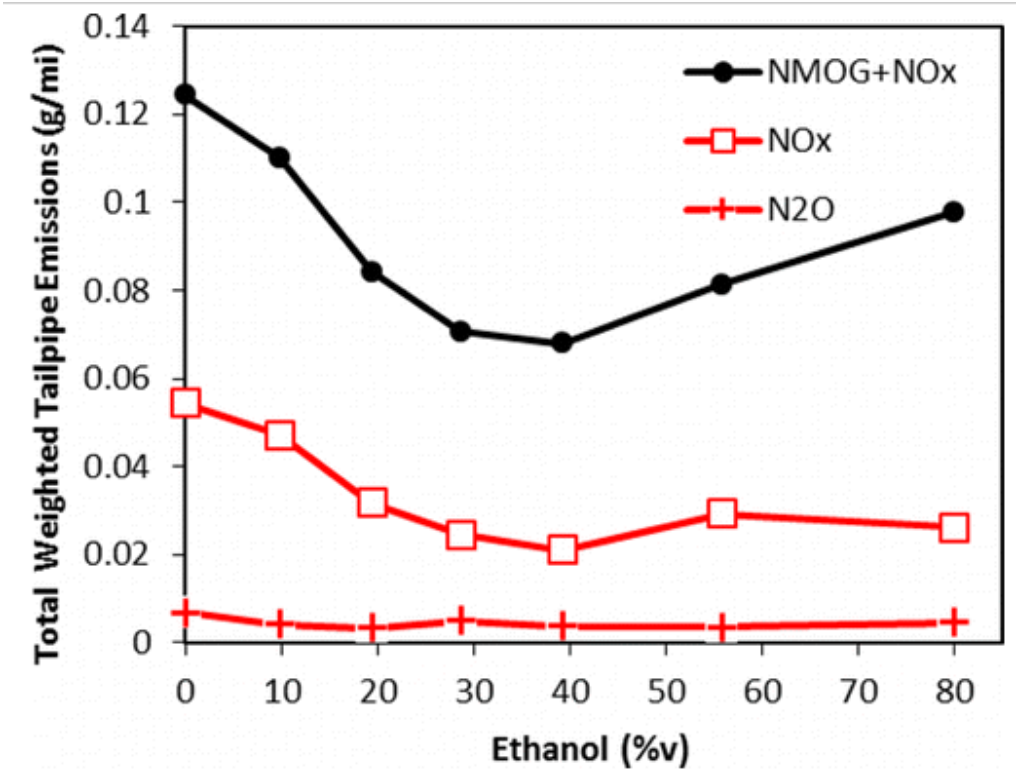


Figure 21. Exhaust Emission Trends for NMOG+NOx, NOx and N_2O (Hubbard, 2014)

This paper varies from MOVES2014 model predictions, which generally indicate increases in nitrogen components as ethanol content increases from 5%.

2.2.9 "Effect of Ethanol – Gasoline Blend on NOx Emission in SI Engine"

While trends in NOx emissions related to various ethanol fuel blends have been reported, with numeric values differing, this report pointed out the inconsistences (Masum, 2013). The report drew upon a large literature review. The report also explores the effects of engine parameters (compression ratio, engine load, equivalence ratio, speed, and cold-start). Trends as previously reported in some cases (e.g., NOx emission decrease with increase in ethanol content, etc.) but note the difference in Figure 22 compared to Figure 21 and even the opposite trend as was presented in Figure 4. The paper also notes that reported trends change in response to variances in engine speed (rpm). Figure 22 shows the trend at 2000 rpm as reported by others (Gravalos, 2011). The steady decrease in NOx for increased ethanol content is apparent and HC decreases until about E40, at which point HC emissions begin to increase. Next consider the results provided for 3500 RPM from another research team shown in Figure 23 (Najafi, 2009). In this case, the NOx emissions continue to increase with increasing ethanol content while HC are shown to continue to decrease. In Figure 22, the trend for NOx was attributed to a reduction in flame temperature (NOx is a function of pressure, temperature and residence time). In Figure 23, the opposite was supposed due to reaching stoichiometric conditions leading to higher temperatures. The two explanations seem to conflict unless the higher RPM is considered to have a larger effect than the fuel blend on combustion parameters. This shows that emissions trends may be significantly affected by variables that need to be more considered in MOVES. Many variables are not easily defined, such as engine speed, and in reality these types of variables are changing with each drive cycle, speed, or due to the weight of the vehicle.

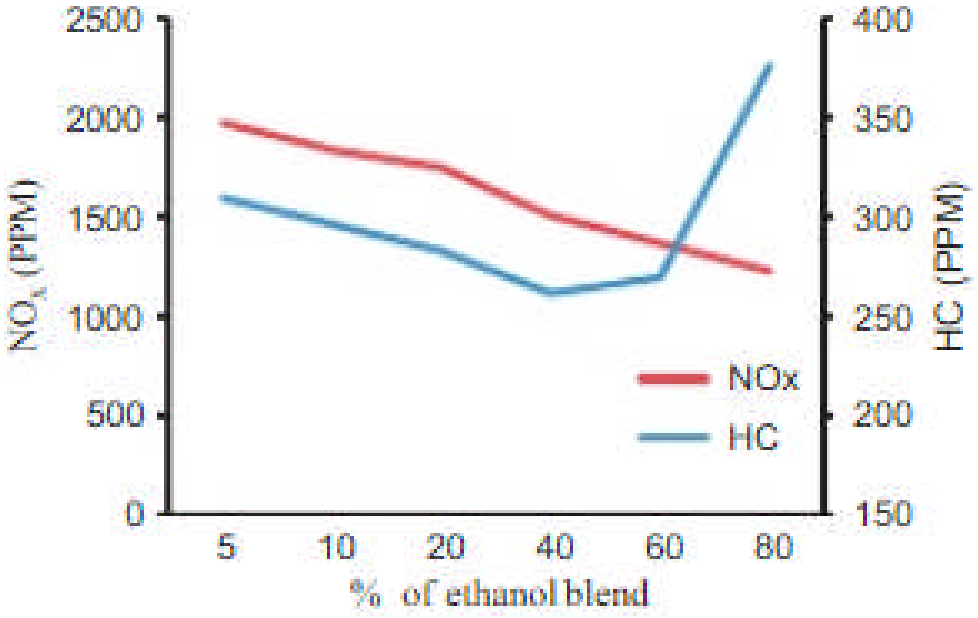


Figure 22. NOx and HC Emissions at 2000 RPM (Gravalos, 2011)

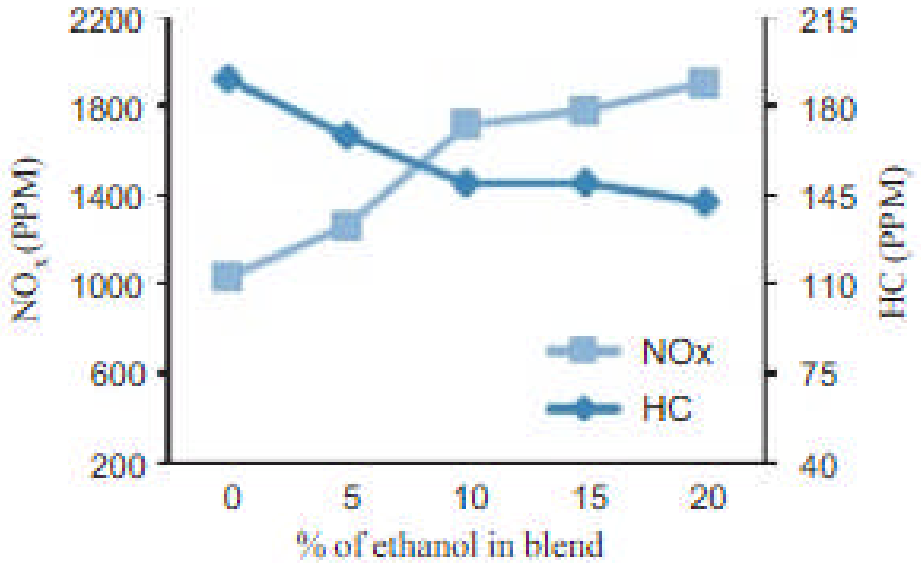


Figure 23. NOx and HC Emission Trends at 3500 RPM (Najafi, 2009)

2.2.10 "Comparative Emissions Testing of Vehicles Aged on E0, E15 and E20 Fuels"

This comprehensive document (Vertin, 2012) examines the effects on emissions due to vehicle driven on fuels with different ethanol content over an extended mileage. Four vehicle types were aged to 120,000 miles from the 2009 fleet and 2 vehicle types, model year 2000, were aged 50,000 miles from the original mileage on the vehicle. Fuels blends tested included E0, E15, and E20. Three of each vehicle type were tested, aged on the three fuel blends. While multiple parameters (e.g., catalyst effects) were being tested, only emission results are discussed. Even with this reduction, showing comprehensive results is difficult since different trends occurred for different vehicles, fuel blends, and by miles of aging. Vertin, et.al, provided detailed graphs for each vehicle type, for three pollutants (NMHC, CO, and NOx) by fuel use and vehicle odometer miles. The interested reader is directed to the report for full details. Only the important findings for exhaust emissions and further detail on evaporative emissions are included in this reporting.

Findings from the measurement of exhaust emissions included:

- Use of the higher ethanol blends, compared to E0, did not produce higher exhaust emissions.
- NMHC and CO exhaust emissions from the E15 and E20 blends were similar or lower than E0. NOx emissions were not statistically different.
- Most (17 of 18) vehicles showed increased NOx emissions with aging.
- Four of the 6 vehicle types tested show that the greater emissions occur with E0.
- Mixed results occurred in the six vehicle types for pollutant trends when E0 was compared to E15 and E20. Use of the ethanol mixed fuels did not show major changes to exhaust components.

Evaporative emissions were also measured during aging. Figure 24 shows the results of this testing for the 2009 model year vehicles. The reader is reminded that MOVES2014 predicts higher emissions based on ethanol effects on seals. It can be seen from the Figure 24 that the results varied and were sometimes higher for E15 than E0 and sometimes lower. While not general trend seems apparent, evaporative emissions of the E15 fuel were less at 120,000 miles for 3 of the 4 vehicle types.

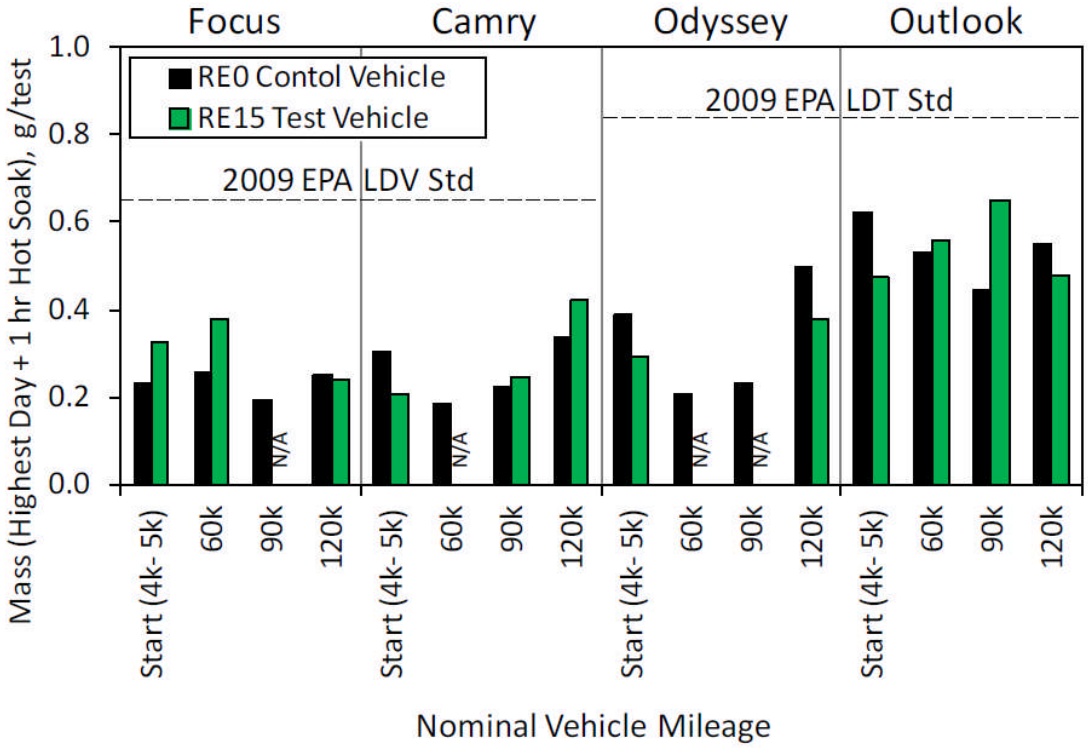


Figure 24. Evaporative Emissions Results for 2009 Model Year Vehicle Types (Vertin, 2012)

2.2.11 Summation of General Reporting

The results from other researchers often show ethanol-related emissions trends that are different than the MOVES2014 results obtained for this study for pollutant trends with increasing ethanol and for evaporative emissions. Changes to some fuel variables may not have as large of an impact on emissions as is predicted in MOVES2014. In some cases not only were magnitudes different but different trends were presented. For example, Maricq shows a decrease in NOx emissions with increased ethanol fuel content whereas MOVES2014 predicts an increase. In addition, real-world splash blends may not have the same attributes as the modeled default match blends used in MOVES, and actual emissions may be different than the emissions predictions from MOVES. Finally, as highlighted by some the papers reviewed, the use of the fuel properties and Fuel Wizard in MOVES must be considered carefully when determining changes due to ethanol blends to prevent inaccurate use of models. Moreover, trends used to determine constants in MOVES equations may need to consider many more variables than are now being considered. One last concern was the effects of using ethanol blends over time. Research by Vertin, et.al., concluded that no increased emissions occurred from vehicle aging (miles driven) using ethanol blends as compared to E0.

3 TESTING OF MOVES2014

The evaluation of MOVES2014 included reviewing inputs and a sensitivity study of fuels available in MOVES, changes with the use of customized fuel properties, and evaporative emission prediction changes. The analysis consisted of four separate test scenarios:

1. Fuel Wizard Ethanol Sensitivity Analysis
2. Splash Blend Analysis
3. Fuel Formulation Parameter Sensitivity Analysis
4. Evaporative Fuel Leak Ethanol Sensitivity Analysis

Categories of inputs overlap and ranges of inputs had to be evaluated. Figure 25 shows a Venn diagram of inputs that were determined to be important in this evaluation. Using this as a starting point, the test cases were defined and the ranges of test values determined. A detailed description of this testing methodology derived for MOVES2014 is included in Appendix A.

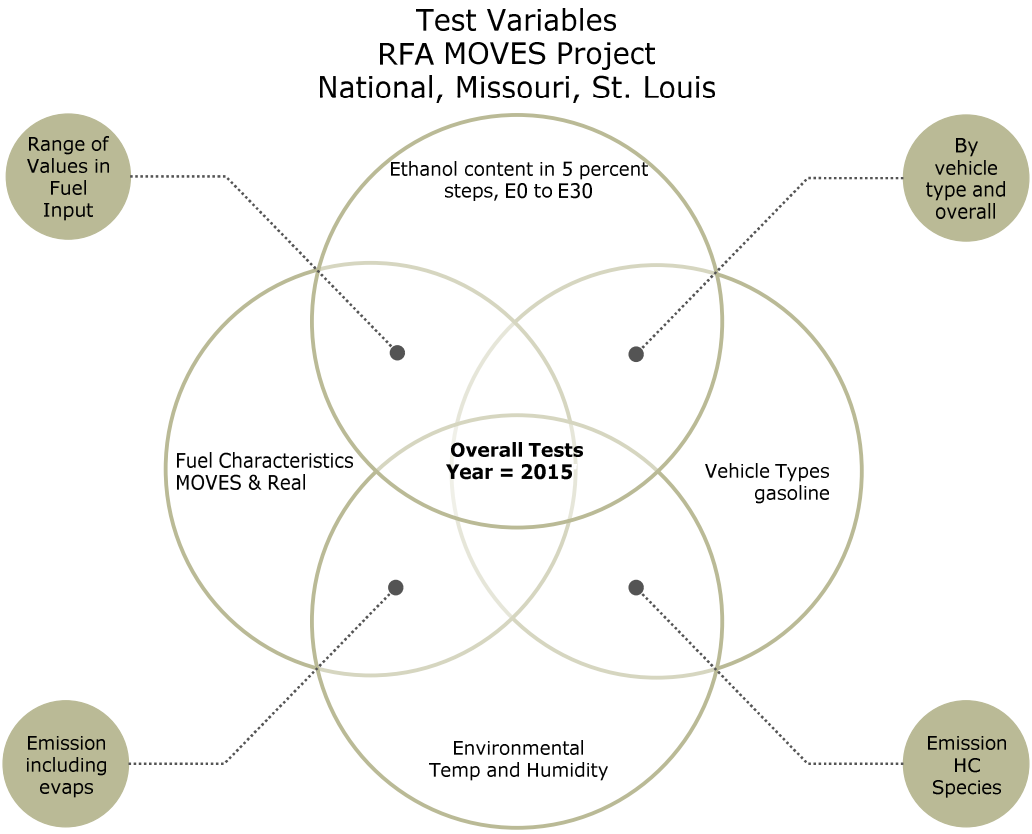


Figure 25. Determination of MOVES Test Matrix

3.1 Base MOVES2014 Test Parameters

Input in the MOVES Run Specification and Project Data Manager (PDM) were kept the same for all four components of the analysis, with the exception being the fuel supply and fuel formulation input data used for each individual MOVES run depending on the test scenario. The run constants are partially based off a National Scale MOVES run for the year 2015 for annual average meteorology and link source type data (fleet mixture). The MOVES Run Specification information, including the parameters held constant and varied is listed in Table 20. This permitted a review of how the isolated changes in fuel input affected the model output. The Project Scale runs for each analysis component consisting of running a single hour for two distinct roadway links where the links represented two highway facility types; urban restricted and unrestricted access. The two facility types allowed two different drive cycles to be evaluated. The urban restricted access drive cycle had an average speed of 35 miles per hour while the urban restricted access facility type had an average speed of 50 miles per hour. Each drive cycle includes all vehicle modes; idle, acceleration, deceleration, and cruise. Fuel Supply and Fuel Formulation Tables were varied for each MOVES run depending on the analysis scenario and are discussed in the following sections.

To determine fuel types from the MOVES2014 default database (version: movesdb20141021cb6v2), the Fuel Supply and Fuel Formulation Tables were reviewed for ranges included as well as average. The year 2015 was used for all analysis and there are a total of 75 unique gasoline fuel formulations for E10 and E15 in the MOVES default database. There are 40 unique summer (June through September) gasoline fuel formulations (gasohol E10 and E15). Four fuel formulations were chosen from the list of 40 summer gasoline fuel formulations based upon the low, mid, and high values of Reid Vapor Pressure (RVP) and aromatic content to form a base with fuel properties varied for each fuel type, resulting in a manageable number of MOVES2014 runs for evaluation. The four base fuels from the MOVES2014 default fuels are Fuel Formulation ID 3202, 3204, 3212, and 3307. The base fuel properties of these fuels is shown in Table 21 for the blends included, E10 and E15. Figure 26 shows the differences graphically with the exception of benzene content. The benzene contents are not included in the graph due to the smaller values resulting in poor user readability. A total of 18,923 unique fuel mixtures occurred in this analysis.

3.2 Fuel Wizard Ethanol Sensitivity Analysis

In the Fuel Wizard sensitivity analysis, the ethanol content for each formulation of fuel properties analyzed was changed in 5% increments from 0% to 30%. Evaluations were made for the four selected fuel types, 10 pollutant types, 2 facility types, and 11 vehicle types.

Table 20. MOVES Run Specification

MOVES Navigation Panel Item	Modeling Parameters	Modeling Parameter Selections
Scale	Model	Onroad
	Domain/Scale	Project
	Calculation Type	Inventory
Time Span	Time Aggregation Level	Hour
	Years	2015
	Months	July
	Days	Weekdays
	Hours	8:00
Geographic Bounds	Region	Custom Domain
	State ID	99
	County ID	1
	GPA Fraction	0
	Barometric Pressure	28.94
	Vapor Adjust	0
	Spill Adjust	0
Vehicles/Equipment	On Road Vehicle Equipment	Gasoline - Combination Short-Haul Truck
		Gasoline -Light Commercial Truck
		Gasoline - Motor Home
		Gasoline - Motorcycle
		Gasoline - Passenger Car
		Gasoline - Passenger Truck
		Gasoline - Refuse Truck
		Gasoline - School Bus
		Gasoline - Single Unit Long-haul Truck
		Gasoline - Single Unit Short-haul Truck
		Gasoline - Transit Bus
Road Type	Selected Road Types	Urban Restricted Access
		Urban Unrestricted Access
Pollutants and Processes (Analysis Components #1,#2, and #3)	Pollutant Processes	Running Exhaust and Crankcase Running Exhaust
	Pollutants	Total Gaseous Hydrocarbons
		Non-Methane Hydrocarbons
		Volatile Organic Compounds
		Carbon Monoxide (CO)

MOVES Navigation Panel Item	Modeling Parameters	Modeling Parameter Selections
		Oxides of Nitrogen (NOX)
		Nitrogen Dioxide (NO2)
		Primary Exhaust PM2.5 - Total
		Primary Exhaust PM2.5 - Species
		Primary Exhaust PM10 - Total
		Sulfur Dioxide (SO2)
		Total Energy Consumption
		Atmospheric CO2
		Ethanol
Pollutants and Processes (Analysis Component #4)	Pollutant Processes	Evaporative Fuel Leaks
	Pollutants	Total Gaseous Hydrocarbons
		Non-Methane Hydrocarbons
		Non-Methane Organic Gases
		Total Organic Gases
		Volatile Organic Compounds
General Output	Mass Units	Grams
	Energy Units	Million BTU
	Distance Units	Miles

Table 21. Fuel Property Ranges for E10 and E15 Used in Analysis

E10	*RVP*	*Aromatic Content*	*Olefin Content*	*Benzene Content*	*e200*	*e300*	*T50*	*T90*
MIN	6.9	17.58	4.44	0.53	44.52	79.95	182.79	279.1
MAX	13.73	25.77	12.52	0.86	57.36	91.2	211.23	341.04
AVG	9.67	22.50	8.80	0.64	50.61	84.59	198.51	320.34
STD	1.72	2.35	2.47	0.07	3.43	2.71	8.46	15.46
E15								
MIN	6.9	14.61	4.97	0.53	52.02	80.58	168.21	276.96
MAX	12.73	24.43	11.34	0.86	63.59	88.1	197.59	338.22
AVG	9.18	19.74	7.97	0.65	58.23	85.30	182.27	318.48
STD	1.55	3.24	2.12	0.08	3.40	2.14	8.69	13.28

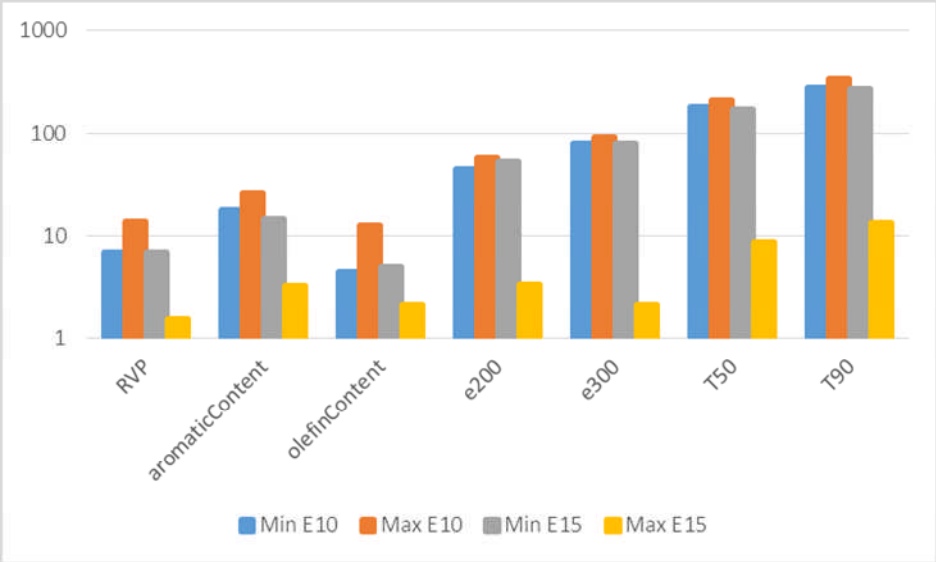


Figure 26. Graphical Comparison of Fuel Property Ranges for E10 and E15 Used in Analysis With the Exception of Benzene Content (units correspond to variable)

When the ethanol content is changed using the Fuel Wizard in MOVES2014, the program automatically adjusts the RVP, aromatic content, olefin content, e200, e300, T50, and T90 parameters, as well as the fuelsubtypeID, to match blends built into MOVES2014. The values for the fuel formulation parameters are shown in Appendix A, Table A.2.

However, when applying a 20% or greater ethanol content in the MOVES Fuel Wizard, the MOVES subtypeID does not adjust the other fuel properties. This important point is discussed in more detail in Section 4.2 and Appendix A.

3.3 Splash Blend Analysis

It was desirable to deviate from the default match blend fuel properties included in MOVES2014 and attempt to evaluate real world splash blends. RFA provided a listing of a base fuel, one match blend and four splash blended fuels in the year 2015. Parameters in the base case were based on the report by Anderson (See Table 18). The splash blends were created by adding denatured fuel ethanol (E98) to an E10 base fuel with RVP kept at a maximum of 7.0 psi assuming a non-attainment market.

The formulations for the base, one match blend, and the splash blends evaluated with MOVES2014 are listed in Table 22. As shown, the fuel blends ranges from E10 to E30 with other parameters being the real-world values that occurred (RVP held constant).

The real-world formulation for splash blends were associated with real summer blend fuel formulations were geographically associated with Atlanta, Detroit, Saint Louis and Kansas City.

Table 22. Listing of Base Fuel, E15 Match Blend and Four Splash Blends Used in Splash Blend Analysis (Provided by RFA 2015)

Formulation Name	RVP	Sulfur	Ethanol	Aromatics	Olefins	Benzene	E200	E300	T50	T90
	psi	*ppm*	*%vol*	*%vol*	*%vol*	*%vol*	*%*	*%*	*deg. F*	*deg. F*
E10 (Reference/ Base Fuel)	7.0	25.0	9.95	23.3	10.1	0.60	51.0	85.0	217.1	308.2
E15 (Match)	7.0	25.0	14.85	23.3	10.1	0.60	51.0	85.0	217.1	308.2
E15 (Splash)	7.0	24.3	14.85	22.1	9.6	0.57	57.0	86.0	167.4	305.9
E20 (Splash)	7.0	23.5	19.85	20.9	9.1	0.54	58.0	86.5	166.5	305.1
E25 (Splash)	7.0	22.5	24.85	19.8	8.6	0.51	57.0	85.5	168.1	303.9
E30 (Splash)	7.0	21.0	29.85	18.6	8.1	0.48	56.0	85.0	170.1	302.0

* Based on Appendix Table A-3 of Anderson, 2014 and discussion with fuel specification experts

3.4 Fuel Formulation Parameter Sensitivity Analysis

For the Fuel Formulation Parameter Sensitivity Analysis the fuel formulation parameters RVP, sulfur level, ethanol volume, aromatic content, olefin content, T50, and T90 were all varied individually while holding all other parameters constant. Starting with the base fuel types, 32 pollutant types, 7 ethanol volume blends (E0 to E30 in 5% increments), 11 vehicle types, and 2 roadway facility types (urban restricted and unrestricted access) were determined for a total of 38,874 different fuels variations that could occur. The reason for the large number of pollutant types is that various species of PM and PM precursors that could be evaluated as well as various hydrocarbon species. The purpose of this analysis was to determine how the variation of each independent fuel formulation property impacted the resulting emissions rates and fuel formulation ID 3202 from the MOVES2014 default database was chosen as the baseline fuel formulation for this analysis to reduce the large number to a more manageable number. Table 23 lists the parameters associated with this fuel formulation ID. Table 24 lists the fuel properties values used in the various MOVES2014 runs. For example, for MOVESRunIDs 1 through 9, RVP was varied while holding all other fuel formulation parameters constant. This same approach was applied for the other fuel formulation parameters listed in the table.

Table 23. Fuel Formulation 3202 Parameters

fuelFormulationID	3202
fuelSubtypeID	12
RVP	7.8
sulfurLevel	30
ETOHVolume	10
aromaticContent	23.23
olefinContent	12.52
benzeneContent	0.61
e200	44.7454
e300	80.4412
T50	210.54
T90	341.04

Table 24. Fuel Formulation Fuel Parameter Sensitivity Analysis Runs

MOVESRunID	Fuel Parameter	Parameter Value
1	RVP	6
2	RVP	6.5
3	RVP	7
4	RVP	7.5
5	RVP	Baseline
6	RVP	8
7	RVP	8.5
8	RVP	9
9	RVP	9.5
10	sulfurLevel	0
11	sulfurLevel	5
13	sulfurLevel	10
14	sulfurLevel	15
15	sulfurLevel	20
16	sulfurLevel	25
17	sulfurLevel	Baseline
18	sulfurLevel	35
19	sulfurLevel	40
20	sulfurLevel	45
21	sulfurLevel	50
22	aromaticContent	0
23	aromaticContent	5
24	aromaticContent	10
25	aromaticContent	15
26	aromaticContent	20
27	aromaticContent	Baseline
28	aromaticContent	25

MOVESRunID	Fuel Parameter	Parameter Value
29	aromaticContent	30
30	aromaticContent	35
31	aromaticContent	40
32	olefinContent	0
33	olefinContent	5
34	olefinContent	10
35	olefinContent	Baseline
36	olefinContent	15
37	olefinContent	20
38	olefinContent	25
40	T50	175
41	T50	200
42	T50	Baseline
43	T50	225
44	T50	250
45	T90	300
46	T90	310
47	T90	320
48	T90	330
49	T90	340
50	T90	Baseline
51	T90	350
52	ETOHVolume	0
53	ETOHVolume	5
54	ETOHVolume	10
55	ETOHVolume	15
56	ETOHVolume	20
57	ETOHVolume	25
58	ETOHVolume	30

3.5 Evaporative Fuel Leak Ethanol Sensitivity Analysis

The MOVES runs used for the Evaporative Fuel Leak Ethanol Sensitivity Analysis were similar to the Fuel Wizard Ethanol Sensitivity analysis in that the MOVES Fuel Wizard was used to adjust the ethanol content. However, only the evaporative fuel leak emissions process was chosen to be run in this analysis, with the Fuel Wizard Ethanol Sensitivity Analysis focused on running exhaust and running and crankcase running exhaust emission processes. Fuel formulation 3202 was again utilized for this analysis. The fuel formulation parameters analyzed are listed as MOVESRunIDs 8 through 14 in Table A.2 of Appendix A.

3.6 Summary of Test Parameters Evaluated

A total of 68,400 fuels make up the MOVES2014 master fuel list. Reducing for only gasoline based fuels, 25,421 fuel combinations from MOVES2014 were originally

identified that could be used in this analysis. Based on available resources a reduction was required. As previously discussed, for the year 2015 a total of 75 unique gasoline fuel formulations (E10 and E15) are in the MOVES2014 default database. By using only the summer (June through September) gasoline formulations, the list of unique formulations was further reduced to 43 for E10 and 37 for E15. Then based on the literature and choosing low, mid, and high values of Reid Vapor Pressure (RVP) and aromatic content, it was possible to reduce the analysis to a base of four fuel formulations from the lists of summer gasoline fuel formulations. Even with this large reduction, ranges of values were evaluated that increased the number of unique variations of fuel back to 18,923 for the Fuel Wizard analysis scenario and 38,874 for the Fuel Formulation analysis scenario when all fuel variables, vehicle types, facility types and pollutants were analyzed. These numbers were reduced to manageable limits based on available resources by using only 4 fuel types in the Fuel Wizard analysis and a single fuel type in the Fuel Formulation analysis and Evaporative Emission Analysis. Fuel blends of E0 to E30 were evaluated in all scenarios. Many ethanol blends were evaluated using manual input for fuel properties that are not part of the MOVES2014 database during the analyses.

4 RESULTS OF MOVES2014 TESTS

4.1 Reporting Format

As would be expected, with several thousand lines of data and 45 columns, all results could not be included in a manageable way in this report. Accordingly, excerpts, important tables and example figures are included to show detail, trends, and support conclusions. In some cases, additional material has been included in Appendix B when thought to be important. Appendix B is actually multiple spreadsheets made available to RFA with inclusive data. Additionally, emission levels are reported to several digits as output by MOVES2014. The extended decimal place results are not meant to imply any degree of precision or accuracy, but only to report in a consistent manner with MOVES2014 output.

4.2 Results from Fuel Wizard Ethanol Sensitivity Analysis

While previously mentioned, an important discovery in MOVES2014 is discussed here with more detail. When running the MOVES2014 Fuel Wizard, a change to the ethanol content causes other fuel properties to automatically change based on matched fuel blends that are included in the MOVES2014 database as Fuel Subtype IDs. These fuel properties are RVP, aromatic content, olefin content, e200, e300, T50, and T90

parameters, as well as the fuelsubtypeID. When the ethanol content input is 20% or greater, the MOVES subtypeID is not adjusted, which results in a default fuel formulation being used by MOVES while executing the model. This default fuel formulation was not what was desired for the sensitivity analysis and for ethanol content of 20% or greater, the fuel subtypeID field had to be manually changed in the Excel table for Fuel Formulation Input to the value of 18 to allow the desired changes. This fact that manual changes must be made to the Excel spreadsheet input is important here and also when splash blends are analyzed to allow the correct fuel properties to be used. *Future users should be aware of how match blends are used in MOVES2014 and manually change values in the Fuel Formulation Input spreadsheet to achieve desired results in cases where the fuel properties are known, such as in splash blends. However, even in cases where fuel properties are manually modified, MOVES 2014 may generate emissions results that appear to conflict with some results reported in the literature.*

As previously described, results are included for 4 fuel types included in the MOVES2014 default database. Results shown here are only for passenger cars since similar trends occur for the other vehicle types (although absolute values change). More information is provided in Appendix B for the other vehicle types. Fuel type, vehicle types, facility types were changed while holding the other variables constant as shown in Table A1.

Table 25 shows a listing for the 10 pollutant categories emission rates evaluated for passenger cars for each of the 4 fuel types for urban restricted access facilities. Table 26 shows the same information for urban unrestricted access facilities.

Table 25. Evaluation Results for Pollutant Emission Rates for Passenger Cars, Urban Restricted Access (emission rates shown for each fuel type and ethanol content are g/mi)

	Fuel Type			
Pollutant				
Ethanol Content	**3202**	**3204**	**3212**	**3307**
CO				
0	1.899497	1.89852	1.925968	1.753357
5	1.839256	1.84574	1.879252	1.691109
10	1.787268	1.800544	1.83718	1.637478
15	1.72435	1.737702	1.776839	1.582057
20	1.67986	1.693256	1.731906	1.541402

	Fuel Type			
Pollutant				
Ethanol Content	**3202**	**3204**	**3212**	**3307**
25	1.651258	1.664494	1.702161	1.51345
30	1.624729	1.637821	1.674584	1.48756
NO_2				
0	0.036429	0.036622	0.036649	0.03529
5	0.037742	0.037952	0.037994	0.036631
10	0.039278	0.039523	0.039565	0.038195
15	0.040946	0.041195	0.041274	0.039906
20	0.043004	0.043277	0.043374	0.041996
25	0.045517	0.045816	0.045925	0.044528
30	0.048591	0.048921	0.049041	0.047615
NOx				
0	0.283049	0.284799	0.284694	0.274075
5	0.29325	0.295142	0.295165	0.284574
10	0.305395	0.30761	0.307616	0.297024
15	0.318647	0.3209	0.321229	0.310716
20	0.335257	0.337721	0.338195	0.327671
25	0.355788	0.358488	0.359059	0.348434
30	0.381301	0.384281	0.384928	0.374129
THC				
0	0.052553	0.051754	0.050757	0.048232
5	0.051814	0.051003	0.050064	0.047505
10	0.053011	0.052303	0.050652	0.048527
15	0.055301	0.054543	0.053978	0.051105
20	0.061184	0.060379	0.059929	0.056478
25	0.071592	0.070572	0.069962	0.065291
30	0.087789	0.086439	0.085589	0.079007
VOC				
0	0.046166	0.045533	0.044761	0.042287
5	0.046331	0.04568	0.044951	0.042367
10	0.04836	0.0478	0.046363	0.044124
15	0.045758	0.045172	0.044773	0.042198
20	0.051855	0.051214	0.050902	0.047759
25	0.060978	0.06015	0.059699	0.05548
30	0.0752	0.074083	0.073423	0.067519
Ethanol				
0	2.64E-05	2.67E-05	2.51E-05	4.33E-05
5	0.000484	0.000481	0.000476	0.000474
10	0.001012	0.001009	0.000982	0.000982

Pollutant / Ethanol Content	Fuel Type 3202	3204	3212	3307
15	0.001036	0.001032	0.001025	0.001076
20	0.001332	0.00133	0.001317	0.001467
25	0.001812	0.001809	0.001781	0.002095
30	0.002626	0.002624	0.002568	0.003186
$PM_{2.5}$				
0	0.00413	0.004102	0.004128	0.003773
5	0.004243	0.004214	0.004242	0.003868
10	0.004362	0.004332	0.004361	0.003968
15	0.004483	0.004451	0.004481	0.004069
20	0.004641	0.004607	0.004639	0.004202
25	0.004843	0.004807	0.004841	0.004371
30	0.00506	0.005021	0.005058	0.004553
PM_{10}				
0	0.004632	0.004601	0.00463	0.004231
5	0.004759	0.004726	0.004757	0.004338
10	0.004892	0.004858	0.00489	0.00445
15	0.005027	0.004991	0.005025	0.004563
20	0.005204	0.005166	0.005202	0.004712
25	0.005431	0.00539	0.005429	0.004902
30	0.005675	0.005631	0.005672	0.005106
SO_2				
0	0.005651	0.005651	0.005651	0.005651
5	0.005768	0.005768	0.005768	0.005768
10	0.005884	0.005884	0.005884	0.005884
15	0.006005	0.006005	0.006005	0.006005
20	0.006131	0.006131	0.006131	0.006131
25	0.006131	0.006131	0.006131	0.006131
30	0.006131	0.006131	0.006131	0.006131
CO_2				
0	295.2506	295.2506	295.2506	295.2506
5	295.2506	295.2506	295.2506	295.2506
10	295.2506	295.2506	295.2506	295.2506
15	295.2506	295.2506	295.2506	295.2506
20	292.2374	292.2374	292.2374	292.2374
25	292.2374	292.2374	292.2374	292.2374
30	292.2374	292.2374	292.2374	292.2374

Table 26. Evaluation Results for Pollutant Emission Rates for Passenger Cars, Urban Unrestricted Access (emission rates shown for each fuel type and ethanol content are g/mi)

	Fuel Type			
Pollutant				
Ethanol Content	**3202**	**3204**	**3212**	**3307**
CO				
0	2.389156	2.389286	2.424446	2.201454
5	2.316546	2.325617	2.367991	2.126512
10	2.253827	2.270997	2.317108	2.061877
15	2.176358	2.193593	2.242662	1.993621
20	2.122058	2.139336	2.187783	1.944028
25	2.087857	2.104942	2.152221	1.910601
30	2.056133	2.073045	2.119246	1.879644
NO_2				
0	0.036693	0.036892	0.036915	0.035545
5	0.038016	0.038231	0.03827	0.036897
10	0.039566	0.039817	0.039855	0.038476
15	0.04125	0.041505	0.041581	0.040205
20	0.043332	0.043611	0.043705	0.04232
25	0.045877	0.046183	0.04629	0.044885
30	0.048996	0.049334	0.049451	0.048019
NOx				
0	0.28673	0.288531	0.288388	0.277625
5	0.297062	0.299011	0.298998	0.28827
10	0.30939	0.31167	0.31164	0.300913
15	0.32285	0.325168	0.325468	0.314832
20	0.339744	0.342282	0.342729	0.332089
25	0.360659	0.36344	0.363984	0.353248
30	0.386691	0.389758	0.390382	0.379474
THC				
0	0.065564	0.064603	0.063416	0.060128
5	0.064627	0.063651	0.062533	0.059199
10	0.066163	0.065315	0.063285	0.060504
15	0.069105	0.06819	0.067537	0.063793
20	0.076608	0.075631	0.075121	0.070633
25	0.089869	0.08862	0.087906	0.08186
30	0.110525	0.108856	0.107837	0.099348
VOC				
0	0.05783	0.057066	0.056142	0.052937

	Fuel Type			
Pollutant Ethanol Content	**3202**	**3204**	**3212**	**3307**
5	0.05805	0.057261	0.056389	0.053042
10	0.060649	0.059976	0.058196	0.055288
15	0.057345	0.056635	0.056174	0.052831
20	0.065101	0.06432	0.06397	0.059898
25	0.076732	0.075713	0.075185	0.069737
30	0.094874	0.093487	0.092693	0.085091
Ethanol				
0	3.09E-05	3.12E-05	2.93E-05	5.06E-05
5	0.000613	0.000609	0.000603	0.000597
10	0.001283	0.001279	0.001244	0.001237
15	0.001304	0.0013	0.001291	0.001342
20	0.001665	0.001662	0.001648	0.001813
25	0.00225	0.002245	0.002212	0.002568
30	0.003239	0.003234	0.003168	0.003874
$PM_{2.5}$				
0	0.00469	0.004658	0.004688	0.004279
5	0.00482	0.004787	0.004818	0.004388
10	0.004957	0.004922	0.004955	0.004503
15	0.005095	0.005058	0.005093	0.004619
20	0.005277	0.005238	0.005275	0.004772
25	0.005509	0.005467	0.005507	0.004967
30	0.005759	0.005714	0.005756	0.005176
PM_{10}				
0	0.005259	0.005224	0.005257	0.004799
5	0.005405	0.005368	0.005403	0.004921
10	0.005559	0.00552	0.005557	0.00505
15	0.005714	0.005673	0.005712	0.005181
20	0.005918	0.005874	0.005915	0.005352
25	0.006178	0.006131	0.006176	0.00557
30	0.006458	0.006408	0.006455	0.005805
SO_2				
0	0.006153	0.006153	0.006153	0.006153
5	0.00628	0.00628	0.00628	0.00628
10	0.006407	0.006407	0.006407	0.006407
15	0.006539	0.006539	0.006539	0.006539
20	0.006677	0.006677	0.006677	0.006677
25	0.006677	0.006677	0.006677	0.006677

	Fuel Type			
Pollutant Ethanol Content	**3202**	**3204**	**3212**	**3307**
30	0.006677	0.006677	0.006677	0.006677
CO_2				
0	321.5006	321.5006	321.5006	321.5006
5	321.5006	321.5006	321.5006	321.5006
10	321.5006	321.5006	321.5006	321.5006
15	321.5006	321.5006	321.5006	321.5006
20	318.2195	318.2195	318.2195	318.2195
25	318.2195	318.2195	318.2195	318.2195
30	318.2195	318.2195	318.2195	318.2195

Several interesting trends occur in MOVES2014 when the ethanol mixtures are compared to gasoline (E0). Emission rates for the urban unrestricted access are always slightly greater for all cases, as would be expected due to the increased average speed and increased fuel use. This trend is shown for CO for Fuel type 3202 in Figure 27. However, the magnitude of increases due to the roadway type is not the same and varies widely by pollutant type (see Figure 28), with a maximum of 26.75% for ethanol emissions (E10 mixture) and a minimum of 0.73% for NO_2 (E5 mixture). CO and hydrocarbon species display the greatest increases, nitrogen species the least increase, while particulate matter, SO_2 and CO_2 are between the other changes. Also, while some trends for pollutants show a constant rate of change, other pollutants do not demonstrate linear trends. Hydrocarbons, most likely affected by speciation constants as described in Section 2.1.5, display the differences in trends. This is exemplified by ethanol when compared to gasoline, showing an increase for E5, the increase staying relatively constant for E10, and then decreasing for increased ethanol blends.

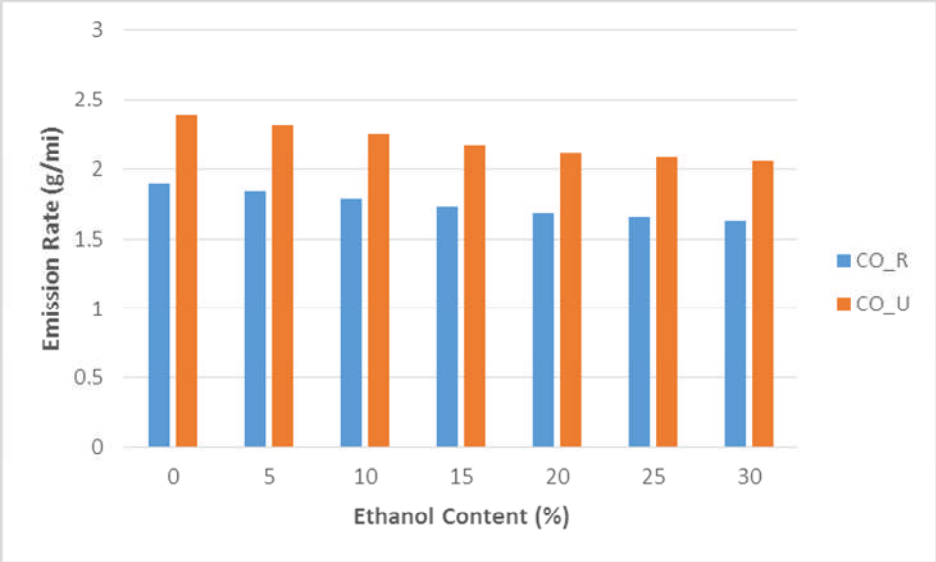


Figure 27. Comparison of CO for Unrestricted Access (CO_U) to Restricted Access (CO_R) for Ethanol Content, Fuel ID 3202

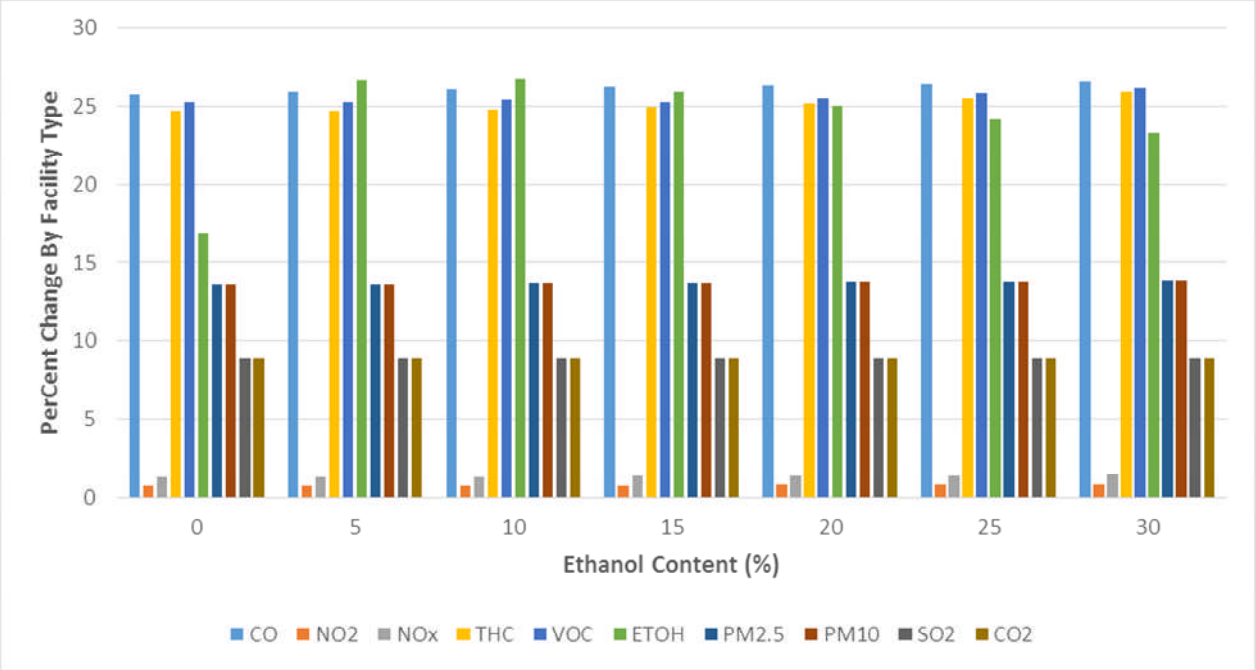


Figure 28. Comparison of Percent Increases by Pollutant Type for Urban Highway Facilities: Restricted Access vs. Unrestricted Access (unrestricted access greater)

The four fuel types also show differences for emission estimates and again, the trends vary by pollutant type. In general, NO_2, NOx, $PM_{2.5}$, and PM_{10} emissions all increase as ethanol content increases with Fuel Formulation 3307, with the same trends as the other formulations but slightly lower absolute values. CO shows a general downward trend across all formulations with increasing ethanol content, with Fuel ID 3307 showing slightly lower absolute values. CO_2 shows that it is a step function, changing at E15 but staying constant at higer ethanol concentrations. SO_2 increases to E20 and then is constant. The results of CO_2 and SO_2 could be related to having to make manual changes for the E20 blends. Three trends are interesting to note and are shown graphically in Figures 29, 30, and 31.

In Figure 29 the trend is apparent, showing an exponential increase by ethanol content for the THC emission rates. Fuel Formulation ID 3307 shows the same trend but has a slightly lower absolute value. This is consistent for other pollutants as noted. A review of Table A.2 shows that fuel 3307 has the lowest RVP and aromatic content of the four fuels. While these are exhaust emissions, RVP may not be a direct effect but could indirectly have effect due to the blends. Aromatic content could be a direct effect as reported by Yao and others (Yao, 2008).

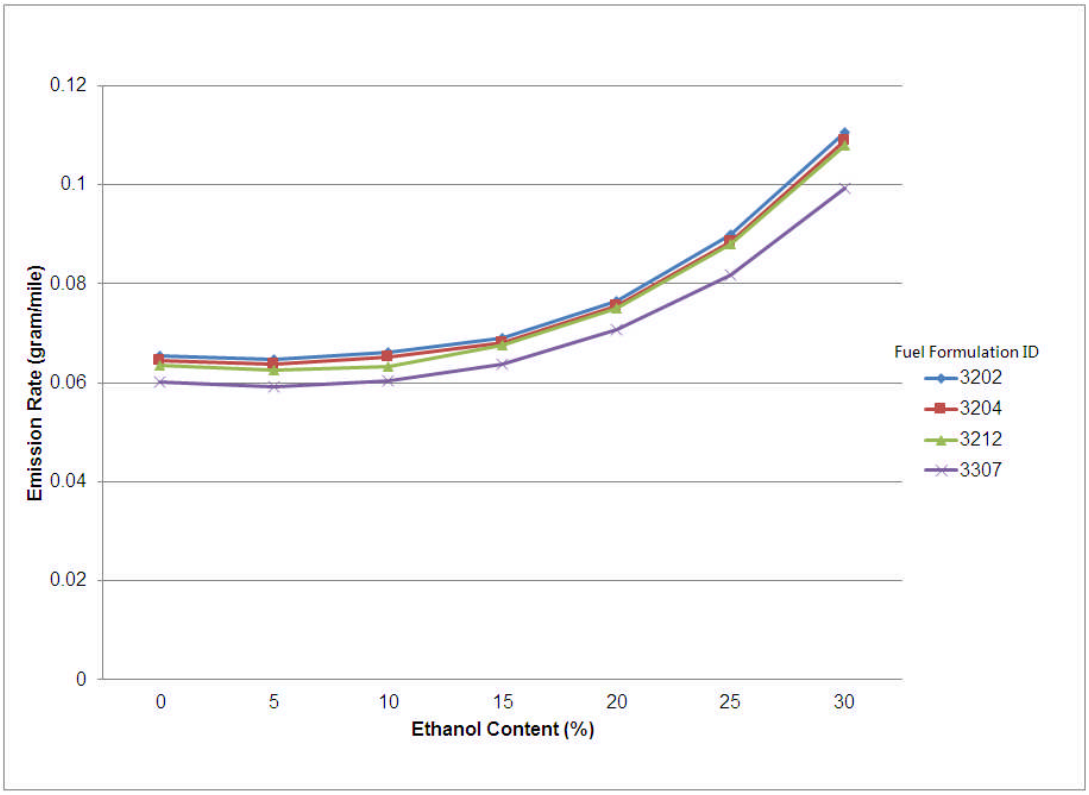


Figure 29. THC Trends with Ethanol Content for the 4 Fuel Formulations

As shown in Figure 30, the effects on VOCs are different than for THC. This matches the speciation adjustment factors discussed in Section 2.1.5 (see Table 10). In this case, VOC slightly increase until E10, decrease at E15 and then increase for the greater ethanol mixtures.

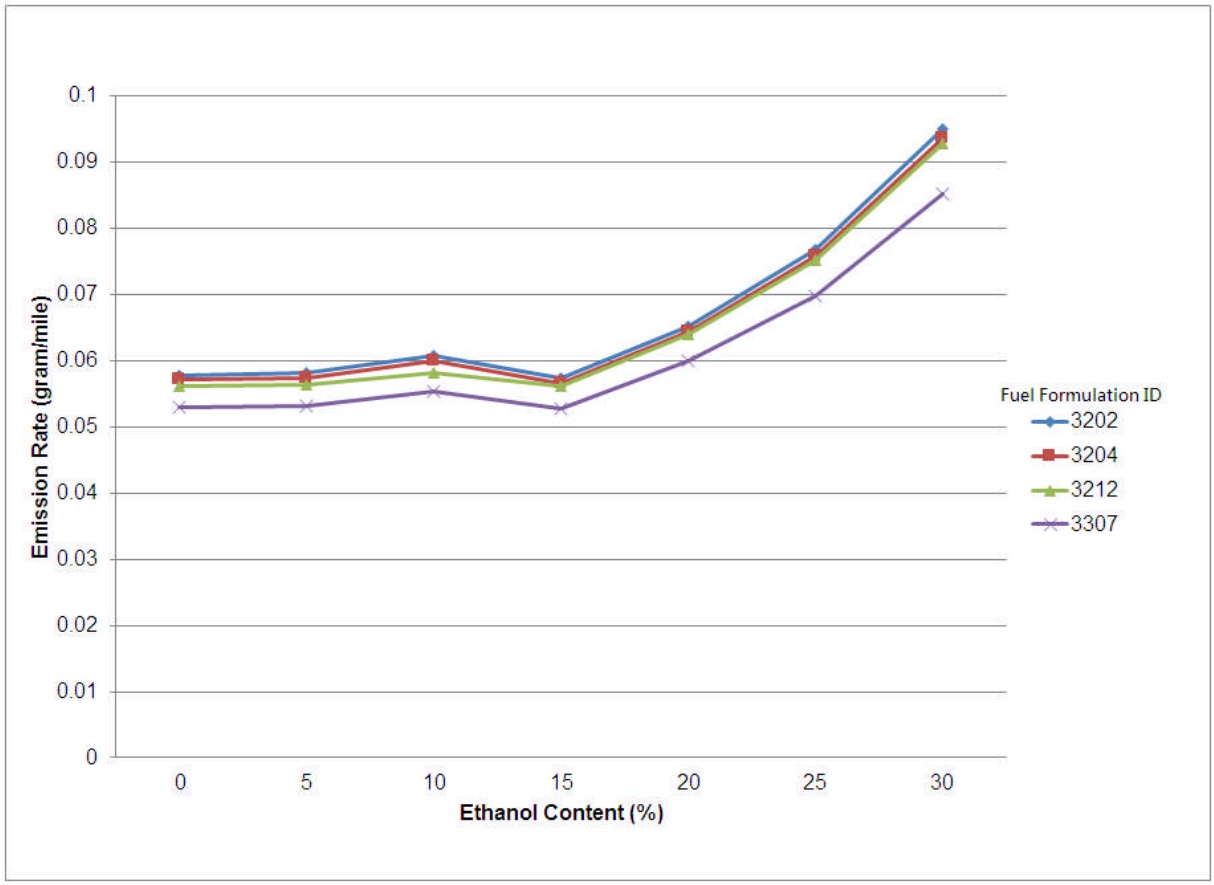


Figure 30. VOC Trends with Ethanol Content for the 4 Fuel Formulations

Ethanol emission rates, with slightly different adjustment factors, had a slightly different trend. While a steady increase occurs with increasing ethanol content in the fuel, there is a plateau from E10 to E15 instead of a decrease, and then the upward trend continues. This is shown in Figure 31.

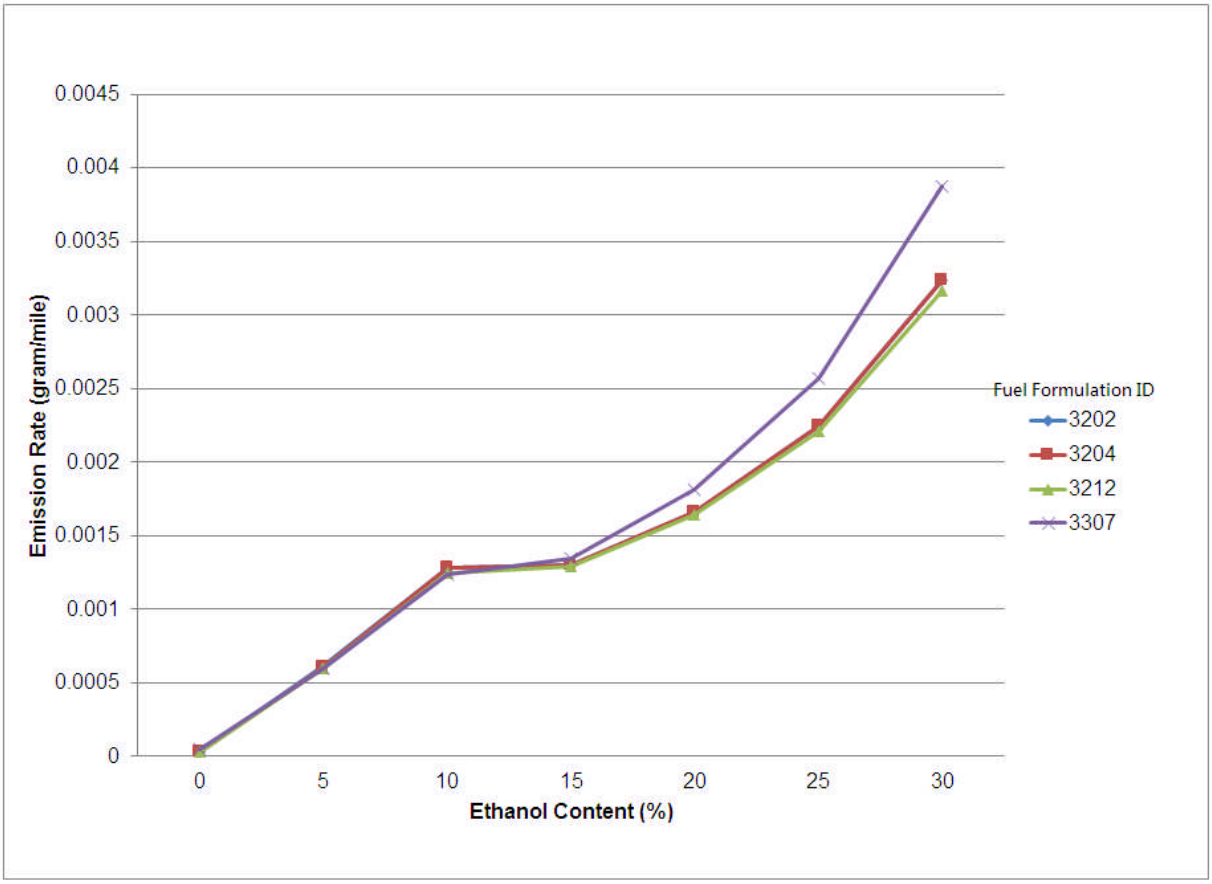


Figure 31. Ethanol Emission Trends with Fuel Ethanol Content for the 4 Fuel Formulations

While implied in the previous discussion on trends, it is important to note that emission rate trends are different for the pollutant types for the matched blends used in MOVES2014 based on the fuels evaluated. To sum the results from MOVES2014:

- CO decreases with increasing ethanol content;
- Nitrogen components increase with increasing ethanol content;
- THC decreases from gasoline to E5 then increases;
- VOC increases to E10, decreases at E15, and increases for E20 to E30;
- Ethanol increases to E10, plateaus to E15, and then increases for E20 and above;
- PM species increase with increasing ethanol content;
- SO_2 increases with increasing ethanol content until E20, then becomes a constant (this could be due to the fact the Fuel Wizard could not be used above E20 and manual input was required);
- CO_2 is a step function, with values above E20 having lower values;

- Changes in ethanol content also affected some emission rates for pollutants that is not understood, such as SO_2, and,
- The urban unrestricted access facility type, with the higher speeds and fuel consumption results in greater emission rates indicating that other parameters such as drive cycle are crucial in all analysis.

4.3 Splash Blend Analysis Results

Based on the splash blend fuel properties supplied by RFA (see Table 22), and formulations for the four geographic areas provided, 14 fuel formulations were evaluated. Table 27 shows the final fuel properties used for this evaluation. In each case MTBE, ETBE, and TAME Volumes were zero as was the biodiesel content, cetane index, and PAH Content. The blends provided were for the Year 2015. As before, both urban restricted access and unrestricted access facilities were evaluated but this time only for passenger cars.

Table 27. Fuel Properties Used for the Splash Blend Analysis

Case	Fuel Formulation ID	Fuel Subtype ID	RVP	Sulfur Level	ETOH Volume	Aromatic Content	Olefin Content	Benzene Content	e200	e300	T50	T90
Reference	3202	12	7	25	9.95	23.3	10.1	0.6	51	85	217.1	308.2
E15 Match	3202	15	7	25	14.85	23.3	10.1	0.6	51	85	217.1	308.2
E15 Splash	3202	15	7	24.3	14.85	22.1	9.6	0.57	57	86	167.4	305.9
E20_Splash	3202	18	7	23.5	19.85	20.9	9.1	0.54	58	86.5	166.5	305.1
E25_Splash	3202	18	7	22.5	24.85	19.8	8.6	0.51	57	85.5	168.1	303.9
E30_Splash	3202	18	7	21	29.85	18.6	8.1	0.48	56	85	170.1	302
ATL E10	3203	12	8	30	10	23.23	12.52	0.61	45.89	80.06	210.02	340.59
ATL E15	3205	15	7	30	15	21.89	11.34	0.61	52.02	80.58	197.59	338.22
DET E10	3220	12	8	30	10	24.94	8.08	0.63	48.73	81.32	205.63	339.62
DET E15	3222	15	7	30	15	23.6	6.9	0.63	54.86	81.84	193.2	337.25
STL E10	3313	12	7.06	30	10	17.13	7.85	0.77	50.98	85.24	193.2	326.7
STL E15	3315	15	7.06	30	15	15.79	6.67	0.77	57.11	85.76	180.77	324.33
KC E10	3237	12	8	30	10	25.67	9.42	0.63	46.42	84.22	208.66	322.65
KC E15	3239	15	7	30	15	24.33	8.24	0.63	52.55	84.74	196.23	320.28

Fuel properties were matched to the formulations shown in Table 27 for this evaluation by manual inputs as needed. The results for the evaluated pollutant species are shown in Table 28. Figure 32 shows the trends for the predicted emission rates. Figures 33

and 34 are subsets of the emission rates to allow the trends of the small emission rates to be seen. Also, results have been grouped by ethanol content to facilitate reader review

A review of the E10 blends for the geographic areas show all to be very close in emission rates with the exception of Saint Louis which has lower emission rates. Olefins and aromatics were less for the Saint Louis fuel, while benzene content was higher. This tends to support use of adjustment factors. However, the Saint Louis E10 emission rates were very close to the reference case, based on the work by Anderson, even though many fuel parameters were different especially for aromatics, olefins, benzene, T50, and T90 (see Table 27). This tends to amplify a finding in the literature review that it is the overall mixture of fuel properties that makes a difference and components are not independent. Accordingly, use of adjustment factors may need to be more robust in the future. However, while these variations occur in the output of MOVES2014 and are interesting, this is a prediction model and any conclusions are very limited unless compared directly to measurements.

Table 28. Emission Rate Results of the Splash Blend Evaluation (g/mi)

Case	CO	Ethanol	NOX	PM_{10}	$PM_{2.5}$	VOC
Reference	2.129148628	0.001218546	0.291738583	0.005029789	0.004485043	0.05361545
ATL E10	2.256267898	0.001284651	0.309964435	0.00555092	0.004949748	0.06061257
ATL E15	2.143873629	0.001297013	0.320852884	0.005667009	0.005053253	0.05662066
DET E10	2.27248748	0.001249183	0.308012974	0.005624377	0.00501524	0.05918767
DET E15	2.161995957	0.001265047	0.319054682	0.005743165	0.005121163	0.05565965
E15 Match	2.089528384	0.00129833	0.305688066	0.005221128	0.004655659	0.05145922
E15 Splash	2.004458844	0.001295897	0.303147284	0.005129365	0.004573848	0.04918167
E20_Splash	1.945068464	0.001742178	0.31671683	0.005260306	0.004690607	0.05482729
E25_Splash	1.89022665	0.002542794	0.332818495	0.005395694	0.004811316	0.06411987
E30_Splash	1.836226856	0.003982174	0.351845226	0.005519511	0.004921729	0.0782568
KC E10	2.231560927	0.001239523	0.30887861	0.00537264	0.004790766	0.05713096
KC E15	2.121479412	0.001267061	0.319864193	0.005482168	0.004888422	0.0528308
STL E10	2.059674434	0.001227355	0.298693908	0.005037927	0.004492296	0.05459265
STL E15	1.977861775	0.001335959	0.312142572	0.005135107	0.004578964	0.05158809

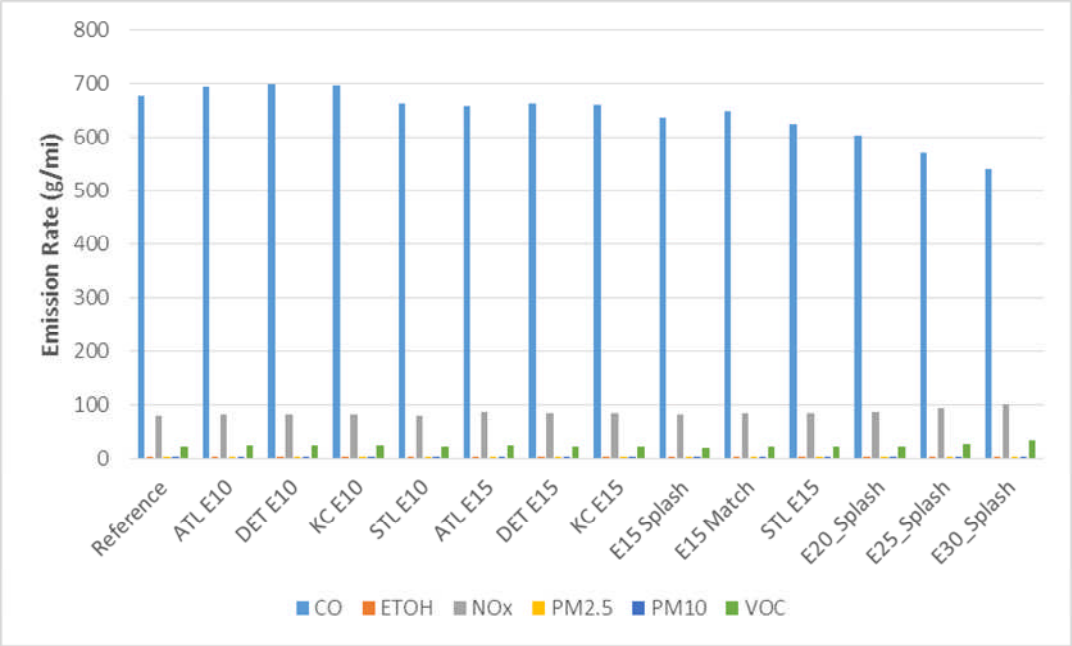


Figure 32. Emission Rates for All Splash Blend Cases

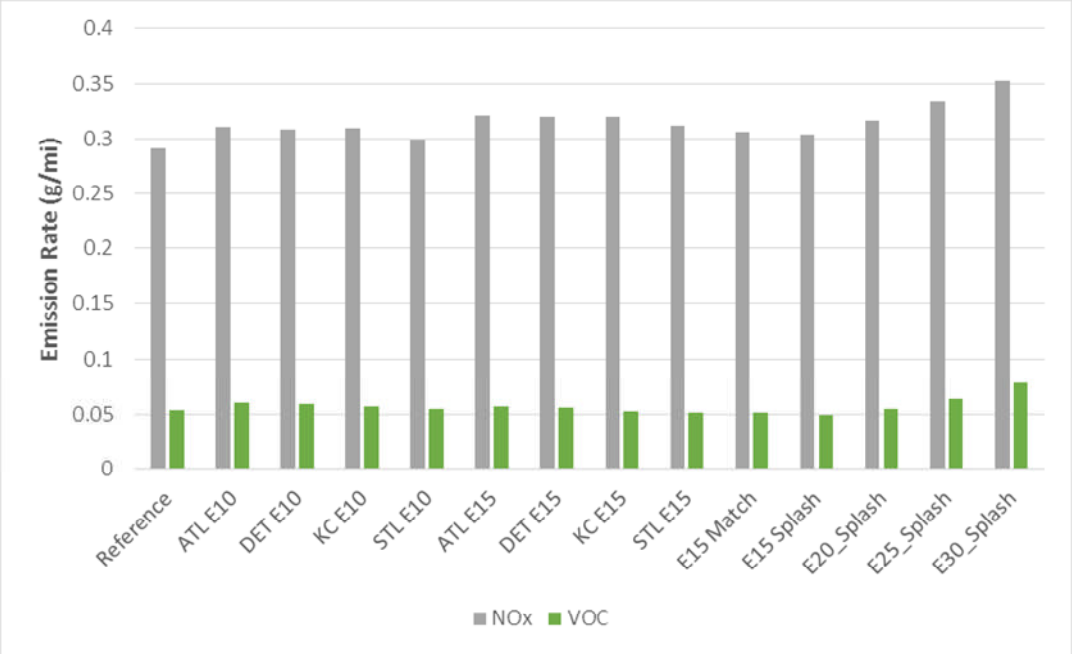


Figure 33. Emission Rates for NOx and VOC for Splash Blend Analyisis

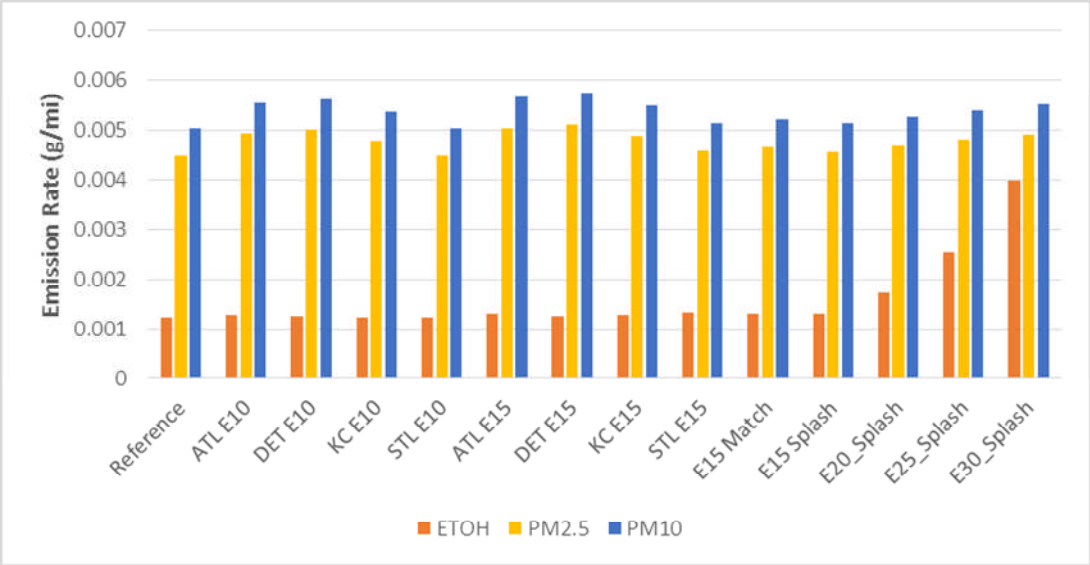


Figure 34. Emission Rates for Ethanol and PM (2.5 and 10) for Splash Blend Analyis

For the E15 blends, emission results for Saint Louis were again less for CO but not for the other emission rates even though again, aromatics and olefins were smaller and benzene content was higher. This again brings consideration to the adjustment factors. No general trend was noted for comparison of the E15 match blend to the geographic region blends.

For the higher ethanol blends, CO is predicted to decrease but all other pollutants analyzed (PM, NOx, ethanol and VOCs) predicted to increase.

In the literature review, how splash blends and match blends may vary was pointed out. Unfortunately, for the two cases supplied (E15 splash and E15 match blend) the fuel properties with the exception of T50 are very similar and as would be expected, so are the predicted emissions (with the exception being that CO is slightly less for the splash blend).

The end results are mixed. Fuels with different fuel formulations sometimes had similar emission rate trends; for example the reference compared to the Saint Louis E10 blends. In other cases, this did not occur.

Also of importance in real world analysis is how much do emission rate predictions vary? Table 29 shows the results in the percent change comparing the minimum predicted value to the maximum predicted value for each pollutant for E10 and E15. It

can be seen that changes do occur with perhaps CO, PM, and VOC emissions being the most important.

Table 29. Percent Change of Emission Rates in the Splash Blend Analysis Comparing the Minimum and Maximum Predicted Values Using Different Fuel Parameters

Ethanol Blends	CO	Ethanol	NOX	PM10	PM2.5	VOC
E10	9.36	5.15	5.88	10.57	10.57	11.54
E15	8.52	5.31	5.23	10.69	10.69	13.14

4.4 Results from the Fuel Formulation Parameter Sensitivity Analysis

In this analysis, the fuel property variables for RVP, sulfur level, ethanol volume, aromatic content, olefin content, T50, and T90 were all varied individually while holding all other parameters constant. This permitted a review of the effect of these fuel properties on the predicted emission rates. The range of values varied was previously shown in Table 24. This evaluation for E0 to E30 included multiple vehicle types, highway facilities, and multiple pollutants as described in Chapter 3.

To show the results effectively, E10 is the base fuel and each variable change for selected emission rates is provided. However, it is first important to investigate how MOVES2014 default fuels change when ethanol content is changed. The reader is reminded for ethanol content above 20%, manual input was required in the Fuels Formulation Excel Spreadsheet. As previously described, this is for the year 2015 and Fuel Formulation ID 3202.

Table 30 shows the emission rates of various pollutant species for the default MOVES2014 cases when ethanol content is changed from E0 to E30 for urban restricted and urban unrestricted access. Table 31 provides the emission rates results for PM precursors. Only passenger cars are shown here for brevity. More results for other vehicle types are included in Appendix B.

As before, it can be seen that the urban unrestricted access, with the higher speeds and fuel consumption results in greater emission rates. Since this has been previously shown, it is not discussed further in this section.

Trends in this analysis also follow the pollutant trends previously discussed at the end of Section 4.2 for CO_2, CO, ETOH, NO_2, NOx, PM_{10}, $PM_{2.5}$, SO_2 and VOC with two very small variances. THC emission rates did not decrease at E5 as it did for the Fuel Formulation 3202 in the previous analysis but continued to increase with increasing ethanol content. Also the plateau for ethanol emissions for E10 and E15 was not as pronounced as in the previous analysis. Overall rates were also slightly higher showing that the Fuel Wizard changes do not exactly match the fuel parameters in this section with E10 as the base fuel.

Table 30. Results of Fuel Formulation Analysis for Pollutant Emission Rates: Passenger Cars (g/mile) (does not include other PM species or precursors)

Ethanol Content (%)	CO2	CO	ETOH	NO2	NMHC	NOx	PM10	PM2.5	SO2	THC	VOC
Urban Restricted Access											
0	295.2506	1.864262	2.87E-05	0.036349	0.047045	0.282737	0.004526	0.004036	0.005651	0.050898	0.044763
5	295.2506	1.824066	0.000481	0.037712	0.047094	0.293192	0.004703	0.004193	0.005768	0.050995	0.045626
10_Base	295.2506	1.787268	0.001012	0.039278	0.048997	0.305395	0.004892	0.004362	0.005884	0.053011	0.04836
15	295.2506	1.753455	0.001057	0.041076	0.053017	0.319623	0.005096	0.004544	0.006005	0.05722	0.04735
20	292.2374	1.722272	0.001358	0.043166	0.059781	0.336411	0.005314	0.004739	0.006131	0.064267	0.054477
25	292.2374	1.693412	0.001831	0.045649	0.070453	0.356655	0.005549	0.004948	0.006131	0.07536	0.064202
30	292.2374	1.666612	0.002632	0.048692	0.087089	0.38187	0.005801	0.005173	0.006131	0.092623	0.079361
Urban Unrestricted Access											
0	321.5006	2.345897	3.36E-05	0.036617	0.058893	0.28645	0.005138	0.004582	0.006153	0.063526	0.056094
5	321.5006	2.297821	0.000608	0.037989	0.05893	0.297023	0.005341	0.004762	0.00628	0.063619	0.057177
10_Base	321.5006	2.253827	0.001283	0.039566	0.061335	0.30939	0.005559	0.004957	0.006407	0.066163	0.06065
15	321.5006	2.213397	0.001332	0.041381	0.066445	0.323834	0.005793	0.005165	0.006539	0.071505	0.059342
20	318.2195	2.176099	0.001701	0.043494	0.075058	0.340901	0.006044	0.005389	0.006677	0.080475	0.068398
25	318.2195	2.141593	0.00228	0.046008	0.088663	0.36152	0.006314	0.00563	0.006677	0.09461	0.080796
30	318.2195	2.109547	0.003255	0.049095	0.109885	0.387243	0.006604	0.005889	0.006677	0.116627	0.100135

Table 31. Results of Fuel Formulation Analysis for PM Precursor Emission Rates: Passenger Cars (g/mile)

Ethanol Content (%)	Aluminum	Ammonium (NH4)	Calcium	Chloride	Elemental Carbon	Iron	Magnesium	Manganese Compounds	Nitrate (NO3)	Non-carbon Organic Matter (NCOM)	Organic Carbon	Potassium	Silicon	Sodium	Sulfate Particulate	Titanium
	Urban Restricted Access															
0	0.0000137	0.0001172	0.0000608	0.0000044	0.000588	0.0000771	0.00000609	0.000016	0.0000122	0.00047	0.002348	0.00000359	0.0000137	0.00000165	0.0001254	0.00000144
5	0.0000142	0.0001219	0.0000633	0.00000458	0.000612	0.0000802	0.00000634	0.000016	0.0000127	0.000489	0.002443	0.00000373	0.0000142	0.00000172	0.0001254	0.00000149
15	0.0000154	0.0001324	0.0000687	0.00000497	0.000664	0.0000871	0.00000689	0.000016	0.0000138	0.000531	0.002653	0.00000406	0.0000154	0.00000186	0.0001254	0.00000162
20	0.0000161	0.0001382	0.0000718	0.00000519	0.000694	0.0000909	0.00000719	0.000016	0.0000144	0.000554	0.00277	0.00000423	0.0000161	0.00000195	0.0001254	0.00000169
25	0.0000168	0.0001445	0.000075	0.00000543	0.000725	0.000095	0.00000752	0.000016	0.000015	0.000579	0.002896	0.00000443	0.0000168	0.00000203	0.0001254	0.00000177
30	0.0000176	0.0001512	0.0000785	0.00000568	0.000759	0.0000995	0.00000787	0.000016	0.0000157	0.000606	0.003031	0.00000463	0.0000176	0.00000213	0.0001254	0.00000185
10_Base	0.0000148	0.0001269	0.0000659	0.00000477	0.000637	0.0000835	0.0000066	0.000016	0.0000132	0.000509	0.002544	0.00000389	0.0000148	0.00000179	0.0001254	0.00000156
	Urban Unrestricted Access															
0	0.0000155	0.000133	0.0000691	0.000005	0.000667	0.0000875	0.00000692	0.0000229	0.0000138	0.000533	0.002666	0.00000407	0.0000155	0.00000187	0.0001423	0.00000163
5	0.0000161	0.0001384	0.0000719	0.0000052	0.000695	0.000091	0.0000072	0.0000229	0.0000144	0.000555	0.002774	0.00000424	0.0000161	0.00000195	0.0001423	0.0000017
15	0.0000175	0.0001505	0.0000781	0.00000565	0.000755	0.000099	0.00000783	0.0000229	0.0000156	0.000603	0.003016	0.00000461	0.0000175	0.00000212	0.0001423	0.00000184
20	0.0000183	0.0001572	0.0000816	0.00000591	0.000789	0.0001034	0.00000818	0.0000229	0.0000163	0.00063	0.003151	0.00000482	0.0000183	0.00000221	0.0001423	0.00000193
25	0.0000192	0.0001644	0.0000854	0.00000618	0.000825	0.0001081	0.00000855	0.0000229	0.0000171	0.000659	0.003295	0.00000504	0.0000192	0.00000231	0.0001423	0.00000201
30	0.0000201	0.0001722	0.0000894	0.00000647	0.000864	0.0001132	0.00000896	0.0000229	0.0000179	0.00069	0.003451	0.00000527	0.0000201	0.00000242	0.0001423	0.00000211
10_Base	0.0000168	0.0001442	0.0000749	0.00000542	0.000724	0.0000949	0.0000075	0.0000229	0.000015	0.000578	0.002891	0.00000442	0.0000168	0.00000203	0.0001423	0.00000177

In Section 4.2, it was shown that MOVES2014 predicts increases in $PM_{2.5}$ and PM_{10} with increasing ethanol content. The same trend also occurs in this analysis. Of interest is that this is also true for all PM precursors or species with the exception of Manganese and Sulfate particles. Sulfur content was held constant so this follows that sulfates are more a function of sulfur content than other parameters. However, SO_2 is predicted to be affected by ethanol content, increasing to E20 and then becoming constant. This tends to indicate changes due to the oxidation process of the fuel. This does not seem to equate to a mass balance for sulfur content however. The constant values for E20 and greater could be due to the required manual input above E20 as previously noted.

Next, the effects on the emission rates for the other selected fuel properties were evaluated. Only unrestricted access will be discussed in this section since the trend for facility type has been shown conclusively. Also, again for brevity, only passenger cars will be discussed with more details in Appendix B.

4.4.1 Aromatics

Table 32 shows the results for changing the aromatic content from 0 to 40% in 5% increments as well as the base case at 23.23%.

Table 32. Changes in Emission Rates Due to Aromatic Content Changes (g/mile)

Aromatic Content (%)	CO2	CO	ETOH	NO2	NMHC	NOx	PM10	PM2.5	SO2	THC	VOC
0	321.5006	1.877357	0.001417	0.036928	0.058894	0.290275	0.004548	0.004056	0.006407	0.063762	0.058101
5	321.5006	1.952394	0.001366	0.037477	0.0594	0.294262	0.004734	0.004221	0.006407	0.064259	0.05863
10	321.5006	2.030596	0.00133	0.038037	0.059917	0.298318	0.004936	0.004401	0.006407	0.064766	0.05917
15	321.5006	2.1121	0.001305	0.038606	0.060444	0.302444	0.005155	0.004597	0.006407	0.065284	0.05972
20	321.5006	2.197048	0.00129	0.039186	0.060982	0.30664	0.005394	0.00481	0.006407	0.065814	0.060281
25	321.5006	2.285597	0.001281	0.039776	0.061531	0.310908	0.005653	0.005041	0.006407	0.066356	0.060853
30	321.5006	2.377882	0.001277	0.040377	0.062091	0.315251	0.005934	0.005292	0.006407	0.066909	0.061437
35	321.5006	2.474098	0.001278	0.040989	0.062662	0.319668	0.00624	0.005564	0.006407	0.067474	0.062031
40	321.5006	2.574396	0.001283	0.041612	0.063244	0.324162	0.006573	0.005861	0.006407	0.068051	0.062637
23.23_Bas	321.5006	2.253827	0.001283	0.039566	0.061335	0.30939	0.005559	0.004957	0.006407	0.066163	0.06065

It can be seen in Table 32 that changes to aromatic content do not affect CO_2 or SO_2. CO, NO_2, NMHC, NOx, PM_{10}, $PM_{2.5}$, THC, and VOCs all show increasing emission rates with increase aromatic content. Ethanol (ETOH) emissions is different from other species in that it shows a decreasing trend with increased aromatics until aromatics are 30% and then increases.

While not shown here, other PM species and precursors were also evaluated. As before, manganese and sulfates remain constant with increasing aromatic content. All other PM species or precursors increase with increasing aromatic content.

4.4.2 Olefins

Olefins were evaluated from 0 to 30%, in 5% increments with the base case at 12.52. Results are shown in Table 33.

Table 33. Changes in Emission Rates Due to Olefin Content Changes (g/mile)

Olefin Content (%)	CO2	CO	ETOH	NO2	NMHC	NOx	PM10	PM2.5	SO2	THC	VOC
0	321.5006	2.262834	0.001325	0.038545	0.063039	0.300132	0.005559	0.004957	0.006407	0.067925	0.062378
5	321.5006	2.257866	0.001308	0.038947	0.062351	0.303773	0.005559	0.004957	0.006407	0.067214	0.06168
10	321.5006	2.254735	0.001291	0.039356	0.061673	0.307488	0.005559	0.004957	0.006407	0.066512	0.060992
15	321.5006	2.253396	0.001275	0.039774	0.061005	0.311279	0.005559	0.004957	0.006407	0.065821	0.060314
20	321.5006	2.254151	0.001259	0.0402	0.060346	0.315145	0.005559	0.004957	0.006407	0.065139	0.059646
25	321.5006	2.257758	0.001243	0.040635	0.059696	0.319089	0.005559	0.004957	0.006407	0.064466	0.058986
30	321.5006	2.265425	0.001227	0.041079	0.059055	0.323113	0.005559	0.004957	0.006407	0.063803	0.058336
12.52_Base	321.5006	2.253827	0.001283	0.039566	0.061335	0.30939	0.005559	0.004957	0.006407	0.066163	0.06065

As with aromatics, CO_2 remains a constant value for increasing olefin content. The PM categories and SO_2 also remain constant. CO emission rates slightly decrease up to an olefin content of 15% and then increases. Ethanol emission rates decrease for increasing olefin content as does NMHC, THC, and VOCs. The emission rates for oxides of nitrogen, including NO_2, increase with increasing olefin content. Except for CO above olefin contents of 15% this tends to indicates increased combustion efficiency and greater head temperatures.

While not shown, no change occurs for the other PM species or precursors.

4.4.3 RVP

RVP was evaluated from 6 to 9.5 psi in 0.5 increments and a base case of 7.8 psi. Table 34 shows the results.

Table 34. Changes in Emission Rates Due to RVP Changes (g/mile)

RVP (psi)	CO2	CO	ETOH	NO2	NMHC	NOx	PM10	PM2.5	SO2	THC	VOC
6	321.5006	2.236248	0.001265	0.039146	0.060958	0.305582	0.005559	0.004957	0.006407	0.065881	0.060203
6.5	321.5006	2.236074	0.00127	0.039262	0.061058	0.306631	0.005559	0.004957	0.006407	0.065955	0.060323
7	321.5006	2.239854	0.001275	0.039378	0.061162	0.307687	0.005559	0.004957	0.006407	0.066032	0.060446
7.5	321.5006	2.247456	0.00128	0.039495	0.06127	0.308749	0.005559	0.004957	0.006407	0.066113	0.060572
7.8_Base	321.5006	2.253827	0.001283	0.039566	0.061335	0.30939	0.005559	0.004957	0.006407	0.066163	0.06065
8	321.5006	2.258816	0.001285	0.039613	0.06138	0.309818	0.005559	0.004957	0.006407	0.066197	0.060702
8.5	321.5006	2.273913	0.00129	0.039731	0.061493	0.310891	0.005559	0.004957	0.006407	0.066284	0.060834
9	321.5006	2.292832	0.001296	0.03985	0.061609	0.311972	0.005559	0.004957	0.006407	0.066375	0.060968
9.5	321.5006	2.315639	0.001301	0.03997	0.061728	0.313058	0.005559	0.004957	0.006407	0.06647	0.061106

CO2, PM, and SO_2 do not change with changes in RVP. All other components shown (CO, ethanol emissions, NO_2, NMHC, NOx, THC, and VOC) increase with increasing RVP content. It should be noted that this is for *exhaust emissions only* and does not include evaporative emissions which are discussed in Section 4.5.

While it is not shown, RVP also does not affect the other PM species or precursors.

4.4.4 Sulfur Levels

Sulfur levels were evaluated from 0 to 50 ppm including the base case at 30 ppm. Table 35 includes the results.

Table 35. Changes in Emission Rates Due to Changes in Sulfur Levels in the Fuel (g/mile)

Sulfur Level (ppm)	CO2	CO	ETOH	NO2	NMHC	NOx	PM10	PM2.5	SO2	THC	VOC
0	321.5006	2.183636	0.001098	0.026524	0.048866	0.217115	0.005512	0.004915	0	0.051786	0.048857
5	321.5006	2.208905	0.00116	0.029106	0.052195	0.241065	0.00552	0.004922	0.001068	0.055478	0.05209
10	321.5006	2.222403	0.001191	0.031204	0.054279	0.254877	0.005528	0.004929	0.002136	0.05788	0.054061
15	321.5006	2.232144	0.001216	0.033297	0.056147	0.268561	0.005535	0.004936	0.003204	0.060059	0.055814
20	321.5006	2.240221	0.00124	0.035387	0.057922	0.282193	0.005543	0.004943	0.004271	0.062141	0.057472
25	321.5006	2.247327	0.001262	0.037477	0.059645	0.295799	0.005551	0.00495	0.005339	0.064169	0.059078
30_Base	321.5006	2.253827	0.001283	0.039566	0.061335	0.30939	0.005559	0.004957	0.006407	0.066163	0.06065
35	321.5006	2.31525	0.001297	0.040217	0.062203	0.313753	0.005567	0.004964	0.007475	0.067145	0.06148
40	321.5006	2.370604	0.001311	0.040817	0.063006	0.317785	0.005574	0.004971	0.008543	0.068052	0.062251
45	321.5006	2.421163	0.001324	0.041376	0.063761	0.321552	0.005582	0.004978	0.009611	0.0689	0.062977
50	321.5006	2.467857	0.001336	0.041902	0.064476	0.325101	0.00559	0.004985	0.010679	0.069702	0.063667

CO_2 is the only pollutant shown in Table 35 that remains constant with all other pollutant emission rates increasing with increased sulfur content. Some emissions increases (e.g., CO, NO2, NMHC, NOx, SO2, THC, VOC) are significant as sulfur content rises.

Other PM species and precursors remain constant with the exception of sulfates as expected (results not shown here).

4.4.5 T50

For the distillation parameter, T50, temperature values of 175 to 250 were evaluated in 25 degree increments with a base temperature value of 210.54. Results have been included in Table 36.

Table 36. Changes in Emission Rates Due to Changes in the T50 Fuel Property (g/mile)

T50 Parameter (°)	CO2	CO	ETOH	NO2	NMHC	NOx	PM10	PM2.5	SO2	THC	VOC
175	321.5006	2.207869	0.001282	0.039566	0.060412	0.30939	0.005559	0.004957	0.006407	0.065022	0.05982
200	321.5006	2.240048	0.001281	0.039566	0.060862	0.30939	0.005559	0.004957	0.006407	0.065577	0.060224
225	321.5006	2.272963	0.001288	0.039566	0.062303	0.30939	0.005559	0.004957	0.006407	0.067357	0.061519
250	321.5006	2.306633	0.001304	0.039566	0.065065	0.30939	0.005559	0.004957	0.006407	0.070768	0.063999
210.54_Bas	321.5006	2.253827	0.001283	0.039566	0.061335	0.30939	0.005559	0.004957	0.006407	0.066163	0.06065

For the T50 parameter, CO_2 is once again not affected. Neither are the nitrogen components, PM, or SO_2. CO increases with increased T50, as do the hydrocarbon species NMHC, THC, and VOC. Ethanol is slightly different in that it first very slightly decreases before it begins to increase.

Other PM species and precursor output emission rates (not shown) were constant.

4.4.6 T90

The T90 fuel property was evaluated from 300 to 360 degrees in increments of 10 and a base case of 341.04. Results have been included in Table 37.

Table 37. Changes in Emission Rates Due to Changes in the T90 Fuel Property (g/mile)

T90 Parameter (°)	CO2	CO	ETOH	NO2	NMHC	NOx	PM10	PM2.5	SO2	THC	VOC
300	321.5006	2.126162	0.001393	0.039566	0.05995	0.30939	0.00492	0.004387	0.006407	0.064452	0.059406
310	321.5006	2.156186	0.001359	0.039566	0.060274	0.30939	0.005063	0.004514	0.006407	0.064852	0.059696
320	321.5006	2.186898	0.00133	0.039566	0.060606	0.30939	0.005213	0.004649	0.006407	0.065263	0.059995
330	321.5006	2.2183	0.001305	0.039566	0.060948	0.30939	0.005373	0.004791	0.006407	0.065684	0.060302
340	321.5006	2.250437	0.001285	0.039566	0.061298	0.30939	0.005541	0.004941	0.006407	0.066117	0.060616
350	321.5006	2.283308	0.001268	0.039566	0.061658	0.30939	0.005718	0.005099	0.006407	0.066561	0.06094
341.04_Bas	321.5006	2.253827	0.001283	0.039566	0.061335	0.30939	0.005559	0.004957	0.006407	0.066163	0.06065

As before, CO_2 was a constant value for all changes in T90. The nitrogen species and SO_2 were also constants as with T50, but not PM. CO increased with increasing values of T90 as did all others (NMHC, PM_{10}, $PM_{2.5}$, THC, and VOC) with the exception of ethanol. Ethanol displayed a decreasing trend with increased T90 values.

Though not shown, except for Manganese and sulfates which remained constant, all other PM species and precursors increased with increasing T90 values.

Of note is that for all evaluations in this section except ethanol content, values remained constant for CO_2. This indicates that this important greenhouse gas is not included in fuel properties changes evaluated except for ethanol content, where a step function showed a decrease in CO_2 above E15.

4.5 Evaporative Fuel Leak Ethanol Sensitivity Analysis Results

Using the methodology as discussed in Section 3.5, a review of predicted evaporative emissions was conducted. A total of 770 evaluations, including 45 parameters were evaluated. Of these, 45 parameters specified were for the fuel properties for a gasoline based fuel with sulfur content, volumes of ETOH, MTBE, ETBE, TAME, aromatic, olefin, benzene, and PAH, as well as volume of BioDiesel Ester, 2200, e300, Centane index, T50 and T90 evaluated. As before, the year of evaluation was 2015 in the warm summer month of July. It was not feasible to include all parameters in this report, but the fuel evaluation is being made available to RFA in Appendix B, a spreadsheet.

Excerpts are shown here to permit discussion of important details. Table 38 shows predicted results for the five reported hydrocarbon classes by vehicle type and for E0 to E30 in 5% increments. This is for Urban Rural Access Facilities. As expected, as described in Sections 2.1.5 and 2.1.9, all species have a constant value for gasoline (E0). As ethanol is added to the mixture, VOC is equal to TOG and NMOG. THC and NMHC are also equal and slightly less due to adjustment factors and that methane is considered insignificant (see Equations 2-5). THC and NMHC are equivalent for all blends including E0.

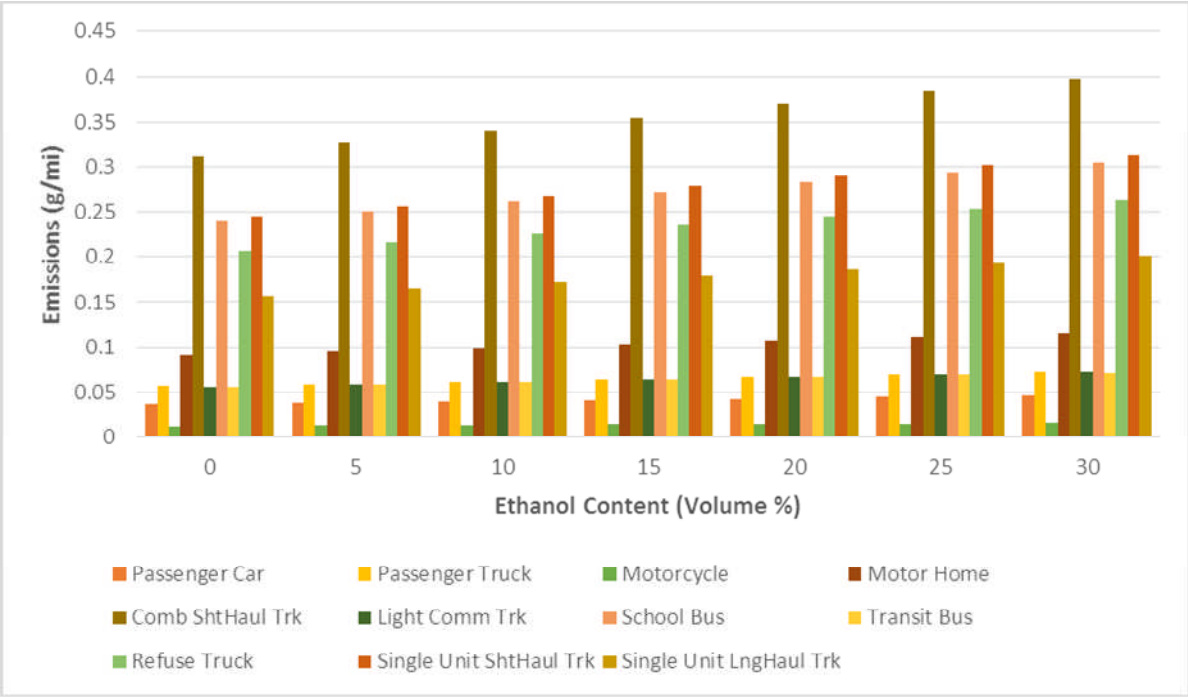
Two other trends are also important for VOC, TOG and NMOG. Evaporative emissions for these species increase in MOVES2014 with increased ethanol blends based on the idea that ethanol leads to greater permeation as described previously. Emissions by vehicle also differ for these species. Figure 35 shows this graphically for only VOC since the trends are the same for VOC, TOG, and NMOG. Figure 35 a) shows results for all vehicles using ethanol blends while Figure 35 b) displays only passenger cars and trucks for better visualization by the reader.

Table 38. Evaporative Emission Rates for Urban Restricted Access Facility by Vehicle Type

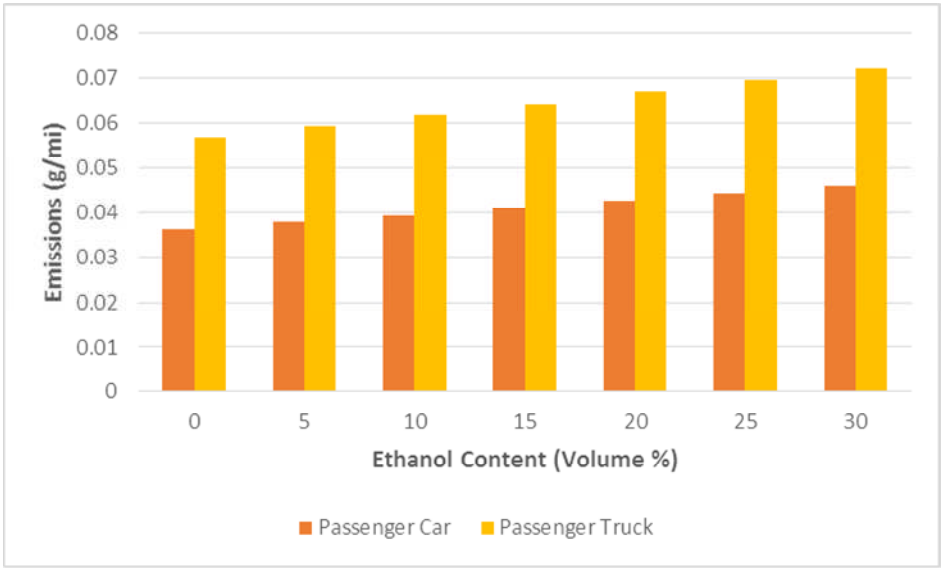
	Emissions (g/mile)				
Vehicle Type					
Ethanol Content	***VOC***	***TOG***	***THC***	***NMOG***	***NMHC***
Passenger Car					
0	0.036108	0.036108	0.036108	0.036108	0.036108
5	0.037757	0.037757	0.036108	0.037757	0.036108
10	0.039406	0.039406	0.036108	0.039406	0.036108
15	0.041055	0.041055	0.036108	0.041055	0.036108
20	0.042704	0.042704	0.036108	0.042704	0.036108
25	0.044353	0.044353	0.036108	0.044353	0.036108
30	0.046001	0.046001	0.036108	0.046001	0.036108
Passenger Truck					
0	0.056697	0.056697	0.056697	0.056697	0.056697
5	0.059286	0.059286	0.056697	0.059286	0.056697
10	0.061875	0.061875	0.056697	0.061875	0.056697
15	0.064464	0.064464	0.056697	0.064464	0.056697
20	0.067053	0.067053	0.056697	0.067053	0.056697
25	0.069642	0.069642	0.056697	0.069642	0.056697

	Emissions (g/mile)				
Vehicle Type					
Ethanol Content	***VOC***	***TOG***	***THC***	***NMOG***	***NMHC***
30	0.072231	0.072231	0.056697	0.072231	0.056697
Motorcycle					
0	0.012279	0.012279	0.012279	0.012279	0.012279
5	0.01284	0.01284	0.012279	0.01284	0.012279
10	0.0134	0.0134	0.012279	0.0134	0.012279
15	0.013961	0.013961	0.012279	0.013961	0.012279
20	0.014522	0.014522	0.012279	0.014522	0.012279
25	0.015083	0.015083	0.012279	0.015083	0.012279
30	0.015643	0.015643	0.012279	0.015643	0.012279
Motor Home					
0	0.090983	0.090983	0.090983	0.090983	0.090983
5	0.095137	0.095137	0.090983	0.095137	0.090983
10	0.099292	0.099292	0.090983	0.099292	0.090983
15	0.103446	0.103446	0.090983	0.103446	0.090983
20	0.107601	0.107601	0.090983	0.107601	0.090983
25	0.111756	0.111756	0.090983	0.111756	0.090983
30	0.11591	0.11591	0.090983	0.11591	0.090983
Combination Short Haul Truck					
0	0.312114	0.312114	0.312114	0.312114	0.312114
5	0.326367	0.326367	0.312114	0.326367	0.312114
10	0.340618	0.340618	0.312114	0.340618	0.312114
15	0.354871	0.354871	0.312114	0.354871	0.312114
20	0.369122	0.369122	0.312114	0.369122	0.312114
25	0.383375	0.383375	0.312114	0.383375	0.312114
30	0.397627	0.397627	0.312114	0.397627	0.312114
Light Commercial Truck					
0	0.056501	0.056501	0.056501	0.056501	0.056501
5	0.059081	0.059081	0.056501	0.059081	0.059081
10	0.061661	0.061661	0.056501	0.061661	0.061661
15	0.064241	0.064241	0.056501	0.064241	0.064241
20	0.066821	0.066821	0.056501	0.066821	0.066821
25	0.069401	0.069401	0.056501	0.069401	0.069401
30	0.07198	0.07198	0.056501	0.07198	0.07198
School Bus					
0	0.239388	0.239388	0.239388	0.239388	0.239388
5	0.25032	0.25032	0.239388	0.25032	0.239388
10	0.261251	0.261251	0.239388	0.261251	0.239388

	Emissions (g/mile)				
Vehicle Type					
Ethanol Content	***VOC***	***TOG***	***THC***	***NMOG***	***NMHC***
15	0.272181	0.272181	0.239388	0.272181	0.239388
20	0.283113	0.283113	0.239388	0.283113	0.239388
25	0.294044	0.294044	0.239388	0.294044	0.239388
30	0.304975	0.304975	0.239388	0.304975	0.239388
Transit Bus					
0	0.056366	0.056366	0.056366	0.056366	0.056366
5	0.058939	0.058939	0.056366	0.058939	0.056366
10	0.061513	0.061513	0.056366	0.061513	0.056366
15	0.064087	0.064087	0.056366	0.064087	0.056366
20	0.066661	0.066661	0.056366	0.066661	0.056366
25	0.069234	0.069234	0.056366	0.069234	0.056366
30	0.071808	0.071808	0.056366	0.071808	0.056366
Refuse Truck					
0	0.207006	0.207006	0.207006	0.207006	0.207006
5	0.216458	0.216458	0.207006	0.216458	0.207006
10	0.22591	0.22591	0.207006	0.22591	0.207006
15	0.235363	0.235363	0.207006	0.235363	0.207006
20	0.244815	0.244815	0.207006	0.244815	0.207006
25	0.254268	0.254268	0.207006	0.254268	0.207006
30	0.26372	0.26372	0.207006	0.26372	0.207006
Single Unit Short-Haul Truck					
0	0.245396	0.245396	0.245396	0.245396	0.245396
5	0.256602	0.256602	0.245396	0.256602	0.245396
10	0.267806	0.267806	0.245396	0.267806	0.245396
15	0.279012	0.279012	0.245396	0.279012	0.245396
20	0.290217	0.290217	0.245396	0.290217	0.245396
25	0.301422	0.301422	0.245396	0.301422	0.245396
30	0.312628	0.312628	0.245396	0.312628	0.245396
Single Unit Long-Haul Truck					
0	0.157378	0.157378	0.157378	0.157378	0.157378
5	0.164565	0.164565	0.157378	0.164565	0.157378
10	0.17175	0.17175	0.157378	0.17175	0.157378
15	0.178937	0.178937	0.157378	0.178937	0.157378
20	0.186123	0.186123	0.157378	0.186123	0.157378
25	0.193309	0.193309	0.157378	0.193309	0.157378
30	0.200496	0.200496	0.157378	0.200496	0.157378



a) Vehicles Using Ethanol Blends



b) Passenger Cars and Trucks Only

Figure 35. Comparative Results for VOC Emissions by Vehicle Type/Ethanol Content for Urban Restricted Access

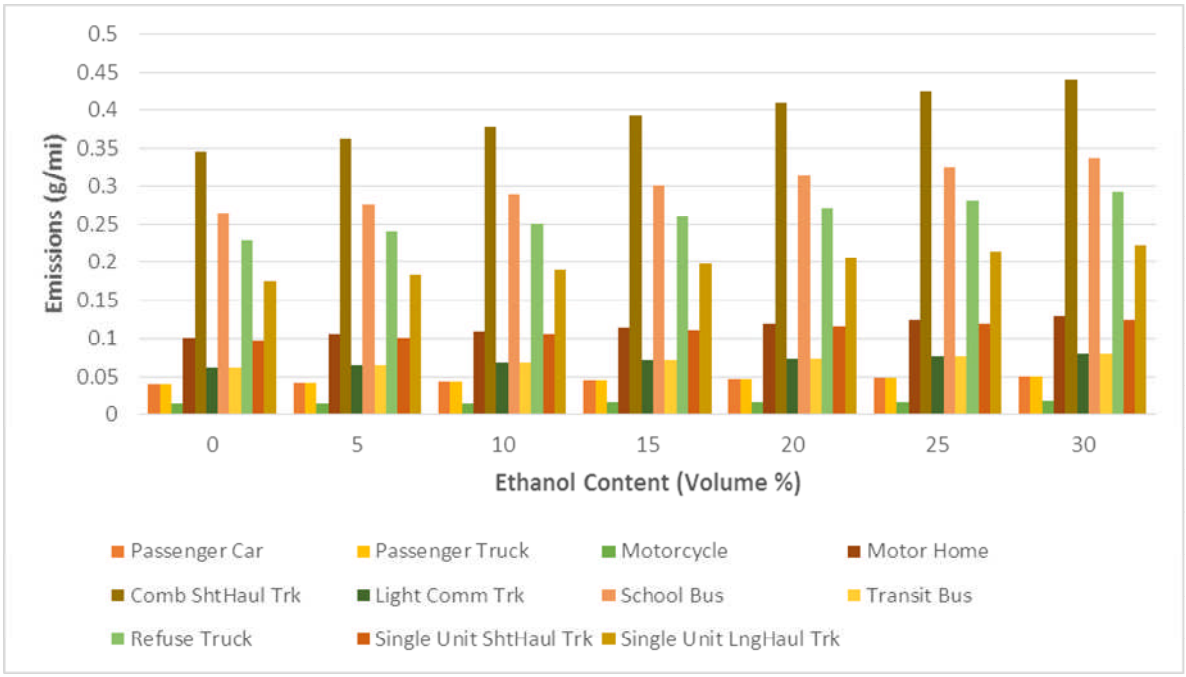
The same methodology was applied for urban unrestricted access facilities. However, since the trends remain the same, only VOC and NMHC are shown. Urban unrestricted access facilities show a slight increase in emissions over urban restricted access facilities. Table 39 displays these values while Figure 36 shows the graphical comparison by vehicle type. Again, Figure 36 has been divided into two parts to better display passenger cars and trucks.

Table 39. Evaporative Emission Rates for Urban Unrestricted Access Facility by Vehicle Type

	Emissions (g/mile)	
Vehicle Type		
Ethanol Content	***VOC***	***NMHC***
Passenger Car		
0	0.040026	0.040026
5	0.041854	0.040026
10	0.043682	0.040026
15	0.045509	0.040026
20	0.047337	0.040026
25	0.049165	0.040026
30	0.050993	0.040026
Passenger Truck		
0	0.040026	0.062862
5	0.041854	0.062862
10	0.043682	0.062862
15	0.045509	0.062862
20	0.047337	0.062862
25	0.049165	0.062862
30	0.050993	0.062862
Motorcycle		
0	0.013589	0.013589
5	0.014209	0.013589
10	0.01483	0.013589
15	0.015451	0.013589
20	0.016071	0.013589
25	0.016692	0.013589
30	0.017312	0.013589
Motor Home		
0	0.100884	0.100884
5	0.10549	0.100884

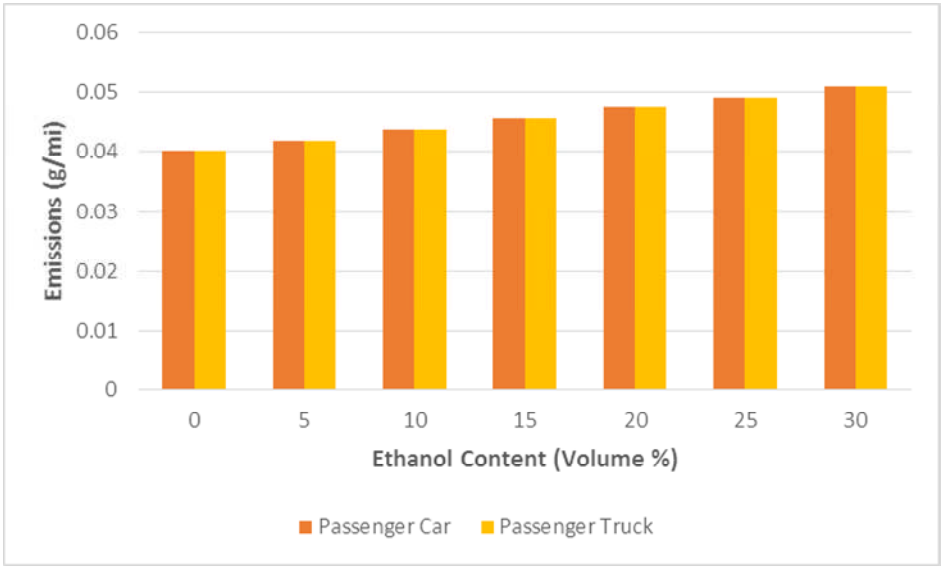
	Emissions (g/mile)	
Vehicle Type		
Ethanol		
Content	***VOC***	***NMHC***
10	0.110097	0.100884
15	0.114703	0.100884
20	0.11931	0.100884
25	0.123917	0.100884
30	0.128523	0.100884
Combination Short Haul Truck		
0	0.346088	0.346088
5	0.361891	0.346088
10	0.377694	0.346088
15	0.393497	0.346088
20	0.4093	0.346088
25	0.425104	0.346088
30	0.440907	0.346088
Light Commercial Truck		
0	0.062644	0.062644
5	0.065505	0.062644
10	0.068365	0.062644
15	0.071226	0.062644
20	0.074086	0.062644
25	0.076947	0.062644
30	0.079807	0.062644
School Bus		
0	0.265442	0.265442
5	0.277563	0.265442
10	0.289684	0.265442
15	0.301805	0.265442
20	0.313926	0.265442
25	0.326046	0.265442
30	0.338167	0.265442
Transit Bus		
0	0.062489	0.062489
5	0.065342	0.062489
10	0.068195	0.062489
15	0.071049	0.062489
20	0.073902	0.062489
25	0.076756	0.062489
30	0.079609	0.062489

	Emissions (g/mile)	
Vehicle Type		
Ethanol Content	***VOC***	***NMHC***
Refuse Truck		
0	0.229567	0.229567
5	0.24005	0.229567
10	0.250532	0.229567
15	0.261015	0.229567
20	0.271497	0.229567
25	0.28198	0.229567
30	0.292463	0.229567
Single Unit Short-Haul Truck		
0	0.097593	0.097593
5	0.10205	0.097593
10	0.106506	0.097593
15	0.110962	0.097593
20	0.115419	0.097593
25	0.119875	0.097593
30	0.124331	0.097593
Single Unit Long-Haul Truck		
0	0.174556	0.174556
5	0.182527	0.174556
10	0.190497	0.174556
15	0.198468	0.174556
20	0.206439	0.174556
25	0.21441	0.174556
30	0.22238	0.174556



a) Vehicles Using Ethanol Blends

b)



c) Passenger Cars and Trucks Only

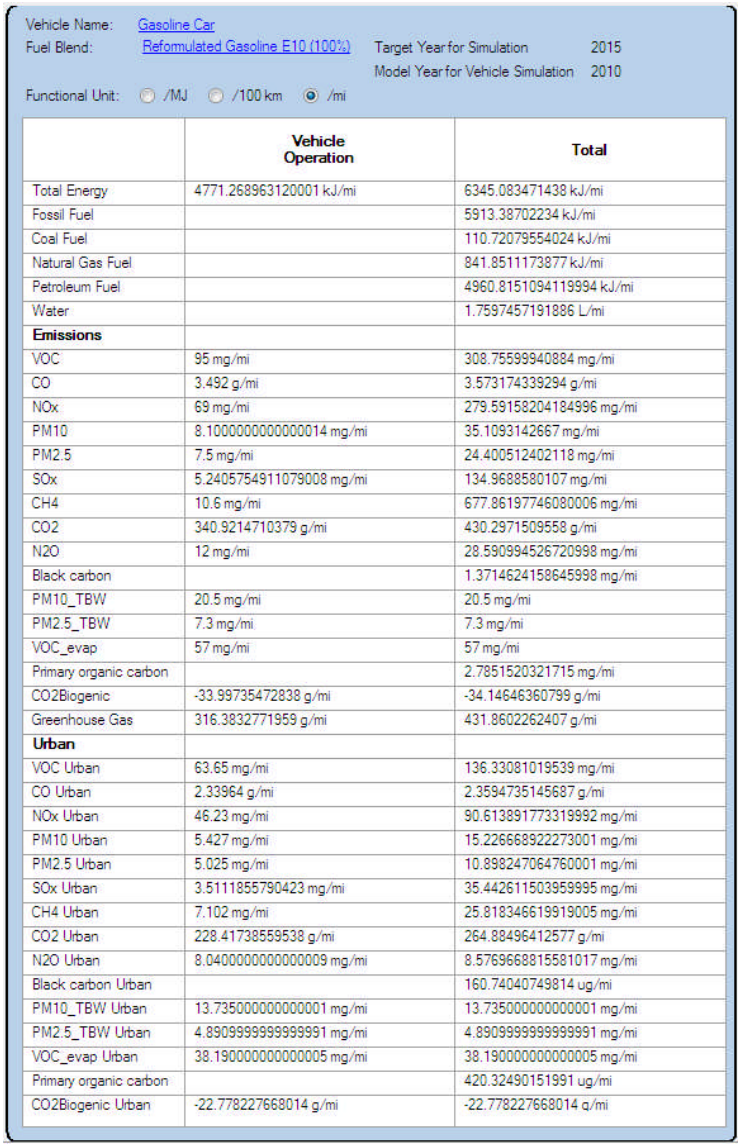
Figure 36. Comparative Results for VOC Emissions by Vehicle Type/Ethanol Content for Urban Unrestricted Access

Important take-aways from this section is that for some hydrocarbon species, the use of ethanol does not affect predicted emissions from MOVES2014 and are the same as pure gasoline (E0). For other hydrocarbon species increasing content of ethanol result in increasing emissions as predicted by MOVES2014. Urban unrestricted access facilities show a slight increase in emissions over urban restricted access facilities.

5 GREET RESULTS

GREET, a model derived at the Argonne National Labs (Argonne, 2014) is primarily meant for greenhouse gas evaluations for the transportation life cycle. However, it includes mobile source components and during MOVES development was heavily entwined in algorithm development. As such, GREET2014, was evaluated for an urban area "gasoline car" using E10 (only option available) in 2015. Figure 37 shows the output of the model and includes the emission rates for 100% E10 fuel. Rates for Vehicle Operation were compared to the E10 base case evaluated in Chapter 4.

The evaluation results, shown in Table 40, indicate that for most pollutants the easy-to-use GREET model tends to over-predict most pollutants compared to MOVES2014, but may provide a "ballpark" estimate that is relatively close to MOVES2014 predictions. However, NOx predictions are vastly different and much less from GREET. Why this occurs must be a fundamental difference in the way the two models report. If evaporative emissions are compared we find 0.043682 vs 0.03819 g/mi for the MOVES2014 and GREET model, respectively, for a prediction of 12.57% less than MOVES2014. Again this emission rate prediction is somewhat close without specifying any fuel parameters. For CO_2, the MOVES2014 models predicts 295.2506 g/mi while GREET predicted 228.4174, an under-prediction of 22.64% as compared to MOVES2014. Notably, however, the primary purpose of GREET is to estimate emissions of CO_2 and other greenhouse gas emissions, and thus the GREET model's approach to GHG emissions is designed more toward this task than MOVES.



Vehicle Name: Gasoline Car
Fuel Blend: Reformulated Gasoline E10 (100%)
Target Year for Simulation 2015
Model Year for Vehicle Simulation 2010
Functional Unit: /MJ /100 km /mi

	Vehicle Operation	Total
Total Energy	4771.268963120001 kJ/mi	6345.083471438 kJ/mi
Fossil Fuel		5913.38702234 kJ/mi
Coal Fuel		110.72079554024 kJ/mi
Natural Gas Fuel		841.8511173877 kJ/mi
Petroleum Fuel		4960.8151094119994 kJ/mi
Water		1.7597457191886 L/mi
Emissions		
VOC	95 mg/mi	308.75599940884 mg/mi
CO	3.492 g/mi	3.573174339294 g/mi
NOx	69 mg/mi	279.59158204184996 mg/mi
PM10	8.100000000000014 mg/mi	35.1093142667 mg/mi
PM2.5	7.5 mg/mi	24.400512402118 mg/mi
SOx	5.2405754911079008 mg/mi	134.9688580107 mg/mi
CH4	10.6 mg/mi	677.86197746080006 mg/mi
CO2	340.9214710379 g/mi	430.2971509558 g/mi
N2O	12 mg/mi	28.590994526720998 mg/mi
Black carbon		1.3714624158645998 mg/mi
PM10_TBW	20.5 mg/mi	20.5 mg/mi
PM2.5_TBW	7.3 mg/mi	7.3 mg/mi
VOC_evap	57 mg/mi	57 mg/mi
Primary organic carbon		2.7851520321715 mg/mi
CO2Biogenic	-33.99735472838 g/mi	-34.14646360799 g/mi
Greenhouse Gas	316.3832771959 g/mi	431.8602262407 g/mi
Urban		
VOC Urban	63.65 mg/mi	136.33081019539 mg/mi
CO Urban	2.33964 g/mi	2.3594735145687 g/mi
NOx Urban	46.23 mg/mi	90.613891773319992 mg/mi
PM10 Urban	5.427 mg/mi	15.226668922273001 mg/mi
PM2.5 Urban	5.025 mg/mi	10.898247064760001 mg/mi
SOx Urban	3.5111855790423 mg/mi	35.442611503959995 mg/mi
CH4 Urban	7.102 mg/mi	25.818346619919005 mg/mi
CO2 Urban	228.41738559538 g/mi	264.88496412577 g/mi
N2O Urban	8.0400000000000009 mg/mi	8.5769668815581017 mg/mi
Black carbon Urban		160.74040749814 ug/mi
PM10_TBW Urban	13.735000000000001 mg/mi	13.735000000000001 mg/mi
PM2.5_TBW Urban	4.8909999999999991 mg/mi	4.8909999999999991 mg/mi
VOC_evap Urban	38.190000000000005 mg/mi	38.190000000000005 mg/mi
Primary organic carbon		420.32490151991 ug/mi
CO2Biogenic Urban	-22.778227668014 g/mi	-22.778227668014 g/mi

Figure 37. Output from the GREET Model for Emission Rates by distance (mass/distance)

Table 40. Results of GREET Model Compared to Base E10 Fuel for Emission Rates (g/mi)

Case	CO	Ethanol	NOX	PM10	PM2.5	VOC
Reference	2.129149	0.001219	0.291739	0.00503	0.004485	0.053615
GREET	2.33964	NA	0.04623	0.005427	0.005025	0.06365
% Difference	9.00	NA	-531.06	7.32	10.75	15.77

The GREET model, which is meant more for overall estimates than project level evaluation, has few fuel parameter inputs for the user to choose and no control over fuel properties without making manual changes. Even so, it provides somewhat close estimates for CO and PM. VOCs have a greater error as does CO_2. NOx was found to be much different.

6 OVERALL TREND COMPARISON

This research has shown that the use of the default fuel list in MOVES2014 may not match what is being blended in the real-world via splash blending. As discussed in the literature review in Section 2.2, other researchers have found ethanol fuel blend emissions trends that appear in many cases to be different than the predictions of the MOVES2014 model. Since MOVES2014 depends upon a series of adjustment factors based on fuel properties, it is important for the user to be aware of this concern and understand the fuel properties that serve as the basis for the adjustments. Using the Fuel Wizard can help users determine specific fuel properties being used. However, for blends over E20, manual input will be required in the Fuel Formulation and Fuel Supply tables. Evaluation of real-world absolute emission rates, beyond what is available in the literature, was not possible because a rigid data set with known fuel properties would be required. There is a need for more research in this area. However general trends were reviewed. How these trends changed were reported for various pollutants. As shown in Figure 38, which includes some previous results presented and the results of this MOVES2014 testing, it can be seen that notable differences occur. For example, Gravalos and Hubbard show NOx to generally decrease as ethanol content increases, but this is not how MOVES2014 predicts NOx emissions for fuels in the E0 to E30 range. Many other emissions trends from the literature are also shown to be different from MOVES2014 predictions. Of interest is how the results of USEPA have changed over time, especially adding the prediction of PM emission rates.

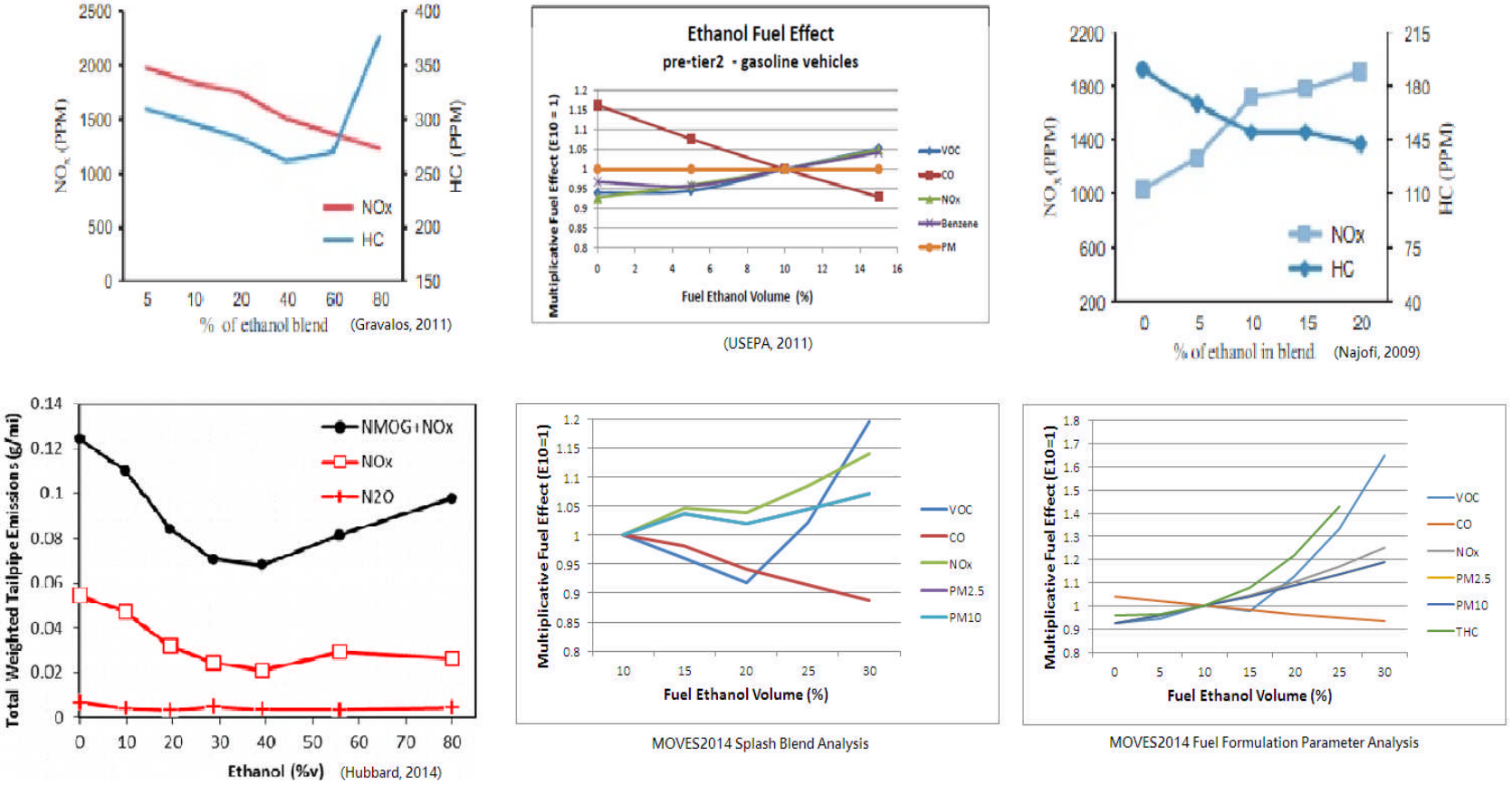


Figure 38. Comparison of Results from This Analysis Compared to Other Researchers

7 CONCLUSIONS

Ethanol, a major consideration for use as an alternative fuel for motor vehicles, represented approximately 10% of the U.S. gasoline fuel supply in 2014. Mixtures of E85 are also commonly used in the U.S. and Europe for flexible-fuel vehicles. Higher ratio blends, such as E25, are in use in countries such as Brazil. Air quality is an important consideration for the use of any fuel used in motor vehicles with accurate prediction of emissions necessary for multi-million dollar decisions. In this report, the methodology and prediction effects of the Motor Vehicle Emission Simulator (MOVES) model were reviewed and evaluated in relation to the use of ethanol fuel blends. The review included information from the literature, input requirements, algorithms, output, and general findings. The evaluation includes modeling of emissions and the sensitivity to ethanol blends during MOVES modeling. Particular attention is placed on mid-level ethanol fuel blends (E15 to E30).

The USEPA began to develop MOVES in 2000 with recommendations made by the National Research Council with EPA reporting initial considerations in 2002 and 2003. Ethanol was not formally addressed until MOVES2004 and EPA has continued this effort in the current version, MOVES2014.

The basic approach in MOVES to predicting fuel property impacts on emission rates has been based on the use of adjustment factors developed using results of fuel and emissions databases. Thus, if the fuels upon which the adjustment factors are based are not representative of real-world market available fuels, then the emissions results predicted by MOVES may not be as accurate as desired for actual on-road emissions. A review of the fuel properties used becomes an important part of the prediction process. The basic principle behind MOVES involves a direct comparison of a base fuel to the target (fuel of concern) with a large series of factors being developed. MOVES2014 includes a large default data base, and a “Fuel Wizard” has been developed for input fuel parameters of non-default fuels. The Fuel Wizard seems to be based on match blending. If different fuel properties are desired, such as used in splash blending, a manual process is required and becomes more difficult.

Reported results of exhaust and evaporative emissions from independent researchers have varied from MOVES2014 predictions. Individual fuel property variables were shown to often display different effects or effects of a different magnitude than predicted by MOVES2014. Real world splash blends may not have the same properties as the modeled default match blends used in MOVES. Additionally, the use of the fuel properties and Fuel Wizard in MOVES must be considered carefully when determining changes due to ethanol blends to prevent inaccurate use of the model. Trends used to

determine constants in equations may need to consider many more variables than are now being considered.

Research of the aging effects on passenger vehicle with ethanol blends were shown to cause no increase in exhaust emissions when compared to E0.

In summary, the evaluation of MOVES included reviewing inputs and a sensitivity study of fuels available in MOVES, changes with the use of customized fuel properties, and evaporative emission prediction changes. This required four separate test scenarios:

1. Fuel Wizard Ethanol Sensitivity Analysis
2. Splash Blend Analysis
3. Fuel Formulation Parameter Sensitivity Analysis
4. Evaporative Fuel Leak Ethanol Sensitivity Analysis

Various sensitivity tests were run for each scenario.

A total of 68,400 fuels make up the MOVES2014 master fuel list. Reductions to a manageable number had to be made for this testing. This resulted in using only gasoline based fuels, choosing only low, mid, and high values of Reid Vapor Pressure (RVP) and aromatic content, from the lists of summer gasoline fuel formulations. Further reductions were possible by reviewing the properties in the literature and in MOVES2014, and selecting four base fuels from the MOVES2014 default fuels for E10 and E15.

An important point for modelers was uncovered. When the ethanol content is changed using the Fuel Wizard in MOVES2014, the program automatically adjusts the RVP, aromatic content, olefin content, e200, e300, T50, and T90 parameters, as well as the fuelsubtypeID, to match blends built into MOVES2014. However, when applying a 20% or greater ethanol content in the MOVES fuel wizard, the MOVES subtypeID does not adjust the other fuel properties. Manual changes to the Fuel Formulation table and Fuel Supply table are required.

Results from all 4 scenarios were important. From the Fuel Wizard Ethanol Sensitivity Analysis, the following trends were noted:

- CO decreases with increasing ethanol content;
- Nitrogen components increase with increasing ethanol content;
- THC decreases from gasoline to E5 then increases;
- VOC increases to E10, decreases at E15, and increases for E20 to E30;
- Ethanol increases to E10, plateaus to E15, and then increases for E20 and above;
- PM species increase with increasing ethanol content;

- SO_2 increases with increasing ethanol content until E20, then becomes a constant (this could be due to the fact the Fuel Wizard could not be used above E20 and manual input was required);
- CO_2 is a step function, with values above E20 having lower values;
- Changes in ethanol content also affected some emission rates for pollutants that is not understood, such as SO_2, and,
- The urban unrestricted access facility type, with the higher speeds and fuel consumption results in greater emission rates indicating that other parameters such as drive cycle are crucial in all analysis.

From the splash blend analysis (E15 splash and E15 match blend) it was found that the fuel properties with the exception of T50 were very similar as are the predicted emissions with the exception being CO is slightly less for the splash blend. Differences in emission rates were shown for one geographic location, Saint Louis. Additionally, emission rates were similar for the Saint Louis E10 blend from the base case even though some fuel properties were different. This points out a need for a more robust adjustment process that should consider the changes in all properties in aggregate, and not independently.

A review of the actual changes in practice was slow conducted showing CO, PM, and VOC emissions to be the most important, especially PM based on current project level analyses now being conducted.

The Fuel Formulation Parameter Sensitivity Analysis, with fuel properties RVP, sulfur level, ethanol volume, aromatic content, olefin content, T50, and T90 analyzed, showed that the urban unrestricted access, with the higher speeds and fuel consumption results in greater emission rates. Trends also followed for the pollutants previously discussed but of interest is that THC emission rates did not decrease at E5 for Fuel Formulation 3202 as for other formulations but did continue to increase with increasing ethanol content. Also the effects for E10 and E15 were slightly different. Overall rates were also slightly higher showing that the Fuel Wizard changes do not exactly match results when the fuel parameters are individually selected.

The USEPA states that ethanol has a unique effect and increases permeation of specific compounds and this was reflected in the results of the Evaporative Fuel Leak Ethanol Sensitivity Analysis, where increasing content of ethanol result in increasing hydrocarbon emissions for most species as predicted by MOVES2014.

The GREET model, designed to predict more overall estimates than project level evaluation, was evaluated and found to be easy to use, with few inputs for the user to choose, and no control over fuel properties without making manual changes. Even so,

it provides somewhat close estimates for CO and PM, a greater error for VOCs and CO_2, and vastly different NOx estimates.

This research has shown that the use of the default fuel list in MOVES2014 may not match what is being blended in the real-world splash blending. Since MOVES2014 depends upon a series of adjustment factors based on fuel properties it is important for the user to be aware of this concern and check the fuel properties by using the Fuel Wizard during input if ethanol blends are to be used. For blends over E20, manual input will be required in the Fuel Formulation and Fuel Supply tables. Evaluation of absolute emission rates was not possible because a rigid data set with known fuel properties would be required. There is a need for more research in this area, especially testing of exhaust emissions with well-defined fuel parameters. General trends were reviewed showing multiple differences in emission rate trends by pollutant. Which is correct can be debated.

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Appendix A: MOVES Fuel Formulation Sensitivity Analysis Data Report

9/16/2015

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A1 Introduction

The information in this document describes modeling input selections utilized for executing the Environmental Protection Agency's (EPA) Motor Vehicle Emission Simulator (MOVES) specific to this analysis. The analysis focused on assessing the impact of emission rates due to varying certain fuel formulation parameters, with a particular focus on ethanol content. The analysis consisted of four separate components:

1. Fuel Wizard Ethanol Sensitivity Analysis
2. Splash Blend Analysis
3. Fuel Formulation Parameter Sensitivity Analysis
4. Evaporative Fuel Leak Ethanol Sensitivity Analysis

The MOVES Run Specification and Project Data Manager (PDM) input data are identical for all four components of the analysis, with exception being the fuel supply and fuel formulation input data used for each individual MOVES run. The data entered into the PDM are partially based off a National Scale MOVES run for the year 2015. Information such as annual average meteorology and link source type data (fleet mixture) were obtained from the 2015 MOVES National Scale Run and utilized for the MOVES Project Level runs for each analysis component. The Project Scale runs for this each analysis component consisted of running a single hour for two distinct roadway links. These links included an urban, unrestricted access road type, with an average speed of 35 miles per hour, as well as an urban restricted access road type with an average speed of 50 miles per hour. The temperature value utilized is based upon the national average temperature of 60.18 degrees Fahrenheit and national average relative humidity of 60.33 percent. Fuel Supply and Fuel Formulation varied for each MOVES run depending on the analysis component. The MOVES Run Specification information utilized for all components of the analysis is listed in Table A1

Table A1. MOVES Run Specification

MOVES Navigation Panel Item	Modeling Parameters	Modeling Parameter Selections
Scale	Model	Onroad
	Domain/Scale	Project
	Calculation Type	Inventory
Time Span	Time Aggregation Level	Hour
	Years	2015
	Months	July
	Days	Weekdays
	Hours	8:00

Geographic Bounds	Region	Custom Domain
	State ID	99
	County ID	1
	GPA Fraction	0
	Barometric Pressure	28.94
	Vapor Adjust	0
	Spill Adjust	0
Vehicles/Equipment	On Road Vehicle Equipment	Gasoline - Combination Short-Haul Truck
		Gasoline -Light Commercial Truck
		Gasoline - Motor Home
		Gasoline - Motorcycle
		Gasoline - Passenger Car
		Gasoline - Passenger Truck
		Gasoline - Refuse Truck
		Gasoline - School Bus
		Gasoline - Single Unit Long-haul Truck
		Gasoline - Single Unit Short-haul Truck
		Gasoline - Transit Bus
Road Type	Selected Road Types	Urban Restricted Access
		Urban Unrestricted Access
Pollutants and Processes (Analysis Components #1,#2, and #3)	Pollutant Processes	Running Exhaust and Crankcase Running Exhaust
	Pollutants	Total Gaseous Hydrocarbons
		Non-Methane Hydrocarbons
		Volatile Organic Compounds
		Carbon Monoxide (CO)
		Oxides of Nitrogen (NOX)
		Nitrogen Dioxide (NO2)
		Primary Exhaust PM2.5 - Total
		Primary Exhaust PM2.5 - Species
		Primary Exhaust PM10 - Total
		Sulfur Dioxide (SO2)
		Total Energy Consumption
		Atmospheric CO2
		Ethanol
Pollutants and Processes (Analysis Component #4)	Pollutant Processes	Evaporative Fuel Leaks
	Pollutants	Total Gaseous Hydrocarbons
		Non-Methane Hydrocarbons
		Non-Methane Organic Gases
		Total Organic Gases
		Volatile Organic Compounds
General Output	Mass Units	Grams
	Energy Units	Million BTU
	Distance Units	Miles

A2 Fuel Wizard Ethanol Sensitivity Analysis

The fuel supply and fuel formulation tables from the MOVES default database (movesdb20141021cb6v2) were reviewed and the summer blend (July) fuel formulations were considered for the analysis. For the year 2015 there are a total of 75 unique gasoline fuel formulations (gasohol E10 and E15) in the MOVES default database. There are 40 unique summer (June through September) gasoline fuel formulations (gasohol E10 and E15) in the moves default database within the total 75 unique formulations. Four fuel formulations were chosen from the list of 40 summer gasoline fuel formulations based upon the low, mid, and high values of Reid Vapor Pressure (RVP) and aromatic content. The ethanol content for each formulation analyzed was changed within the MOVES fuel wizard by 5% increments from 0% to 30%. The original ethanol content for each analyzed fuel formulation was 10%. The MOVES fuel wizard automatically adjusts the RVP, aromatic content, olefin content, e200, e300, T50, and T90 parameters, as well as the fuelsubtypeID, based upon the ethanol content chosen. However, when applying a 20% or greater ethanol content in the MOVES fuel wizard, the MOVES subtypeID is not adjusted. This resulted in a default fuel formulation being used by MOVES while executing the model. In order to run a fuel formulation with an ethanol content of 20% or greater, the fuel subtypeID field was manually changed to the value of 18 in the fuel formulation input file. It was observed that the MOVES fuel wizard does not adjust any other fuel formulation parameters for ethanol content values greater than 20%. Table A2 lists the fuel formulations modeled for the Fuel Wizard Sensitivity Analysis.

Table A2. Fuel Wizard Ethanol Sensitivity Analysis Fuel Formulations

MOVESRunID	fuelFormulationID	fuelSubtypeID	RVP	sulfurLevel	ETOHVolume	aromaticContent	olefinContent	benzeneContent	e200	e300	T50	T90
1	3307	10	5.92	30	0	18.67	11.58	0.53	48.7144	82.7006	202.44	330.77
2	3307	14	6.42	30	5	17.66	11.35	0.53	50.2677	82.8953	199.27	329.885
3	3307	12	6.92	30	10	16.65	11.12	0.53	51.821	83.09	196.1	329
4	3307	15	6.92	30	15	15.7567	10.3333	0.53	55.9109	83.4376	187.753	327.42
5	3307	18	6.92	30	20	15.31	9.93997	0.53	57.956	83.6114	183.58	326.63
6	3307	18	6.92	30	25	15.31	9.93997	0.53	57.956	83.6114	183.58	326.63
7	3307	18	6.92	30	30	15.31	9.93997	0.53	57.956	83.6114	183.58	326.63
8	3202	10	6.8	30	0	25.25	12.98	0.61	41.6388	80.0518	216.88	342.81
9	3202	14	7.3	30	5	24.24	12.75	0.61	43.1921	80.2465	213.71	341.925
10	3202	12	7.8	30	10	23.23	12.52	0.61	44.7454	80.4412	210.54	341.04
11	3202	15	7.8	30	15	22.3367	11.7333	0.61	48.8353	80.7888	202.193	339.46
12	3202	18	7.8	30	20	21.89	11.34	0.61	50.8804	80.9626	198.02	338.67
13	3202	18	7.8	30	25	21.89	11.34	0.61	50.8804	80.9626	198.02	338.67
14	3202	18	7.8	30	30	21.89	11.34	0.61	50.8804	80.9626	198.02	338.67
15	3204	10	7.8	30	0	25.25	12.98	0.61	42.8981	80.5512	214.31	340.54
16	3204	14	8.3	30	5	24.24	12.75	0.61	44.4514	80.7459	211.14	339.655
17	3204	12	8.8	30	10	23.23	12.52	0.61	46.9	80.45	207.97	338.77
18	3204	15	8.8	30	15	22.3367	11.7333	0.61	50.0946	81.2882	199.623	337.19
19	3204	18	8.8	30	20	21.89	11.34	0.61	52.1397	81.462	195.45	336.4
20	3204	18	8.8	30	25	21.89	11.34	0.61	52.1397	81.462	195.45	336.4
21	3204	18	8.8	30	30	21.89	11.34	0.61	52.1397	81.462	195.45	336.4
22	3212	10	8.7	30	0	26.96	8.54	0.63	46.186	81.2134	207.6	337.53
23	3212	14	9.2	30	5	25.95	8.31	0.63	47.7393	81.4081	204.43	336.645
24	3212	12	9.7	30	10	24.94	8.08	0.63	50.87	82.17	201.26	335.76
25	3212	15	9.7	30	15	24.0467	7.29333	0.63	53.3825	81.9504	192.913	334.18
26	3212	18	9.7	30	20	23.6	6.9	0.63	55.4276	82.1242	188.74	333.39
27	3212	18	9.7	30	25	23.6	6.9	0.63	55.4276	82.1242	188.74	333.39
28	3212	18	9.7	30	30	23.6	6.9	0.63	55.4276	82.1242	188.74	333.39

A3 Splash Blend Analysis

The Renewable Fuel Association (RFA) provided splash blend fuel formulations, listed in Table A3, that were modeled with MOVES.

Table A3. Splash Blend Fuel Formulations

Formulation Name	RVP	Sulfur	Ethanol	Aromatics	Olefins	Benzene	E200	E300	T50	T90
	psi	*ppm*	*%vol*	*%vol*	*%vol*	*%vol*	*%*	*%*	*deg. F*	*deg. F*
E10 (Reference/Base Fuel)	7.0	25.0	9.95	23.3	10.1	0.60	51.0	85.0	217.1	308.2
E15 (Match)	7.0	25.0	14.85	23.3	10.1	0.60	51.0	85.0	217.1	308.2
E15 (Splash)	7.0	24.3	14.85	22.1	9.6	0.57	57.0	86.0	167.4	305.9
E20 (Splash)	7.0	23.5	19.85	20.9	9.1	0.54	58.0	86.5	166.5	305.1
E25 (Splash)	7.0	22.5	24.85	19.8	8.6	0.51	57.0	85.5	168.1	303.9
E30 (Splash)	7.0	21.0	29.85	18.6	8.1	0.48	56.0	85.0	170.1	302.0

* Based on Appendix Table A-3 of Anderson et al/SAE Int. J. Fuels Lubr./Volume 7, Issue 3 (Nov. 2014) and discussion with fuel specification experts

Each formulation listed in Table A3 was modeled with MOVES, along with the summer blend E10 and E15 fuel formulations associated with Atlanta, Detroit, Saint Louis and Kansas City. Table A4 lists all the fuel formulations and associated parameters modeled for the Splash Blend Analysis.

Table A4. Splash Blend Analysis Fuel Formulations

MOVESRunID	Case	fuelFormulationID	fuelSubtypeID	RVP	sulfurLevel	ETOHVolume	aromaticContent	olefinContent	benzeneContent	e200	e300	T50	T90
1	Reference	-	12	7	25	9.95	23.3	10.1	0.6	51	85	217.1	308.2
2	E15 Match	-	15	7	25	14.85	23.3	10.1	0.6	51	85	217.1	308.2
3	E15 Splash	-	15	7	24.3	14.85	22.1	9.6	0.57	57	86	167.4	305.9
4	E20_Splash	-	18	7	23.5	19.85	20.9	9.1	0.54	58	86.5	166.5	305.1
5	E25_Splash	-	18	7	22.5	24.85	19.8	8.6	0.51	57	85.5	168.1	303.9
6	E30_Splash	-	18	7	21	29.85	18.6	8.1	0.48	56	85	170.1	302
7	ATL E10	3203	12	8	30	10	23.23	12.52	0.61	45.89	80.06	210.02	340.59
8	ATL E15	3205	15	7	30	15	21.89	11.34	0.61	52.02	80.58	197.59	338.22
9	DET E10	3220	12	8	30	10	24.94	8.08	0.63	48.73	81.32	205.63	339.62
10	DET E15	3222	15	7	30	15	23.6	6.9	0.63	54.86	81.84	193.2	337.25
11	STL E10	3313	12	7.06	30	10	17.13	7.85	0.77	50.98	85.24	193.2	326.7
12	STL E15	3315	15	7.06	30	15	15.79	6.67	0.77	57.11	85.76	180.77	324.33
13	KC E10	3237	12	8	30	10	25.67	9.42	0.63	46.42	84.22	208.66	322.65
14	KC E15	3239	15	7	30	15	24.33	8.24	0.63	52.55	84.74	196.23	320.28

A4 Fuel Formulation Parameter Sensitivity Analysis

For the Fuel Formulation Parameter Sensitivity Analysis the fuel formulation parameters RVP, sulfur level, ethanol volume, aromatic content, olefin content, T50, and T90 were all varied individually while holding all other parameters constant. The purpose of this analysis was to determine how the variation of each independent fuel formulation parameter impacts the resulting emissions rates. Fuel formulation 3202 from the MOVES default database was chosen as the baseline fuel formulation for this analysis. Table A5 lists the parameters associated with fuel formulation 3202.

Table A5. Fuel Formulation 3202 Parameters

fuelFormulationID	3202
fuelSubtypeID	12
RVP	7.8
sulfurLevel	30
ETOHVolume	10
aromaticContent	23.23
olefinContent	12.52
benzeneContent	0.61
e200	44.7454
e300	80.4412
T50	210.54
T90	341.04

Table A6 lists which parameter and the associated value used for each MOVES run. For example, for MOVESRunIDs 1 through 9, RVP was varied while holding all other fuel formulation parameters constant. This same approach was applied for the other fuel formulation parameters listed in Table A6.

Table A6. Fuel Formulation Fuel Parameter Sensitivity Analysis Runs

MOVESRunID	Fuel Parameter	Parameter Value
1	RVP	6
2	RVP	6.5
3	RVP	7
4	RVP	7.5

5	RVP	Baseline
6	RVP	8
7	RVP	8.5
8	RVP	9
9	RVP	9.5
10	sulfurLevel	0
11	sulfurLevel	5
13	sulfurLevel	10
14	sulfurLevel	15
15	sulfurLevel	20
16	sulfurLevel	25
17	sulfurLevel	Baseline
18	sulfurLevel	35
19	sulfurLevel	40
20	sulfurLevel	45
21	sulfurLevel	50
22	aromaticContent	0
23	aromaticContent	5
24	aromaticContent	10
25	aromaticContent	15
26	aromaticContent	20
27	aromaticContent	Baseline
28	aromaticContent	25
29	aromaticContent	30
30	aromaticContent	35
31	aromaticContent	40
32	olefinContent	0
33	olefinContent	5
34	olefinContent	10
35	olefinContent	Baseline
36	olefinContent	15
37	olefinContent	20
38	olefinContent	25
40	T50	175
41	T50	200
42	T50	Baseline
43	T50	225
44	T50	250
45	T90	300
46	T90	310
47	T90	320
48	T90	330
49	T90	340
50	T90	Baseline
51	T90	350
52	ETOHVolume	0
53	ETOHVolume	5
54	ETOHVolume	10
55	ETOHVolume	15
56	ETOHVolume	20
57	ETOHVolume	25
58	ETOHVolume	30

A5 Evaporative Fuel Leak Ethanol Sensitivity Analysis

The MOVES runs associated with the Evaporative Fuel Leak Ethanol Sensitivity Analysis is similar to the Fuel Wizard Ethanol Sensitivity analysis in that the MOVES Fuel Wizard was used to adjust the ethanol content. However, only the evaporative fuel leak emissions process was chosen to be run in this analysis, while the Fuel Wizard Ethanol Sensitivity Analysis focused on running exhaust and running and crankcase running exhaust emission processes. Fuel formulation 3202 was utilized for this analysis. The fuel formulation parameters analyzed are listed as MOVESRunIDs 8 through 14 in Table A2 of Section A2.

Appendix B: Tabular and Graphical Results from Analysis

Appendix B is a very large listing of data, tables, and figures. It was found to be more efficient to place this information in a spreadsheet to provide as a part of this report and with the use of Pivot tables and figures allow more flexibility in data review.
