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EFFECTS OF LIGHT-DUTY VEHICLE EMISSIONS ON OZONE AND PM WITH PAST, PRESENT, AND FUTURE CONTROLS: TIER 0 VERSUS OTHER SCENARIOS

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Effects of Light-duty Vehicle Emissions on Ozone and PM with Past, Present, and Future Controls: Tier 0 versus Other Scenarios

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Light duty vehicle (LDV) emissions standards in the US have become increasingly stricter since the 1970s and more stringent vehicle emission regulations for gasoline-fueled LDVs (g-LDVs) are being considered by agencies to attain compliance with national ambient ozone and fine particulate matter ($PM_{2.5}$) standards. In a prior CRC study (A-76-1), ENVIRON modeled the impact of past, present and potential future US Federal emissions standards for on-road gasoline-fueled LDVs on ozone and $PM_{2.5}$ concentrations in the eastern US. Specifically, we modeled four hypothetical 2022 g-LDV emissions scenarios in addition to a 2008 Tier 2 scenario: (1) 2022 Tier 1 scenario (assuming that only Tier 1 standards are implemented in 2022), (2) 2022 Tier 2 scenario (assuming that no standards beyond Tier 2 are implemented in 2022), (3) 2022 LEV-III scenario (assuming that the California LEV-III standard is adopted nationwide) and (4) 2022 LDV zero-out scenario (assuming there are no g-LDV emissions in 2022).

In the current study, we modeled two additional g-LDV emissions scenarios in which Tier 0 g-LDV standards, which were first implemented in 1981, were applied to the 2008 base year and 2022 future year, i.e., we assume no additional g-LDV standards were implemented. We then examined (a) differences in ozone and $PM_{2.5}$ in 2008 between the Tier 0 and Tier 2 scenarios, (b) incremental benefits in calendar year 2022 of ozone and $PM_{2.5}$ resulting from the successive g-LDV emission standards ranging from Tier 0 to LEV-III, and (c) a comparison of these benefits vis-a-vis a scenario involving the complete removal of g-LDV emissions. Reductions in emissions of nitrogen oxides (NOx), volatile organic compounds (VOC) and sulfur dioxide (SO_2) due to gasoline sulfur reductions mandated by the LEV-III standard are not considered.

The Motor Vehicle Emission Simulator (MOVES, version 2010a) was used for deriving on-road vehicle emissions. Air quality modeling was performed with the Comprehensive Air Quality Model with Extensions (CAMx, version 5.40). Modeling was conducted over a 12 km horizontal resolution domain in the eastern US nested within a 36 km continental US (CONUS) domain. As before, the focus of the current study is the eastern US with additional emphasis placed on four urban areas – Atlanta, Detroit, Philadelphia and St. Louis. All simulations were conducted for a winter month (February) and summer month (July). Inputs other than motor vehicle emissions such as meteorology and emissions from other source sectors were obtained from the prior study.

The 2008 Tier 0 scenario represents a g-LDV fleet where model years prior to 1981 had pre-Tier 0 controls and model years 1981-2008 met the Tier 0 standards. Similarly, for the 2022 Tier 0 scenario, all g-LDV model years 1991-2022 met the Tier 0 standards. All other vehicle classes in each inventory meet the appropriate present-day controls for 2008 or 2022. The Tier 0 g-LDV inventories were built by scaling the g-LDV emissions in the Tier 2 scenarios for 2008 and 2022. The Tier 2 scenario inventories had been developed earlier at the county and Source Classification Code (SCC) level by running MOVES by county for approximately 220 representative counties for February and July in 2008 and 2022. The SCCs in the inventory are fleet-average age, using the national age distribution in MOVES for most counties including St.

Louis and three area-specific age distributions for Detroit, Atlanta, and Philadelphia. Scaling factors to represent the ratio of "Tier 0" emissions to "Tier 2" emissions by pollutant and g-LDV SCC were developed to match this resolution (average-age for the nation and St. Louis, area-specific average-age for Detroit, Atlanta, and Philadelphia). The scaling factors were developed from emission factors at the by-model-year level of detail. The final scaling factors apply to the inventory at the average-age level of detail by SCC, pollutant and emission process. The age distributions and corresponding influence of by-model-year emission standards are incorporated in the average-age scaling factors developed separately for the nation, St. Louis, Detroit, Atlanta, and Philadelphia.

If light-duty vehicle emissions standards had not increased in stringency beyond the level of the 1981 Tier 0 controls, g-LDVs would have accounted for approximately 33% and 30% of all anthropogenic NOx and VOC emissions, respectively, on average winter and summer days in the continental US in 2008. Among the four urban areas evaluated, wintertime VOC and primary $PM_{2.5}$ emissions were highest in the Detroit area due, in part, to the increase in cold start emissions. In summer, Atlanta had the highest LDV emissions of NOx, VOC and $PM_{2.5}$ among the four urban areas, due to a combination of higher ambient temperatures and higher VMT. The Tier 2 standard reduced the g-LDV NOx and VOC emissions almost in half by 2008, helping reduce the July monthly averaged daily maximum 8-hour ozone by up to 6.0 ppb. Among the four urban sites evaluated, the summertime ozone reduction was largest in the city with the highest monthly averaged daily maximum 8-hour ozone, Atlanta, where the average daily maximum of 87.5 ppb was reduced by 4.3 ppb from the Tier 0 to Tier 2 standards. The 2008 Tier 0 g-LDVs accounted for only 2% to 3.5% of the total anthropogenic $PM_{2.5}$ emissions. The monthly average $PM_{2.5}$ concentrations in the eastern US were up to 1.9 $\mu g/m^3$ lower in February and up to 2 $\mu g/m^3$ lower in July in Tier 2 compared to Tier 0 concentrations of approximately 40 $\mu g/m^3$ due to reductions in NOx, VOC and primary $PM_{2.5}$ emissions. Among the four cities studied, Philadelphia had the highest monthly averaged $PM_{2.5}$ concentration (29.0 $\mu g/m^3$) in Tier 0 and the largest reduction (1.6 $\mu g/m^3$) after applying Tier 2 controls.

If no controls beyond Tier 0 are implemented through2022, g-LDVs would have accounted for almost half of all anthropogenic NOx emissions. Instead the additional controls through Tier 2 result in g-LDVs becoming one of the smallest US source sectors for NOx emissions, reducing their contribution to only 10% of all anthropogenic NOx in the US. Similarly, in the 2022 Tier 0 scenario, g-LDVs were the second largest source of US VOCs behind area sources, accounting for about a third of all anthropogenic VOCs emitted. With the implementation of the standards through Tier 2, the g-LDV VOC contribution dropped to 8% of all anthropogenic VOC emissions, with emissions less than area sources, non-EGU point sources, and off-road sources. $PM_{2.5}$ emissions from g-LDVs were low compared to all other emission sources in all emission scenarios, ranging from 2.5% (Tier 0) to 1.5% (Tier 2) of all anthropogenic emissions in the summer, and 4.5% (Tier 0) to 2.3% (Tier 2) of winter anthropogenic emissions.

The incremental modeled ozone and $PM_{2.5}$ benefits in 2022 due to progressively stringent g-LDV standards are consistent with the changes in the emissions of the precursors. The application of Tier 1 standards reduced the monthly averaged summertime daily maximum 8-

hour ozone by up to 8.4 ppb in the eastern US in 2022 relative to the Tier 0 scenario. The subsequent introduction of Tier 2 standards resulted in additional modeled reductions in ozone of up to 10.0 ppb in 2022. Of the four urban sites evaluated, Atlanta had the highest 2022 Tier 0 ozone levels (83.4 ppb) and benefitted the most from both the Tier 1 and Tier 2 controls with incremental reductions of 6.7 and 8.7 ppb, respectively.

Ozone benefits from reducing g-LDV emissions beyond Tier 2 levels are relatively very small in 2022. If the California LEV-III program were applied on a nationwide basis, the modeled incremental summertime ozone benefits (expressed in terms of the monthly average daily maximum 8-hour ozone concentrations) at the four selected urban sites would improve by no more than 0.1 ppb relative to those observed in a Tier 2 scenario. With complete removal of g-LDV emissions by 2022, ozone could improve by up to 1.5 ppb in Detroit, 2.2 ppb in St. Louis, 2.6 ppb in Philadelphia, and 3.6 ppb in Atlanta from the Tier 2 levels – all less than half of the corresponding benefit in transitioning from Tier 1 to Tier2.

The large reductions in NOx and VOC emissions from g-LDVs between Tier 0 and Tier 2 result in relatively large reductions in ozone concentrations. As g-LDVs become relatively smaller sources of NOx and VOCs by 2022 compared to other source sectors, additional reductions to g-LDV emissions are modeled to return lower ozone benefits. Similarly, modeling results show that additional controls on g-LDVs beyond Tier 2 will have limited $PM_{2.5}$ benefits by 2022. The maximum reduction in $PM_{2.5}$ concentrations from Tier 2 levels in the eastern US is 0.1 $\mu g/m^3$ (from approximately 20 $\mu g/m^3$) in the LEV-III scenario in summer and winter and 1.9 $\mu g/m^3$ (from approximately 24 $\mu g/m^3$) in the bounding scenario of zero g-LDV emissions in winter. The benefits from complete removal of g-LDV emissions in summer are lower than those in winter.

Some additional improvements in ozone and $PM_{2.5}$ would be realized due to LEV-III after the program phases in fully in 2028. Also, some additional air quality benefits would be realized due to reductions in NOx, VOC and SO_2 emissions from gasoline sulfur reductions mandated by the LEV-III standard.

1. INTRODUCTION

On-road mobile sources in the United States are a large source of nitrogen oxides (NOx) and volatile organic compounds (VOC) emissions, which are precursors to ozone production. Over the past four decades, emissions and fuel standards for gasoline-burning light duty vehicles (g-LDVs) have become increasingly stringent; this has helped lower NOx and VOC emissions from highway vehicles by 50% and 75%, respectively, between 1970 and 2005 despite a two-fold increase in the total vehicle miles traveled (VMT) on highways (Kryak, 2010); highway particulate matter (PM) emissions have also been reduced over 50% during the same period. Even though on-road mobile emissions have been substantially reduced, they continue to be examined for further potential emission reductions to assist in compliance with the ozone and $PM_{2.5}$ National Ambient Air Quality Standards (NAAQS).

Previous work for the Coordinating Research Council in A-76-1 compared the ozone and $PM_{2.5}$ impacts from four different light duty vehicle emission scenarios across the US (Vijayaraghavan et al., 2012). In that study, modeling was performed with the Motor Vehicle Emission Simulator (MOVES) (EPA, 2010a) and the Comprehensive Air Quality Model with Extensions (CAMx) (ENVIRON, 2011) for the 2022 future year in hypothetical scenarios that assumed that the g-LDV emissions followed Tier 1, Tier 2 and LEV-III standards as described below.

Of the scenarios studied in A-76-1, the Tier 1 scenario had the least stringent level of controls on g-LDVs. The Tier 1 program instituted standards for Total Hydrocarbons, carbon monoxide (CO), NOx, and PM for 1994-2003 model year vehicles with a phase-in for the early years. Tier 2 represents the current level of g-LDV controls, which were first applied to 2004 model-year vehicles and phased in completely in 2009. The LEV-III scenario assumed nationwide adoption of more-stringent California LEV-III emission standards across the country; gasoline sulfur reductions were not modeled in this scenario. Finally, an additional scenario, LDVZ, (LDV zero-out) was conducted in which all g-LDV emissions were set to zero. Model results showed the largest reduction in ozone and $PM_{2.5}$ when moving from Tier 1 to Tier 2 standards. The implementation of additional LDV controls similar to LEV-III would result in relatively very small additional improvements in ozone and $PM_{2.5}$ concentrations by 2022. The complete elimination of gasoline-fueled LDV emissions in 2022 was predicted to result in improvements in ozone and $PM_{2.5}$ concentrations from Tier 2 levels that were generally smaller than the improvements obtained in switching from Tier 1 to Tier 2.

In the current study, MOVES and CAMx were applied to model additional g-LDV emissions scenarios in which Tier 0 standards, which were first implemented in 1981, were applied to the 2008 base year and 2022 future year. Incremental benefits from each control scenario were again examined. Section 2 contains a description of the CAMx inputs and the emissions methodology and processing. The model results are discussed in Section 3 including a comparison of ozone and $PM_{2.5}$ benefits in 2008 from Tier 0 and Tier 2 controls and from the five g-LDV scenarios in 2022 from least to most stringent -- Tier 0, Tier 1, Tier 2, LEV-III, and LDVZ. A summary is presented in Section 4.

2. MODEL INPUTS

CAMx is a state-of-the science regional 3-D photochemical air quality model that simulates transport and dispersion, atmospheric chemical transformations, and deposition of trace gases and aerosols. CAMx version 5.40 was used to model the ozone and $PM_{2.5}$ impacts from the Tier 0 g-LDV emission standards in both the 2008 base and 2022 future year. Each scenario was run for the entire month of February and July to represent winter and summer, respectively.

2.1. MODEL DOMAIN

CAMx was configured with a 36 km resolution domain that covered the entire continental US and southern Canada and northern Mexico, and a 12km nested grid that covered much of the central and eastern US, as shown in Figure 2-1. The domains use the same Lambert Conformal Projection (LCP) as used by the Regional Planning Organizations (center at 40N, 97W with true latitudes at 33N and 45N). The four urban areas highlighted in this report – Atlanta, Detroit, Philadelphia, and St. Louis -- are all inside the 12 km domain.

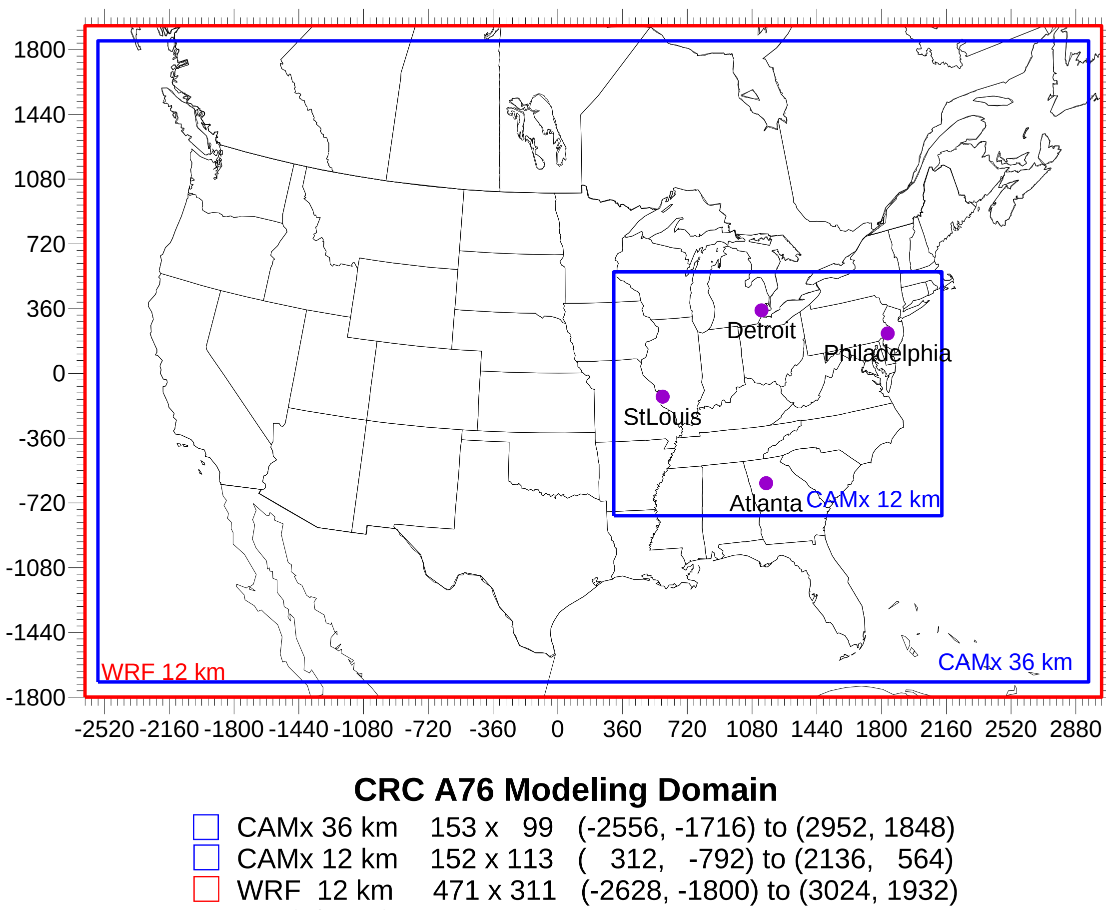


Figure 2-1. CAMx modeling domains.

2.2. MODEL INPUTS OTHER THAN EMISSIONS

CAMx inputs were prepared for the 36 and 12 km modeling domains for February and July, 2008 and their corresponding half-month “spin-up” periods. The model spin-up refers to modeling performed over an initial 15-day period to minimize the effect of the initial concentrations. Input files required include meteorology, land use, albedo-haze-ozone, photolysis rates, initial and boundary conditions, and emissions. The same input files were applied to all 2008 and 2022 future year runs except the emission files. Inputs other than motor vehicle emissions were obtained from the A-76-1 study (Vijayaraghavan et al., 2012). A description of these inputs is provided below for completeness.

2.2.1. Meteorology

The Advanced Research WRF (Weather Research and Forecasting) model version 3.2 was run by the EPA for the continental US in 12 km resolution. The WRF configuration included the Asymmetrical Convective Model version 2 (ACM2) PBL, Pleim-Xiu land surface model, and the Kain Fritsch cumulus scheme. These 12 km WRF outputs were used to generate the meteorological input files for both the CAMx 36 and 12 km domains using the WRFCAMx version 3.1 converter.

WRFCAMx was configured to extract 26 vertical layers of meteorological data up to 14 km using the layer mapping structure shown in Table 2-1. A layer averaging scheme that combined multiple WRF layers into single CAMx layers was applied to selected layers to focus on the photochemical simulation in the lower to mid troposphere and to reduce computational time.

WRFCAMx outputs six binary gridded CAMx files for each date and modeling domain, providing the following meteorological data for each hour of the day:

- Height/pressure
- Wind
- Temperature
- Vertical diffusivity (kv)
- Moisture
- Cloud/rain

An ascii-format snow-cover file listing the grid cells that had snow cover during any hour of each date is also generated.

Table 2-1. Vertical layer structure of WRF and CAMx.

WRF Vertical Layers					CAMx Vertical Layers			
k (WRF)	sigma	Pressure (mb)	Approx. Height(m)	Approx. Depth(m)	k (CAMx)	sigma	Approx. Height(m)	Approx. Depth (m)
34	0.000	50	19532	3330				
33	0.050	97.5	16202	2257				
32	0.100	145	13945	1739	26	0.100	13945	1739
31	0.150	192.5	12206	1426	25	0.150	12206	1426
30	0.200	240	10780	1216	24	0.200	10780	1216
29	0.250	287.5	9564	1063	23	0.250	9564	1063
28	0.300	335	8501	947	22	0.300	8501	1802
27	0.350	382.5	7554	855				
26	0.400	430	6699	781	21	0.400	6699	1500
25	0.450	477.5	5919	719				
24	0.500	525	5200	667	20	0.500	5200	1290
23	0.550	572.5	4532	623				
22	0.600	620	3910	584	19	0.600	3910	1134
21	0.650	667.5	3326	550				
20	0.700	715	2775	419	18	0.700	2775	419
19	0.740	753	2357	303	17	0.740	2357	303
18	0.770	781.5	2054	293	16	0.770	2054	293
17	0.800	810	1761	191	15	0.800	1761	191
16	0.820	829	1570	187	14	0.820	1570	187
15	0.840	848	1383	184	13	0.840	1383	184
14	0.860	867	1199	180	12	0.860	1199	180
13	0.880	886	1018	177	11	0.880	1018	177
12	0.900	905	841	87	10	0.900	841	174
11	0.910	914.5	754	87				
10	0.920	924	667	86	9	0.920	667	171
9	0.930	933.5	581	85				
8	0.940	943	496	84	8	0.940	496	84
7	0.950	952.5	412	84	7	0.950	412	84
6	0.960	962	328	83	6	0.960	328	83
5	0.970	971.5	245	82	5	0.970	245	82
4	0.980	981	163	41	4	0.980	163	41
3	0.985	985.75	122	41	3	0.985	122	41
2	0.990	990.5	81	41	2	0.990	81	41
1	0.995	995.25	40	40	1	0.995	40	40
0	1.000	1000	0					

2.2.2. Landuse

The CAMx landuse file contains the fractional distribution of each landuse category and leaf area index (LAI) for each grid cell, which is needed to define surface resistances for dry deposition calculations and to set the default surface roughness lengths. For the Zhang dry deposition scheme, there are 26 landuse categories, as listed in Table 2-2.

Table 2-2. CAMx landuse categories for the Zhang dry deposition scheme.

Category Number	Land Cover Category
1	Water
2	Ice
3	Inland Lake
4	Evergreen Needleleaf Trees
5	Evergreen Broadleaf Trees
6	Deciduous Needleleaf Trees
7	Deciduous Broadleaf Trees
8	Tropical Broadleaf Trees
9	Drought Deciduous Trees
10	Evergreen Broadleaf Shrubs
11	Deciduous Shrubs
12	Thorn Shrubs
13	Short Grass and Forbs
14	Long Grass
15	Crops
16	Rice
17	Sugar
18	Maize
19	Cotton
20	Irrigated Crops
21	Urban
22	Tundra
23	Swamp
24	Desert
25	Mixed Wood Forests
26	Transitional Forest

The landuse/landcover (LULC) data comes from the North America Land Cover (NALC) database for the year 2000 (Latifovic, 2002), which was developed jointly by the Natural Resources Canada - Canada Centre for Remote Sensing, and the USGS EROS Data Center as part of the larger Global Land Cover 2000 project implemented by the Global Vegetation Monitoring Unit, Joint Research Center (JRC) of the European Commission. The North American database was compiled using satellite data collected at a spatial resolution of 1 km.

The data was obtained from http://edc2.usgs.gov/glcc/nadoc2_0.php as a GIS raster dataset. The 29-category LULC data were then cross referenced to the 26 CAMx landuse categories as shown in Table 2-3.

Table 2-3. LULC mapping between the NALC database and the 26 categories for the Zhang dry deposition scheme.

NALC Category	CAMx Landuse Category	NALC Description
1	8	Tropical or Sub-tropical Broadleaved Evergreen Forest - Closed Canopy
2	8	Tropical or Sub-tropical Broadleaved Deciduous Forest - Closed Canopy
3	7	Temperate or Sub-polar Broadleaved Deciduous Forest - Closed Canopy
4	4	Temperate or Sub-polar Needleleaved Evergreen Forest - Closed Canopy
5	4	Temperate or Sub-polar Needleleaved Evergreen Forest - Open Canopy
6	25	Temperate or Sub-polar Needleleaved Mixed Forest - Closed Canopy
7	25	Temperate or Sub-polar Mixed Broadleaved or Needleleaved Forest - Closed Canopy
8	25	Temperate or Sub-polar Mixed Broadleaved or Needleleaved Forest - Open Canopy
9	10	Temperate or Subpolar Broadleaved Evergreen Shrubland - Closed Canopy
10	11	Temperate or Subpolar Broadleaved Deciduous Shrubland - Open Canopy
11	10	Temperate or Subpolar Needleleaved Evergreen Shrubland - Open Canopy
12	10	Temperate or Sub-polar Mixed Broadleaved and Needleleaved Dwarf-Shrubland - Open Canopy
13	14	Temperate or Subpolar Grassland
14	14	Temperate or Subpolar Grassland with a Sparse Tree Layer
15	13	Temperate or Subpolar Grassland with a Sparse Shrub Layer
16	22	Polar Grassland with a Sparse Shrub Layer
17	22	Polar Grassland with a Dwarf-Sparse Shrub Layer
18	15	Cropland
19	15	Cropland and Shrubland/woodland
20	4	Subpolar Needleleaved Evergreen Forest Open Canopy - lichen understory
21	13	Unconsolidated Material Sparse Vegetation (old burnt or other disturbance)
22	21	Urban and Built-up
23	24	Consolidated Rock Sparse Vegetation
24	1	Water bodies
25	24	Burnt area (resent burnt area)
26	2	Snow and Ice
27	23	Wetlands
28	23	Herbaceous Wetlands
29	10	Tropical or Sub-tropical Broadleaved Evergreen Forest - Open Canopy

The leaf area index data were based on databases from the Model of Emissions of Gases and Aerosols from Nature (MEGAN) biogenic emissions model, which were obtained as ArcGIS raster grid files at http://acd.ucar.edu/~guenther/MEGAN/MEGAN.htm. The LAI data represent monthly averaged datasets for the 2001 calendar year in approximately 1 km resolution.

A suite of GIS and Perl-based processors were used to prepare land cover and LAI input datasets for CAMx. Arc Macro Language (AML) scripts were used to process the raster-based and vector-based GIS data and export ASCII datasets for subsequent processing with Perl scripts and FORTRAN programs. A CAMx landuse file was prepared for both the 36 km and 12 km domains.

2.2.3. Albedo-haze-ozone

The CAMx preprocessor, AHOMAP version 4, was used to create an ASCII-format file containing albedo, haze, and ozone column data. The program reads the CAMx landuse files for both domains and the daily Total Ozone Mapping Spectrometer (TOMS) data in 1 degree resolution, which were downloaded for each episode date from http://ozoneaq.gsfc.nasa.gov/OMIOzone.md. All daily ozone column datasets within the same month were run together so that there would only be one output file per month.

The output file lists 5 categorical values for albedo, 3 for haze, and 5 for ozone. Each grid cell was assigned a bin number associated with these categorical values. For albedo, a bin value was assigned to all modeling domains. For haze opacity, a default uniform field was generated for the coarse grid only. For ozone, the coarse grid was output for all time periods in which ozone column data was provided.

The optional daily snow cover fields generated from WRFCAMx were appended to these files to account for the short waves reflecting off the earth's surface due to the snow, which would result in more photolytic reactions.

2.2.4. Clear-sky photolysis rates

Version 4.8 of the Tropospheric Ultraviolet and Visible (TUV) radiative transfer preprocessor is used to create a lookup table listing the clear-sky photolysis rates for each combination of albedo, haze, and ozone column categorical values at various heights above the ground. The TUV program was run once for each episode month for the Carbon Bond 2005 (CB05) chemical mechanism. The photolysis rates are internally adjusted for hourly cloud conditions on each grid during the CAMx simulation.

2.2.5. Initial and boundary conditions

Data for initial and boundary conditions for the 36 km domain were obtained from the global chemical transport model, the Model for Ozone and Related chemical Tracers, version 4 (MOZART). The MOZART outputs were obtained from http://www.acd.ucar.edu/wrf-chem/mozart.shtml and were downloaded for the modeling periods in 2008.

MOZART outputs are in 2.8 by 2.8 degree horizontal resolution and 28 vertical layers in 6-hour intervals. Data were first converted to IOAPI format using the NCF2IOAPI program. Then, the

GLOBAL_2_LAMBC program was used to vertically interpolate the data onto the CAMx domain and remap the species to CB05 speciation. The CMAQ2CAMX program was applied to convert the boundary conditions to CAMx format and time-interpolate the 6-hourly data to hourly boundary conditions.

After a review of the boundary conditions, ozone concentrations were capped at 500 ppb to minimize the impacts of high stratospheric ozone propagating downwards, particularly over the mountain states. Also, over the Gulf of Mexico, the southern boundary frequently had ground-level primary fine particulate concentrations from MOZART well over 35 $\mu g/m^3$ when air over the Gulf is expected to be relatively clean. In the initial CAMx runs, the use of these fine particulate concentrations in the boundary conditions led to large over predictions throughout the Gulf States and Ohio Valley. Due to the abnormally high values of primary fine particulates from MOZART in the southern boundary, they were removed from the boundary conditions. We note that if these were included, the relative contribution of g-LDVs would be even lower.

A generic set of initial conditions was created using the ICBCPREP program such that the concentration of each species was uniform in all layers across the domain. As discussed earlier, a 15-day spin-up period that began on January 17 and June 16 for February and July, respectively, was applied to flush away the impacts of the initial conditions.

2.3. EMISSIONS

The CAMx emission files incorporate emissions from on-road mobile, non-road, area and point sources, biogenic sources, fires and sea salt. All emission components were held constant for each model year except for the g-LDV emissions. This study focuses on the impacts from different on-road mobile scenarios, so they are discussed first.

2.3.1. On-road mobile emissions

In phase 1 of the CRC A-76 project, several emission inventory scenarios were developed, each using the MOVES2010a model with database version ‘movesdb20100830.’ In each emissions standards scenario, gasoline light duty vehicle emissions changed but those from all other vehicles types remained constant. The specific vehicle classes included in g-LDV are the following:

1. Light-duty gasoline vehicles (LDGV, passenger cars)
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)

Prior on-road mobile emissions inventory scenarios developed for February and July include:

- 2008 Baseline (As-Is)
- 2022 Tier 1
- 2022 Tier 2 (As-Is)

- 2022 LEV-III
- 2022 g-LDV Zero Out

In all cases, the MOVES emissions were speciated to the 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 VOCs were converted to the CB05 chemical mechanism using VOC speciation profiles derived from EPA's SPECIATE database, version 4.3 (EPA, 2011b). PM emissions were speciated to CAMx species following methods outlined by Baek and DenBleyker (Baek, 2010). On-road mobile sources generated using MOVES at the county level were allocated to the 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). Additional details can be found by referring to "Effects of light duty gasoline vehicle emission standards in the United States on ozone and particulate matter" (Vijayaraghavan et al., 2012).

The following new scenarios described in this report build upon the previous work and provide additional context for the incremental benefit of successive g-LDV emission controls:

- 2008 Tier 0
- 2022 Tier 0

Tier 0 emission standards were first applied in the US to year 1981 vehicles and g-LDVs with Tier 1 controls did not enter the fleet until 1994. The 2008 Tier 0 scenario represents a g-LDV fleet where model years prior to 1981 had pre-Tier 0 controls and model years 1981-2008 met the Tier 0 standards. Similarly, for the 2022 Tier 0 scenario, all g-LDV model years 1991-2022 met the Tier 0 standards. All other vehicle classes in each inventory meet the appropriate present-day controls for 2008 or 2022.

The new Tier 0 scenarios are built by scaling the g-LDV emissions in the As-Is (i.e., Tier 2) on-road inventory scenarios for 2008 and 2022. The As-Is scenarios have already been created at the county and SCC level by running MOVES in inventory mode by county for approximately 200 representative counties for February and July, 2008 and 2022 for CRC A-76, phase 1. The SCCs in the inventory are fleet-average age, using the national age distribution in MOVES for most counties including St. Louis and three area-specific age distributions for Detroit, Atlanta, and Philadelphia.

Because the SCCs in the baseline inventories are fleet-average-age SCC level, scaling factors to represent the ratio of "Tier 0" emissions to "As-Is" emissions by pollutant and g-LDV SCC were developed to match this resolution (average-age for the nation and St. Louis, area-specific average-age for Detroit, Atlanta, and Philadelphia). The scaling factors were developed from emission factors at the by-model-year level of detail. The final scaling factors apply to the inventory at the average-age level of detail by SCC, pollutant and emission process. The age distributions and corresponding influence of by-model-year emission standards are incorporated in the average-age scaling factors developed separately for the nation, St. Louis, Detroit, Atlanta, and Philadelphia.

“By model-year” Emission Factors

MOVES runs for the calendar years 2008 and 2022 without any modification provide emissions by model year representing emission control technologies that were historically in place in the federal g-LDV fleet and part of the MOVES model. Figure 2-2 shows the percent of g-LDVs meeting each emission standard by model year. For example, in 1990, 100% of the fleet complied to a Tier 0 emission standard. Beginning in 1994, a phase-in year, 40% of vehicles met Tier 1 emission standards and 60% met Tier 0. Emission standards increase in stringency with time. Each calendar year MOVES run includes 31 model years of vehicles, as indicated in Figure 2-2 for the 2008 and 2022 fleets.

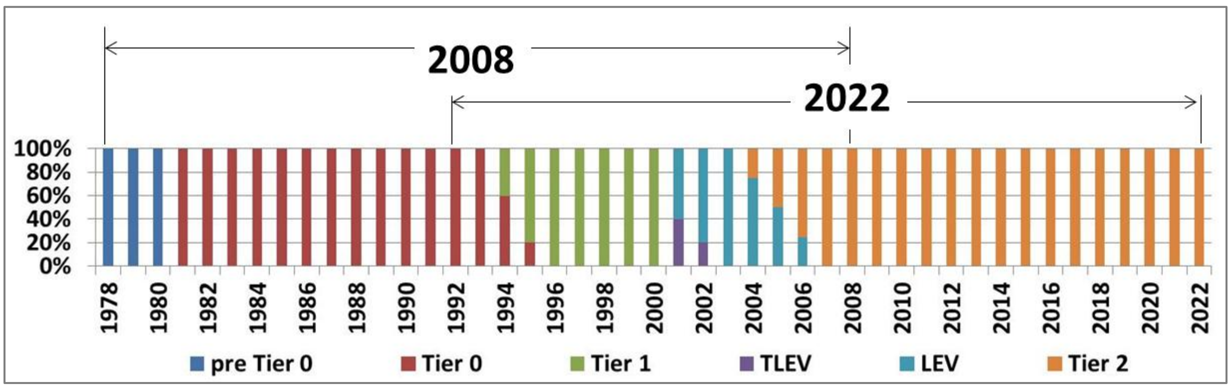


Figure 2-2. Percent of g-LDV fleet meeting each emission standard by model year for vehicles operating in years 2008 and 2022.

The differences between emission factors in each model year are the emission standards to which vehicles were certified in the year they were built, and the degree to which the vehicle emission controls have deteriorated (determined by vehicle age in MOVES).

Our approach to building 2008 and 2022 Tier 0 scenario fleets was to run MOVES by model year to capture Tier 0 vehicles at a variety of deterioration levels to simulate each age of Tier 0 vehicle present in 2008 and 2022 fleets. For example, a model year 2008 Tier 0 vehicle in the calendar year 2008 was represented by the 1993 model year emission factor in a 1993 calendar year MOVES run while all other model parameters are held constant to represent 2008 vehicle conditions (e.g., fuel formulations, air conditioning penetration rates, etc.)

All historical g-LDV model years up to and including 1993 were used directly as they occur in the MOVES model for our scenario development because these model years were historically pre-Tier 0 or Tier 0 vehicles. 1994 model years and newer are represented by Tier 0 model years with the appropriate age (and deterioration) for the 2008 or 2022 fleet.

Figure 2-3 compares the by-model-year emission factors between the As-Is (Tier 2) Scenario and the Tier 0 Scenario for the fleet of gasoline passenger cars (LDGV) in-use in calendar year 2008. Emission factors shown are July 2008 running exhaust HC from gasoline passenger cars (light duty gasoline vehicles, LDGV).

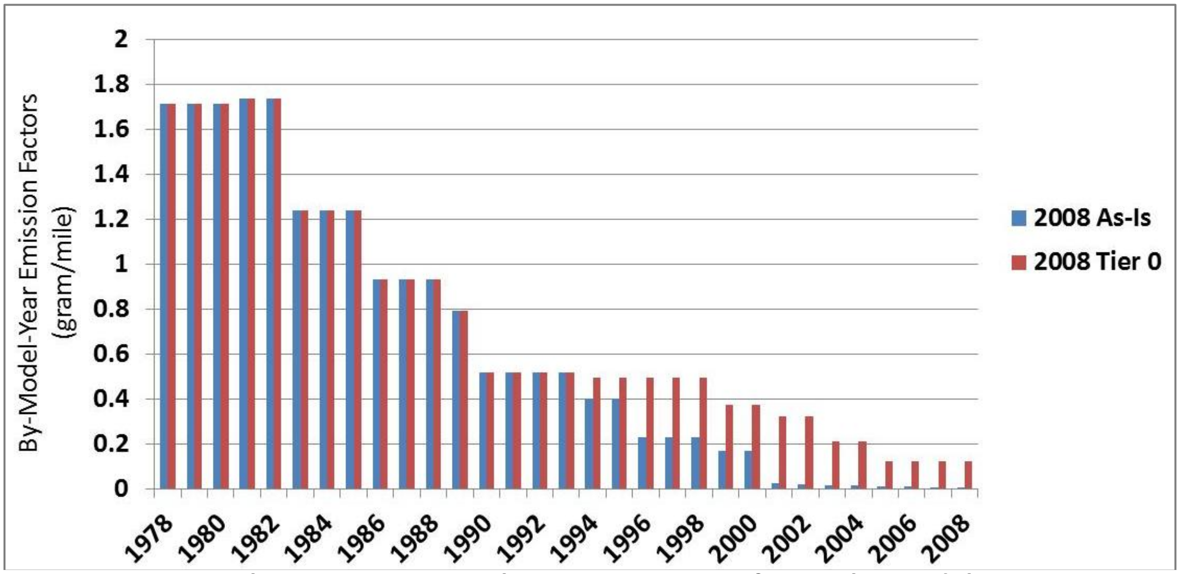


Figure 2-3. 2008 July LDGV running exhaust HC emission factors by model year: comparison of as-is (Tier 2) and Tier 0 scenarios.

Figure 2-4 shows the analogous data for the fleet of LDGVs in-use in calendar year 2022. Note that by 2022, only 1992 and 1993 model year emission factors match between scenarios. The relative benefit of the As-Is (Tier 2) scenario compared to the Tier 0 scenario will be more fully realized in 2022 than 2008.

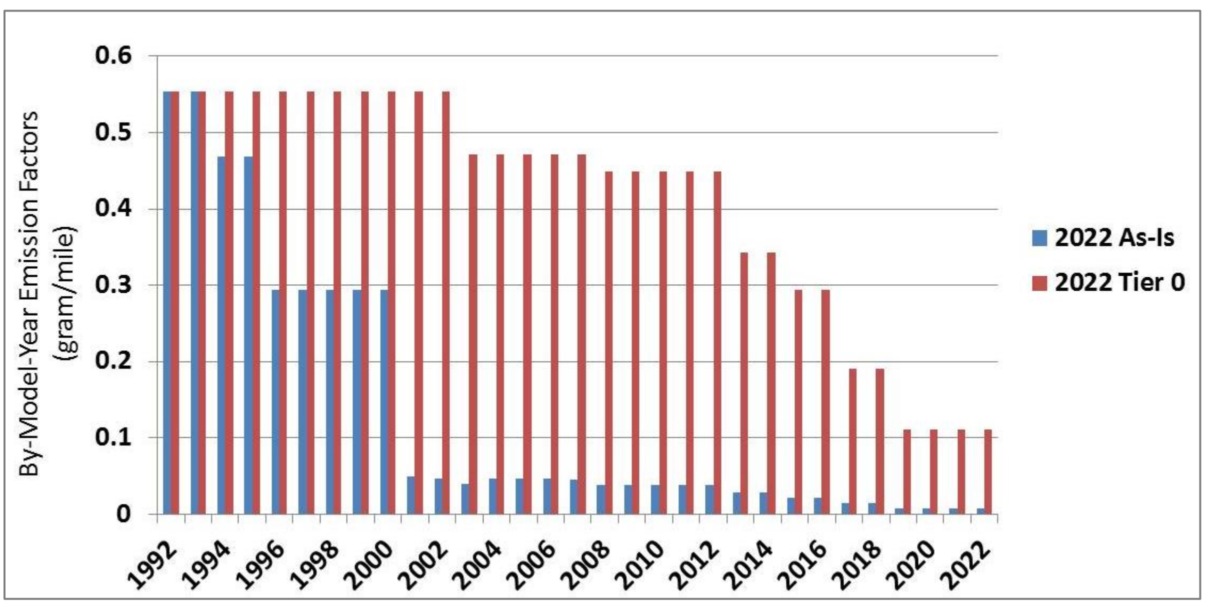


Figure 2-4. 2022 July LDGV running exhaust HC emission factors by model year: comparison of as-is (Tier 2) and Tier 0 scenarios.

Similar sets of two-scenario emission factor results were generated for the full scope of the on-road Tier 0 scenario inventory adjustments to be made, which included:

- Three vehicle classes (LDGV, LDGT1, and LDGT2)
- Two months and two calendar years (February, July, 2008, 2022)
- All pollutants (HC, CO, NOx, NH3, SO2, PM_{10}, $PM_{2.5}$) and emission processes (running, starts, evaporative modes, brake wear, and tire wear)

Each set of As-Is (Tier 2) and Tier 0 scenario emission factors by model year were turned into the fleet-wide, average-age scaling factors by applying Equations (1) through (3) described below. First, each set of by-model-year emission factors were aggregated to the fleet-wide age level according to Equation 1, which shows the weighted averaging using travel fractions. This was done separately for each geographic area.

$$EF_{s,y,m,v,j,k,a} = \sum_{i=i_0}^{i_{30}} \left(\left(EF_{s,y,m,v,i,j,k} \right) \times TF_{v,i,a} \right) \quad \text{[Eqn. 1]}$$

where $EF_{s,y,m,v,j,k,a}$ = Average-age emission factor, by scenario, year, month, vehicle class, pollutant, emission process, and geographic area

s = Scenario {As-Is, Tier 0}

y = Scenario Year {2008, 2022}

m = Scenario Month {February, July}

v = Vehicle Class {LDGV, LDGT1, LDGT2}

i = age of vehicle, from 0 to 30 years old {*i* = *y* - (model year)}

j = Pollutant {HC, CO, NOx, NH_3, SO_2, PM_{10}, $PM_{2.5}$}

k = Process {running exhaust, start exhaust, evaporative modes, brake wear, and tire wear}

TF = Travel Fraction, see Eqn. 2.

a = geographic area {Nation, St. Louis, Detroit, Atlanta, Philadelphia}

The average-age emission factors calculated by Equation 1 are the weighted average of the by-model-year emission factor, and the weighting applied is the percentage of total miles driven in each model year, termed *Travel Fractions*. The travel fractions are fractions that sum to unity over 31 vehicle model years; they vary by vehicle class and geographic area. Equation 2 shows the calculation of travel fractions and Figure 2-5 shows the resulting travel fractions for LDGVs for the Nation and St. Louis, Detroit, Atlanta, and Philadelphia.

$$TF_{i,v,a} = \frac{\left(MAR_{i,v}\right)\left(ADF_{i,v,a}\right)}{\sum_{i=i_0}^{i_{30}} \left(MAR_{i,v} \times ADF_{i,v,a}\right)} \quad \text{[Eqn. 2]}$$

where $TF_{i,v,a}$ = fraction of fleet-wide travel performed by vehicles of age *i*

i = age of vehicle, from 0 to 30 years old {*i* = *y* - (model year)}

v = Vehicle Class {LDGV, LDGT1, LDGT2}

a = geographic area {Nation, St. Louis, Detroit, Atlanta, Philadelphia}

MAR = MOVES nationwide default Mileage Accumulation Rate, the annual miles driven by vehicle age *i*, vehicle *v*

ADF = Age Distribution Fraction, the fraction of registered vehicles of age *i,* vehicle *v*, geographic area *a*

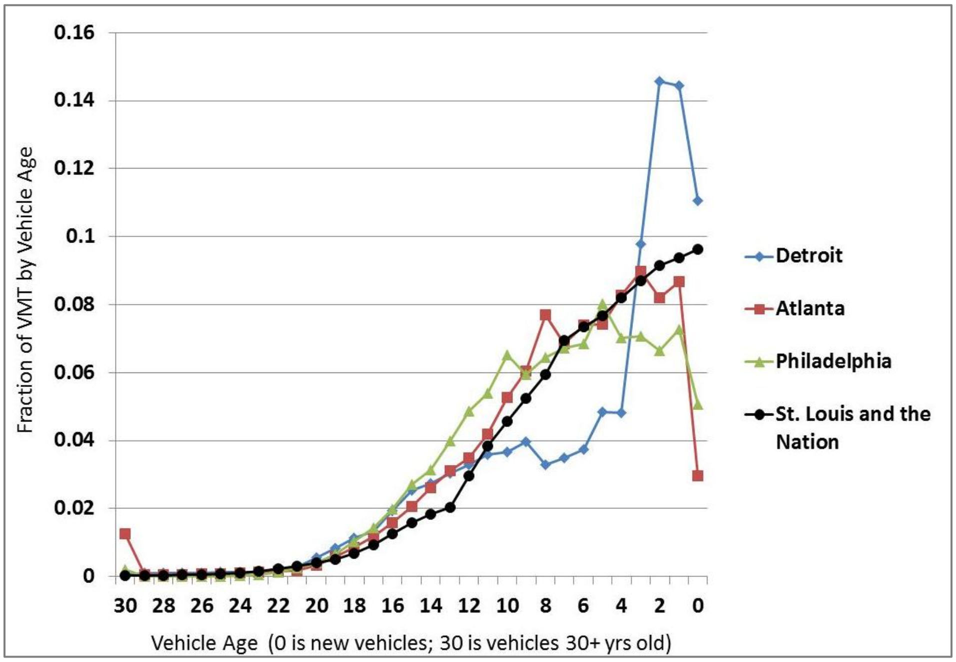


Figure 2-5. LDGV travel fractions by geographic area.

The travel fractions shown in Figure 2-5 are different by geographic area due to unique age distributions (*ADF* term in Equation 2) of the vehicle population. The age distributions for Detroit, Atlanta, and Philadelphia represent the 2005 distribution of vehicle ages in the three cities Atlanta, Detroit and Philadelphia, and the MOVES national default age distribution for St. Louis and the rest of the nation. Detroit stands out from the other areas for having a greater proportion of new vehicles (age 0-3) compared with Atlanta, Philadelphia, or the nation.

Finally, the ratios of scenario average-age emission factors were computed according to Equation 3. These ratios are the scaling factors that are directly multiplied with the corresponding baseline emissions in the 2008 and 2022 As-Is (Tier 2) inventories to create the 2008 and 2022 Tier 0 inventories.

$$Factor_{y,m,v,j,k,a} = \frac{(EF_{Tier\ 0})_{y,m,v,j,k,a}}{(EF_{As-Is})_{y,m,v,j,k,a}} \qquad \text{[Eqn. 3]}$$

where $Factor_{y,m,v,j,k,a}$ = scaling factor applied to the As-Is (Tier 2) scenario inventories

y = Scenario Year {2008, 2022}

m = Scenario Month {February, July}

v = Vehicle Class {LDGV, LDGT1, LDGT2}

j = Pollutant {HC, CO, NOx, NH_3, SO_2, PM_{10}, $PM_{2.5}$}

k = Process {running exhaust, start exhaust, evaporative modes, brake wear, and tire wear}

a = geographic area {Nation, St. Louis, Detroit, Atlanta, Philadelphia}

There are no other differences between the As-Is (Tier 2) and Tier 0 emissions inventories other than the adjustments to the g-LDV emissions within the US. Canada and Mexico on-road emissions were not adjusted. The 2008 and 2022 Canadian on-road emissions were based on the 2005 and 2020 NEI, respectively. The Mexican on-road emissions were based on the 2005 NEI for both the 2008 and 2022 modeling years.

2.3.2. Other emissions

Emissions from other source categories were obtained from the prior A-76-1 study and held constant across all scenarios. A description is provided below. Emissions from anthropogenic area and point sources in 2008 in the continental US (CONUS) were developed from version 1.5 of the 2008 NEI (EPA, 2011a). Emissions from these source categories for the 2022 emissions scenarios were prepared from the 2020 NEI inventory (EPA, 2010c) and held constant from 2020 to 2022. The 2020 NEI was developed by the EPA by projecting the 2005-based v4 modeling platform emissions to 2020.

Anthropogenic area and point emissions for Canada for the 2008 base case and 2022 scenarios within the 36 km grid were prepared from and set equal to emissions in the 2005 NEI (EPA, 2011c) and the 2020 NEI, respectively.

Anthropogenic area and point emissions for Mexico within the 36 km grid for the 2008 base case were prepared from the 2005 NEI and held constant between the 2008 and 2022 scenarios due to lack of additional information.

The 2008 non-road mobile source emissions in the CONUS were developed from the 2008 NEI. The NEI non-road emissions are based on the National Mobile Inventory Model (NMIM) using county specific fuel properties, meteorological parameters and non-default local activity data for areas where such activity data has been provided to EPA as part of its NEI development efforts. The NMIM model was used to generate county level estimates of 2022 non-road emissions in the CONUS for February and July. 2008 emissions from locomotives/harbor craft, aircraft and commercial marine vessels were also obtained from the 2008 NEI. The 2022 emissions from locomotives/harbor craft, aircraft and commercial marine vessels were obtained from the 2020 NEI and forecast two years through 2022 following forecast methods applied by EPA (2008a), FAA (2010) and EPA (2009), respectively.

The 2008 biogenic emissions were developed using the Model of Emissions of Gases and Aerosols from Nature (MEGAN v. 2.04; Guenther et al., 2006). MEGAN uses gridded emission factors that are based on global datasets for 11 species (CO, nitric oxide, isoprene and other VOCs) and four functional plant types and plant leaf area index. Biogenic emissions were held constant from 2008 to 2022.

Wildfire emission inventories for 2008 were derived from the Blue Sky Framework SMARTFIRE database (http://www.getbluesky.org) and processed using version 3.12 of the Emissions Processing System (EPS) tool. Wildfire emissions were held constant in all emissions scenarios.

Sea salt emissions inventories of particulate sodium, chloride and sulfate for 2008 were prepared using the meteorological fields driven by WRF (temperature, pressure, winds) and land cover information. Sea salt emissions were also not altered from the 2008 to 2022 scenarios.

3. MODELING RESULTS

The 2008 and 2022 Tier 0 g-LDV emissions scenarios were modeled using MOVES and CAMx in the current study. These runs, in conjunction with the runs performed in the first phase of the project, were used to evaluate the incremental ozone and $PM_{2.5}$ benefits from increasingly stringent g-LDV emissions standards. Table 3-1 provides a list of all CAMx emissions scenarios modeled. All runs consisted of a monthly simulation in February representing winter and one in July representing summer.

Table 3-1. List of CAMx emission scenarios

Gasoline LDV emissions scenario	First year emissions standard implemented	Years modeled
Tier 0	1981	2008 and 2022
Tier 1	1994	2022
Tier 2 (As-is)	2004	2008 and 2022
LEV-III	2015	2022
LDV zero-out	--	2022

The 2008 Tier 0 scenario represents a g-LDV fleet where 1981-2008 model year vehicles met Tier 0 standards and vehicles from before model year 1981 had pre-Tier 0 controls. By calendar year 2022, all g-LDVs in the fleet (1991-2022) would have met the Tier 0 standards. Tier 1 required more stringent emission standards beginning with 1994 model year g-LDVs. Tier 2 controls, which are currently in place, were applied to g-LDVs beginning with the 2004 model year. The California LEV-III standard is applicable to 2015-2028 vehicles (up to 2025 for ozone precursors – non-methane organic gases (NMOG) and NOx) so the hypothetical nationwide LEV-III scenario will not achieve complete phase-in by 2022.

3.1. 2008 SCENARIOS

3.1.1. Emissions

Table 3-2 compares the g-LDV emission totals for VOC, NOx and $PM_{2.5}$ in the Tier 0 and Tier 2 scenarios on an average winter day in 2008. Emission totals are listed for five geographic areas, including: the continental US (CONUS), Atlanta, Detroit, Philadelphia, and St. Louis. A similar table of 2008 emissions for an average summer day is shown in Table 3-3.

In 2008, if emissions standards had not increased in stringency after MY 1981 (Tier 0 scenario), g-LDVs would have emitted 12,775 short tons/day (TPD) of VOCs on an average summer day, and a slightly lower amount in the winter. The g-LDVs accounted for nearly 90% of all on-road mobile VOC emissions, and 30% of all anthropogenic VOC emissions during both seasons in the Tier 0 scenario, as seen in Table 3-4. The adoption of more stringent Tier 2 emission controls reduced the VOC emissions in the CONUS by 42% and 50% relative to the Tier 0 scenario on an average winter and summer day, respectively, with g-LDVs contributing approximately 18-21%

of all anthropogenic VOC emissions during the two seasons in 2008 (also see Vijayaraghavan et al., 2012).

NOx emissions from g-LDVs in the 2008 Tier 0 scenario totaled nearly 20,000 TPD in the CONUS on an average summer day and were 14% lower in the winter. The g-LDV emissions accounted for a third of all anthropogenic emissions and two-thirds of all on-road mobile emissions in both winter and summer. Tier 2 reduced NOx emissions by 45 and 47% in the winter and summer, respectively, with g-LDV NOx emissions now constituting one-fifth of all anthropogenic emissions (also see Vijayaraghavan et al., 2012). The g-LDV NOx emissions are always higher in the summer than winter in the CONUS and at the four urban areas.

Table 3-2. Comparison of 2008 g-LDV emission totals in the Tier 0 and Tier 2 scenarios on an average winter day.

Region	Tier 0 [TPD]	Tier 2 [TPD]	Emissions Change [TPD]	% Change
VOC				
CONUS	12,478	7,193	-5,286	-42%
Atlanta	188	114	-75	-40%
Detroit	215	113	-102	-48%
Philadelphia	103	59	-45	-43%
St Louis	122	74	-48	-39%
NOx				
CONUS	17,565	9,594	-7,971	-45%
Atlanta	266	156	-110	-41%
Detroit	262	117	-145	-55%
Philadelphia	130	73	-57	-44%
St Louis	174	98	-75	-43%
$PM_{2.5}$				
CONUS	382	277	-105	-27%
Atlanta	5.7	4.3	-1.4	-24%
Detroit	8.1	5.5	-2.6	-32%
Philadelphia	3.9	2.8	-1.1	-29%
St Louis	4.3	3.2	-1.1	-26%

$PM_{2.5}$ emissions from g-LDVs in Tier 0 were twice as high in the winter than in the summer in the CONUS. The g-LDVs accounted for a very small fraction of all anthropogenic $PM_{2.5}$ emissions, 4% and 2% in winter and summer, respectively. The Tier 2 program reduced the g-LDV $PM_{2.5}$ emissions totals by 27% in winter and 22% in summer.

Of the four urban areas evaluated for calendar year 2008, Detroit showed the greatest reduction in NOx, VOC, and $PM_{2.5}$ emissions when comparing the Tier 0 and the Tier 2 scenarios. This can be attributed to the fact that, of the four urban areas, Detroit has the highest proportion of new vehicles represented in its g-LDV in-use fleet which magnifies the, differences in model-year emission factors and results in a stronger benefit when implementing the new more stringent standards.

Table 3-3. Comparison of 2008 g-LDV emission totals in the Tier 0 and Tier 2 scenarios on an average summer day.

Region	Tier 0 [TPD]	Tier 2 [TPD]	Emissions Reduction [TPD]	% Change
VOC				
CONUS	12,775	6,326	6,449	-50%
Atlanta	203	110	93	-46%
Detroit	177	74	103	-58%
Philadelphia	100	47	53	-53%
St Louis	123	63	60	-49%
NOx				
CONUS	19,992	10,587	9,405	-47%
Atlanta	303	173	130	-43%
Detroit	274	118	156	-57%
Philadelphia	148	80	67	-46%
St Louis	197	108	89	-45%
$PM_{2.5}$				
CONUS	172	134	38	-22%
Atlanta	3.1	2.5	0.6	-20%
Detroit	2.5	1.9	0.6	-23%
Philadelphia	1.6	1.2	0.3	-22%
St Louis	1.8	1.4	0.4	-21%

Table 3-4. 2008 Tier 0 fraction of emissions from gasoline light duty vehicles.

Region	% of All Anthropogenic	% of All On-road Mobile
Winter		
VOC	30%	92%
NOx	33%	65%
$PM_{2.5}$	3.5%	47%
Summer		
VOC	29%	91%
NOx	33%	67%
$PM_{2.5}$	1.9%	26%

3.1.2. Air Quality

Figure 3-1 shows spatial plots of the daily maximum 8-hour ozone averaged over all days in July,2008 (we focus on July because summertime ozone is of primary interest in the eastern US). The top row shows monthly averages in the 2008 Tier 0 scenario for the 36 km and 12km domains on the left and right panels, respectively. The middle row shows the monthly average in the 2008 Tier 2 scenario, and the bottom shows the difference in monthly averaged 8-hour ozone between the Tier 0 and Tier 2 scenarios, representing the July 2008 ozone benefits in the Eastern US resulting from the historical progression to the more stringent Tier 2 standards.
In July, the highest monthly averaged daily maximum 8-hour ozone was modeled in southern California (at 98 ppb) in the 2008 Tier 0 scenario in the 36 km domain while Washington DC had the highest ozone in the 12 km domain at 96 ppb. When the g-LDV NOx and VOC emissions were reduced 47% and 50% from Tier 0 standards, the monthly average 8-hour ozone was lowered by up to 6.0 ppb in the 12 km domain as modeled in the 2008 Tier 2 scenario. The largest reductions were located primarily east of the Appalachians. In urban areas, the ozone benefits were smaller. Most notably, the smallest positive benefit occurred for New York City and the benefit was, in fact, negative for Chicago.

Table 3-5 compares the monthly averaged daily maximum 8-hour ozone in the four urban areas considered. All values tabulated are those modeled in the CAMx 12 km resolution grid cell located in the geographic center of the specified urban area. In July, Atlanta experienced the highest ozone in the Tier 0 scenario (87.5 ppb) while Detroit was lowest at 60.4 ppb. The more-stringent Tier 2 controls helped lower 8-hour ozone at all four sites in July. Atlanta benefitted the most as the average daily maximum 8-hour ozone was reduced 4.3 ppb. Detroit, where NOx and VOC reductions were the greatest, only averaged 1.0 ppb less ozone, suggesting a smaller contribution to ozone from g-LDVs at this location.

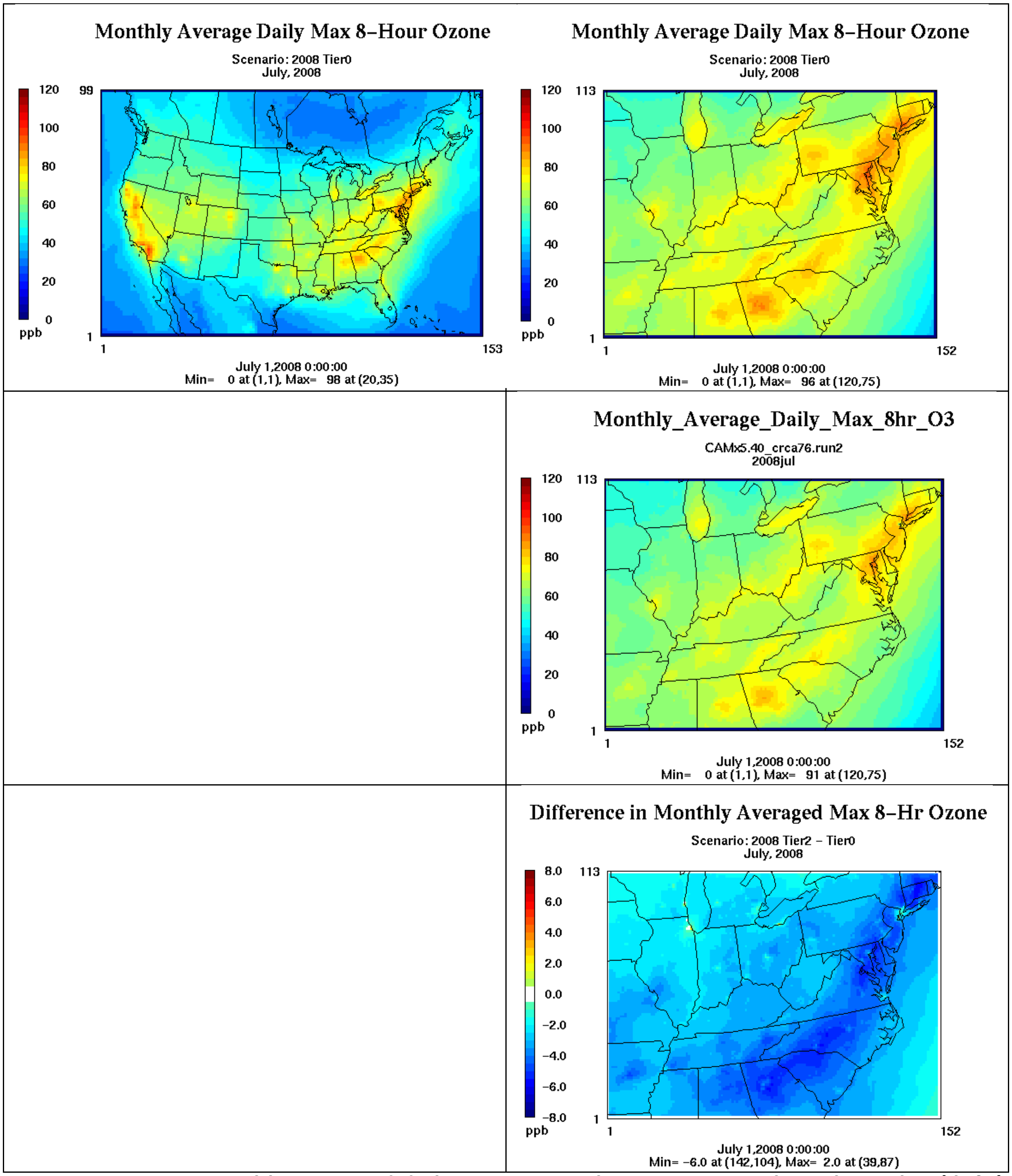


Figure 3-1. 2008 monthly-averaged daily maximum 8-hour ozone in July in the 36 km (left) and 12 km (right) domains in the Tier 0 scenario (top) and in the Tier 2 scenario in the 12 km domain(center row), and difference in monthly-averaged daily maximum 8-hour ozone between Tier 0 and Tier 2 (bottom panel).

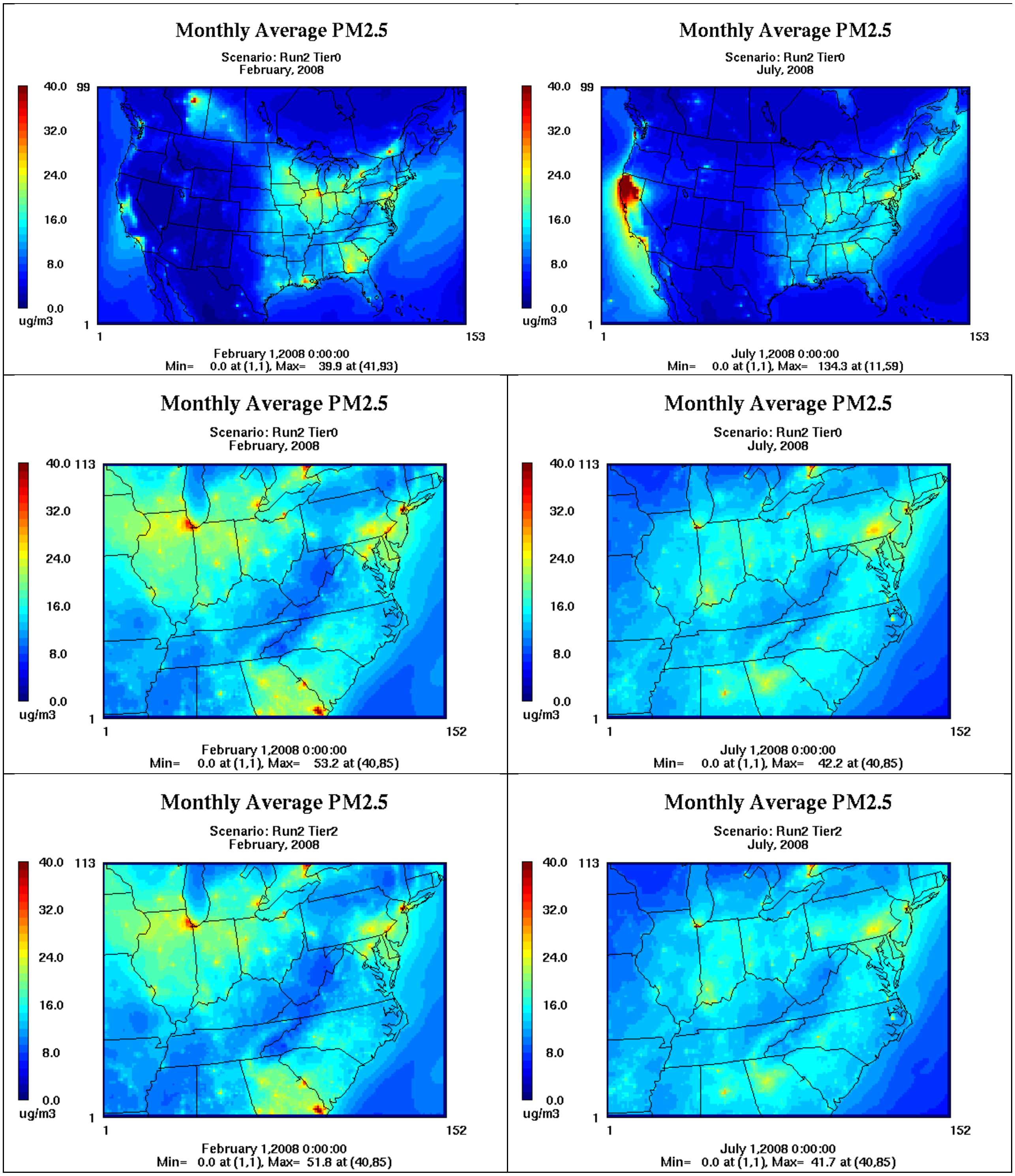
Table 3-5. Monthly averaged daily maximum 8-hour ozone and their differences at four urban sites in July 2008.

Urban Area	2008 Tier 0 [ppb]	2008 Tier 2 [ppb]	2008 Tier 2 – Tier 0 [ppb]	[%]
Atlanta	87.5	83.3	-4.3	-4.9
Detroit	60.4	59.4	-1.0	-1.6
Philadelphia	85.3	81.9	-3.4	-4.0
St Louis	75.6	73.1	-2.5	-3.3

Figure 3-2 shows the spatial distribution of monthly averaged $PM_{2.5}$ concentrations in February and July in the Tier 0 and Tier 2 scenarios and also shows the difference between these two scenarios. In Tier 0, $PM_{2.5}$ was highest in northern California in July, where numerous wildfires generated high concentrations of organic carbon particulate matter. In most other areas, $PM_{2.5}$ tended to be higher in February than July, including Chicago, where the 12 km domain peak of 53 $\mu g/m^3$ in February was 11 $\mu g/m^3$ higher than in July. The four urban areas each experienced a monthly average $PM_{2.5}$ concentration between 25 and 30 $\mu g/m^3$ in the Tier 0 scenario in February with smaller concentrations in July, as listed in Table 3-6.

The Tier 2 standards helped reduce the monthly average of $PM_{2.5}$ by up to 1.9 and 2.0 $\mu g/m^3$ in February and July, respectively (see Figure 3-2). In February, the largest reductions could be found at the urban centers and along the Northeast Corridor, where nitrate reductions accounted for the majority of the $PM_{2.5}$ reduction. All four urban sites were reduced by at least 1.0 $\mu g/m^3$ in February, representing a 4-6% reduction in $PM_{2.5}$ (see Table 3-6).

In July, the largest $PM_{2.5}$ reductions were located in western Ohio and southeastern Pennsylvania. The Tier 2 controls lowered $PM_{2.5}$ concentrations at all four urban areas, but the magnitude of the reductions were about half the size of the February reductions. Particulate nitrate again showed the largest reduction.


Monthly Average PM2.5
Scenario: Run2 Tier0
February, 2008
40.0
32.0
24.0
16.0
8.0
0.0
ug/m3
99
1
1
153
February 1,2008 0:00:00
Min= 0.0 at (1,1), Max= 39.9 at (41,93)
Monthly Average PM2.5
Scenario: Run2 Tier0
July, 2008
40.0
32.0
24.0
16.0
8.0
0.0
ug/m3
99
1
1
153
July 1,2008 0:00:00
Min= 0.0 at (1,1), Max= 134.3 at (11,59)
Monthly Average PM2.5
Scenario: Run2 Tier0
February, 2008
40.0
32.0
24.0
16.0
8.0
0.0
ug/m3
113
1
1
152
February 1,2008 0:00:00
Min= 0.0 at (1,1), Max= 53.2 at (40,85)
Monthly Average PM2.5
Scenario: Run2 Tier0
July, 2008
40.0
32.0
24.0
16.0
8.0
0.0
ug/m3
113
1
1
152
July 1,2008 0:00:00
Min= 0.0 at (1,1), Max= 42.2 at (40,85)
Monthly Average PM2.5
Scenario: Run2 Tier2
February, 2008
40.0
32.0
24.0
16.0
8.0
0.0
ug/m3
113
1
1
152
February 1,2008 0:00:00
Min= 0.0 at (1,1), Max= 51.8 at (40,85)
Monthly Average PM2.5
Scenario: Run2 Tier2
July, 2008
40.0
32.0
24.0
16.0
8.0
0.0
ug/m3
113
1
1
152
July 1,2008 0:00:00
Min= 0.0 at (1,1), Max= 41.7 at (40,85)

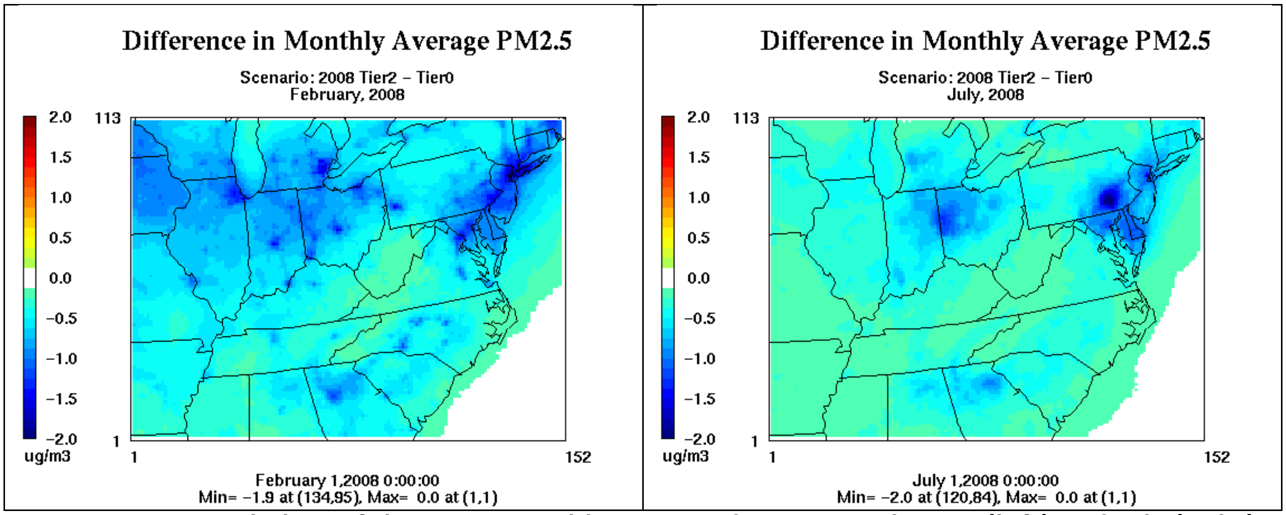


Figure 3-2. Spatial plots of the 2008 monthly-averaged $PM_{2.5}$ in February (left) and July (right) in the 36 km Tier 0 scenario(top), 12 km Tier 0 scenario (second row), 12 km Tier 2 scenario (third row), and differences between Tier 2 and Tier 0 (bottom).

Table 3-6. 2008 monthly averaged $PM_{2.5}$ concentrations and differences at four urban sites.

Urban Area	2008 Tier 0 [μg/m^3]	2008 Tier 2 [μg/m^3]	2008 Tier 2 – Tier 0 [μg/m^3]	[%]
February				
Atlanta	25.7	24.5	-1.2	-4.8
Detroit	27.7	26.1	-1.5	-5.6
Philadelphia	29.0	27.4	-1.6	-5.5
St Louis	25.9	24.8	-1.1	-4.3
July				
Atlanta	24.5	23.9	-0.6	-2.4
Detroit	15.9	15.4	-0.5	-3.2
Philadelphia	21.1	20.3	-0.8	-3.6
St Louis	19.2	18.8	-0.4	-1.9

3.2. 2022 SCENARIOS

As discussed above, CAMx was used to model five scenarios in the 2022 future year in which only emissions from g-LDVs differed. Results are presented below for emissions and air quality.

3.2.1. Emissions

The g-LDV emissions totals by geographic area (CONUS, Atlanta, Detroit, Philadelphia, and St Louis) from the five scenarios– Tier 0, Tier 1, Tier 2, LEV-III, and LDVZ – are listed in Tables 3-7 and 3-8 for a typical winter and summer day, respectively. Differences between the scenario totals for CONUS are shown in Table 3-9. A comparison of the g-LDV emissions with the total 2022 anthropogenic emissions is listed in Table 3-10.

In the 2022 Tier 0 scenario, g-LDVs emitted approximately 24,000 TPD NOx, 15,000 TPD VOC and 200 TPD $PM_{2.5}$ on a typical summer day across the CONUS in 2022. All of these emissions were higher than their corresponding 2008 Tier 0 emission totals since the vehicle miles travelled were projected to be higher. The Tier 0 NOx was 20% higher in 2022 than in 2008 in both winter and summer; VOC and $PM_{2.5}$ emissions were 10 to 15% higher. The 2022 Tier 0 g-LDV emissions accounted for 46% of all anthropogenic NOx emissions and 33% of all anthropogenic VOC emissions in the summer. Tier 0 $PM_{2.5}$ emissions from g-LDVs were 4% and 2% of all anthropogenic sources in the winter and summer, respectively, in both 2008 and 2022.

Evaluation of the four urban areas in 2022 showed little variation in the percent reduction of NOx, VOC, or $PM_{2.5}$ emissions. This holds true for relative emissions reductions achieved by transitioning from Tier 0 toward Tier 2 as well as the additional expected benefit of moving from Tier 2 to LEV-III. The main difference in urban area age distributions between the four urban areas (Figure 2-5) was that Detroit had a significantly higher proportion of model year vehicles age 0-3; Detroit also had significantly lower proportion of model year vehicles aged 4-10 compared to Atlanta, Philadelphia, and St. Louis. For older model years (age 11-31), the four age distributions are similar. The 2022 Tier 0 scenario is not impacted by age distribution at all because all 31 vehicle model years meet the Tier 0 standard. The 2022 Tier 2 and LEV-III scenarios' Tier 2 and LEV-II technologies affect vehicles age 0-14 and age 0-7, respectively. Because the phase-in periods for 2022 scenarios and model years with significant differences in age distribution did not tend to overlap, all areas experience similar changes in emissions.

The 2022 Tier 2 g-LDV NOx, VOC, and $PM_{2.5}$ emissions were all considerably lower than their corresponding 2008 Tier 2 emissions since the Tier 2 standards, which were phased in beginning in 2004, penetrate further into the 2022 fleet.

Figure 3-3 shows line charts that compare the total 2022 g-LDV emissions in the CONUS in the five emission scenarios (from the least to most stringent standards from left to right). Both winter and summer showed steep declines in emissions from Tier 0 to Tier 1 and from Tier 1 to Tier 2 for the ozone precursors, and subsequently a plateau when transitioning to LEV-III.

Summertime NOx and VOC emission reductions were largest between Tier 0 to Tier 1; NOx was reduced 10,767 TPD (45%) and VOCs were lowered 8,596 TPD (59%) in the CONUS. The NOx TPD reductions from Tier 1 to Tier 2 were nearly as large as those from Tier 0 to Tier 1 for both winter and summer emissions (Tables 3-7 and 3-8). The summertime average day NOx values for the CONUS in Table 3-8 were 13,300 TPD NOx (Tier 1) and 3,200 TPD (Tier 2), representing a 76% reduction achieved by moving to the more stringent Tier 2 emission standard. VOCs in summer were reduced 59% from Tier 1 levels. Table 3-10 shows that at Tier 2 levels, g-LDVs contributed only 10% of all anthropogenic NOx emissions, down from 46% in Tier 0; g-LDV VOC emissions were reduced from 33% to 8% of all anthropogenic VOCs.

The LEV-III emission scenario further reduced summertime NOx and VOC by only 127 TPD (4%) and 166 TPD (7%), respectively, over Tier 2 standards. These reductions were over an order of magnitude smaller than the changes from Tier 0 to Tier 1 and from Tier 1 to Tier 2. Considering that the Tier 2 NOx and VOC emissions had already been reduced 87% and 83%, respectively, from Tier 0 levels, the potential for further emission reductions in g-LDVs to further reduce ozone and $PM_{2.5}$ concentrations was small.

In the hypothetical scenario where all emissions from g-LDVs are removed (LDVZ scenario), an additional 3000 TPD NOx and 2300 TPD VOC are reduced over LEV-III standards on an average summer day, but these constitute less than half of the emission reductions when either Tier 1 or Tier 2 standards were applied.

$PM_{2.5}$ reductions between Tier 0 and Tier 2 were not as large as the VOC and NOx reductions in either winter or summer. Wintertime Tier 2 $PM_{2.5}$ emissions were cut in half from the Tier 0 scenario whereas NOx and VOC emissions were reduced over 80% each. $PM_{2.5}$ emissions are reduced only 8% in the winter in transitioning from Tier 2 to LEV-III.

Figure 3-4 summarizes the 2022 CONUS average summer day anthropogenic emissions for VOC, NOx and $PM_{2.5}$ in the five scenarios. The columns on the right represent total emissions in 2022 from the different anthropogenic source sectors except g-LDVs – area sources, electricity generating units (EGUs), non-EGU point sources, off-road sources, and non-g-LDV on-road mobile sources, all of which were unchanged in all 2022 runs. The g-LDV emissions are shown on the left to facilitate comparison of the magnitude of the g-LDV on-road emissions with the other source sectors.

In the 2022 Tier 0 scenario, g-LDVs accounted for almost half of all summertime anthropogenic NOx emissions. The Tier 0 and Tier 1 g-LDVs emitted more NOx than any other anthropogenic emission group; additional controls through Tier 2 result in the g-LDVs becoming the smallest US source sector for NOx emissions, reducing its contribution to 10% of the anthropogenic NOx inventory.

The g-LDVs in the Tier 0 scenario were the second largest source of VOCs behind area sources, accounting for about a third of all anthropogenic VOCs emitted. They remained second highest in Tier 1 despite a 59% reduction from Tier 0 levels in the summer. Additional controls from Tier 2 helped lower the g-LDV contribution to only 8% of all anthropogenic VOC emissions, emitting less than area sources, non-EGU point sources and off-road sources.

$PM_{2.5}$ emissions from g-LDVs were low compared to all other emission sources in all emission scenarios, ranging from 2.5% (Tier 0) to 1.5% (Tier 2) of all anthropogenic emissions in the summer, and 4.5% (Tier 0) to 2.3% (Tier 2) of winter anthropogenic emissions.

Table 3-7. Comparison of 2022 g-LDV emission totals on an average winter day.

Location	Tier 0 (TPD)	Tier 1 (TPD)	Tier 2 (TPD)	LEV-III (TPD)	LDVZ (TPD)
VOC					
CONUS	13700	7376	2685	2525	0
Atlanta	203	101	34	32	0
Detroit	219	114	36	34	0
Philadelphia	117	57	20	18	0
St Louis	133	73	27	25	0
NOx					
CONUS	21050	11932	2987	2868	0
Atlanta	316	177	43	41	0
Detroit	298	168	36	35	0
Philadelphia	158	92	18	18	0
St Louis	205	116	31	30	0
$PM_{2.5}$					
CONUS	429.8	286.6	215.0	198.5	0
Atlanta	5.9	4.1	3.1	2.9	0
Detroit	8.8	5.7	4.2	3.4	0
Philadelphia	4.4	2.9	2.1	2.0	0
St Louis	4.8	3.3	2.4	2.3	0

Table 3-8. Comparison of 2022 g-LDV emission totals on an average summer day.

Location	Tier 0 (TPD)	Tier 1 (TPD)	Tier 2 (TPD)	LEV-III (TPD)	LDVZ (TPD)
VOC					
CONUS	14650	6054	2508	2341	0
Atlanta	228	90	34	31	0
Detroit	204	72	28	26	0
Philadelphia	120	42	17	15	0
St Louis	142	58	25	23	0
NOx					
CONUS	24050	13283	3173	3046	0
Atlanta	368	200	47	45	0
Detroit	315	171	35	33	0
Philadelphia	180	101	18	18	0
St Louis	235	129	33	32	0
$PM_{2.5}$					
CONUS	192.8	143.1	118.6	112.5	0
Atlanta	3.2	2.5	2.1	1.9	0
Detroit	2.8	2.1	1.8	1.6	0
Philadelphia	1.8	1.3	1.1	1.1	0
St Louis	2.0	1.5	1.2	1.2	0

Table 3-9. Change in 2022 g-LDVs emissions due to each successive standard.

	Tier 0 to Tier 1 (TPD, %)	Tier 1 to Tier 2 (TPD, %)	Tier 2 to LEV-III (TPD, %)	LEV-III to LDVZ (TPD, %)
Winter				
VOC	-6324 (-46%)	-4691 (-64%)	-160 (-6%)	-2525 (-100%)
NOx	-9118 (-43%)	-8946 (-75%)	-118 (-4%)	-2868 (-100%)
$PM_{2.5}$	-143 (-33%)	-72 (-25%)	-16 (-8%)	-199 (-100%)
Summer				
VOC	-8596 (-59%)	-3546 (-59%)	-166 (-7%)	-2341 (-100%)
NOx	-10767 (-45%)	-10110 (-76%)	-127 (-4%)	-3046 (-100%)
$PM_{2.5}$	-50 (-26%)	-25 (-17%)	-6 (-5%)	-112 (-100%)

Table 3-10. Fraction of Anthropogenic Emissions from gas-burning LDVs in 2022

	Tier 0	Tier 1	Tier 2	LEV-III	LDVZ
Winter					
VOC	32%	20%	8%	8%	0%
NOx	45%	32%	10%	10%	0%
$PM_{2.5}$	4.5%	3.0%	2.3%	2.1%	0.0%
Summer					
VOC	33%	17%	8%	7%	0%
NOx	46%	32%	10%	10%	0%
$PM_{2.5}$	2.5%	1.9%	1.5%	1.5%	0.0%

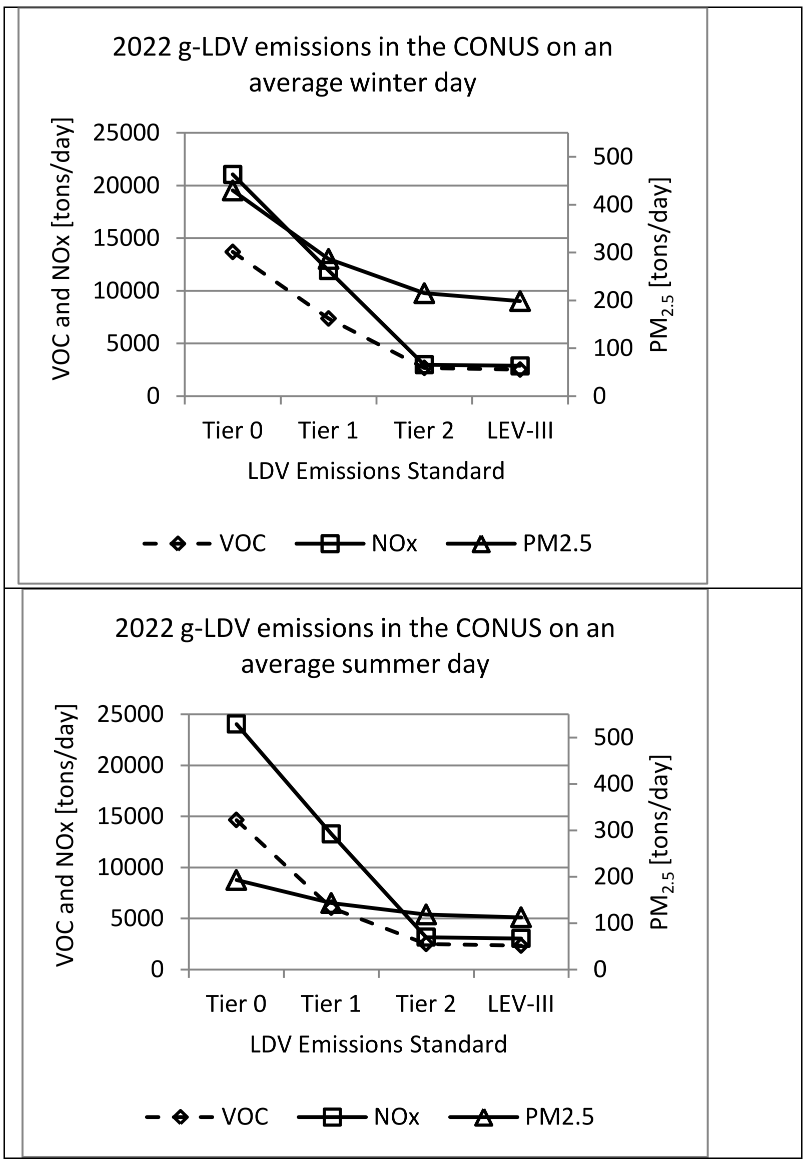


Figure 3-3. VOC, NOx, and $PM_{2.5}$ emissions from g-LDVs in each 2022 scenario on an average winter day (top) and average summer day (bottom).

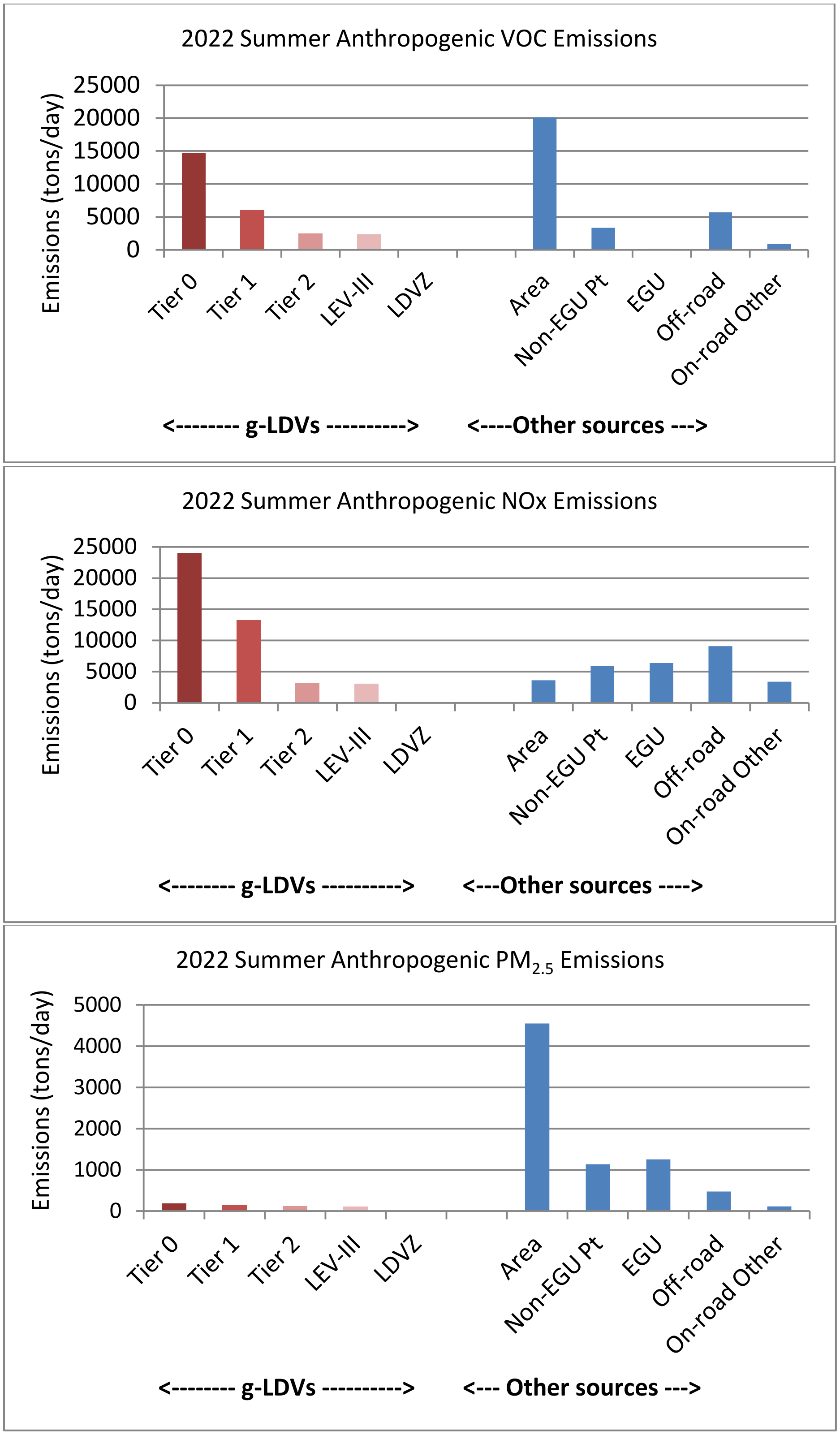


Figure 3-4. Comparison of g-LDV emissions in the continental US in 2022 with other emission source sectors.

3.2.2. Air Quality

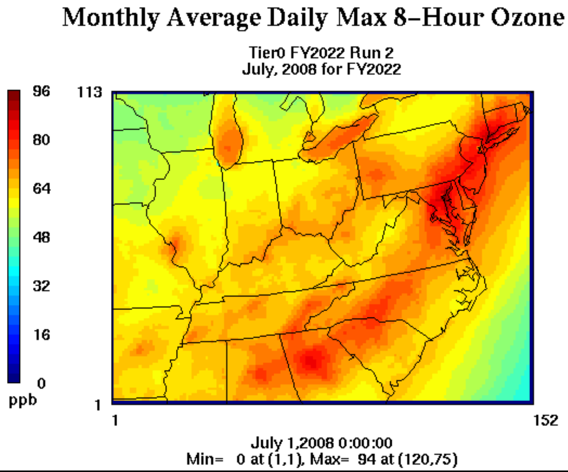
Figure 3-5 shows spatial plots of the daily maximum 8-hour ozone in the 12 km domain averaged over July 2022 on the left, and the incremental differences between successive standards on the right. In all scenarios, the 12 km domain peak was located near Washington DC. The highest monthly averaged 8-hour ozone is 94 ppb in the Tier 0 scenario. With Tier 1 controls, where NOx and VOC emissions were reduced 45% and 59%, respectively, the monthly averaged ozone dropped by up to 8.4 ppb, with a 6 ppb reduction in Washington DC. With additional strengthening of the standard from Tier 1 to Tier 2, the peak ozone in Washington DC was reduced further by 9 ppb following NOx and VOC reductions of 76% and 59%, respectively (the largest reduction across the domain is 10 ppb).

When considering the transition from Tier 2 to LEV-III, the 4% reduction in g-LDV NOx emissions and 7% reduction in VOCs by 2022 had a relatively very small impact on ozone. The more stringent LEV-III standards did not reduce the monthly average daily maximum 8-hour ozone more than 0.2 ppb anywhere inside the 12 km domain.

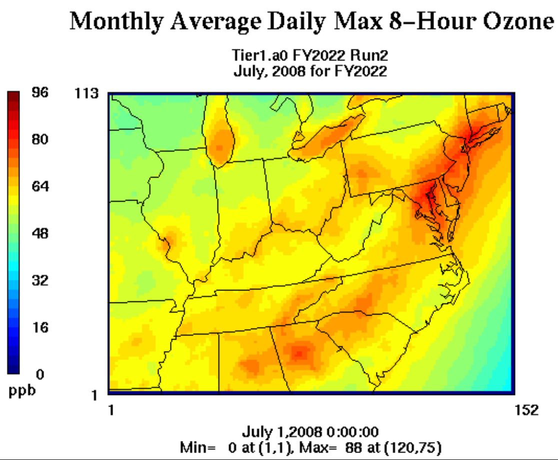
NOx and VOC emissions from g-LDVs were reduced 3046 TPD and 2341 TPD, respectively from the LEV-III to LDV zero-out scenario. These represent the final 13% and 16% of the Tier 0 NOx and VOC emissions, respectively, that had not been reduced in any of the other standards. In this scenario, monthly-averaged 8-hour ozone was reduced up to 4.0 ppb, with a 3 ppb reduction at Washington DC. These ozone benefits are much smaller than the ozone reductions found when applying either Tier 1 or Tier 2 standards over the prior standard. This provides an approximate upper bound (monthly-averaged daily maximum 8-hour ozone reduction of 4 ppb) on the total ozone benefit achievable with complete removal of g-LDV emissions.

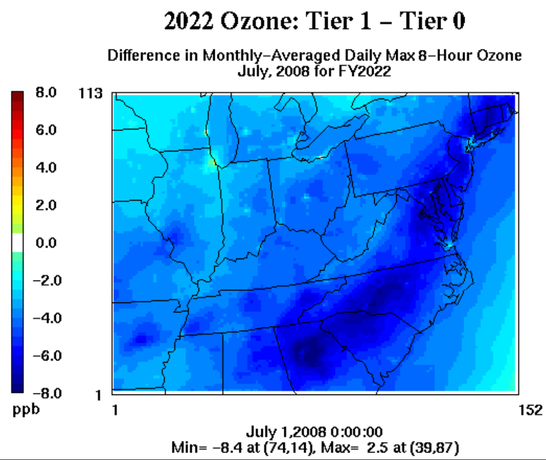
The ozone benefits followed a similar trend at the four urban sites. Table 3-11 lists the monthly averaged daily maximum 8-hour ozone and the ozone benefit from each successive emissions standard. Figure 3-6 shows the monthly averaged daily maximum 8-hour ozone in July 2022 by urban location for each of the five emissions scenarios. Of the four urban areas evaluated, Atlanta had the highest monthly-averaged daily maximum 8-hour ozone in the 2022 Tier 0 scenario and also had the largest incremental reduction in each successive control scenario. The Atlanta levels dropped 6.7 ppb with Tier 1 standards and another 8.7 ppb when applying Tier 2 controls. Detroit, where the 2022 Tier 0 monthly average ozone of 59.7 ppb was the lowest among the four areas, also showed the least ozone benefits. The LEV-III standard offers no more than a 0.1 ppb reduction from Tier 2 ozone at any of these four sites in 2022. If all g-LDVs released no emissions, ozone could not be reduced more than 1.4 to 3.5 ppb compared to the LEV-III scenario for each of the four cities. These reductions are less than half of the ozone benefits observed when comparing the differences between the Tier 1 and Tier 2 scenarios.

Tier 0

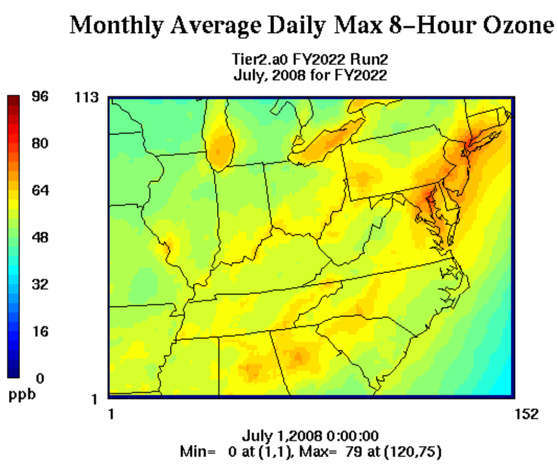


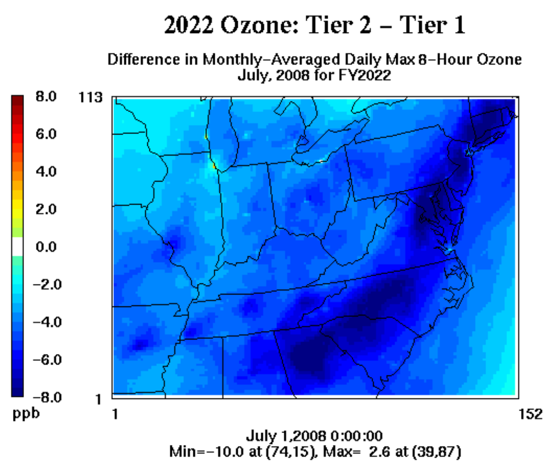
Tier 1





Tier 2





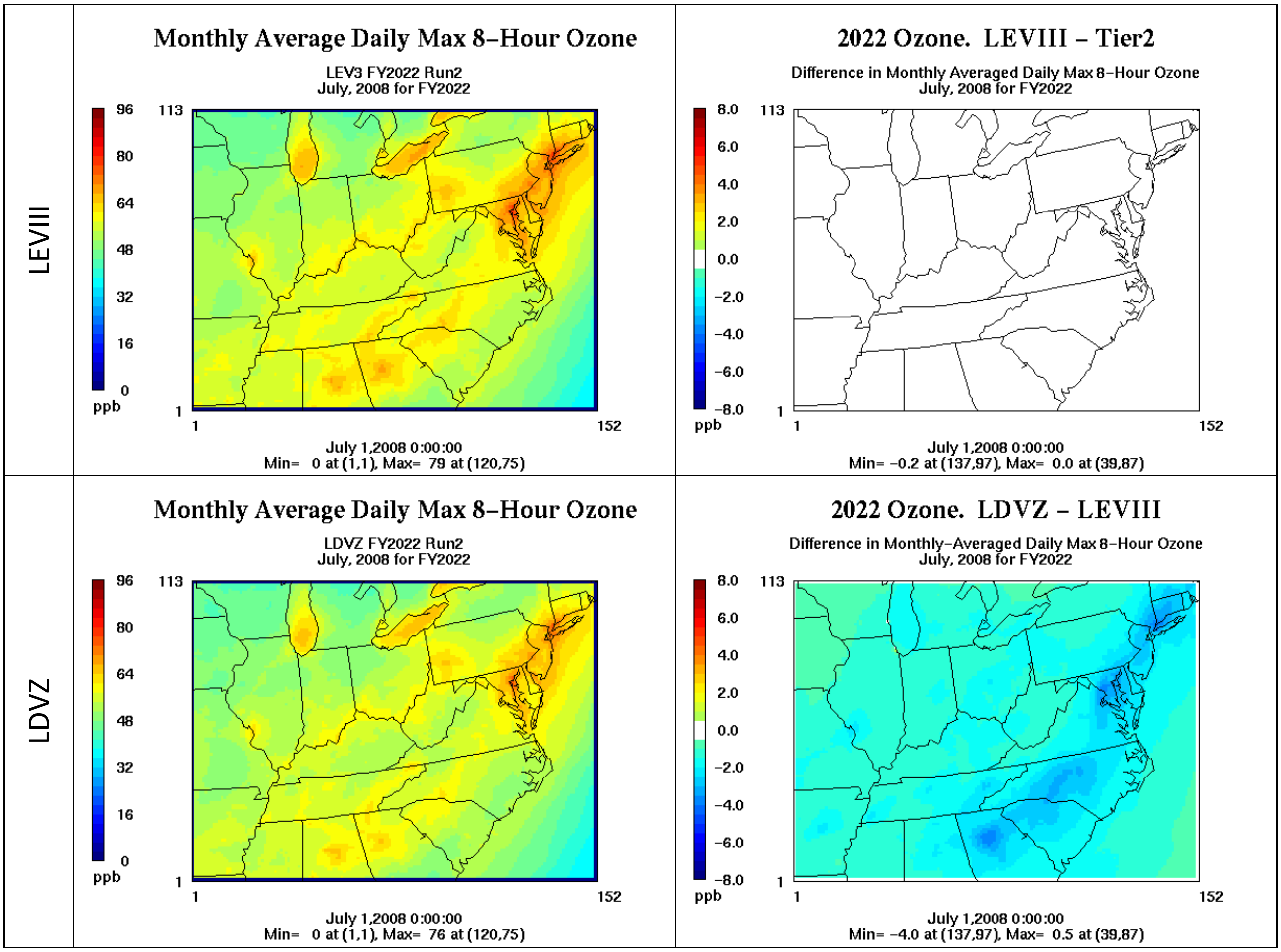


Figure 3-5. Spatial plots of monthly average daily maximum 8-hour ozone in July 2022 in the five scenarios (left) and the differences between successive scenarios (right).

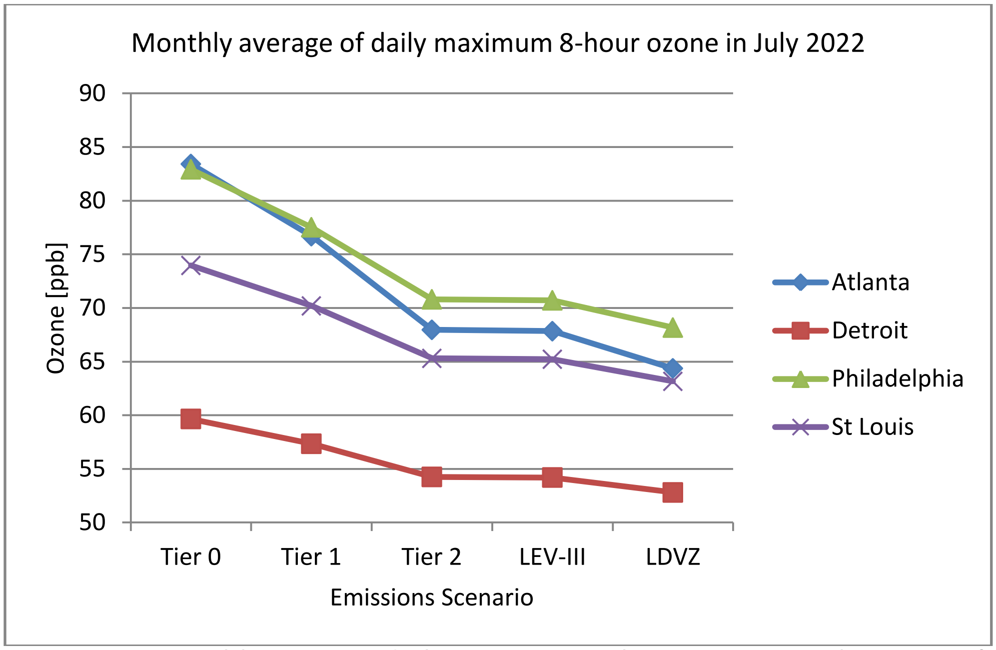


Figure 3-6. Monthly average daily maximum 8-hour ozone in July 2022 at four urban locations in five emission scenarios.

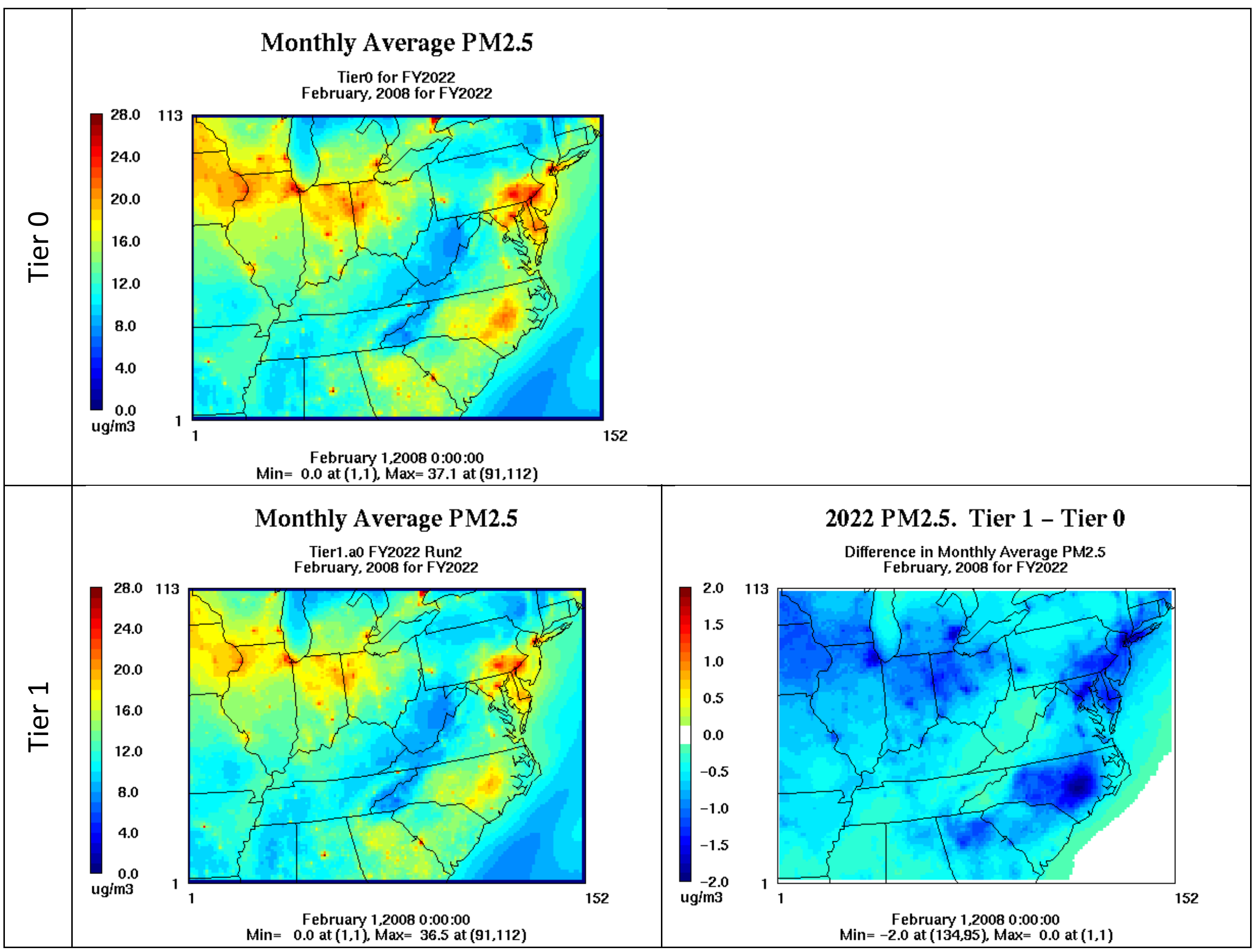
Table 3-11. Monthly average daily maximum 8-hour ozone in July 2022 and the change between successive scenarios at four urban locations.

Max (ppb)	Tier 0	Tier 1	Tier 2	LEV-III	LDVZ
Atlanta	83.4	76.7	68.0	67.8	64.4
Detroit	59.7	57.3	54.3	54.2	52.8
Philadelphia	82.9	77.5	70.8	70.7	68.2
St. Louis	74.0	70.2	65.3	65.2	63.2
Differences [ppb]		**Tier1 – Tier0**	**Tier 2 – Tier1**	**LEV-III – Tier2**	**LDVZ – LEV-III**
Atlanta		-6.7	-8.7	-0.1	-3.6
Detroit		-2.3	-3.1	-0.1	-1.5
Philadelphia		-5.4	-6.7	-0.1	-2.6
St. Louis		-3.8	-4.9	-0.1	-2.2

The spatial distribution of the 2022 Tier 0 monthly average $PM_{2.5}$ concentration in February in the 12 km domain is shown in the top panel of Figure 3-7. The higher $PM_{2.5}$ concentrations could be found over a widespread area near southeastern Pennsylvania, eastern North Carolina, and the northern Ohio Valley; the 12 km domain peak surface concentration is 37 $\mu g/m^3$.

The additional panels in the figure show monthly average $PM_{2.5}$ concentrations from the four other scenarios on the left and differences between successive control scenarios on the right. The Tier 1 ambient $PM_{2.5}$ was lower by up to 2.0 μg/compared to the Tier 0 scenario due to the reductions in g-LDV NOx, VOC and $PM_{2.5}$ emissions. The $PM_{2.5}$ benefits in transitioning from the Tier 1 to Tier 2 scenario are similar (up to 2.1 μg/m^3). The transition to LEV-III results in relatively very small $PM_{2.5}$ benefits over Tier 2; the largest reduction was only 0.1 μg/m^3. If there were no emissions from g-LDVs, the monthly average ambient $PM_{2.5}$ could be reduced by up to 1.9 μg/m^3 over LEV-III concentrations, with the largest reductions occurring in urban areas.

Table 3-12 lists the monthly $PM_{2.5}$ concentrations at four urban locations in February 2022; these are also illustrated in the line plot in Figure 3-8. Of the four urban areas evaluated, Philadelphia had the highest February Tier 0 monthly average $PM_{2.5}$ concentration at 24.7 μg/m^3 while Atlanta was lowest at 18.6 μg/m^3. Both the Tier 1 and Tier 2 controls added monthly averaged $PM_{2.5}$ benefits between 1 and 2 μg/m^3 at all four urban sites while LEV-III offered no more than a 0.1 μg/m^3 benefit. The LDVZ scenario resulted in a reduction of the monthly average $PM_{2.5}$ by an additional 0.9 to 1.5 μg/m^3.



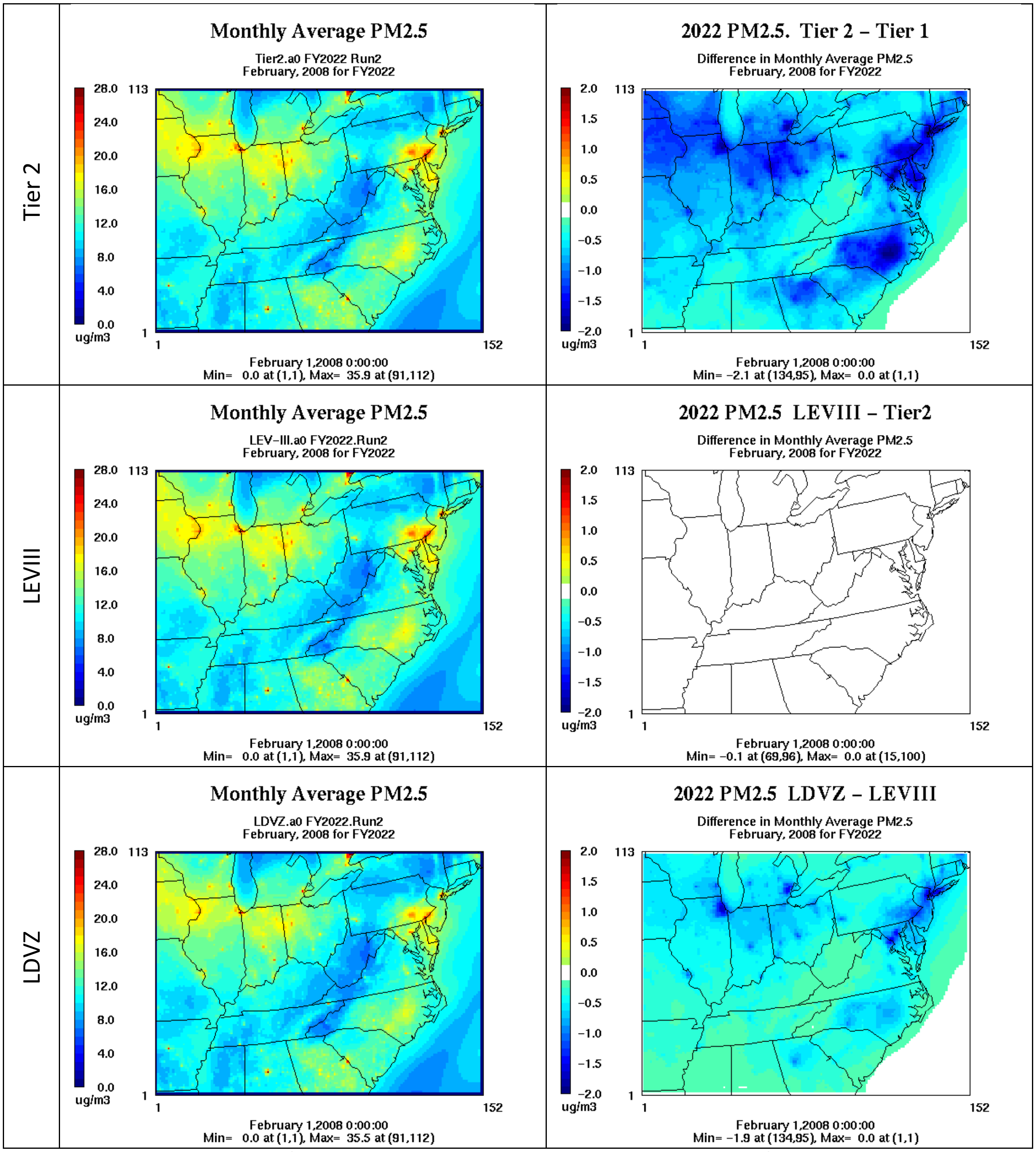


Figure 3-7. Spatial plots of monthly average $PM_{2.5}$ in February 2022 in five emission scenarios (left) and the differences between successive scenarios (right).

Table 3-12. Monthly average $PM_{2.5}$ in February 2022 and the changes between successive scenarios at four urban locations.

Max [ppb]	Tier 0	Tier 1	Tier 2	LEV-III	LDVZ
Atlanta	18.6	17.3	16.0	16.0	15.1
Detroit	22.1	20.4	18.5	18.4	16.9
Philadelphia	24.7	23.1	21.2	21.2	19.8
St. Louis	21.7	20.4	19.2	19.1	18.2
Differences [ppb]		**Tier1 – Tier0**	**Tier 2 – Tier1**	**LEV-III – Tier2**	**LDVZ – LEV-III**
Atlanta		-1.3	-1.3	0.0	-0.9
Detroit		-1.7	-1.9	-0.1	-1.5
Philadelphia		-1.6	-1.9	-0.1	-1.4
St. Louis		-1.2	-1.3	0.0	-0.9

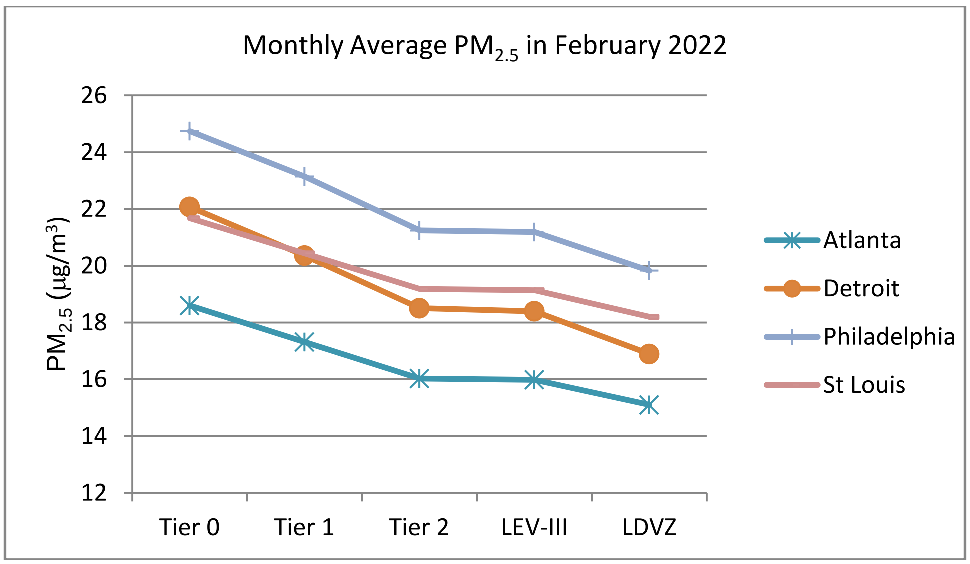
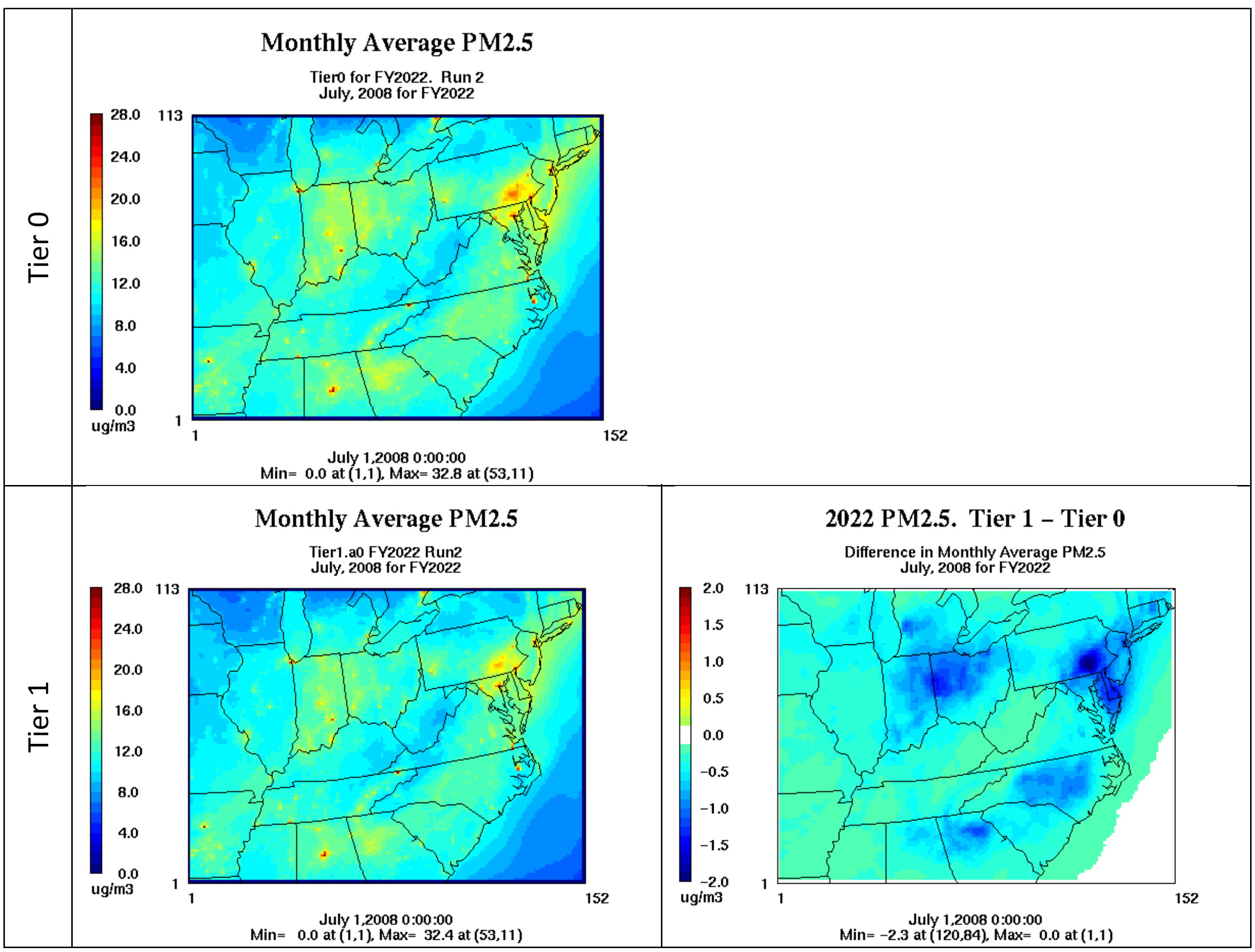


Figure 3-8. Monthly average $PM_{2.5}$ in February 2022 at four urban locations in five emission scenarios.

The left panels of Figure 3-9 show spatial plots of the July 2022 monthly averaged $PM_{2.5}$ for each of the five scenarios with the least to the most stringent g-LDV standards from top to bottom; the right panels show differences between successive scenarios. The modeled Tier 0 monthly average $PM_{2.5}$ concentration was generally lower in July than in February. Southeastern Pennsylvania continued to experience high $PM_{2.5}$ concentrations. The peak modeled concentration in July was 33 $\mu g/m^3$.

Although the $PM_{2.5}$ emission reductions were smaller in July than in February, the maximum reduction of 2.3 μg/m^3 after Tier 1 controls was higher than in February. The Tier 2 controls added up to another 2.1 μg/m^3 reduction in $PM_{2.5}$ concentrations. The LEV-III scenario offered relatively very small (< 0.1 μg/m^3) benefits to the monthly $PM_{2.5}$ in July. The maximum monthly average $PM_{2.5}$ reduction after removing all g-LDV emissions is approximately 0.8 μg/m^3 compared to the LEV-III scenario.

Table 3-13 lists the monthly average $PM_{2.5}$ concentrations at the four urban sites for the five scenarios in July 2022. Figure 3-10 illustrates the differences in $PM_{2.5}$ between the scenarios in a line chart. The incremental $PM_{2.5}$ benefits at the four urban sites, as measured by comparing the differences between successive emissions standard scenarios, were always smaller in July than in February. All incremental benefits were less than 1.0 μg/m^3. Philadelphia had the highest modeled July average $PM_{2.5}$ concentration at 17.0 μg/m^3 and showed the largest incremental reduction when applying Tier 1 standards (0.9 μg/m^3 reduction), Tier 2 standards (another 0.9 μg/m^3 reduction), and when removing g-LDV emissions completely (another 0.4 μg/m^3 reduction). Applying additional LEV-III controls over Tier 2 had a relatively very small impact on reducing $PM_{2.5}$ concentrations ($\leq$0.1 μg/m^3) in each of the four cities.



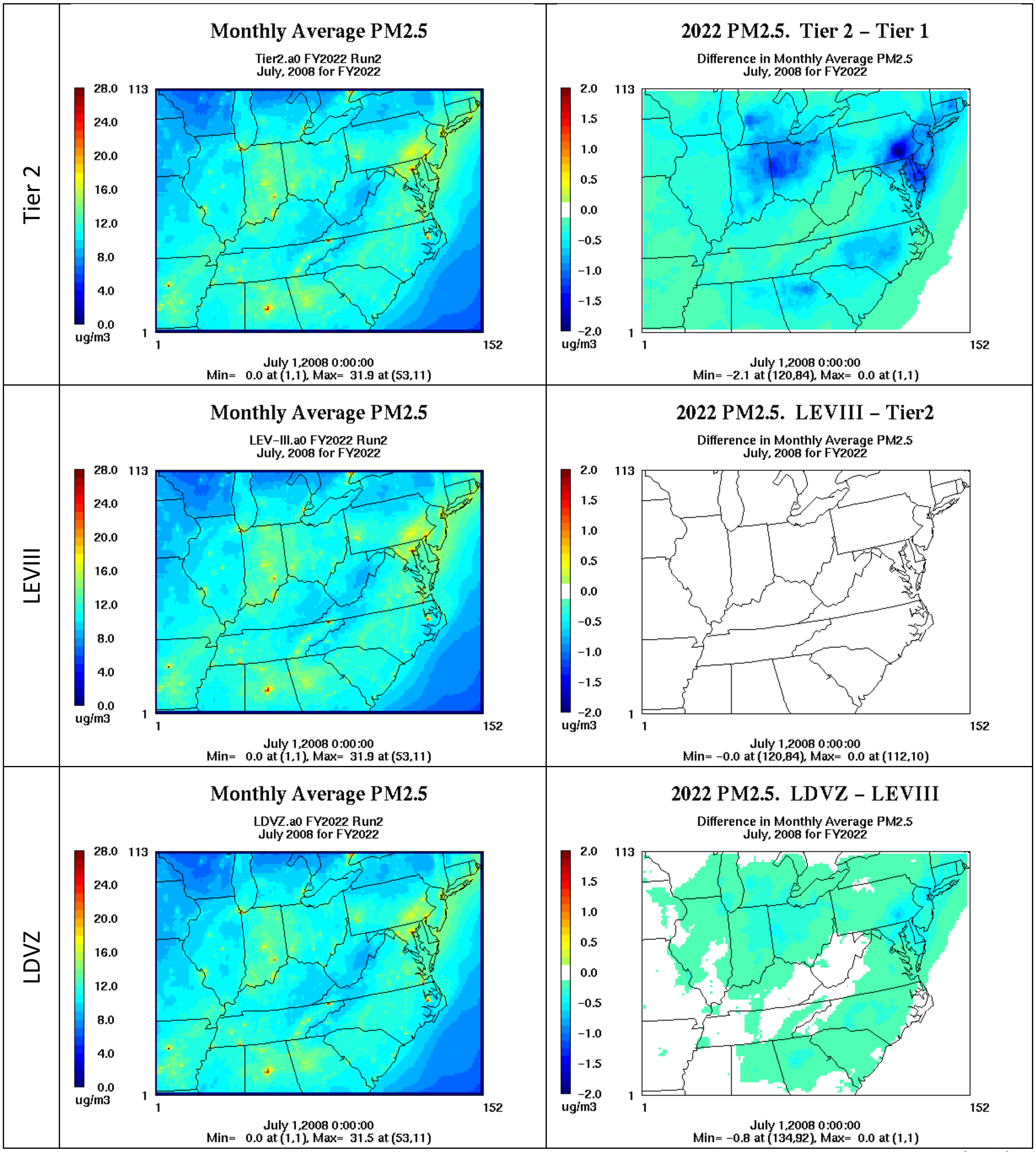


Figure 3-9. Spatial plots of monthly average $PM_{2.5}$ in July 2022 in five emission scenarios (left) and the differences between successive scenarios.

Table 3-13. Monthly average $PM_{2.5}$ in July 2022 and the changes between successive scenarios at four urban locations.

Max [ppb]	Tier 0	Tier 1	Tier 2	LEV-III	LDVZ
Atlanta	16.7	16.0	15.5	15.4	15.1
Detroit	14.5	13.9	13.4	13.4	13.1
Philadelphia	17.0	16.1	15.2	15.2	14.8
St. Louis	16.4	15.9	15.5	15.5	15.2
Differences [ppb]		**Tier1 – Tier0**	**Tier 2 – Tier1**	**LEV-III – Tier2**	**LDVZ – LEV-III**
Atlanta		-0.7	-0.6	0.0	-0.4
Detroit		-0.5	-0.5	0.0	-0.3
Philadelphia		-0.9	-0.9	0.0	-0.4
St. Louis		-0.4	-0.4	0.0	-0.3

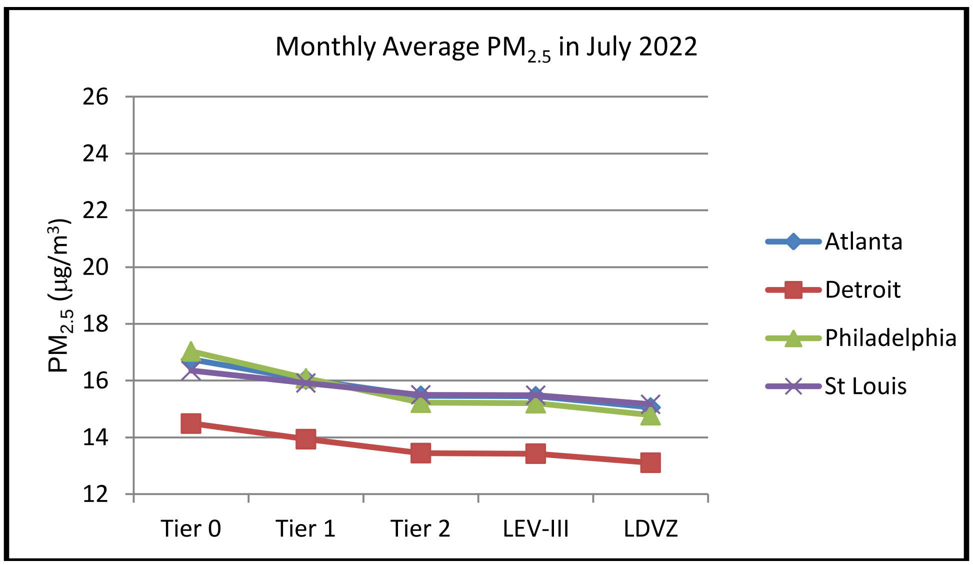


Figure 3-10. Monthly average $PM_{2.5}$ in July 2022 at four urban locations in five emission scenarios.

4. SUMMARY

MOVES and CAMx were applied to model nationwide g-LDV Tier 0 scenarios in February and July in 2008 and 2022. The Tier 0 standards, which were first implemented in 1981, were assumed to be the only standards in place in these scenarios. The results from the current work and a prior study (CRC A-76-1) were examined together to examine ozone and $PM_{2.5}$ differences between the Tier 0 and Tier 2 standards implementation in 2008 and to evaluate these differences in five g-LDV emission scenarios in 2022 from least to most stringent – Tier 0, Tier 1, Tier 2, LEV-III and LDVZ (the zero-out LDV scenario). The Tier 1 scenario assumed that the standards first applied to 1994 vehicles were still in place. Tier 2 applied the current g-LDV standards. LEV-III assumed that the stricter California standards currently in place would apply to the nationwide fleet of g-LDVs; the effects of gasoline sulfur reductions were not modeled. The LDVZ scenario assumed that there were no g-LDV emissions nationwide.

If emissions standards were no more stringent than Tier 0 in 2008, g-LDVs would have accounted for approximately 33% and 30% of all anthropogenic NOx and VOC emissions, respectively, on an average summer/winter day in the continental US. The Tier 2 standard reduced the g-LDV NOx and VOC emissions almost in half by 2008, helping reduce the July monthly averaged daily maximum 8-hour ozone by up to 6.0 ppb. Among the four urban sites evaluated (Atlanta, Detroit, Philadelphia, and St. Louis), the summertime ozone reduction was largest in Atlanta, the city with the highest monthly averaged daily maximum 8-hour ozone, where the average daily peak was reduced by 4.3 ppb (from 87.5 ppb) between the 2008 Tier 0 and Tier 2 scenarios.

The 2008 Tier 0 scenario g-LDVs accounted for only 3.5% of the total anthropogenic $PM_{2.5}$ emissions in the winter and 1.9% in the summer. The phasing in of progressively more stringent NOx, VOC and primary $PM_{2.5}$ emissions standards up to and including the Tier 2 controls contributed to monthly average $PM_{2.5}$ concentrations that were up to 1.9 $\mu g/m^3$ lower in February and up to 2 $\mu g/m^3$ lower in July in the Tier 2 scenario compared to concentrations of approximately 40 $\mu g/m^3$ modeled in the Tier 0 case. For the four cities evaluated, Philadelphia had the highest monthly averaged $PM_{2.5}$ concentration (29.0 $\mu g/m^3$) in 2008 in the Tier 0 scenario and the largest reduction (1.6 $\mu g/m^3$) when applying additional controls through Tier 2.

If emissions standards were no more stringent than Tier 0 in 2022, g-LDVs would have accounted for almost half of all anthropogenic NOx emissions. The Tier 0 and Tier 1 g-LDVs emitted more NOx than any other anthropogenic emission group in the US; additional controls due to Tier 2 resulted in g-LDVs becoming the smallest US source sector for NOx emissions, reducing its contribution to only 10% of all anthropogenic NOx. Also, g-LDVs in the 2022 Tier 0 scenario were the second largest source of VOCs behind area sources, accounting for about a third of all anthropogenic VOCs emitted. With additional controls through Tier 2, the g-LDV contribution in 2022 decreases to only 8% of all anthropogenic VOC emissions, emitting less than area sources, non-EGU point sources and off-road sources.

Wintertime nationwide VOC and NOx emissions in 2022 were reduced by 46% and 43%, respectively, from the Tier 0 to Tier 1 scenarios and by 64% and 75%, respectively, from the Tier 1 to Tier 2 scenarios. In contrast, these emissions dropped by only 4-6% from the Tier 2 to LEV-III scenarios. Similarly, summertime VOC and NOx emissions in 2022 decreased by 45-59% from Tier 0 to Tier 1 and by 59-76% from Tier 1 to Tier 2 but only by 4-7% in strengthening the standard from Tier 2 to LEV-III. At all four urban areas studied, VOC and NOx emissions decreased by more than 40% (and in some instances by over 50%) from the Tier 0 to Tier 1 scenarios and again from Tier 1 to Tier 2, but less than 5% from the Tier 2 to LEV-III scenarios.

$PM_{2.5}$ emissions from g-LDVs showed a similar trend, i.e., much smaller reductions with the LEV-III standard in 2022 compared to incremental reductions obtained with Tier 1 and Tier 2 (5-8% nationwide for LEV-III versus 26-33% for the Tier 1 change and 17-25% for the Tier 2 change). In addition, g-LDV $PM_{2.5}$ emissions were relatively low compared to all other emission sources in all 2022 emission scenarios, ranging from 2.5% (Tier 0) to 1.5% (Tier 2) of all anthropogenic emissions in the summer, and 4.5% (Tier 0) to 2.3% (Tier 2) of winter anthropogenic emissions.

Modeled ozone and $PM_{2.5}$ benefits by 2022 due to successive g-LDV standards are consistent with the differences in the emissions of the precursors discussed above. The application of Tier 1 standards reduced the monthly averaged summertime daily maximum 8-hour ozone up to 8.4 ppb. When Tier 2 standards were applied, up to 10.0 ppb reductions in ozone were modeled from Tier 1 ozone levels. Atlanta, which had the highest 2022 Tier 0 ozone among the four urban sites evaluated (83.4 ppb), also benefited the most among these areas from both the Tier 1 and Tier 2 controls; the two standards lowered ozone by an additional 6.7 and 8.7 ppb, respectively.

Ozone benefits from further reductions in g-LDV emissions are modeled to be relatively very small in 2022. If the California LEV-III controls were applied on a nationwide basis, the ozone benefits at the four selected urban sites would improve no more than 0.1 ppb from Tier 2 concentrations in the summer. If all g-LDVs were emission-free in 2022, ozone could improve up to 1.5 ppb in Detroit to 3.6 ppb in Atlanta from the Tier 2 levels – less than half of the benefits in transitioning from Tier 1 to Tier2. Actual benefits may be lower because emissions increases due to the increase in electricity generation to replace the g-LDV fleet are not considered here. The large reductions in NOx and VOC emissions from g-LDVs between Tier 0 and Tier 2 helped lower ozone by the levels discussed earlier. As g-LDVs become relatively smaller sources of NOx and VOCs by 2022 compared to other source sectors, additional reductions in g-LDV emissions result in lower ozone benefits.

Similarly, modeling results show that controls on g-LDVs have limited benefits by 2022 for reducing $PM_{2.5}$ concentrations beyond the Tier 2 levels in the eastern US. The maximum reduction in $PM_{2.5}$ concentrations by 2022 in transitioning from the Tier 2 to LEV-III standards is less than 0.1 $\mu g/m^3$ in summer and winter and up to 1.9 $\mu g/m^3$ in winter and 0.8 $\mu g/m^3$ in summer after complete removal of g-LDV emissions.

A key source of uncertainty in this study is introduced by the incomplete phase-in of the LEV-III standard by 2022, the basis year for comparing emission standards. Some additional improvements in ozone and PM are expected beyond 2022 as the LEV-III standard fully phases in and more LEV-III vehicles enter the fleet. Also, NOx, VOC and SO_2 reductions due to gasoline sulfur reductions that were not considered here could result in additional improvements in air quality.

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