



# **Effects of Light-duty Vehicle Emissions Standards and Gasoline Sulfur Level on Ambient Ozone**

## **Final Report**

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## Acronyms and Abbreviations

API	American Petroleum Institute
ARB	Air Resources Board, California
CAMx	Comprehensive Air Quality Model with Extensions
CB05	Carbon Bond Mechanism 5
CO	Carbon monoxide
CONUS	Continental United States
CRC	Coordinating Research Council
EPA	Environmental Protection Agency
g-LDV	Gasoline fueled light duty vehicle
LDGV	Light duty gasoline vehicles (passenger cars)
LDGT1	Light duty gasoline trucks weighing less than 6,000 lbs
LDGT2	Light duty gasoline trucks weighing between 6,001 and 8,500 lbs
LEV	Low Emission Vehicle
MDA8	Maximum daily 8-hr average
MOBILE6	Mobile emission modeling software
MOVES	Motor Vehicle Emission Simulator
NOx	Oxides of nitrogen
O3	Ozone
ppb	parts per billion
ppm	parts per million
PM	Particulate matter
PM SO4	Particulate sulfate
SCC	Standard classification code
SO2	Sulfur dioxide
SPECIATE	Speciation database
THC	Total hydrocarbons
VMT	Vehicle miles traveled
VOC	Volatile organic compound
WRF	Weather Research and Forecast Model

## Executive Summary

More stringent vehicle emission regulations and fuel property standards are being considered in the United States to improve air quality and attain compliance with national ambient ozone standards. We present a computer modeling study of the impact of past, present and potential future US Federal emissions standards for on-road gasoline-fueled light duty vehicles (g-LDVs) on summertime ground-level ambient ozone concentrations in the eastern US.

The US Environmental Protection Agency (EPA) Motor Vehicle Emission Simulator (MOVES) model was used to derive on-road vehicle emissions. This was complemented by a suite of other advanced emissions models for developing other source inventories. Air quality modeling was performed with the Comprehensive Air Quality Model with Extensions (CAMx). Modeling was conducted over a 12 km horizontal resolution domain in the eastern US nested within a 36 km continental US (CONUS) domain.

This work builds off prior modeling conducted by ENVIRON (Vijayaraghavan et al, 2012) for the Coordinating Research Council (CRC, Project A-76-1) which included the simulation of a 2008 base case to establish satisfactory model performance in addition to the following four hypothetical 2022 g-LDV emissions scenarios:

1. 2022 Tier 1 scenario (assumed that only Tier 1 vehicle standards have been implemented in 2022); however, sulfur levels were reduced from Tier 1 levels per the MOVES representation of Tier 2 sulfur implementation
2. 2022 Tier 2 scenario (assumed that no standards beyond Tier 2 have been implemented in 2022)
3. 2022 LEV III scenario (assumed that the California LEV III standards have been adopted nationwide; however, pre-LEV III vehicles were assumed to be operated on Tier 2 sulfur levels)
4. 2022 LDV zero-out scenario (assumed there are no g-LDV emissions in 2022)

In the CRC effort, the future year fuel sulfur in all scenarios complied with a standard of 30 ppm sulfur except in California where the counties used lower sulfur. The scenarios listed above did not coordinate the fuel sulfur assumptions within MOVES with the vehicle technology assumptions. The purpose of the current study is to update the 2022 LEV III and Tier I scenario exhaust emissions from the CRC effort so that they reflect a gasoline sulfur level appropriate to the emission control technology, model effects on ground-level ozone and compare incremental changes relative to the 2022 Tier 2 scenario. Two 2022 scenarios were modeled in the current study for a summer month (July):

1. 2022 Tier 1 scenario with gasoline sulfur level reflecting that typical of the time period during which the Tier 1 vehicle emissions standards were in effect.
2. 2022 LEV III scenario with gasoline sulfur level reflecting the LEV III standard.

The Tier 2 scenario already matched the vehicle technology and fuel sulfur assumptions and therefore did not require further modeling.

The July 1999 gasoline sulfur levels as represented in the MOVES database were used for the 2022 Tier 1 scenario. The g-LDV VMT-weighted average gasoline sulfur in the MOVES database in July 1999 over counties in the lower 48 states was 228 ppm. For the LEV III scenario, gasoline sulfur levels were modeled as 1/3 of the county-specific sulfur values in the MOVES database used to represent Tier 2 gasoline fuels. This approach was deemed to best approximate the reduction in gasoline sulfur content from a Tier 2 average of 30 ppm to a potential future federal “Tier 3” 10 ppm average standard. For this scenario the California Air Resources Board (ARB) Predictive Model was used to develop adjustments reflecting the impact of gasoline sulfur by technology group for total hydrocarbons (THC), oxides of nitrogen (NOx) and carbon monoxide (CO).

Nationwide g-LDV emissions of volatile organic compounds (VOCs), CO and NOx in the July 2022 Tier 2 scenario are lower by 62%, 51% and 80%, respectively, than those for the Tier 1 case. The corresponding reductions are much smaller (8%, 7% and 11%, respectively) when comparing the LEV III to the Tier 2 scenario.

The modeling results show that large benefits in ground-level ozone concentrations will have accrued in 2022 as a direct result of the transition from Tier 1 to Tier 2 g-LDV emissions standards and lower gasoline sulfur levels. These benefits include up to 30.2 ppb reductions in the monthly maximum and up to 27.1 ppb reductions in the monthly mean of daily maximum 8-hr average (MDA8) ozone concentrations. However, nationwide implementation of more stringent LDV emissions standards similar to LEV III along with further reductions in gasoline sulfur content would yield only very small additional improvements in 2022 summertime ozone concentrations, even when considering the in-use fleet emissions impact of the lower gasoline sulfur content. Peak monthly MDA8 ozone concentrations would be reduced by no more than 1.2 ppb, with reductions in mean monthly MDA8 ozone concentrations of no more than 0.5 ppb. Some further reductions in ozone would likely be realized in the post-2022 timeframe after the LEV III emission standards for NOx and non-methane organic gases are fully phased into the new vehicle fleet in model year 2025.

# 1. Introduction

This study examines the effect of historical, current and potential future gasoline-fueled light-duty vehicle (g-LDV) emission standards including mandated gasoline fuel sulfur reductions on ambient ground-level ozone in the eastern United States (US). The study builds upon prior work conducted by ENVIRON for the Coordinating Research Council (CRC, Project A-76-1).

In the prior work (Vijayaraghavan et al., 2012), ENVIRON modeled a 2008 base case for air quality model performance evaluation and four 2022 emissions scenarios with increasingly stricter emission standards for g-LDVs to estimate the incremental and cumulative effect of g-LDV emissions controls on ambient air quality. The four 2022 scenarios modeled were:

1. 2022 Tier 1 scenario (assume that only US Federal Tier 1 standards are implemented through 2022)
2. 2022 Tier 2 scenario (assume that the current emissions standards, up to US Federal Tier 2 standards, are implemented through 2022)
3. 2022 LEV III scenario (assume that the California LEV III standard is adopted nationwide)
4. 2022 g-LDV zero-out scenario (assume there are no g-LDV emissions in 2022)

All simulations were conducted for a winter month (February) and summer month (July).

The 2022 Tier 1 scenario in the CRC study aimed to answer the question: “what if the US had not switched from Tier 1 to Tier 2 standards by 2022?” The 2022 Tier 2 case reflects a scenario with current Tier 2 emissions standards that are not revised through 2022. The 2022 LEV III scenario addresses the potential impact of further tightening g-LDV emission standards from Tier 2 to a nationwide LEV III standard.

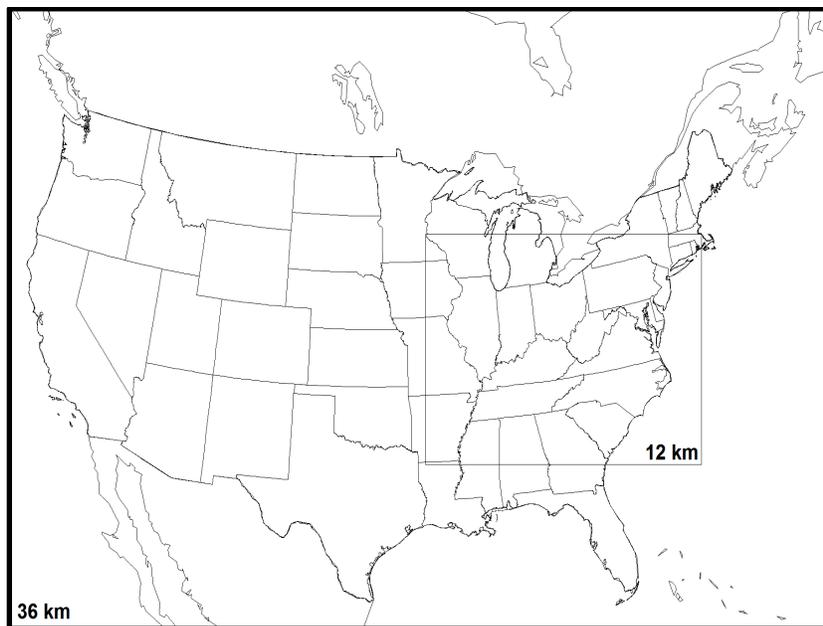
The g-LDV emission differences among the 2022 scenarios for the CRC study were due solely to technology changes in the g-LDV fleet. Gasoline sulfur content was set to the default value from the MOVES model database in all scenarios as discussed below. The purpose of the current study is to update the 2022 LEV III and Tier I scenario g-LDV exhaust emissions so that they reflect a gasoline sulfur level appropriate to the emission control technology, model effects on ground-level ozone and compare incremental changes relative to the 2022 Tier 2 scenario.

## 2. Methods

### 2.1 MODELING DOMAIN AND SCENARIOS

The air quality simulations were conducted with the Comprehensive Air Quality Model with Extensions (CAMx) (ENVIRON, 2011) using on-road emissions inventories derived using the Motor Vehicle Emission Simulator (MOVES) (EPA, 2010) and other model inputs as discussed below. We applied version 5.40 of CAMx with the Carbon Bond 5 (CB05) chemical mechanism and version 2010a of MOVES. The CAMx modeling domain (see Figure 1) extends over the

continental US (CONUS) at 36 km horizontal resolution with an inner nested domain at 12 km resolution over part of the eastern US. The domain has a pressure-based vertical structure with 26 layers with the model top at 145 mb or approximately 17 km above mean sea level.



**Figure 1. Air quality modeling domain.**

Two emissions scenarios were modeled:

3. 2022 Tier 1 scenario with gasoline sulfur level reflecting that typical of the time period during which the Tier 1 standard was in effect, as described below.
4. 2022 LEV III scenario with appropriate gasoline sulfur level as discussed below.

Both scenarios were modeled for a summer month (July).

## **2.2 METEOROLOGY**

CAMx modeling for the 2022 scenarios was driven by year 2008 meteorological fields from the Weather Research and Forecast (WRF) model – Advanced Research WRF (ARW) core (Skamarock et al., 2008). WRF output meteorological fields at 12 km horizontal resolution over the continental US were obtained from the EPA (Gilliam, R., personal communication, 2011). The CAMx input meteorological files for the nested 36 and 12 km resolution domains developed from the WRF files in the CRC study were used in the current work. Data in 34 WRF vertical layers extending up to 50 mb altitude are mapped to 26 layers in CAMx extending up to 145 mb (approximately 15-18 km). A performance evaluation of the WRF meteorological outputs and CAMx-ready meteorology showed satisfactory performance (Vijayaraghavan et al., 2012).

## 2.3 EMISSIONS INVENTORIES

The two scenarios modeled for the current work apply partial modifications of the on-road mobile emissions inventories developed under CRC A76-1 (Vijayaraghavan et al, 2012). All other emissions sources, biogenic and anthropogenic besides on-road mobile, are identical between the CRC effort and the current work. For on-road mobile sources, the portion of the inventories modified includes only exhaust VOC, CO, NO<sub>x</sub>, SO<sub>2</sub> and particulate sulfate (PM SO<sub>4</sub>) emissions from gasoline light duty vehicles (g-LDVs). Emissions from heavy duty gasoline vehicles, motorcycles, and all diesel vehicles did not change.

### 2.3.1 Overview of On-road Mobile Emissions

The MOVES model-based on-road mobile emissions inventories from the CRC effort were all built on the assumption that g-LDVs in 2022 operated on gasoline in compliance with Tier 2 gasoline sulfur standards with the exception of California. The purpose of the following sections is to document the data and assumptions used to develop emissions inventories that reflect different sulfur levels than Tier 2 in-use by g-LDVs in the two scenarios. The group of vehicle types collectively referred to as g-LDV includes three categories:

1. Light-duty gasoline vehicles (LDGV)
2. Light-duty gasoline trucks weighing less than 6,000 lbs (LDGT1)
3. Light-duty gasoline trucks weighing between 6,001 and 8,500 lbs (LDGT2)

The Tier 1 program instituted standards for Total Hydrocarbons (THC), carbon monoxide (CO), oxides of nitrogen (NO<sub>x</sub>), and particulate matter (PM) for 1994-2003 model year vehicles with a phase-in for the early years (the prior standard was the federal Tier 0 program that applied to 1981-1993 model year vehicles). The Tier 2 program instituted gasoline sulfur and vehicle emission standards for model years 2004 onwards and phased in completely in 2007 for the three categories of g-LDVs considered in this study. The California LEV III standards apply to vehicle model years 2015 to 2028, with the phase-in for ozone precursors, NO<sub>x</sub> and volatile organic compounds (VOCs), completed by 2025. In the LEV III phase-in schedule, by year 2022 the expected LEV III sales percent would be 73%. The Tier 1 and LEV III scenario g-LDV technology distributions in the 2022 fleet are summarized below in Tables 1 and 2, respectively.

**Table 1. Tier 1 Scenario 2022 g-LDV Fleet Technology Composition by Model Year.**

Model Year Group	Tier 1	Tier 0
2022 – 1996	100%	
1995	80%	20%
1994	40%	60%
1993 – 1992		100%

**Table 2. LEV III Scenario 2022 g-LDV Fleet Technology Composition by Model Year.**

Model Year Group	LEV III	Tier 2	LEV	TLEV	Tier 1	Tier 0
2022	73%	27%				
2021	64%	36%				
2020	55%	45%				
2019	45%	55%				
2018	36%	64%				
2017	27%	73%				
2016	18%	82%				
2015	9%	91%				
2014 – 2007	0%	100%				
2006		75%	25%			
2005		50%	50%			
2004		25%	75%			
2003		0%	100%			
2002			80%	20%		
2001			60%	40%		
2000 – 1996					100%	
1995					80%	20%
1994					40%	60%
1993 – 1992						100%

**2.3.2 Gasoline sulfur levels**

When EPA unveiled the Tier 2 vehicle emission standards, they also mandated cleaner, lower-sulfur gasoline fuel on a similar implementation schedule. The reason for coupling the fuel sulfur standards alongside vehicle emission standards is that sulfur is known to impede the performance of catalytic converters. The MOVES gasoline sulfur content data underlying the previous 2022 on-road emissions inventories used in the CRC study represent, with some exceptions, compliance with the current Tier 2 nationwide 30 ppm average standard. The exceptions include California as well as some areas in Arizona and Texas which have lower than 30 ppm standard gasoline sulfur contents. The MOVES database contains sulfur values on a county-by-county basis that are based on survey data, shown in Table 3. The lower-48 state, weighted average gasoline sulfur content in the MOVES database which underpinned the previous three July 2022 scenarios in the CRC effort was 21 ppm.<sup>1</sup> Gasoline sulfur levels were substantially higher prior to the implementation of the Tier 2 emission standards starting in 2000. During the 1990s, when g-LDVs certified to Tier 1 standards dominated the in-use fleet, the average sulfur content of regular grade gasoline typically fell within the range of 200 to 360 ppm according to semiannual survey reports of motor vehicle gasoline properties published by

<sup>1</sup> The weighting factors were July 2022 g-LDV relative VMT fractions by county in the lower-48 states.

the National Institute for Petroleum and Energy Research (Dickson et al., 1994). In the future, it is likely that the EPA will propose regulations that lower gasoline sulfur from the current Tier 2 average of 30 ppm down to 10 ppm. Since it was desired to model the emissions from g-LDVs under both a Tier 1 scenario with higher gasoline sulfur and an LEV III scenario with lower gasoline sulfur, adjustment factors were required in order to appropriately translate the MOVES Tier 2 based emissions estimates.

**Table 3. July 2022 Gasoline Sulfur Content in MOVES2010a database.**

<b>Gasoline Sulfur (ppm)</b>	<b>Number of Counties</b>
7.8	51
16.9	22
21.6	115
22.3	27
22.6	692
22.9	563
23.3	1,320
26.5	320

The county-specific sulfur levels for the LEV III and Tier 1 scenarios were selected in the following manner.

For the LEV III scenario, the gasoline sulfur level was assumed to be 1/3 of the Tier 2 sulfur value shown in the underlying MOVES2010a database, i.e. the reduction from a 30 ppm average to a 10 ppm average sulfur standard. As refiners would likely produce sulfur below 10 ppm and that margin of compliance is unknown, one third of the existing (2022 Tier 2) gasoline sulfur is a realistic estimate for a LEV III scenario gasoline fuel. The exception to this is California which has the 7.8 ppm gasoline sulfur content; thus, LEV III scenario emissions from California counties were not adjusted.

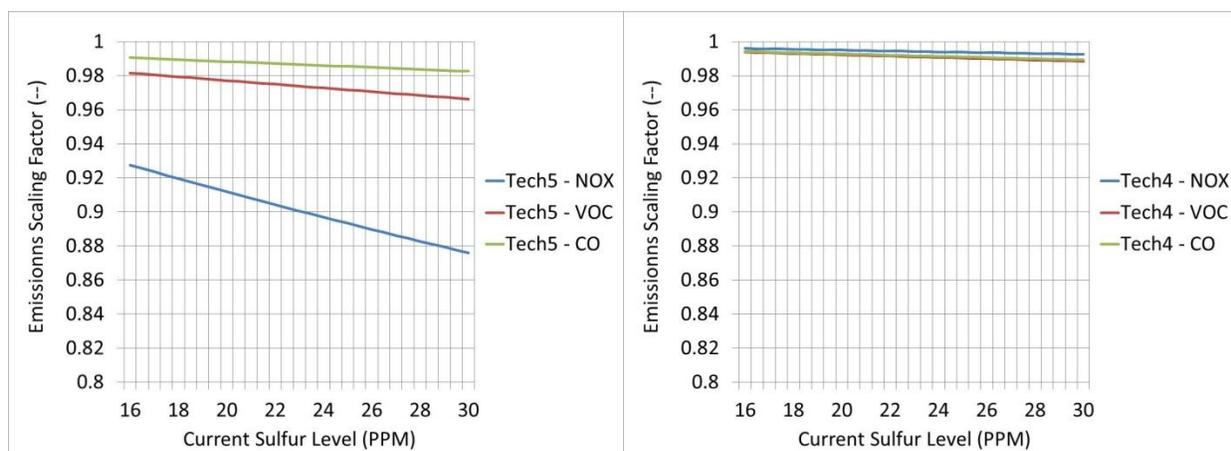
For the Tier 1 scenario, two historic years were available in the MOVES model database to represent in-use gasoline sulfur levels during the Tier 1 era: 1999 and 2000. In 2000 the U.S. EPA was already beginning to provide incentives for early compliance to the Tier 2 fuel sulfur standard (EPA, 2008). Therefore, the year 1999 MOVES gasoline sulfur data was used to select an appropriate gasoline sulfur level as the basis for developing the factors to adjust the 2022

Tier 1 scenario g-LDV emissions. The weighted average gasoline sulfur in the MOVES database in July 1999 over the lower-48 states including California was 228 ppm.

### 2.3.3 Sulfur effects on LDV emissions

#### LEV III sulfur effects

Under API auspices, the California Air Resources Board (ARB) Predictive Model was used to develop the adjustment factors for translating the MOVES emissions estimates from a 30 ppm S basis to a 10 ppm S basis, and these were provided to ENVIRON (J. Uihlein, Chevron, personal communication, 2011). Emissions estimates were obtained from a copy of the spreadsheets used for compliance with the ARB gasoline regulations. All Predictive Model gasoline properties were set at the ARB flat limits except for sulfur, which was varied from 5 ppm to 30 ppm in 5 ppm increments. The other property values do not affect the results because 1) sulfur does not interact with any other gasoline property in the Predictive Model and 2) the relationships are ultimately used to calculate an emissions ratio rather than absolute emissions. The predicted THC, NOx, and CO emissions rates in g/mi (“EXP(PREDICTION)” on the spreadsheets) were recorded for Tech Groups 4 and 5 at each sulfur level. A regression of the predicted emissions rates on sulfur content was then performed in order to generate a set of linear equations for each pollutant emission for each Tech Group. The Predictive Model-based adjustment factors are the ratio of the emissions prediction at 1/3 the input sulfur level divided by the emissions prediction at the input sulfur level, valid over the range of 15 to 30 ppm input sulfur. Figure 2 shows the regressions for Tech 5 (left) and Tech 4 (right) vehicles.



**Figure 2. ARB Predictive Model Based Emissions Scaling Factors for Technology Group 5 (left) and Technology Group 4 (right).**

The adjustment factors from Figure 2 were used to scale the MOVES model estimates of g-LDV running and start exhaust VOC, CO, and NOx emissions on the basis of vehicle model year. Tech 5 adjustments were applied to model years 1996-2022 while Tech 4 adjustments

were applied to 1992-1995. For consistency, the SO<sub>2</sub> and PM SO<sub>4</sub> emissions from g-LDVs also were scaled by a factor of 1/3 directly in the on-road inventory.

### Tier 1 sulfur effects

For the Tier 1 scenario, ENVIRON used MOVES2010a to model sulfur effects on emissions from Tier 0 and Tier 1 g-LDVs corresponding to a sulfur increase from 21 to 228 ppm. The MOVES model’s sulfur effect algorithms are the same as in MOBILE6, and they are based on relevant test data for pre-Tier 2 vehicles and higher sulfur fuel. To determine the emissions effects on running and start exhaust VOC, CO, and NO<sub>x</sub>, MOVES was run at 228 and 21 ppm sulfur holding all other fuel parameters constant. The ratios of emissions at 228 to 21 ppm are shown in Table 4 for running and start exhaust, respectively.

**Table 4. MOVES2010a ratio of g-LDV emissions at 228 ppm over emissions at 21 ppm.**

Technology	Running Exhaust			Start Exhaust		
	CO	VOC	NO <sub>x</sub>	CO	VOC	NO <sub>x</sub>
Tier 1	1.2176	1.383	1.174	0.9272	1.0314	1.2139
Tier 0	1.2475	1.2453	1.088	0.9320	1.0244	1.1147

Tier 1 emissions adjustments apply to model year 1994-2022 vehicles while Tier 0 adjustments apply to model years 1992 and 1993. For consistency with the modeled increase in gasoline sulfur content, SO<sub>2</sub> and PM SO<sub>4</sub> emissions from g-LDVs were also increased by a factor of 228/21 directly in the on-road inventory.

### **2.3.4 LDV emissions adjustment methodology**

The application of sulfur-based emissions adjustments to the LEV III and Tier 1 inventories was similar between the two scenarios. The low-sulfur adjustments in LEV III and the high-sulfur adjustments in Tier 1 scenarios apply to individual model years of g-LDVs but the original scenario inventories to be updated have a fleetwide average age level of detail. Thus the first step was to aggregate the “by model year” adjustments to fleetwide adjustment factors.

### LEV III Scenario Fleetwide Adjustments

Equations 1 through 3 explain how the “by model year” low-sulfur emissions effects from Figure 2 were incorporated into the LEV III scenario inventory. Predictive Model emissions ratios applied to by-model-year emissions of ozone precursor pollutants according to technology type (Tech 4 or Tech 5) are shown below in Equations 1a and 1b.

For  $1992 \leq i < 1996$  (Tech 4) [Eqn. 1a]

$$Emissions_{i,j,k,l \sim 10 ppm S} = (Emissions_{i,j,k,l \sim 30 ppm S}) \times (R_{Tech 4})_k$$

For  $1996 \leq i \leq 2022$  (Tech 5)

[Eqn. 1b]

$$Emissions_{i,j,k,l \sim 10 ppm S} = (Emissions_{i,j,k,l \sim 30 ppm S}) \times (R_{Tech 5})_k \times (P_{non LEV III}) + (Emissions_{i,j,k,l \sim 30 ppm S}) \times (P_{LEV III})$$

Where  $i$  = Model Year

$j$  = Vehicle Class: LDGV, LDGT1, LDGT2

$k$  = Pollutant: NOx, VOC, CO

$l$  = Emissions Process: running exhaust, start exhaust

$\sim$  = The approximate sulfur level: county levels reflect sub-30ppm compliance levels (vis-a-vis sub-10ppm)

$R_{Tech4/5}$  = Emissions ratio adjustment factor for pollutants  $k$  from Figure 2

$P_{non LEV III}$  = Percent of fleet as sum of Tier 2, Tier 1, LEV, TLEV, and Tier 0 in Table 2

$P_{LEV III}$  = Percent of LEV III fleet.

Equations 2 and 3 show how the by model year emissions using Equation 1a and 1b sum from by model year to the fleetwide level. Equation 2 shows how the by model year emissions are combined using a travel fraction weight. We note that the unadjusted MOVES inventory for the July 2022 LEV III Scenario already contains fleetwide emissions by SCC and county; these fleetwide emissions reflect the exact same travel fractions used in Equation 2 and shown in Figure 3. The by model year detail was necessary to incorporate sulfur effects by technology group, which is the only reason the travel fractions must be applied externally, as shown here.

$$Emissions_{j,k,l \sim 10 ppm S} = \sum_{i=1992}^{2022} \{ (Emissions_{i,j,k,l \sim 10 ppm S}) \times TF_{i,j} \} \quad [Eqn. 2]$$

Where  $i$  = Model Year

$j$  = Vehicle Class: LDGV, LDGT1, LDGT2

$k$  = Pollutant: NOx, VOC, CO

$l$  = Emissions Process: running exhaust, start exhaust

$\sim$  = The approximate sulfur level: county levels reflect sub-30ppm compliance levels (vis-a-vis sub-10ppm).

$TF$  = Travel Fraction

Equation 3 shows the calculation of travel fractions, which are fractions that sum to 1 over the 31 model years for each vehicle class for the 2022 calendar year. A travel fraction simply

represents model year contribution to the overall vehicle class VMT activity. They are calculated as the product of annual mileage accumulation and registration fraction, normalized by vehicle class.

$$TF_{i,j} = \frac{MAR_{i,j} \times ADF_{i,j}}{\sum_i (MAR_{i,j} \times ADF_{i,j})} \quad [\text{Eqn. 3}]$$

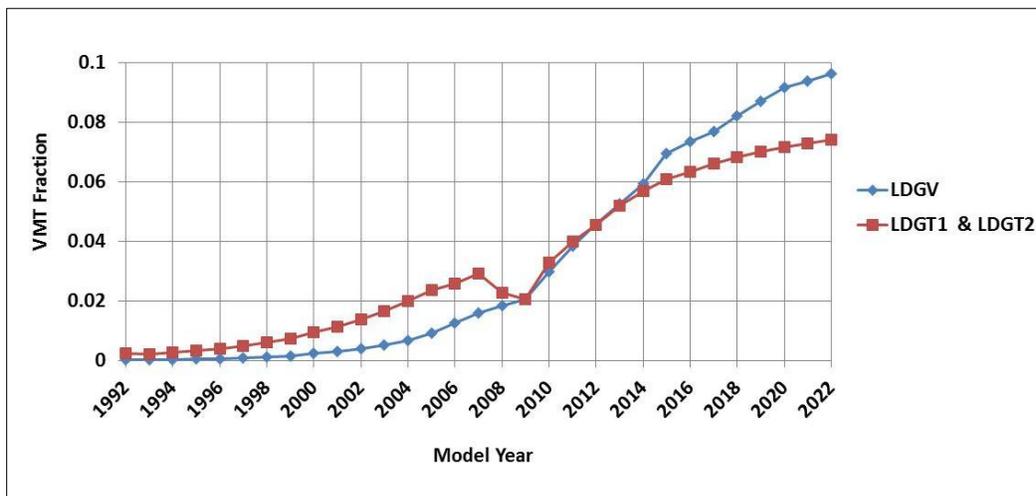
where  $i$  = Model Year

$j$  = Vehicle Class: LDGV, LDGT1, LDGT2

$MAR$  = Mileage Accumulation Rate, the annual miles driven by model year  $i$ , vehicle  $j$

$ADF$  = Age Distribution Fraction, the fraction of registered vehicles in model year  $i$

The travel fractions for LDGV, LDGT1, and LDGT2 are shown visually below in Figure 3. We note that LDGT1 and LDGT2 have identical VMT distributions to each other and that LDGVs have a higher relative proportion of VMT in the 2015-2022 model years compared to the trucks.



**Figure 3. Year 2022 Travel Fractions for LDGV, LDGT1, and LDGT2 vehicles.**

Equation 2 was applied twice—to sum the sulfur-adjusted emissions (~10 ppm) and also to sum the original unadjusted emissions (~30 ppm). The ratio of these two applications of Equation 2 produced fleetwide scaling factors that were multiplied directly with g-LDV emissions in the July 2022 LEV III scenario inventory. This final step to determine VOC exhaust, CO and NOx adjustments is shown in Equation 4.

$$\text{Final Adjustment Factor}_{j,k,l} = \frac{\text{Emissions}_{j,k,l \sim 10 \text{ ppm S}}}{\text{Emissions}_{j,k,l \sim 30 \text{ ppm S}}} \quad [\text{Eqn. 4}]$$

Where  $j$  = Vehicle Class: LDGV, LDGT1, LDGT2

$k$  = Pollutant: NOx, VOC, CO

$l$  = Emissions Process: running exhaust, start exhaust

$Emissions_{j,k,l \sim 10 ppm S}$  = Emissions adjusted for ~1/3 sulfur

$Emissions_{j,k,l \sim 30 ppm S}$  = Unadjusted emissions

The fleetwide adjustments were multiplied on the basis of representative county<sup>2,3</sup> (except California where no adjustments are applied), g-LDV type, pollutant, and emission process (start or running exhaust). Table 5 shows the range of fleetwide sulfur adjustments by representative county applied to the unadjusted LEV III scenario inventory to arrive at the final adjusted LEV III inventory.

**Table 5. Representative County ranges of fleet average emissions scaling factors, LEV III scenario.**

Vehicle	CO	VOC	NOx
<b>Running</b>			
LDGV	0.9868 - 0.9915	0.9731 - 0.9826	0.9027 - 0.9339
LDGT1	0.9862 - 0.9911	0.9733 - 0.9827	0.9043 - 0.935
LDGT2	0.9862 - 0.9911	0.9733 - 0.9827	0.9043 - 0.935
<b>Starts</b>			
LDGV	0.9869 - 0.9916	0.9733 - 0.9827	0.9019 - 0.9334
LDGT1	0.9861 - 0.9910	0.9718 - 0.9817	0.8969 - 0.9300
LDGT2	0.9861 - 0.9910	0.9718 - 0.9817	0.8969 - 0.9300

The adjustments to the SO<sub>2</sub> and SO<sub>4</sub> inventory are not a function of model year so they were performed in a later stage of emissions processing than adjustments to VOC, CO and NOx. Equation 5 shows the fleetwide emissions adjustments for SO<sub>2</sub> and SO<sub>4</sub> to account for the reduction in gasoline sulfur.

$$Emissions_{j,k,l \sim 10 ppm S} = \frac{1}{3} (Emissions_{j,k,l \sim 30 ppm S}) \quad [Eqn. 5]$$

Where  $j$  = Vehicle Class: LDGV, LDGT1, LDGT2

$k$  = Pollutant: SO<sub>2</sub>, PM<sub>10</sub> SO<sub>4</sub>, PM<sub>2.5</sub> SO<sub>4</sub>

<sup>2</sup> A representative county is a county representing a group of counties with similar motor vehicle emission factors, as determined by fuel properties, inspection maintenance programs, fleet age distributions, and other parameters.

<sup>3</sup> Representative county basis is required for applying adjustments for consistency with original inventory development efforts for the CRC.

*l* = Emissions Process: running exhaust, start exhaust

~ = The approximate sulfur level: county levels reflect sub-30ppm compliance levels (vis-a-vis sub-10ppm).

### Tier 1 Scenario Fleetwide Adjustments

The methodology described above in the LEV III scenario is generally applicable to the Tier 1 scenario. We provide below the corresponding equations and fleetwide scaling factors. The by model year high-sulfur emissions adjustments to g-LDVs are shown below in Equations 6a and 6b. These are analogous to the low-sulfur adjustments in Equations 1a and 1b.

For  $i = \{1992, 1993\}$  (Tier 0) [Eqn. 6a]

$$Emissions_{i,j,k,l \text{ at } 228 \text{ ppm } S} = (Emissions_{i,j,k,l \text{ at } 21 \text{ ppm } S}) \times (R_{\text{Tier } 0})_k$$

For  $1994 \geq i \geq 2022$  (Tier 1) [Eqn. 6b]

$$Emissions_{i,j,k,l \text{ at } 228 \text{ ppm } S} = (Emissions_{i,j,k,l \text{ at } 21 \text{ ppm } S}) \times (R_{\text{Tier } 1})_k$$

Where  $i$  = Model Year

$j$  = Vehicle Class: LDGV, LDGT1, LDGT2

$k$  = Pollutant: NOx, VOC, CO

$l$  = Emissions Process: running exhaust, start exhaust

$R_{\text{Tier } 0/1}$  = Emissions ratio adjustment factor for pollutants  $k$  shown in Table 4

The next step was to sum the high-sulfur adjusted emissions from Equations 6a and 6b over model year using travel fractions as shown in Equation 7. This equation was also applied to unadjusted emissions by model year to determine the overall fleetwide scaling factors shown in Equation 8.

[Eqn. 7]

$$Emissions_{j,k,l \text{ at } 228 \text{ ppm } S} = \sum_{i=1992}^{2022} \{(Emissions_{i,j,k,l \text{ at } 228 \text{ ppm } S}) \times TF_{i,j}\}$$

Where  $i$  = Model Year

$j$  = Vehicle Class: LDGV, LDGT1, LDGT2

$k$  = Pollutant: NOx, VOC, CO

$l$  = Emissions Process: running exhaust, start exhaust

TF = Travel Fraction (previously defined in Equation 3 and illustrated in Figure 3)

[Eqn. 8]

$$\text{Final Adjustment Factor}_{j,k,l} = \frac{\text{Emissions}_{j,k,l \text{ 228 ppm S}}}{\text{Emissions}_{j,k,l \sim 30 \text{ ppm S}}}$$

Where  $j$  = Vehicle Class: LDGV, LDGT1, LDGT2

$k$  = Pollutant: NOx, VOC, CO

$l$  = Emissions Process: running exhaust, start exhaust

$\text{Emissions}_{j,k,l \text{ 228 ppm S}}$  = Fleetwide emissions adjusted for 228 ppm sulfur

$\text{Emissions}_{j,k,l \sim 30 \text{ ppm S}}$  = Fleetwide emissions, unadjusted

The same fleetwide adjustments were applied to every county (including California) in the lower-48 states. The adjustments were applied on the basis of g-LDV type, pollutant, and emission process (start or running exhaust). Table 6 shows the fleetwide sulfur adjustments applied to the unadjusted Tier 1 scenario inventory to arrive at the final adjusted Tier 1 inventory.

**Table 6. Fleet average emissions scaling factors, Tier 1 scenario.**

Vehicle	CO	VOC	NOx
<b>Running</b>			
LDGV	1.2177	1.3810	1.1730
LDGT1	1.2187	1.3738	1.1700
LDGT2	1.2187	1.3738	1.1700
<b>Starts</b>			
LDGV	0.9273	1.0314	1.2131
LDGT1	0.9274	1.0312	1.2092
LDGT2	0.9274	1.0313	1.2092

The effect of increasing the nationwide gasoline sulfur content from 21 ppm to 228 ppm increases running exhaust g-LDV emissions of CO, VOC, and NOx by 22%, 37-38%, and 17% respectively. For g-LDV start exhaust, the CO decreases by 7%, and the VOC and NOx increase by 3% and 21% respectively. The somewhat unexpected decrease in CO start emissions with increasing sulfur content is noted in EPA's on-road emissions modeling documentation as being counterintuitive but supported by real-world data (EPA, 2001).

Equation 9 shows the fleetwide adjustments to the SO<sub>2</sub> and SO<sub>4</sub> emissions inventories that were made to account for the higher Tier 1 gasoline sulfur levels.

$$Emissions_{j,k,l \text{ at } 228 \text{ ppm } S} = \frac{228}{21} (Emissions_{j,k,l \sim 30 \text{ ppm } S}) \quad [\text{Eqn. 9}]$$

Where  $j$  = Vehicle Class: LDGV, LDGT1, LDGT2

$k$  = Pollutant: SO<sub>2</sub>, PM<sub>10</sub>, SO<sub>4</sub>, PM<sub>2.5</sub>, SO<sub>4</sub>

$l$  = Emissions Process: running exhaust, start exhaust

$Emissions_{j,k,l \sim 30 \text{ ppm } S}$  = Unadjusted emissions

### 2.3.5 Conversion of on-road emissions to CAMx-ready emissions files

The on-road emissions for July from MOVES for both emissions scenarios were speciated to CAMx model species, temporally allocated to hourly emissions, and spatially allocated to grid cells using version 2.7 of the Sparse Matrix Operator Kernel Emissions (SMOKE) model. Average day emissions were adjusted to account for day-of-week and hour-of-day effects based on SCC codes. Emission estimates for total VOC were converted to the CB05 chemical mechanism in CAMx using VOC speciation profiles derived from EPA's SPECIATE database, version 4.3 (EPA, 2011). On-road mobile sources generated using MOVES at the county level were allocated to CAMx 36 km and 12 km grid cells using spatial surrogates derived with the Spatial Surrogate Tool (<http://www.epa.gov/ttn/chief/emch/spatial/spatialsurrogate.html>).

### 2.4 OTHER MODEL INPUTS

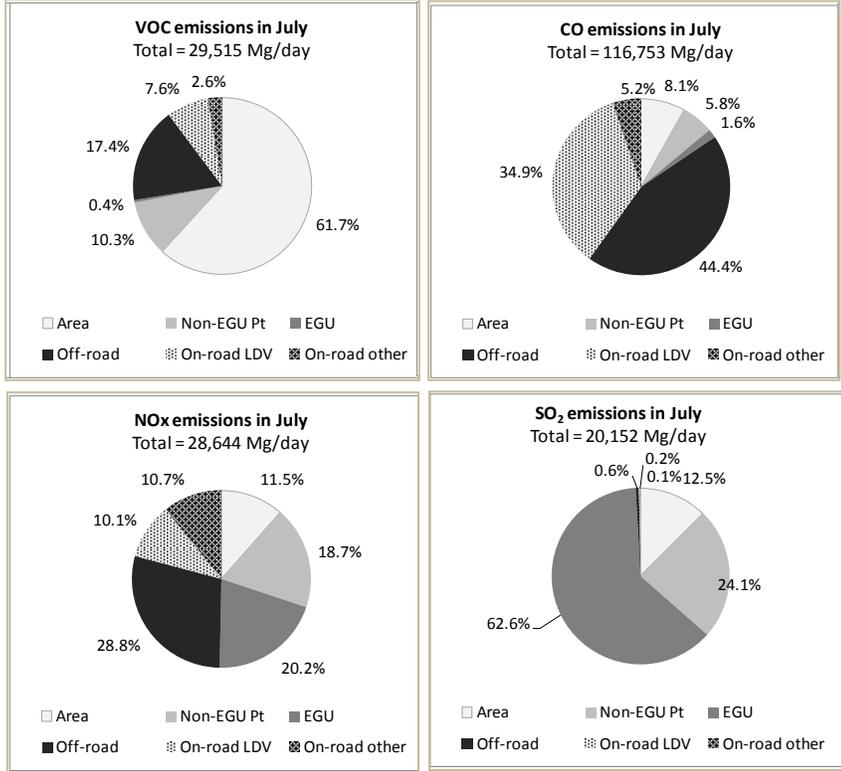
Other model inputs (e.g., boundary concentrations of ozone and precursors for the 36 km domain, landuse/ landcover data, photolysis rates) required for ozone modeling were obtained from the CRC study and were held the same across the 2022 scenarios.

## 3. Results and Discussion

### 3.1. EMISSIONS AND AIR QUALITY IN 2022 SCENARIOS

#### 3.1.1 Emissions

The total CONUS anthropogenic emissions and the relative contributions of the major source sectors in the CRC 2022 Tier 2 scenario are shown in Figure 4. These are described in detail in Vijayaraghavan et al., 2012 and are provided here for reference. The on-road LDV emissions of the two main ozone precursors VOC and NO<sub>x</sub> constitute approximately 8% and 10%, respectively, of the total US anthropogenic inventory in 2022 in the Tier 2 scenario. Emissions from source sectors other than on-road sources are held constant between this scenario and the other 2022 scenarios.



**Figure 4. Estimated anthropogenic emissions in the continental US in the 2022 Tier 2 scenario (source: Vijayaraghavan et al., 2012).**

A comparison of average day g-LDV emissions of VOC, CO, NO<sub>x</sub>, and SO<sub>2</sub> between the Tier 1, Tier 2, and LEV III scenario inventories is presented in Table 7. The benefit by 2022 from advancing to Tier 2 controls in 2004 rather than remaining at Tier 1 is reflected by large decreases in g-LDV ozone precursor emissions of 62%, 51%, and 80%, for VOC, CO and NO<sub>x</sub>, respectively. There are also large (92%) reductions in SO<sub>2</sub>; however these do not directly affect ozone concentrations. The additional benefits expected by 2022 with partial LEV III technology penetration are further reductions of 8%, 7% and 11% in VOC, CO and NO<sub>x</sub> emissions, respectively.

**Table 7. July 2022 emissions in the continental US from gasoline light-duty vehicles.**

Pollutant	Tier 1 Scenario (Mg/day)	Tier 2 Scenario (Mg/day)	Tier 2 Benefit (T2-T1)/T1	LEV III Scenario (Mg/day)	LEV III Benefit (LIII-T2)/T2
VOC	6,061	2,275	-62%	2,096	-8%
CO	83,585	40,813	-51%	37,773	-7%
NO <sub>x</sub>	14,222	2,879	-80%	2,551	-11%
SO <sub>2</sub>	620.3	48.4	-92%	17.5	-64%

However, the benefits are smaller when looking at the emissions reductions in the context of total on-road emissions. For example, while g-LDVs make up 88% of the nationwide total 2022 July day VMT of 10.5 billion miles, they comprise less than half of the on-road NOx. Table 8 summarizes the total on-road emissions from the three scenarios. We note that the incremental benefit of the LEV III scenario would be even lower when considering the change in all US anthropogenic emissions because VOC and NOx constitute one-tenth or less of the US inventory in 2022 (see Figure 4).

**Table 8. July 2022 emissions in the continental US from all on-road motor vehicles.**

Pollutant	Tier 1 Scenario (Mg/day)	Tier 2 Scenario (Mg/day)	Tier 2 Benefit (T2-T1)/T1	LEV III Scenario (Mg/day)	LEV III Benefit (LIII-T2)/T2
VOC	6,827	3,040	-55%	2,861	-6%
CO	89,670	46,898	-48%	43,857	-6%
NOx	17,277	5,935	-66%	5,607	-6%
SO <sub>2</sub>	633.5	61.6	-90%	30.7	-50%

### 3.1.2 Air Quality

Prior to air quality modeling of the 2022 scenarios, a 2008 CAMx scenario was run to evaluate the model performance (Vijayaraghavan et al., 2012). The 2008 CAMx predictions of 1-hour and 8-hour average ozone concentrations were evaluated against measurements in the AIRS/AQS network (EPA, 2002) and the Clean Air Status and Trends Network (CASTNET, 2011). Model predictions of PM<sub>2.5</sub> mass and components were compared to daily (24-hour) average measurements in the AIRS/AQS and IMPROVE (IMPROVE, 1995) networks. Overall, model performance was good both for ozone and PM<sub>2.5</sub> mass and components.

Model simulation results for ozone in 2022 are presented in Figures 5 and 6. We present the spatial distribution of the monthly mean of daily maximum 8-hr ozone concentrations in Figure 5 and differences in these monthly means between pairs of 2022 LDV scenarios in Figure 6.

In 2022, if emissions standards for new g-LDVs (and also if gasoline sulfur levels) were no more stringent than those that had been in place during the timeframe of the Tier 1 requirements, then the monthly mean of daily maximum 8-hr average (MDA8) ozone concentrations could be as high as 89 ppb in the eastern US with values exceeding 60 ppb in most areas and parts of Georgia and the New York/New Jersey/D.C. corridor experiencing more than 80 ppb.

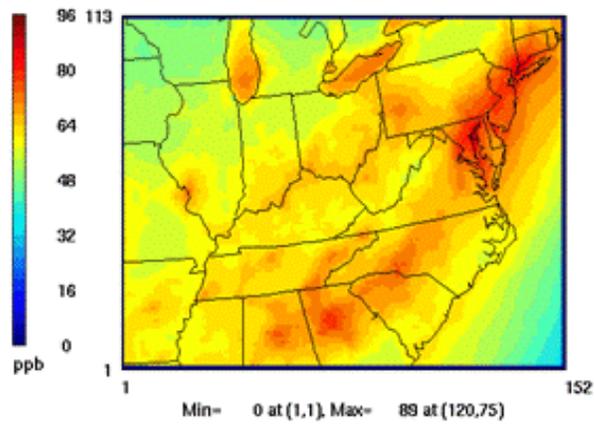
Strengthening the new g-LDV emissions standards and introducing federal gasoline sulfur requirements as represented by the transition from Tier 1 to Tier 2 reduces the monthly mean of daily 8-hr ozone maxima by over 6 ppb (5–10%) in July 2022 in large parts of the eastern US, and by up to 11.9 ppb (15.2%) in central Georgia (see top panel of Figure 6). There are some

areas on the western shore of Lake Michigan (Milwaukee and Chicago) that experience a slight increase (up to 3.3 ppb or 7.6%) in the monthly mean of daily maximum 8-hr ozone from the Tier 1 to Tier 2 scenarios. The increases in ozone in these urban areas despite reductions in LDV NO<sub>x</sub> emissions from the Tier 1 scenario suggest that NO<sub>x</sub> that was otherwise titrating ozone becomes unavailable due to the Tier 2 LDV emissions reductions.

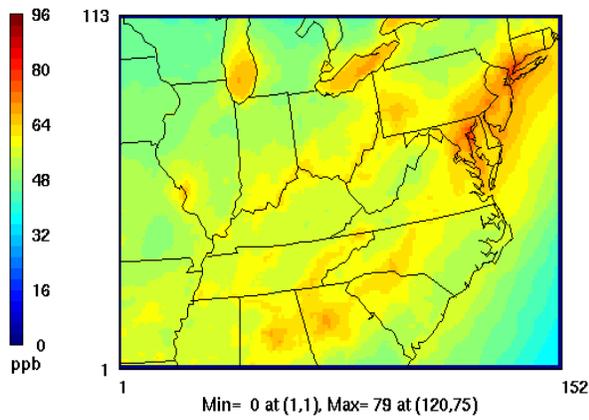
Switching from Tier 2 to a nationwide LEV III program in conjunction with a reduction in gasoline sulfur to a 10 ppm average yields at most a 0.5 ppb (0.7%) reduction in the monthly mean MDA8 ozone concentration anywhere in the eastern US domain in July 2022 (see bottom left and right panels of Figure 6). We note that the LEV III standard for NO<sub>x</sub> + non-methane organic gas emissions from new g-LDVs will not be fully phased in until model year 2025. Thus, the results shown represent the air quality benefits achievable by 2022. We expect some additional improvements in ozone to occur in the post 2022 time period as a result of the complete phase-in of the LEV III standard.

Even when considering the monthly peak of MDA8 ozone levels, the largest benefit of the LEV III standard compared to the Tier 2 standard in the same model grid cell anywhere in the model domain is small (1.2 ppb (1.2%), near Washington, D.C.) relative to the Tier 2 benefit over Tier 1 (27.1 ppb (25.0%), near Atlanta). When considering differences in MDA8 ozone concentrations across pairs of scenarios but on the same date for every model grid cell, the largest benefit from Tier 1 to Tier 2 is 30.2 ppb (26.6%, near Atlanta) and the largest LEV III benefit over Tier 2 is 1.2 ppb (1.2%, near Washington, D.C.).

### Tier 1



### Tier 2



### LEV III

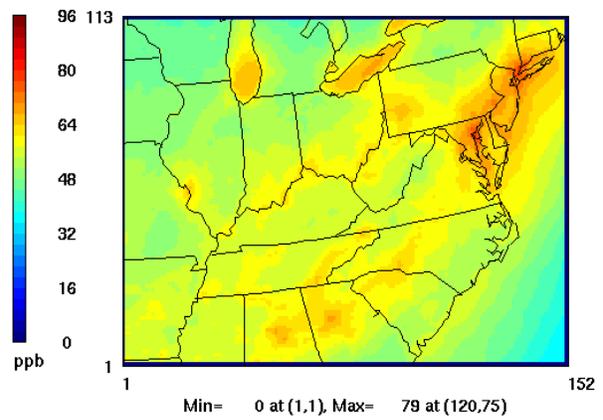
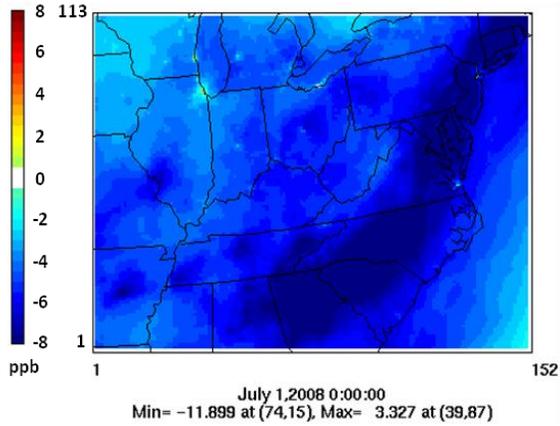
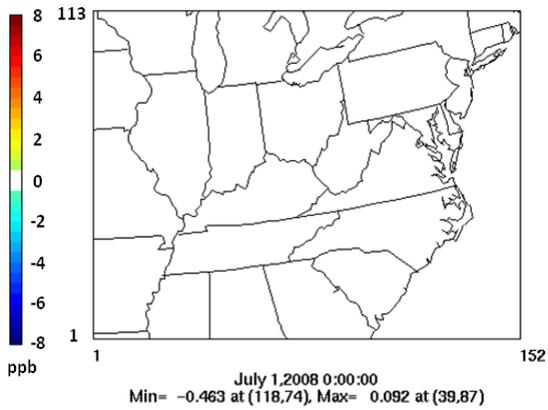


Figure 5. Monthly mean of daily maximum 8-hr ozone in July in 2022 scenarios: Tier 1, Tier 2, LEV III.

Tier 2 – Tier 1



LEV III – Tier 2



LEV III – Tier 2

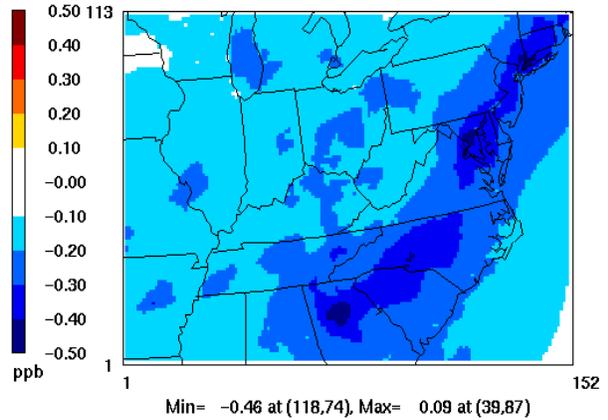


Figure 6. Differences in monthly mean of daily maximum 8-hr ozone in July in 2022 scenarios: Tier 2 – Tier 1 (top), LEV III – Tier 2 (bottom, two different color scales).

### **3.2 Conclusion**

Overall, the modeling results suggest that large improvements in summertime ambient ground-level ozone concentrations resulted from the switch from Tier 1 to Tier 2 standards. However, relatively very small additional reductions in 2022 ozone levels are predicted to result from the transition to a Federal standard similar to the California LEV III standard, even when considering emissions reductions due to a lower gasoline sulfur content in the LEV III scenario. These results are consistent with the relatively small change in emissions between the Tier 2 and LEV III scenarios compared to the change between Tier 1 and Tier 2 scenarios and the fact that Tier 2 LDV emissions of key ozone precursors constitute a relatively small fraction of the total inventory.

The main limitation of this study is introduced by the lack of complete phase-in of the LEV III standard by 2022, the basis year for comparing emission standards. Some slight additional improvements in ozone beyond 2022 are expected as the LEV III standard fully matures. Some other key sources of uncertainty include assumed growth and control factors for other anthropogenic emissions, and limitations in the data used to develop VOC speciation profiles.

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