Draft Final Report

2010 OZONE PROJECTIONS FOR THE 2010 BASE CASE AND 2010 SENSITIVITY TESTS AND 2010 OZONE SOURCE APPORTIONMENT MODELING FOR THE DENVER 8-HOUR OZONE STATE IMPLEMENTATION PLAN

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EXECUTIVE SUMMARY

Due to violations of the 0.08 parts per million (ppm) 8-hour ozone National Ambient Air Quality Standard (NAAQS) based on 2005-2007 air quality data, in November 2007 the Denver Metropolitan Area (DMA) reverted to an 8-hour ozone nonattainment area. This requires the DMA to develop an 8-hour ozone State Implementation Plan (SIP) that demonstrates the area will achieve the 0.08 ppm 8-hour ozone NAAQS by 2010. The Denver Regional Air Quality Council (RAQC), in consultation with the Colorado Department of Health and Environment (CDPHE) Air Pollution Control Division (APCD), contracted with ENVIRON International Corporation and their subcontractor Alpine Geophysics, LLC to develop the photochemical modeling databases necessary to demonstrate that the DMA will achieve the 0.08 ppm 8-hour ozone NAAQS by 2010.

OVERVIEW OF APPROACH

The Comprehensive Air-quality Model with extensions (CAMx; www.camx.com) was set up for a June-July 2006 episode on a 36/12/4 km grid with the 4 km domain focused on Colorado. Meteorological inputs were prepared using the MM5 meteorological model whose results and evaluation are discussed by McNally and co-workers (2008). An initial emissions inventory was prepared using the SMOKE emissions modeling system and a preliminary 2006 base case was performed. A preliminary model performance evaluation was conducted and diagnostic sensitivity tests performed to identify an optimal model configuration for simulating ozone formation in the DMA (Morris et al., 2008b). A revised final CAMx 2006 base case (Run 17) simulation was performed and a comprehensive model performance evaluation was conducted (Morris et al., 2008c). Although there were some model performance issues on some of the modeling days during the June-July 2006 episode, usually due to an ozone underestimation bias, on a vast majority of the modeling days the ozone model performance achieved EPA's model performance goals that along with the other model performance metrics indicated that the model was simulating the observed ozone sufficiently well for use in making ozone projections. Furthermore, on most days the model reproduced the observed VOC/NOx ratios in Denver quite well suggesting that the model is simulating the same chemical regimes as observed as well.

2010 BASE CASE OZONE PROJECTIONS

The procedures given in EPA's 8-hour ozone modeling guidance were used to project current year 8-hour ozone Design Values (DVC) to obtain projected future year 2010 8-hour ozone Design Values (DVF) at each of the DMA monitoring sites (EPA, 2007). These procedures use the 2006 and 2010 base case modeling results in a relative fashion whereby modeled relative response factors (RRFs) are used to scale the current year 8-hour ozone Design Value (DVC) to obtain the projected future year 8-hour ozone Design Value (DVF):

$$DVF = DVC \times RRF$$

For the Denver 2010 ozone projections, with one exception, the DVCs were based on the 8-hour ozone Design Values from the 2005-2007 period (i.e., the three year average of the fourth

highest daily maximum 8-hour ozone concentration at each monitor). The exception to this was for the Fort Collins West (FTCW) monitor that started monitoring in 2006 so that the two year average of the fourth highest daily maximum 8-hour ozone concentrations was used from 2006-2007 for FTCW.

Table ES-1 summarizes the projected 8-hour ozone Design Values (DVF) at the DMA monitoring sites for the 2010 base case simulation using the CAMx 2006 and 2010 base case modeling results and EPA recommended default ozone projection procedures described above. The maximum projected 8-hour ozone Design Value is 84 ppb and occurs at both the Rocky Flats North (RFNO) and Fort Collins West (FCTW) monitoring sites (see column 5 in Table ES-1). As this value is 84 ppb or lower, then the 2010 base case modeling results pass the modeled attainment demonstration test. However, because the maximum projected 8-hour ozone Design Values lie between 82 and 87 ppb, then a WOE analysis is required. Although the EPA 8-hour ozone projection procedure is to truncate the final projected DVF for comparisons with the NAAQS, in column 6 of Table ES-1 we present the DVFs to the nearest tenth of a ppb before truncation. In this case we see that the projected 2010 base case DVFs at RFNO and FTCW are both 84.9 ppb.

Also shown in Table ES-1 are the RRFs and the cut-off thresholds used in selecting days and number of days used in calculating the RRF. The EPA desire to use at least 10 modeled days is satisfied using the Denver June-July 2006 modeling period. In order to achieve that many modeled days, the cut-off threshold had to be reduced from 74 ppb to 78 ppb depending on the monitor, with the RFNO and FTCW monitors using a 78 and 76 ppb thresholds, respectively.

The level of ozone reductions in the projected Design Values appears to be greater the further away from central Denver the monitor resides. In fact, ozone is estimated to increase very slightly at the monitors in or immediately downwind of the urban core. This is due to the reductions in on-road mobile sources NOx emissions that increase ozone in the urban core. The ozone increases are due to less ozone titration due to reduction in the primary emitted NOx emissions and/or less inhibition effect that high NOx concentrations have on ozone formation. As one moves away from the Denver urban core, the ozone increases between 2006 and 2010 turn into no change and then to ozone decreases. The distance from the Denver urban core when the ozone increases change to ozone decreases varies by day due to changes in emissions (e.g., weekday versus weekend day) and changes in meteorology. The RFNO monitor lies near the modeled ozone increase-to-decrease cross over distance, which explains why the model projected 2010 Design Value is relative insensitive to the changes in emissions from 2006 to 2010 at this site (85.0 to 84.9 ppb, a 0.1 ppb reduction); of the 10 days used to construct the RRF for RFNO there are some days of ozone increases and some with ozone decreases. At the FTCW monitoring site, on the other hand, the model is more responsive (1.1 ppb ozone reduction) as it is an area where the modeled ozone changes either stay the same or are reduced between 2006 and 2010.

Figure ES-1 display the results of EPA's unmonitored area analysis for the 2010 base case. DVCs in excess of 80 ppb are estimated to the south, west and northwest of Denver stretching to Fort Collins and then west of Fort Collins (Figure ES-1, left). In fact, the unmonitored area procedure estimates that there are current-year DVCs in excess of the 85 ppb NAAQS occurring in 12 grid cells to the west of the Fort Collins monitoring sites. The projected DVFs for the 2010 base case (Figure ES-1, right) have greatly reduced the spatial extent of the DVFs in excess of 80 ppb occurring to the south, west and northwest of Denver and the 12 cells with DVCs exceeding

the 85 ppb NAAQS have been reduced by half to 6 grid cells in the 2010 base case emissions scenario. EPA stresses that the unmonitored area analysis is much more uncertain than the modeled attainment test at the monitors. And whereas additional emissions controls would likely be needed to eliminate continued violations at the monitor, such actions may not be appropriate for the unmonitored area analysis.

Table ES-1. Current-year (DVC) and projected future-year (DVF) 8-hour ozone Design Values using the CAMx 2006 and 2010 base case modeling results.

			2005-07	2010 Base Case				
Site ID	Monitor Name	County	DVC	DVF	DVF	RRF	Cutoff	#days
80013001	Welby	Adams	70.0	70	70.2	1.0042	77.0	11
80050002	Highland	Arapahoe	78.0	77	77.3	0.9916	78.0	14
80130011	S. Boulder Creek	Boulder	81.0	80	80.8	0.9976	78.0	10
80310002	Denver - CAMP	Denver	56.0	56	56.0	1.0017	78.0	10
80310014	Carriage	Denver	74.0	74	74.1	1.0022	78.0	10
80350004	Chatfield State Park	Douglas	84.0	83	83.4	0.9934	78.0	11
80410013	USAF Academy	El Paso	73.0	72	72.0	0.9873	75.0	10
80410016	Manitou Springs	El Paso	74.0	73	73.7	0.9966	74.0	10
80590002	Arvada	Jefferson	79.0	79	79.2	1.0026	78.0	10
80590005	Welch	Jefferson	75.0	75	75.0	1.0004	78.0	10
80590006	Rocky Flats North	Jefferson	85.0	84	84.9	0.9994	78.0	10
80590011	NREL	Jefferson	82.0	82	82.3	1.0039	78.0	11
80690011	Fort Collins - West	Larimer	86.0	84	84.9	0.9874	76.0	10
80691004	Fort Collins	Larimer	74.0	73	73.0	0.9878	76.0	12
81230009	Greeley - Weld Tower	Weld	78.0	77	77.7	0.9964	75.0	10
GTH161	Gunnison	Gunnison	68.0	67	67.8	0.9984	74.0	10
ROM206	Larimer	Larimer	76.0	75	75.2	0.9903	77.0	10
ROM406	Larimer	Larimer	76.0	75	75.2	0.9903	77.0	10

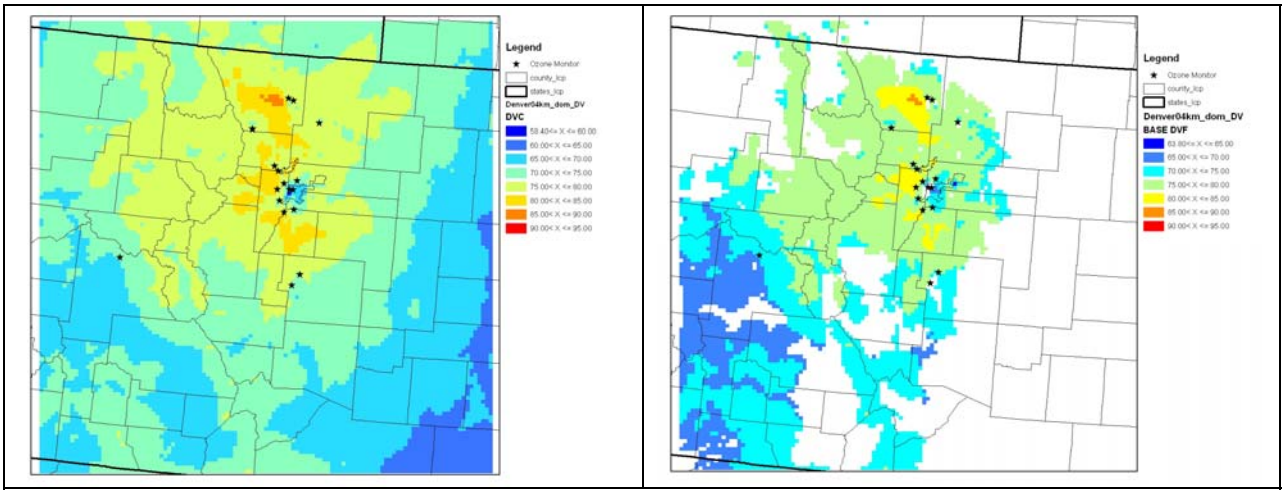

Figure ES-1. Current-year interpolated 8-hour ozone Design Values (DVC; left) and projected future-year 8-hour ozone Design Values (DVF; right) for the 2010 base case simulation.

2010 SENSITIVITY TEST RESULTS

Sixteen (16) 2010 emissions reductions sensitivity tests were conducted with the CAMx modeling system. Most of these emission reduction sensitivity tests reduced VOC and/or NOx emissions from a specific source category either just within the Denver nonattainment area (NAA) or within the entire state of Colorado. Ozone projections were made at each of the monitoring sites for each of the 2010 sensitivity tests. We also performed the unmonitored area analysis for each sensitivity test to better understand the spatial extent of any ozone benefits or adverse effects. All sensitivity tests modified emissions from the 2010 base case emissions scenario.

Table ES-2 displays the results of the 2010 sensitivity tests in terms of VOC, NOx and CO emission reductions from the 2010 base case, changes in projected 8-hour ozone Design Values at the key RFNO and FTCW monitoring sites, maximum difference in 2010 8-hour ozone Design Values anywhere in the DMA and maximum difference in daily maximum 8-hour ozone concentrations anywhere in the DMA and on any of the modeling days.

Mobile Source Emissions: The first three sensitivity tests examined the sensitivity of 2010 ozone projections to on-road mobile source emissions. Reducing on-road mobile sources VOC emissions 20% in the DMA reduces the projected DVFs at RFNO and FTCW by 0.2 and 0.1 ppb, respectively. The 7 psi RVP gasoline in on-road mobile source gasoline vehicles reduces the DVFs by 0.1 ppb at both monitors. And the zero percent ethanol penetration scenario in the on-road and non-road mobile source gasoline engines increases the DVF at RFNO by 0.1 ppb, and has no effect at FTCW.

Oil and Gas VOC Emissions: VOC emissions from O&G sources in the NAA were reduced by 20% (b1-sens04) and 40% (b1-sens04d) in two of the 2010 emissions sensitivity tests. The O&G VOC emission reductions had little effect at the RFNO monitor, but reduced the projected DVF at the FTCW monitor by 0.1 and 0.2 ppb, respectively. The spatial maps of differences in the DVFs show a large area of ozone benefits due to the O&G VOC reductions centered on the O&G production area in Weld County. The RFNO monitor is right at the edge of this benefits area. Note that the Denver EAC SIP modeling of the June-July 2002 episode saw more transport from the Weld County O&G production area down to the RFNO monitor, so these results are partly an artifact of the meteorological conditions of the June-July 2006 modeling period. The O&G VOC emissions clearly have an effect on ozone formation in the Fort Collins area. In fact, the 6 grid cells west of Fort Collins that are projected to still violate the 0.08 ppm 8-hour ozone NAAQS in the 2010 base case (Figure ES-1, right) are reduced to 4 and 3 grid cells in the 20% and 40% O&G VOC emission reduction sensitivity scenarios. Clearly VOC emission reductions from O&G sources in Weld County would benefit ozone attainment in the Fort Collins area and likely elsewhere in the Denver NAA under other meteorological conditions.

Combined VOC & NOx Sensitivity Simulations: Sensitivity simulations b1-sens04b and b1-sens04c looked at combined VOC and NOx emissions reductions from area, non-road point and O&G emissions in the NAA. Although both simulations reduced VOC emissions by 20%, NOx emissions were reduced by 20% in sens04b and by 30% in sens04c allowing us to isolate the effects of the NOx controls. Several of the other sensitivity tests also allow us to isolate the effects of the VOC and NOx controls in these two sensitivity tests for each source category. The b1-sens04b 20% VOC/NOx emissions reduction scenario reduces the DVF at RFNO by 0.5 ppb. This is due to reductions in the RFNO ozone DVF of approximately 0.1 ppb from area source

VOC (b1-sens07), 0.1 ppb from O&G VOC (b1-sens04), 0.2 ppb from non-road VOC (b1-sens06) and 0.2 ppb from point and O&G source NOx (b1-sens05). An additional 0.2 ppb ozone reduction in the RFNO DVF is obtained when the NOx reduction is increased from 20% to 30%. At the FTCW monitor, the effects of the NOx emission reductions alone are even greater. The 20% VOC/NOx reduction gives a 1.1 ppb reduction in the ozone DVF at the FTCW monitor; increasing the NOx reduction by another 10% increases the ozone reduction at the FTCW monitor by another 0.5 ppb (total 1.6 ppb reduction). This suggests that a majority of the ozone benefits at FTCW are due to the NOx emission reductions. Although as noted above, VOC emission reductions from O&G sources in the NAA are also beneficial for reducing ozone in the Forth Collins area. With the exception of a couple grid cells of isolated ozone increases, the effects of the combined VOC/NOx controls are wide-spread reductions in ozone throughout the DMA.

State-Wide Sensitivity: The state-wide sensitivity tests produce nearly the same ozone benefits at DMA monitors as the controls in the NAA alone. This is seen most clearly by comparing b1-sens05 with b1-sens08 that examine a 20% reduction in NOx emissions from point and O&G sources in, respectively, the NAA and Colorado. They produce the same ozone reduction at RFNO (0.2 ppb) and the state-wide reduction produces slightly more ozone reduction at FTCW (0.6 ppb) than the NAA controls alone (0.5 ppb). At this time we have only evaluated the effects of the state-wide emission reduction sensitivity tests within the DMA. There are likely more ozone benefits due to the Colorado state-wide emission reductions outside of the DMA that may be important given the new lower (March 2008) ozone NAAQS.

Bark Beetle Sensitivity: The effects of accounting for the Bark Beetle infestation on biogenic emissions have small effects on the DVFs in the DMA (0.1 ppb reduction). Thus, the 2010 Denver ozone projections are not affected by the Bark Beetle infestation.

The 2010 emissions sensitivity tests show higher ozone sensitivity to reducing NOx emissions than reducing VOC emissions. Although there are small areas of ozone increases due to NOx emissions reductions in the Denver urban core, and at the locations (grid cells) of some point sources, the overall ozone reduction benefits of the NOx controls outweigh the ozone increases. Furthermore, the locations of the highest ozone increases due to NOx reductions are monitoring sites with low ozone concentrations. Although the ozone benefits of VOC reductions do not seem as great as those from NOx reductions, VOC emissions reductions do reduce ozone somewhat and do not exhibit any ozone increases as seen with the NOx emissions reductions. In particular, the VOC emissions reductions from O&G sources have ozone benefits in the Fort Collins area and particular the key FTCW ozone monitor.

Table ES-2. Results of the Denver 2010 emission sensitivity tests.

Test	Description	Emissions (TPD)			% Anthro (%)			DV Ozone (PPB)		Grid DV Ozone(ppb)*		Grid Diff. Ozone (ppb)**	
		CO	VOC	NOx	CO	VOC	NOx	RFNO	FTCW	Max.	Min.	Max.	Min.
2006.a3	Current Year 8-Hour Ozone Design Value							85	86				
b1	2010 Base Case	-386.0	-42.2	-50.1	-10.2%	-5.3%	-5.6%	84.9	84.9				
b1-sns01	20% VOC On-Road NAA	0.0	-22.8	0.0	0.0%	-3.0%	0.0%	-0.2	-0.1	0.1	-0.2	0.1	-0.6
b1-sns02	Evap VOC On-Road in NAA (7 psi RVP)	-46.9	-9.8	-0.3	-1.4%	-1.3%	0.0%	-0.1	-0.1	0.1	-0.1	-0.2	-0.3
b1-sns03	0% Ethanol in NAA	323.3	-3.8	-2.0	9.5%	-0.5%	-0.2%	0.1	0.0	0.4	0.0	1.3	-0.2
b1-sns04	20% VOC O&G in NAA	0.0	-48.2	0.0	0.0%	-6.4%	0.0%	0.0	-0.1	0.0	-0.4	0.0	-0.8
b1-sns04b	20% VOC & NOx Ar, Pnt, Non-Rd and O&G in NAA	0.0	-72.5	-41.3	0.0%	-9.6%	-4.9%	-0.5	-1.1	1.8	-1.4	3.2	-3.3
b1-sns04c	20% VOC & 30% NOx Ar, Pnt, Non-Rd, O&G in NAA	0.0	-72.5	-62.0	0.0%	-9.6%	-7.4%	-0.7	-1.6	2.8	-2.0	5.1	-4.7
b1-sns04d	40% VOC O&G in NAA	0.0	-96.3	0.0	0.0%	-12.7%	0.0%	-0.1	-0.2	0.1	-0.7	0.1	-1.7
b1-sns05	20% NOx Pnt & O&G NAA	0.0	0.0	-20.6	0.0%	0.0%	-2.5%	-0.2	-0.5	0.3	-0.8	1.7	-2.0
b1-sns06	20% VOC Non-Rd in NAA	0.0	-12.7	0.0	0.0%	-1.7%	0.0%	-0.2	-0.1	0.0	-0.2	0.0	-0.8
b1-sns07	20% VOC Area in NAA	0.0	-7.5	0.0	0.0%	-1.0%	0.0%	-0.1	-0.1	0.0	-0.1	0.0	-0.2
b1-sns08	20% NOx Pnt & O&G CO	0.0	0.0	-78.0	0.0%	0.0%	-9.3%	-0.2	-0.6	1.1	-1.0	2.2	-2.2
b1-sns09	20% VOC O&G in CO	0.0	-67.2	0.0	0.0%	-8.9%	0.0%	0.0	-0.1	0.1	-0.3	0.1	-0.8
b1-sns10	20% VOC & NOx Point & O&G in CO	0.0	-77.5	-78.0	0.0%	-10.2%	-9.3%	-0.3	-0.6	0.9	-1.2	2.1	-2.7
b1-sns11	20% NOx Point & O&G in NAA + 20% NOx Pawnee	0.0	0.0	-23.0	0.0%	0.0%	-2.7%	-0.2	-0.5	0.3	-0.8	1.7	-2.0
b1-sns12a	Effects of increase in Bark Beetle 2006 to 2010	-8.4	-87.8	-0.3	-0.2%	-11.6%	0.0%	0.0	-0.1	0.1	-0.1	0.1	-0.1
b1-sns12b	Effects of 2010 Bark Beetle infestation	-21.1	-233.5	-0.8	-0.6%	-30.8%	-0.1%	-0.1	-0.1	0.1	-0.1	0.3	-0.3

2010 OZONE SOURCE APPORTIONMENT MODELING

The Anthropogenic Precursor Culpability Assessment (APCA) version of the CAMx ozone source apportionment was applied using the 2010 base case inventory with the emissions segregated into 8 source categories and 11 source regions. The source categories are presented in Table ES-3 and the geographic source regions are given in Table ES-4. Ozone source apportionment is obtained for each source group, which consist of a source region and source category (e.g., on-road mobile sources from the 7-County Denver Metro area). As the contributions of ozone from initial concentrations (IC) and boundary conditions (BC) are always obtained, this results in ozone source apportionment to 90 separate source groups in the Denver ozone source apportionment modeling (90 = 8 x 11 + 2).

The CAMx ozone source apportionment uses reactive tracers that operate in parallel to the host model. For each source group, there are four tracers corresponding to the source group's VOC and NOx concentrations (V_i and N_i) and ozone formed that is attributable to the source groups VOC concentrations ($O3V_i$) or NOx concentrations ($O3N_i$). In the original Ozone Source Apportionment Technology (OSAT) ozone source apportionment approach implemented in CAMx, when ozone is formed in a grid cell it is attributable to a source group based on the relative contributions of the source groups VOC or NOx concentration to the total VOC or NOx concentration in that grid cell based on a determination of whether the ozone formed was under VOC-limited or NOx-limited conditions. Thus, in OSAT the O3V and O3N reactive tracers indicate how much of the ozone is formed under VOC-limited versus NOx-limited conditions. This results in OSAT assigning ozone to biogenic VOCs, which is not necessarily control strategy relevant information as they are uncontrollable. The APCA version of source apportionment only assigns ozone formed to biogenic (uncontrollable) sources when it is due to the interaction of biogenic VOC with biogenic NOx. When ozone is formed under VOC-limited conditions due to the interaction of biogenic VOC with anthropogenic NOx, a case where OSAT would assign it to the biogenic VOC (O3V) source group, APCA redirects the assignment to the anthropogenic NOx (O3N) source group. Thus, with APCA the O3V and O3N tracers no longer represent ozone formed under VOC-limited and NOx-limited conditions.

The source apportionment results were analyzed at each of the ozone monitor sites in the DMA. At each monitor location, for each day, the 8-hour average ozone results for each period over 70 ppb were averaged to develop a composite contribution.

Example displays for a high ozone day (July 29th) at the Rocky Flats North monitor are presented in Figure ES-2. APCA ozone source apportionment modeling results for other days and other monitors are presented in Appendix C. The results show significant day-to-day and monitor-to-monitor variations. Figure ES-2a presents the ozone results including the boundary conditions, that is, the contribution from sources outside the 12 km domain. Of the 76.1 ppb of ozone estimated at the monitor, ~48 ppb (two-thirds) was transported into the 12 km domain and ~18 ppb (one-third) was attributed to sources in the seven-county Denver Metro area. Figure ES-2b presents the same results as ES-2a, but without the boundary conditions plotted and the vertical scale expanded to better resolve the source region contributions. This figure shows that of the ~18 ppb from Metropolitan Denver sources, ~10 ppb was from motor vehicles, ~5 ppb was from non-road mobile sources with the balance from other sources. Figure ES-2c presents the ozone formed that is attributable to anthropogenic NOx concentrations, whereas Figure ES-2d presents the ozone formed attributable to anthropogenic and biogenic VOC concentrations. These two

figures suggest that emission reductions from anthropogenic NOx sources will be more effective at reducing ozone in the model than reductions from anthropogenic VOC sources, although both VOC and NOx controls will reduce ozone. The Fort Collins West monitor shows similar contributions as the Rocky Flats North monitor except the highest contributions are from sources in the Larimer/Weld County source region and oil and gas sources from Larimer/Weld county have a large contribution.

The source apportionment results vary by day and by location. However, several overall trends emerge, namely:

- Regional ozone transport into the 12 km domain is the largest contributor, often accounting for more than two-thirds of the total ozone;
- At the Denver Metropolitan monitors the largest contributors are Denver Metropolitan metro area motor vehicle and non-road sources;
- At the Fort Collins and Greeley monitors, the largest contributors tend to be Larimer and Weld County motor vehicles, non-road sources and oil and gas sources, and Denver Metropolitan sources;
- The majority of the ozone formed is attributable to anthropogenic NOx emissions.

In interpreting these results it is important to keep in mind that these source apportionment results are based on the Denver SIP 2006 modeling episode and are meteorologically dependent. For instance, the source apportionment modeling in support of the Denver Early Action Compact using a 2002 ozone episode showed more impact of sources in Northern Colorado into the Denver Metropolitan area.

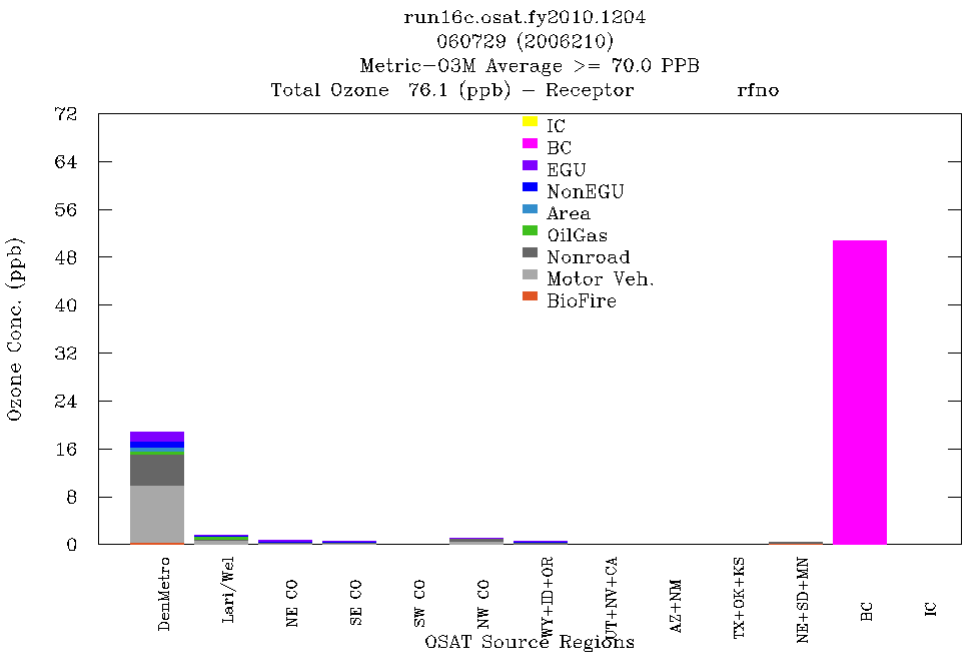

Figure ES-2a. Rocky Flats North source apportionment for 29 July including boundary conditions.

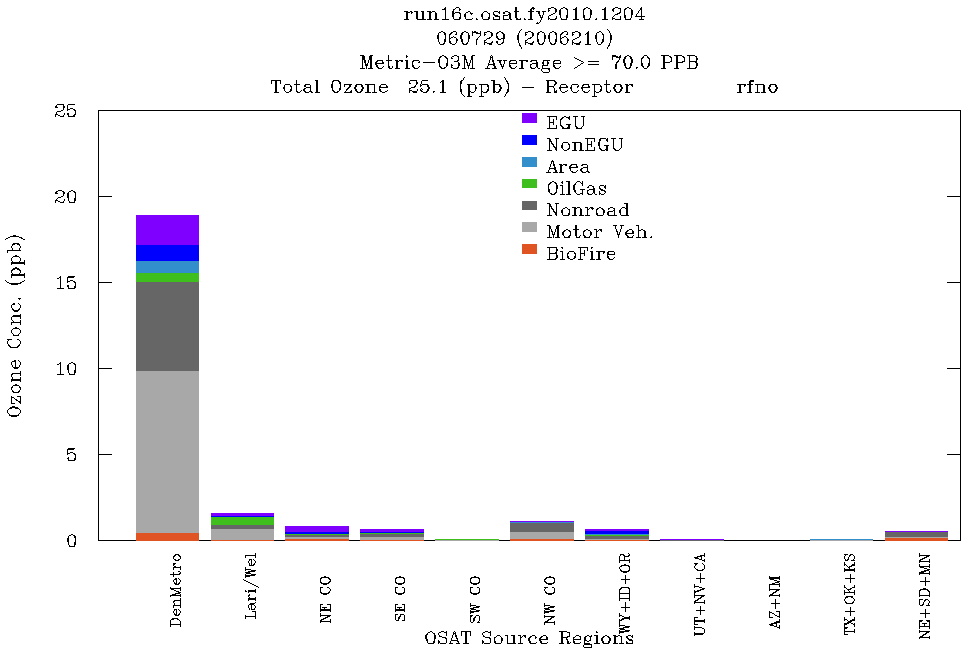

Figure ES-2b. Rocky Flats North source apportionment for 29 July excluding boundary conditions.

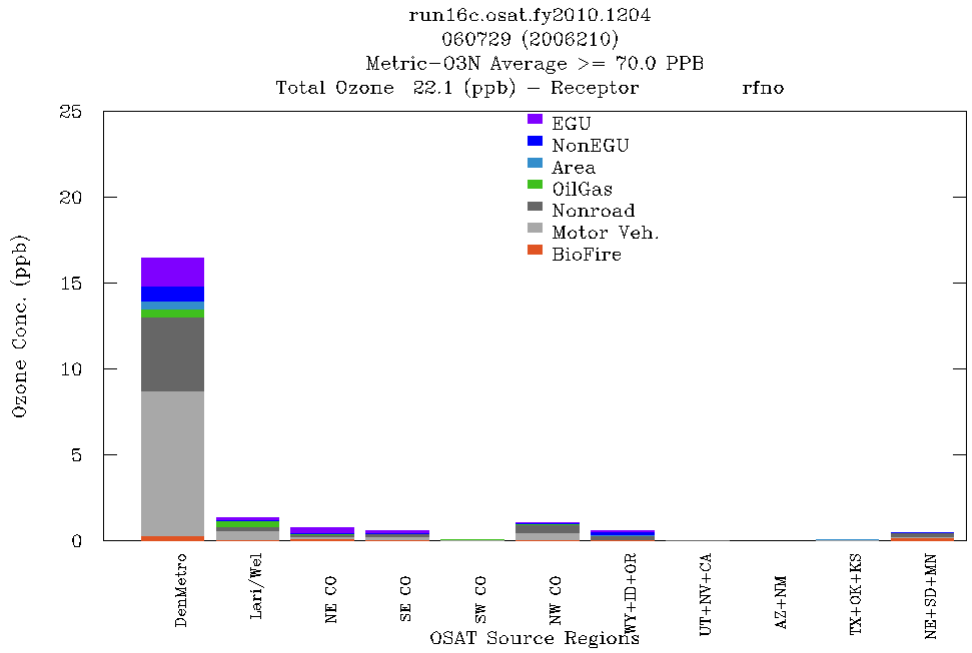

Figure ES-2c. Rocky Flats North source apportionment for 29 July attributable to anthropogenic NOx emissions.

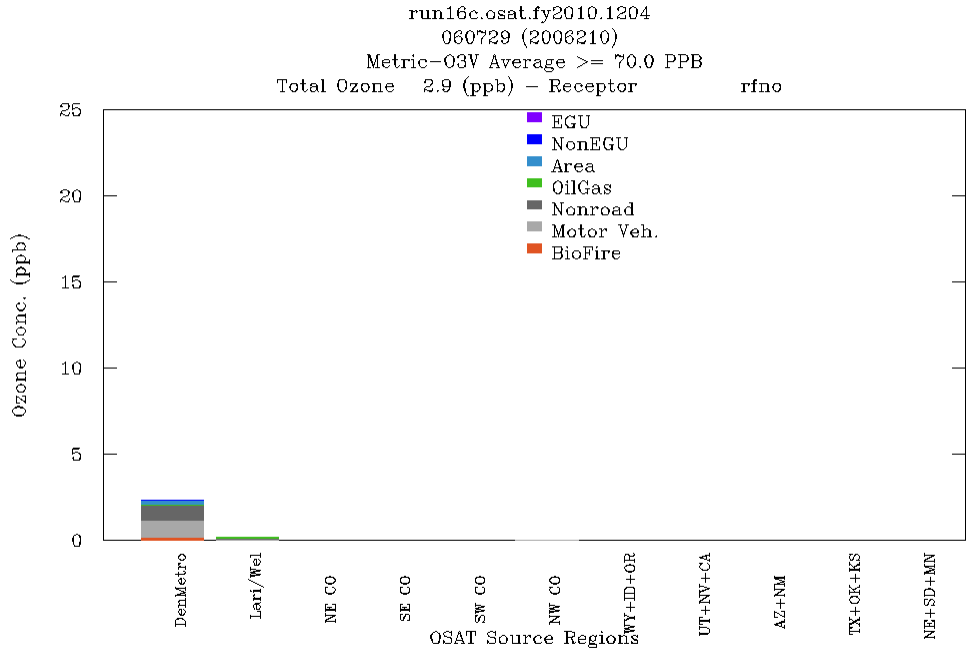

Figure ES-2d. Rocky Flats North source apportionment for 29 July attributable to anthropogenic and biogenic VOC emissions.

CONCLUSIONS OF 2010 OZONE PROJECTIONS AND EMISSIONS SENSITIVITY TESTS

The 2010 emissions reduction sensitivity tests and 2010 ozone source apportionment modeling provide consistent results. The source apportionment modeling estimates that when daily maximum 8-hour ozone concentrations are greater than 70 ppb then approximately two-thirds of the ozone in the DMA is coming from outside of the Denver 12 km modeling domain (roughly outside of Colorado and adjacent states). Most of the remainder one-third of the ozone comes from sources within the Denver 9-county NAA. For the Rocky Flats North monitoring site on July 29, 2006, the 2010 ozone source apportionment results suggest that half of the locally generated ozone comes from on-road mobile sources, with ~1/4 from non-road mobile source, 1/8 from EGU point sources and the remainder 1/8 from area, non-EGU and oil and gas (O&G) sources from the 7-County Denver area. For the Forth Collins West monitoring sites a similar breakdown in source categories is seen only sources from Larimer/Weld Counties contribute more than sources from the 7-County DMA and O&G emissions from Larimer/Weld Counties are major contributors as well.

The APCA ozone source apportionment attributes most of the ozone formed to anthropogenic NOx emissions rather than anthropogenic and biogenic VOC emissions. This suggests that anthropogenic NOx control may be a viable path toward reducing ozone concentrations. The 2010 sensitivity modeling also suggests that NOx emissions reductions are effective at reducing ozone concentrations. However, the 2010 emissions sensitivity tests also saw areas where the NOx emission reductions resulted in ozone increases. These areas include isolated grid cells at the locations of some point sources and within the Denver urban core. The extent of the ozone increases due to the NOx controls in the Denver urban core varied day-to-day due to changes in emissions (e.g., weekday versus weekend day) and meteorology. However, the overall benefits for reducing ozone from the NOx controls out weigh the adverse effects of the ozone increases, although care should be taken in the level and types of NOx emissions controlled to limit the adverse effects. Although the VOC emission reductions do not produce as large ozone reduction as the NOx controls at some key sites (e.g., Fort Collins West), they always reduce ozone or have no effect and no adverse effects of VOC emissions reductions are seen.

Thus, an ozone reduction path using either NOx and/or VOC emission reductions appear to be a viable paths in the Denver area. The VOC emission reductions always reduce ozone or have no or very little effect. Although the ozone reductions due to the NOx controls are larger and more widespread, there are also local ozone increases due to the NOx controls that need to be considered.

1.0 INTRODUCTION

1.1 BACKGROUND

Ozone air quality in the Denver Metropolitan Area (DMA) has been near the 8-hour ozone National Ambient Air Quality Standard (NAAQS) of 0.08 ppm (exceedance defined by values of 85 ppb or higher) for several years. In December 2002, the Denver Regional Air Quality Council (RAQC) and Colorado Department of Health and Environment (CDPHE) Air Pollution Control Division (APCD) and others entered into an 8-hour ozone Early Action Compact (EAC) with the U.S. Environmental Protection Agency (EPA). EPA's EAC allows an area to submit an enforceable 8-hour ozone State Implementation Plan (SIP) by March 2004 that demonstrates attainment of the 8-hour ozone NAAQS by 2007. In return, EPA will defer the classification of an area as nonattainment until 2007. Based on 2005-2007 measured air quality, the DMA violated the 0.08 ppm 8-hour ozone NAAQS, so in November 2007 the DMA reverted to an 8-hour ozone nonattainment area and is required to prepare an 8-hour ozone State Implementation Plan (SIP) that demonstrates attainment by 2010. The contracting team of ENVIRON International Corporation, and their subcontractor Alpine Geophysics, LLC, were selected by the RAQC and CDPHE to perform the 2010 8-hour ozone attainment demonstration modeling for the new SIP.

On March 12, 2008, EPA promulgated a new primary ozone NAAQS that has the same form as the 0.08 ppm 8-hour ozone NAAQS, but lowers the threshold from 0.08 ppm (85 ppb) to 0.075 ppm (75 ppb). Of the ~14 ozone monitors in the greater DMA, half have 2005-2007 8-hour ozone DVs that are 75 ppb or higher. The current Denver 8-hour ozone SIP modeling effort addresses the 0.08 ppm 8-hour ozone NAAQS, the new 0.075 ppm 8-hour ozone NAAQS will be addressed in the future.

1.2 PURPOSE

The fifth generation Mesocale Model (MM5) meteorological model (Anthes and Warner, 1978; Dudhia, 1993), the Sparse Matrix Operating Kernel Emissions (SMOKE) modeling system (Coats, 1996) and the Comprehensive Air-quality Model with extensions (CAMx) photochemical grid model (ENVIRON, 2008) are being used to model ozone in the Denver area for a June-July 2006 modeling period for the purposes of demonstrating attainment of the 8-hour ozone standard by 2010. The 8-hour ozone modeling activities being performed by the ENVIRON/Alpine Modeling Team consists of the following activities:

- Development of a Denver 8-hour ozone SIP attainment demonstration Modeling Protocol (Morris et al., 2007; http://www.ozoneaware.org/documents/DraftFinalProtocolDenver8-HourOzoneNov282007.pdf);
- MM5 meteorological modeling and model performance evaluation (McNally et al., 2008a);
- Development of a preliminary 36/12/4 km photochemical modeling database for the June-July 2006 episode, the DMA, and initial model performance evaluation, sensitivity test modeling and identification of optimal model configuration for simulating ozone in the DMA (Morris et al., 2008b);

- Final base case modeling and model performance evaluation for the June-July 2006 DMA episode (Morris et al., 2008c);
- 2010 base case modeling, emission sensitivity tests and ozone source apportionment modeling (this document); and
- 2010 control strategy modeling (in progress).

1.3 OVERVIEW OF MODELING APPROACH

Figure 1-1a displays the MM5 (red) and CAMx (blue) 36/12/4 km modeling domains used in the Denver 8-hour ozone modeling study. The CAMx model was first applied to the 36 km continental U.S. domain using boundary conditions (BCs) from a global climate air quality model (Figure 1-1a). The CAMx 2006 and 2010 base case modeling results from the 36 km continental U.S. domain simulation are then processed to generate BCs for the CAMx 12/4 km domain (Figure 1-1b) and the, respectively, 2006 12/4 km base case and 2010 12/4 km base case and sensitivity simulations. The CAMx simulations for the 12/4 km domains were run using two-way interactive grid nesting (i.e., pollutants can flow back and forth between the 12 km and 4 km domains to account for recirculation).

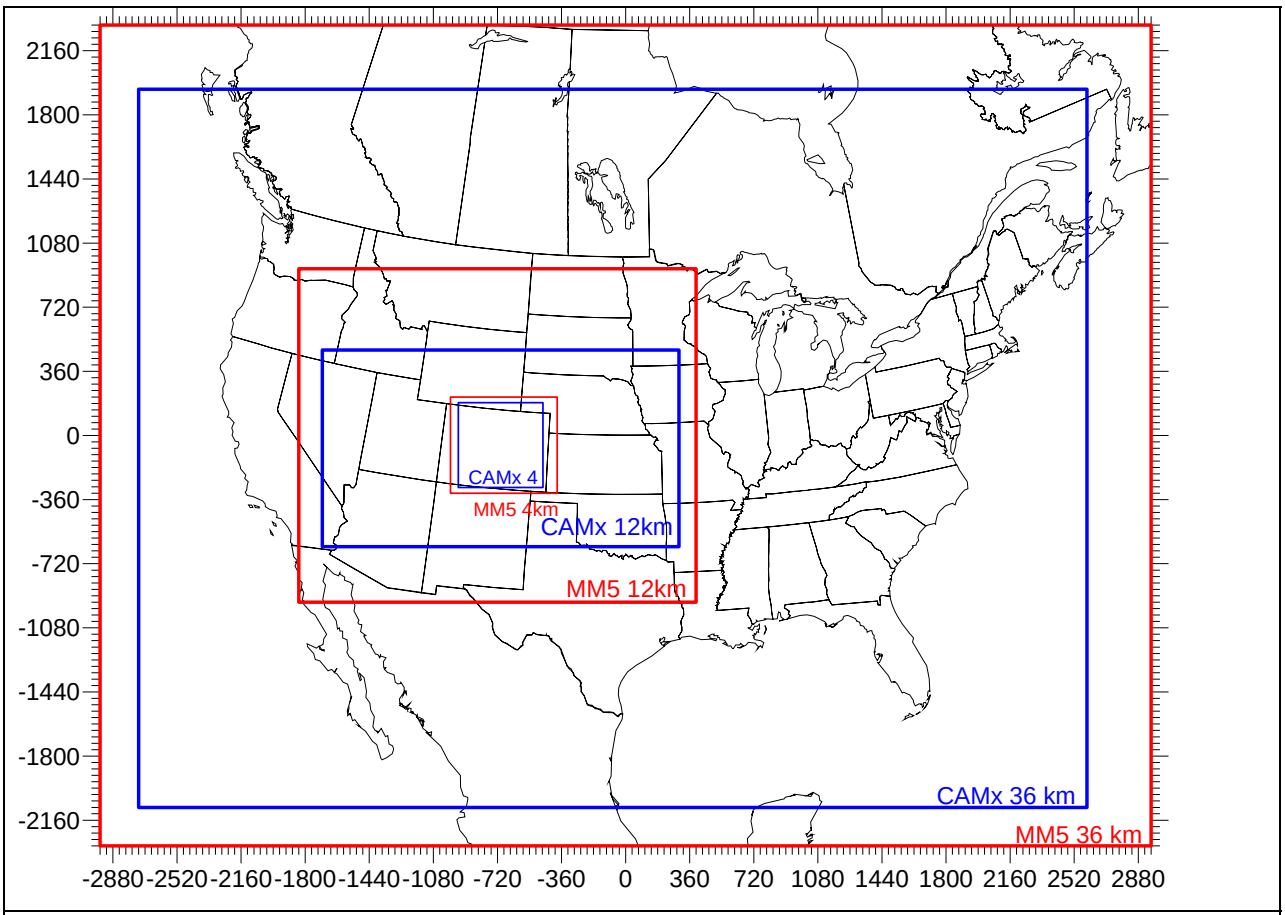

Figure 1-1a. Nested 36/12/4 km modeling domains for the Denver 8-hour ozone modeling study. Blue line domains are for CAMx/SMOKE domains that are nested in the MM5 red line domains.

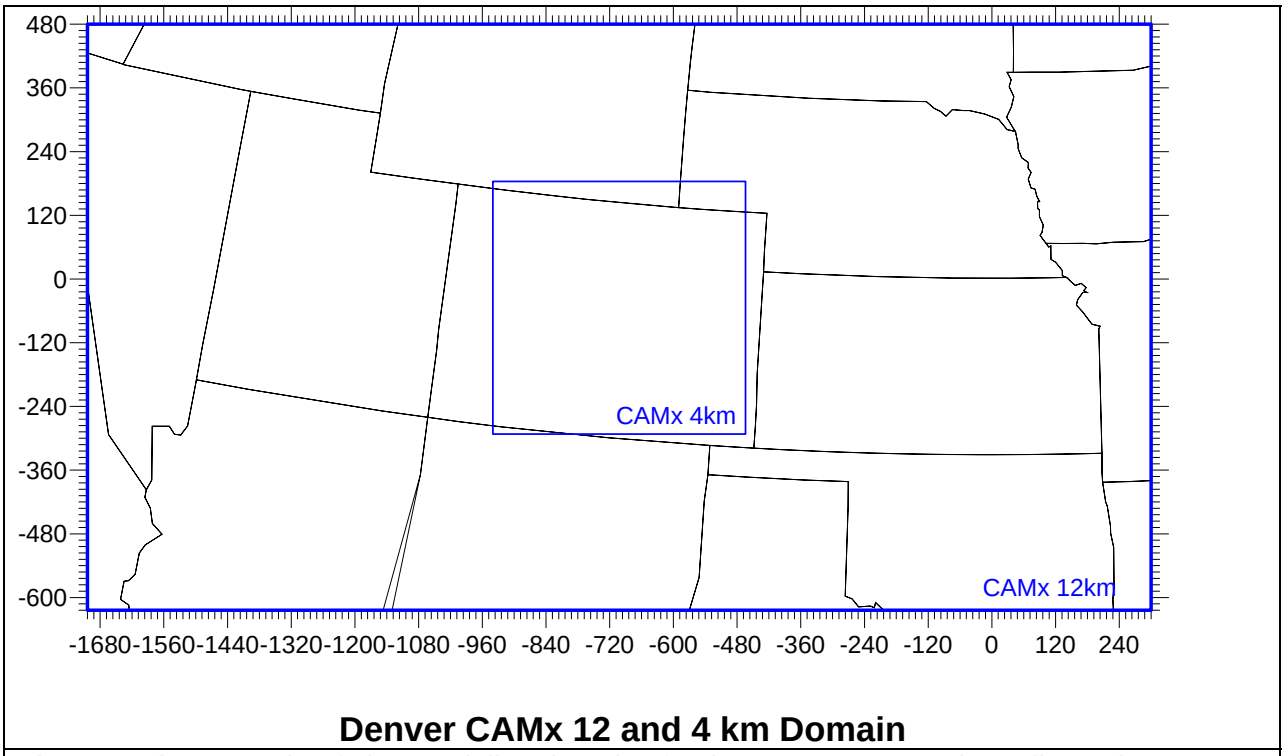

Figure 1-1b. Nested 12/4 km modeling domains for the Denver CAMx air quality and SMOKE emissions modeling.

1.4 2010 EMISSIONS MODELING APPROACH

The 2010 base case emissions were prepared using the same procedures as used to prepare the final 2006 base case emissions scenario (Morris et al., 2008b). The CDPHE/APCD provided 2010 emissions for all anthropogenic emission sources except oil and gas (O&G) emissions in the Denver-Julesburg Basin for which 2010 emissions from the WRAP Phase III O&G emissions development project were utilized (Bar-Ilan et al., 2008b). Outside of Colorado the 2010 anthropogenic emissions were based on the WRAP 2002 and 2018 emissions inventories. CAMx-ready emissions were generated using the Sparse Matrix Operator Kernel Emissions (SMOKE) emissions modeling system (Coats, 1996) for all anthropogenic emissions categories except on-road mobile sources in the DMA, which used the Consolidated Community Emissions Processing Tool (ConCEPT) modeling system (Loomis et al., 2005). The same biogenic emissions were used for the 2010 base case as were used for the final 2006 base case biogenic emissions were based on the Model of Emissions of Gases and Aerosols from Nature (MEGAN) biogenic emissions model (Guenther and Wiedinmyer, 2004). Emissions from fires were also kept constant between the 2006 base case and 2010 base case emission scenarios.

2.0 2010 OZONE PROJECTIONS

2.1 INTRODUCTION

This section presents the 2010 ozone Design Value projections for the 2010 base case and the 2010 emission sensitivity scenarios. These projections are made using the CAMx modeling results for the 2006 base case (Morris et al., 2008b,c) and the 2010 base case and emission sensitivity scenarios. The EPA Modeled Attainment Test Software (MATS) tool was used to make the 2010 8-hour ozone Design Value projections.

2.2 OZONE PROJECTION PROCEDURES

The EPA modeling guidance for 8-hour ozone attainment demonstration modeling contain specific procedures that use current-year and future-year modeling results in a relative fashion to scale current-year observed 8-hour ozone Design Values to project future-year 8-hour ozone Design Values for comparisons with the NAAQS (EPA, 2007). The EPA guidance projection procedures were used to estimate 2010 8-hour ozone Design Values for the 2010 base case and 2010 sensitivity simulations. If the future-year Design Value for a monitor is less than or equal to 84 ppb, the modeled attainment test is passed. If the future-year Design Value is greater than or equal to 85 ppb, the modeled attainment test is not passed. If the future-year Design Value lies between 82 and 87 ppb, a weight of evidence (WOE) determination is required that provides corroborative information that attainment will be achieved in the future-year.

The EPA guidance procedure for projecting future-year 8-hour ozone Design Values has been codified in EPA's Modeled Attainment Test Software (MATS; http://www.epa.gov/ttn/scram/modelingapps_mats.htm). This procedure starts with a current-year observed 8-hour ozone Design Value (DVC) for each monitor. The modeling results are then used to scale the observed 8-hour ozone DVC to obtain a future-year 8-hour ozone Design Value projection (DVF). This is done through the calculation of model-estimated relative response factors (RRFs) that are the ratio of the model-estimated 8-hour ozone concentrations for the future-year to current-year emission scenarios. The RRF is monitor-specific and is used to scale the current year observed design value (DVC) to estimate the projected future-year 8-hour ozone design value (DVF):

$$DVF = DVC \times RRF$$

The RRF is defined as the ratio of the average of the maximum 8-hour ozone concentrations "near a monitor" for the future-year emissions scenario to the average for the current year base case emissions scenario. The EPA default definition of "near a monitor" is to select the maximum model-estimated daily maximum 8-hour ozone concentrations from an array of grid cells centered on the monitor. The size of the array of grid cells centered on the monitor is grid cell size dependent and for the 4 km grid cell resolutions used in the Denver modeling, EPA recommends use of an array of 7 x 7 grid cells centered on the monitor (EPA, 2007).

EPA's 8-hour ozone modeling guidance includes the following language for selecting the current-year observed 8-hour ozone design values that are used in the modeled attainment demonstration test:

> *"For the modeled attainment tests we recommend using the average of the three design value periods which include the baseline inventory year…The average of the three design value periods best represents the baseline concentration, while taking into account the variability of meteorology and emissions (over a five year period)."* (EPA, 2007, pg. 22).

For the Denver modeling that used the 2006 baseline inventory and modeling year, that would mean the current year 8-hour ozone Design Value (DVC) would be based on the average of three years of Design Values from 2004-2006, 2005-2007 and 2006-2008. As the 2008 ozone season is not yet complete, the 2006-2008 8-hour ozone Design Values can not yet be calculated. We considered using the average of two years of Design Values from 2004-2006 and 2005-2007, but in that case none of the DVCs would be violating the 8-hour ozone NAAQS. Thus, we used the 2005-2007 Design Value as the starting current-year Design Value (DVC) in the 2010 ozone projections for all monitors but one. This is appropriate as the 2005-2007 8-hour ozone Design Values are the very ones that resulted in Denver being declared an 8-hour ozone nonattainment area in November 2007. The one exception to this is for the Fort Collins West monitor that started operating in 2006 so a "2-year" 8-hour ozone Design Value will be used (i.e., average of fourth highest daily maximum 8-hour ozone concentrations from 2006 and 2007). Table 2-1 displays the fourth highest daily maximum 8-hour ozone concentrations at monitors in the Denver area and the 2005-2007 Design Values that were used as the DVC starting point for the future-year ozone projections. The use of these DVCs was agreed to by RAQC, CDPHE and EPA early on in the process and was stated in the Modeling Protocol (Morris et al., 2007).

EPA recommends that at least of 10 modeling days be included in the calculation of the RRFs and future-year design values with an absolute 5 day minimum. The criterion for using an episode day in calculating the episode average Design Value for that monitor is that the modeled daily maximum 8-hour ozone near the monitor exceeds a minimum threshold value. EPA recommends use of an 85 ppb threshold in the future-year 8-hour ozone Design Value calculations, but if insufficient number of days are available to calculate the RRFs then this threshold can be reduced by 1 ppb until sufficient modeling days are obtained, or until a 70 ppb floor is obtained. When the 70 ppb threshold floor is reached and there are less than 5 days available for calculating a RRF, then no RRF is calculated. For the Denver June-July 2006 modeling, we were able to calculate RRFs for all monitors in the DMA using 10 days or more of modeling results and never achieved the 70 ppb threshold floor.

In the final step of the modeled attainment test, the projected future-year 8-hour ozone Design Value is truncated to the nearest ppb and then compared with the NAAQS; if it is 84 ppb or lower at all monitors in the area then the modeled attainment test is passed. As noted above, even if the modeled attainment test is passed, if there are any projected 8-hour ozone Design Values above 82 ppb, then a weight of evidence (WOE) analysis is required that presents corroborative evidence that attainment would be achieved. Even if the modeled attainment test is not passed, if the projected future-year 8-hour ozone Design Values at all monitors are 87 ppb or lower, a WOE attainment demonstration may still be conducted.

Table 2-1. Fourth highest daily maximum 8-hour ozone concentrations (ppm) at monitoring sites in the Denver area during 2005, 2006 and 2007 and 2005-2007 8-hour ozone Design Values that is used as the current-year Design Value (DVC) starting point for the 2010 8-hour ozone projections.

Site Name	2005 4th Maximum 8-Hour Average Value (ppm)	2006 4th Maximum 8-Hour Average Value (ppm)	2007 4th Maximum 8-Hour Average Value (ppm)	2005 - 2007 3-Year Average 4th Maximum Value (ppm)
Welby	0.073	0.069	0.070	0.070
Highland	0.080	0.081	0.075	0.078
S. Boulder Creek	0.076	0.082	0.085	0.081
Denver – CAMP	0.051	0.062	0.057	0.056
Carriage	0.074	0.072	0.076	0.074
Chatfield State Park	0.084	0.086	0.082	0.084
USAF Academy	0.077	0.072	0.071	0.073
Manitou Springs	0.075	0.076	0.072	0.074
Arvada	0.078	0.082	0.078	0.079
Welch	0.064	0.081	0.080	0.075
Rocky Flats North	0.077	0.090	0.090	**0.085**
NREL	0.079	0.083	0.085	0.082
Fort Collins – West	---	0.087	0.085	**0.086***
Fort Collins	0.076	0.078	0.069	0.074
Greeley – Weld Tower	0.078	0.082	0.074	0.078
Rocky Mountains NP	0.075	0.076	0.078*	0.076

* Fort Collins West monitor started in 2006 so a 2-year average 4th maximum 8-hour ozone concentrations is used

EPA's 8-hour ozone projection procedure also includes an unmonitored area analysis that has also been codified in MATS. The unmonitored area analysis uses the future-year 8-hour ozone Design Value projection procedure described above applied to each grid cell in the modeling domain. In this procedure, the current-year Design Values (DVC) are first interpolated to each grid cell in the modeling domain. This interpolation scheme uses the modeled concentration gradients in its interpolation procedures. RRFs are then obtained for each grid cell in the modeling domain using the procedures described above except using the actual modeled daily maximum 8-hour ozone concentrations in each grid cell (co-located) rather than values near the grid cell. The same rules are used to assure there are sufficient days to calculate a robust and reliable RRF. Namely, pick the highest days above a threshold value so that at least 10 modeling days are used in the RRFs by reducing the threshold from 85 ppb until the 70 ppb floor is reached. If with the 70 ppb floor there are 5 or more days the RRF is still used. However, for grid cells in which there are less than 5 modeling days with daily maximum 8-hour ozone concentrations greater than 70 ppb no RRF is calculated and consequently no 2010 projected DVF is obtained for that grid cell.

2.3 OZONE PROJECTIONS FOR THE 2010 BASE CASE

The EPA recommended procedures for projecting future year 8-hour ozone Design Values and the MATS tool were used with the CAMx 2006 and 2010 base case modeling results to project 2010 8-hour ozone Design Values at monitors in the Denver area. Table 2-2 shows the total VOC, NOx and CO emissions in Colorado for the 2006 and 2010 base case and three representative days from the June-July 2006 modeling period (including a weekday and weekend

days). The anthropogenic emissions are for the state of Colorado, whereas the biogenic emissions are for the 4 km grid domain, which matches the state of Colorado reasonably well (see Figure 1-1). The anthropogenic VOC, NOx and CO emissions are projected to be reduced by 5.3%, 3.3% and 10.1% between 2006 and 2010 on the weekday selected (July 21). When accounting for the presence of biogenic emissions, the percent reduction of NOx and CO emissions between 2006 and 2010 are reduced a little, but for the VOC emissions the 5.3% reduction in anthropogenic VOC emissions is reduced to 0.6% reduction when accounting for total emissions state-wide in Colorado.

Table 2-2. Summary of 2006 and 2010 base case VOC, NOx and CO emissions in Colorado for July 21-23, 2006.

	Anthropogenic				Biogenic
	2006 Base	2010 Base	Difference (TPD)	Difference (%)	(TPD)
VOC (TPD)					
July 21 (Friday)	807.0	764.0	-43.0	-5.3%	3795.1
July 22 (Saturday)	807.2	775.0	-32.2	-4.0%	4596.3
July 23 (Sunday)	799.0	771.1	-27.8	-3.5%	4960.3
NOx (TPD)					
July 21 (Friday)	862.6	833.8	-28.8	-3.3%	39.4
July 22 (Saturday)	715.3	713.0	-2.3	-0.3%	42.4
July 23 (Sunday)	704.4	699.1	-5.3	-0.7%	51.2
CO (TPD)					
July 21 (Friday)	3840.2	3452.3	-388.0	-10.1%	575.1
July 22 (Saturday)	4281.9	3979.4	-302.5	-7.1%	647.7
July 23 (Sunday)	4284.6	4016.9	-267.7	-6.2%	722.6

Table 2-3 summarizes the projected 8-hour ozone Design Values (DVF) at the DMA monitoring sites for the 2010 base case simulation using the CAMx 2006 and 2010 base case modeling results and EPA recommended default ozone projection procedures described above. The maximum projected 8-hour ozone Design Value is 84 ppb and occurs at both the Rocky Flats North (RFNO) and Fort Collins West (FCTW) monitoring sites (see column 5). As this value is 84 ppb or lower, then the 2010 base case modeling results pass the modeled attainment demonstration test. However, because the maximum projected 8-hour ozone Design Values lie between 82 and 87 ppb, then a WOE analysis is required. Although the EPA 8-hour ozone projection procedure is to truncate the final projected DVF for comparisons with the NAAQS, in column 6 we present the DVFs to the nearest tenth of a ppb before truncation. In this case we see that the projected 2010 base case DVFs at RFNO and FTCW are both 84.9 ppb.

Also shown in Table 2-3 is the RRF and the cut-off threshold used in selecting days and number of days used in calculating the RRF. The EPA desire to use at least 10 modeled days is satisfied using the Denver June-July 2006 modeling period. In order to achieve that many modeled days, the cut-off threshold had to be reduced to 74 ppb to 78 ppb depending on the monitor, with the RFNO and FTCW monitors using a 78 and 76 ppb threshold, respectively.

The level of ozone reductions in the projected Design Values appears to be greater the further away from central Denver the monitor resides. In fact, ozone is estimated to increase very slightly at the monitors in or immediately downwind of the urban core. This is due to the reductions in on-road mobile sources NOx emissions that increase ozone in the urban core. This ozone increase due to NOx emission reductions is due to less ozone titration from a reduction of

the primary emitted NO emissions ($NO + O_3 \rightarrow NO_2 + O_2$) and/or less NOx inhibition effect on ozone formation that high NOx concentrations have as a termination step to the radical cycle ($NO_2 + OH \rightarrow HNO_3$). This effect is seen in difference plots in daily maximum 8-hour ozone concentrations between the 2010 and 2006 base case simulations shown in Figure 2-1 for four days. These four days were selected because they were four common days out of the ~10 that were used in the 2010 Design Value projections for both the RFNO and FTCW monitoring sites. Most of the NOx emission reductions between the 2006 and 2010 base cases occur in the DMA, as shown in Figure 2-2. This is the area that experiences ozone increases from 2006 to 2010 (Figure 2-1). As one moves away from the Denver urban core, the ozone increases between 2006 and 2010 turn into no change and then to ozone decreases. The distance from the Denver urban core when the ozone increases change to ozone decreases varies by day due to changes in emissions (e.g., weekday versus weekend day) and changes in meteorology. The RFNO monitor lies near the modeled ozone increase-to-decrease cross over distance, which explains why the model projected 2010 Design Value is relative insensitive to the changes in emissions from 2006 to 2010 at this site (85.0 to 84.9 ppb, a 0.1 ppb reduction); of the 10 days used to construct the RRF for RFNO there are some days of ozone increases and some with ozone decreases. This effect is seen in the ozone difference plots for four of the ten days used in developing the RRF for the RFNO monitoring site. At the FTCW monitoring site, on the other hand, the model is more responsive (1.1 ppb ozone reduction) as it is an area far enough away from the Denver urban core where the modeled ozone changes either stay the same or are reduced between 2006 and 2010.

Table 2-3. Current-year (DVC) and projected future-year (DVF) 8-hour ozone Design Values using the CAMx 2006 and 2010 base case modeling results.

Site ID	Monitor Name	County	2005-07 DVC	2010 Base Case DVF	DVF	RRF	Cutoff	#days
80013001	Welby	Adams	70.0	70	70.2	1.0042	77.0	11
80050002	Highland	Arapahoe	78.0	77	77.3	0.9916	78.0	14
80130011	S. Boulder Creek	Boulder	81.0	80	80.8	0.9976	78.0	10
80310002	Denver - CAMP	Denver	56.0	56	56.0	1.0017	78.0	10
80310014	Carriage	Denver	74.0	74	74.1	1.0022	78.0	10
80350004	Chatfield State Park	Douglas	84.0	83	83.4	0.9934	78.0	11
80410013	USAF Academy	El Paso	73.0	72	72.0	0.9873	75.0	10
80410016	Manitou Springs	El Paso	74.0	73	73.7	0.9966	74.0	10
80590002	Arvada	Jefferson	79.0	79	79.2	1.0026	78.0	10
80590005	Welch	Jefferson	75.0	75	75.0	1.0004	78.0	10
80590006	Rocky Flats North	Jefferson	85.0	84	84.9	0.9994	78.0	10
80590011	NREL	Jefferson	82.0	82	82.3	1.0039	78.0	11
80690011	Fort Collins - West	Larimer	86.0	84	84.9	0.9874	76.0	10
80691004	Fort Collins	Larimer	74.0	73	73.0	0.9878	76.0	12
81230009	Greeley - Weld Tower	Weld	78.0	77	77.7	0.9964	75.0	10
GTH161	Gunnison	Gunnison	68.0	67	67.8	0.9984	74.0	10
ROM206	Larimer	Larimer	76.0	75	75.2	0.9903	77.0	10
ROM406	Larimer	Larimer	76.0	75	75.2	0.9903	77.0	10

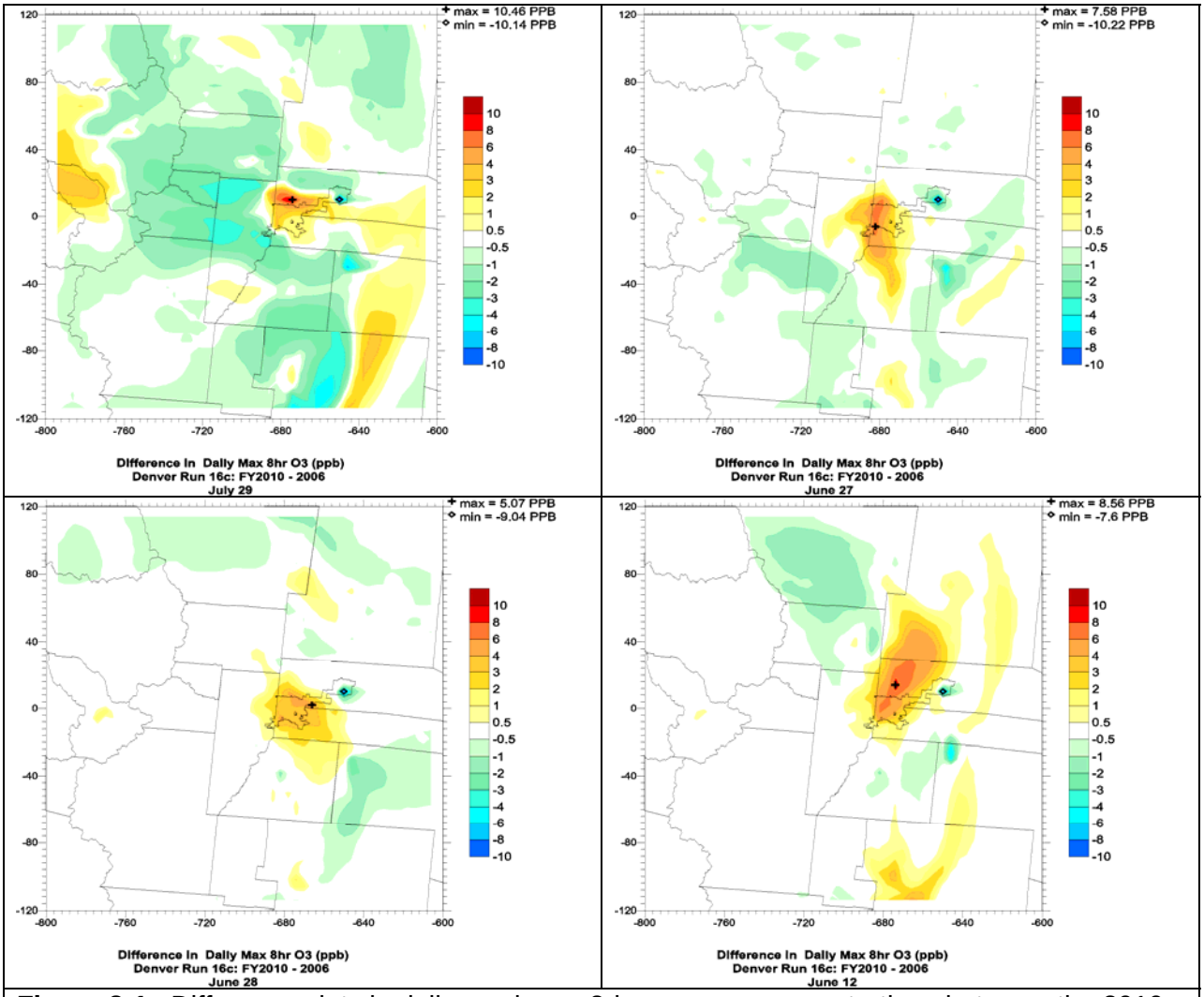

Figure 2-1. Difference plots in daily maximum 8-hour ozone concentrations between the 2010 and 2006 base case CAMx simulations for July 29 (top left), June 27 (top right), June 28 (bottom left) and June 12 (bottom right), 2006.

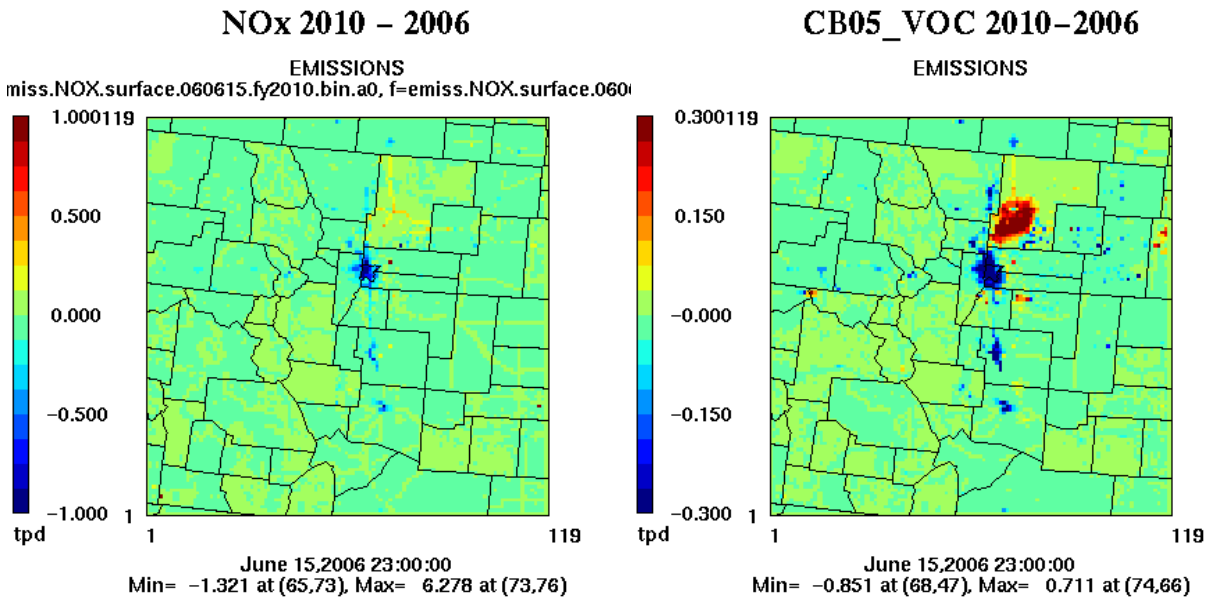

Figure 2-2. 2010 minus 2006 base case emissions difference plots for NOx (left) and VOC (right).

Figure 2-3 displays the results of the 8-hour ozone DVF projections using the unmonitored area analysis from MATS. Figure 2-3a displays the interpolated fields of the current year Design Values (DVCs). DVCs in excess of 80 ppb are estimated to the south, west and northwest of Denver stretching to Fort Collins and then west of Fort Collins. In fact, the MATS interpolation procedures estimates that current-year DVCs in excess of the 85 ppb NAAQS occur in 12 grid cells to the west of the Fort Collins sites (Figure 2-3a). The projected DVFs for the 2010 base case (Figure 2-3b) have greatly reduced the spatial extent of the DVFs in excess of 80 ppb occurring to the south, west and northwest of Denver and the 12 cells with DVCs exceeding the 85 ppb NAAQS have been reduced by half to 6 grid cells in the 2010 base case emissions scenario.

EPA guidance stresses that the unmonitored area test has more uncertainties than the projections at the monitors and it should be treated separately from the monitor based attainment test (EPA, 2007). EPA further notes that while it is expected that additional emission controls are needed to eliminate predicted violations of the monitor based test, the same requirements may not be appropriate in unmonitored areas. In any event, EPA recommends that areas of predicted violations in the unmonitored area test be scrutinized and understood to determine whether they are likely to exist in the ambient air or whether they may be caused by an error or uncertainties in the modeling system. At a minimum, it may be appropriate to deploy additional ozone monitors to such areas. In the case of the Denver ozone modeling, higher ozone concentrations are estimated west of Fort Collins than at the locations of the two monitors in Fort Collins on some days and this does not appear to be due to an error in the modeling system. Whether it may be due to uncertainties in the modeling system can not be determined. However, the placement of the Fort Collins West monitor west of the original Fort Collins monitor in 2006 has found much higher observed ozone in the ambient air, it does not seems implausible that even higher values could exist even further west from Fort Collins.

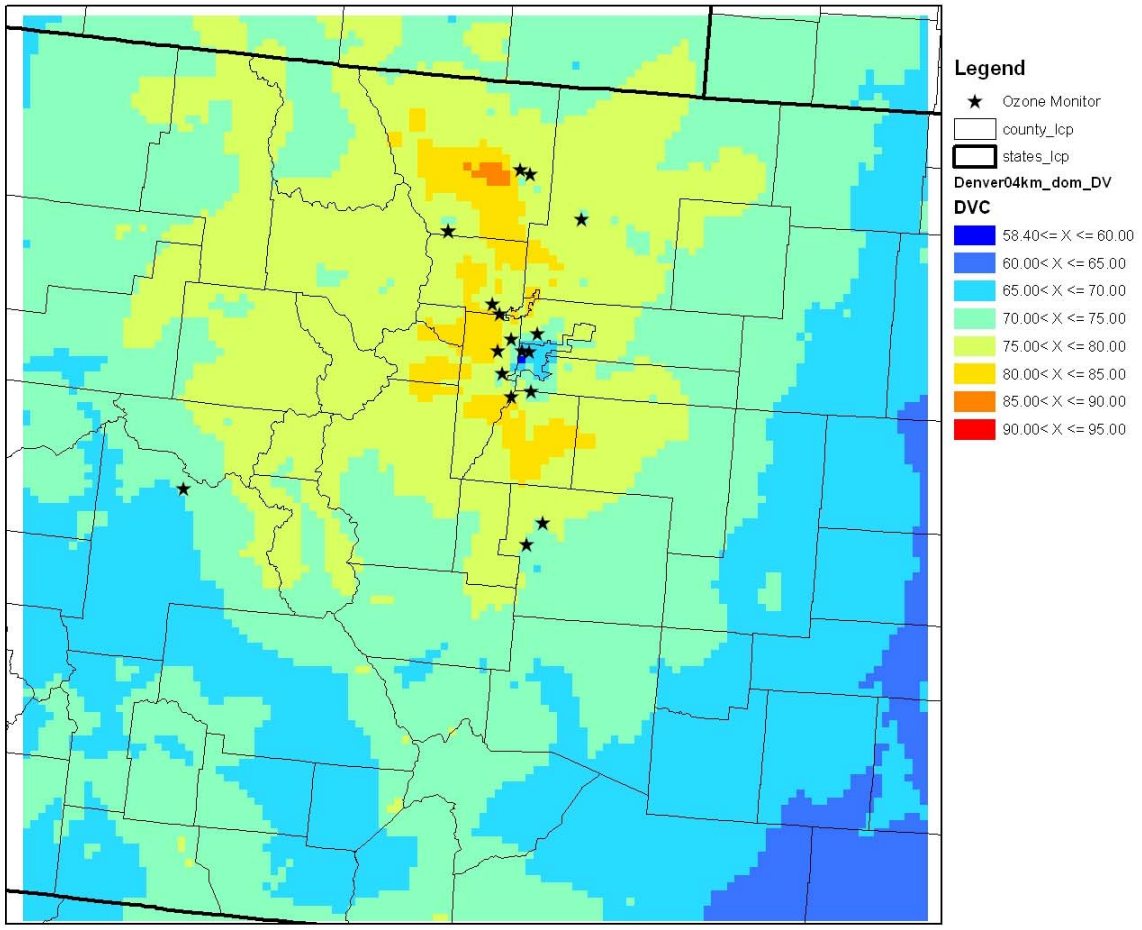

Figure 2-3a. Current-year 8-hour ozone Design Values (DVC) interpolated by the MATS tool.

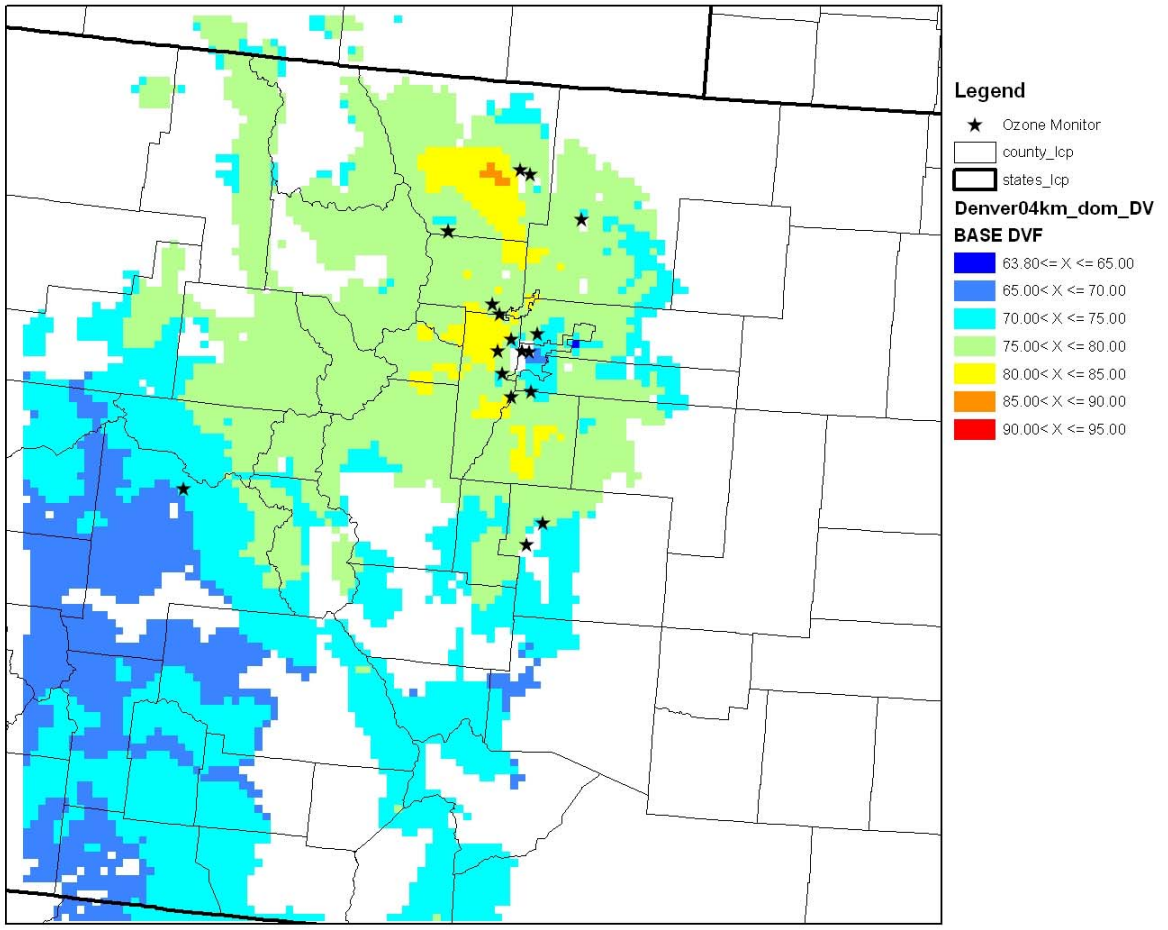

Figure 2-3b. Projected 2010 8-hour ozone Design Values (DVF) generated by the MATS tool for the 2010 base case emissions scenario.

2.4 2010 SENSITIVITY TESTS

Sixteen (16) 2010 emissions reductions sensitivity tests were conducted with the CAMx modeling system. Most of these emission reduction sensitivity tests reduced VOC and/or NOx emissions from a specific source category either just within the Denver nonattainment area (NAA) or within the entire state of Colorado. Ozone projections were made at each of the monitoring sites for each of the 2010 sensitivity tests. We also performed the unmonitored area analysis for each sensitivity test to better understand the spatial extent of any ozone benefits or adverse effects. Table 2-4 describes each of the sensitivity tests. All sensitivity tests modified emissions from the 2010 base case emissions scenario.

The first three sensitivity tests examined the sensitivity of 2010 ozone formation to on-road mobile sources emissions within the Denver NAA. The first 2010 sensitivity test (b1-sens01) examined a 20% across-the-board reduction in VOC emissions from on-road mobile sources in the NAA. The second sensitivity test examined the effects of reducing evaporative VOC emissions from on-road mobile sources by specifying a baseline gasoline Reid Vapor Pressure (RVP) of 7 psi. Thus, with the assumed 85% ethanol market penetration in 2010 with a 1 psi waiver and a 7.8 psi RVP for the base case gasoline, this results in a reduction in the average RVP of gasoline in the Denver NAA from 8.65 psi in the 2010 base case to 7.85 psi in the b1-sen02 2010 sensitivity case. The third mobile source sensitivity test assumed zero ethanol market penetration in the NAA and accompanying changes in on-road and non-road mobile gasoline engines' VOC, NOx and CO emissions.

The next 11 sensitivity tests listed in Table 2-4 (b1-sens04 to b1-sens11) are self explanatory with reductions in VOC and/or NOx from specifically identified source categories either just within the Denver NAA or throughout Colorado.

The final two sensitivity tests were designed to assess the sensitivity that the Bark Beetle infestation would have on biogenic VOC emissions and projected 2010 ozone concentrations. The MEGAN biogenic emissions model was used to estimate the effects the Bark Beetle infestation would have on biogenic emissions. The 2006 and 2010 base case MEGAN biogenic emissions simulations assumed no Bark Beetle infestation. Estimates of the spatial extent of the Bark Beetle infestation from 2006 and 2010 were obtained from Dr. Christine Wiedinmyer of the National Center for Atmospheric Research (NCAR) and MEGAN was rerun assuming that biogenic emissions were reduced over the infestation areas to obtain two new sets of biogenic emission inputs accounting for the extent of Bark Beetle infestation in 2006 and 2010. The first Bark Beetle infestation sensitivity test was designed to determine whether the reductions in biogenic emissions due to the changes in Bark Beetle infestation between 2006 and 2010 would affect the 2010 ozone projections (b1-sens12a). This was accomplished by reducing biogenic emissions from the MEGAN no Bark Beetle simulation used in the 2006 and 2010 base case simulations by the reductions in the biogenic emissions estimates between the MEGAN 2006 and 2010 Bark Beetle infestation emissions estimates. The second Bark Beetle sensitivity test was designed to determine whether the differences of with or without Bark Beetle effects on biogenic emission would affect ozone formation so used the MEGAN 2010 Bark Beetle infestation biogenic emission estimates with all other emissions identical to the 2010 base case simulation.

Table 2-4. Description of 2010 sensitivity tests performed using the Denver CAMx 12/4 km modeling system.

Sens Test	Description
2006.a3	2006 base case and current year 8-hour Ozone Design Value (DVC)
b1	2010 Base Case
b1-sns01	20% reduction in VOC on-road mobile sources in NAA
b1-sns02	Evaporative VOC on-road mobile sensitivity in NAA using 7 psi RVP gasoline
b1-sns03	0% Ethanol penetration in NAA
b1-sns04	20% reduction in VOC from O&G sources in NAA
b1-sns04b	20% reduction in VOC & NOx from area, point, non-road and O&G sources in NAA
b1-sns04c	20% VOC & 30% NOx reduction in area, point, non-road and O&G sources in NAA
b1-sns04d	40% reduction in VOC from O&G sources in NAA
b1-sns05	20% reduction in NOx from point & O&G sources in NAA
b1-sns06	20% reduction in VOC from non-road mobile sources in NAA
b1-sns07	20% reduction in VOC from area sources in NAA
b1-sns08	20% reduction in NOx from point & O&G sources in Colorado
b1-sns09	20% reduction in VOC from O&G sources in Colorado
b1-sns10	20% reduction in VOC & NOx from point & O&G sources in Colorado
b1-sns11	20% reduction in NOx from point & O&G in NAA + 20% reduction in NOx from Pawnee
b1-sns12a	Effects of increase in Bark Beetle infestation 2006 to 2010
b1-sns12b	Effects of 2010 Bark Beetle infestation

Table 2-6 displays the results of the 2010 sensitivity tests in terms of VOC, NOx and CO emission reductions from the 2010 base case, changes in projected 8-hour ozone Design Values at the key RFNO and FTCW monitoring sites, maximum difference in 2010 8-hour ozone Design Values anywhere in the DMA and maximum difference in daily maximum 8-hour ozone concentrations anywhere in the DMA and on any of the modeling days. Projected 8-hour ozone Design Values for the 2010 sensitivity tests and all of the monitoring sites are given in Appendix A. Spatial maps of differences in the projected DVFs between the 2010 sensitivity simulations and the 2010 base case are shown in Appendix B.

Mobile Source Emissions: Reducing on-road mobile sources VOC emissions 20% in the DMA reduces the projected DVFs at RFNO and FTCW by 0.2 and 0.1 ppb, respectively. The 7 psi RVP gasoline in on-road mobile source gasoline vehicles reduces the DVFs by 0.1 ppb at both monitors. And the zero percent ethanol penetration scenario in the on-road and non-road mobile source gasoline engines increases the DVF at RFNO by 0.1 ppb, and has no effect at FTCW. The spatial maps (Appendix B) show that the reductions in the DVF due to the 20% mobile sources VOC control are small, in the 0.05 to 0.5 ppb range across the DMA. The reductions for the 7 psi scenario are even smaller. And the ozone increases in the no ethanol scenario are comparable to the reductions in the 20% VOC mobile scenario.

Oil and Gas VOC Emissions: VOC emissions from O&G sources in the NAA were reduced by 20% (b1-sens04) and 40% (b1-sens04d) in two of the 2010 emissions sensitivity tests. The O&G VOC emission reductions had little effect at the RFNO monitor, but reduced the projected DVF at the FTCW monitor by 0.1 and 0.2 ppb, respectively. The spatial maps of differences in the DVFs show a large area of ozone benefits due to the O&G VOC reductions centered on the O&G production area in Weld County. The RFNO monitor is right at the edge of this benefits area. Note that the Denver EAC SIP modeling of the June-July 2002 episode saw more transport from the Weld County O&G production area down to the RFNO monitor, so these results are

partly an artifact of the meteorological conditions of the June-July 2006 modeling period. The O&G VOC emissions clearly have an effect on ozone formation in the Fort Collins area. In fact, the 6 grid cells west of Fort Collins that are projected to still violate the 0.08 ppm 8-hour ozone NAAQS in the 2010 base case (Figure 2-3b) are reduced to 4 and 3 grid cells in the 20% and 40% O&G VOC emission reduction sensitivity scenarios. Clearly VOC emission reductions from O&G sources in Weld County would benefit ozone attainment in the Fort Collins area and likely elsewhere in the Denver NAA under other meteorological conditions.

Combined VOC & NOx Sensitivity Simulations: Sensitivity simulations b1-sens04b and b1-sens04c looked at combined VOC and NOx emissions reductions from area, non-road point and O&G emissions in the NAA. Although both simulations reduced VOC emissions by 20%, NOx emissions were reduced by 20% in sens04b and by 30% in sens04c allowing us to isolate the effects of the NOx controls. Several of the other sensitivity tests also allow us to isolate the effects of the VOC and NOx controls in these two sensitivity tests for each source category. The b1-sens04b 20% VOC/NOx emissions reduction scenario reduces the DVF at RFNO by 0.5 ppb. This is due to reductions in the RFNO ozone DVF of approximately 0.1 ppb from area source VOC (b1-sens07), 0.1 ppb from O&G VOC (b1-sens04), 0.2 ppb from non-road VOC (b1-sens06) and 0.2 ppb from point and O&G source NOx (b1-sens05). An additional 0.2 ppb ozone reduction in the RFNO DVF is obtained when the NOx reduction is increased from 20% to 30%. At the FTCW monitor, the effects of the NOx emission reductions alone is even greater. The 20% VOC/NOx reduction gives a 1.1 ppb reduction in the ozone DVF at the FTCW monitor, increasing the NOx reduction by another 10% increases the ozone reduction at the FTCW monitor by another 0.5 ppb (total 1.6 ppb reduction). This suggests that a majority of the ozone benefits at FTCW are due to the NOx emission reductions. Although as noted above, VOC emission reductions from O&G sources in the NAA are also beneficial for reducing ozone in the Forth Collins area. With the exception of a couple grid cells of isolated ozone increases, the effects of the combined VOC/NOx controls are wide-spread reductions in ozone throughout the DMA (Appendix B).

State-Wide Sensitivity: The state-wide sensitivity tests produce nearly the same ozone benefits at DMA monitors as the controls in the NAA alone. This is seen most clearly by comparing b1-sens05 with b1-sens08 that examine a 20% reduction in NOx emissions from point and O&G sources in, respectively, the NAA and Colorado. They produce the same ozone reduction at RFNO (0.2 ppb) and the state-wide reduction produces slightly more ozone reduction at FTCW (0.6 ppb) than the NAA controls alone (0.5 ppb). At this time we have only evaluated the effects of the state-wide emission reduction sensitivity tests within the DMA. There are likely more ozone benefits due to the Colorado state-wide emission reductions outside of the DMA that may be important given the new lower (March 2008) ozone NAAQS.

Bark Beetle Sensitivity: The effects of accounting for the Bark Beetle infestation on biogenic emissions have small effects on the DVFs in the DMA (0.1 ppb reduction). An examination of the difference plots in Appendix B shows small areas of ozone decreases in the DMA and small areas of ozone increases on the western slopes of the Rocky Mountains. This is because ozone formation in the DMA occurs under a mixture of VOC-limited and NOx-limited conditions, whereas ozone formation in the western slope is primarily NOx-limited. The Bark Beetle infestation reduces VOC emissions that in turn reduce ozone in the DMA under VOC-limited ozone formation conditions. However, over the western slope small ozone increases occur because of the reduction in biogenic VOC emissions which in turn reduce the reaction of olefin VOC species (e.g., isoprene) with ozone thereby increasing ozone concentrations slightly.

Table 2-5. Results of 2010 sensitivity tests.

Test	Description	Emissions (TPD)			% Anthro (%)			DV Ozone (PPB)		Grid DV Ozone(ppb)*		Grid Diff. Ozone (ppb)**	
		CO	VOC	NOx	CO	VOC	NOx	RFNO	FTCW	Max.	Min.	Max.	Min.
2006.a3	Current Year 8-Hour Ozone Design Value							85	86				
b1	2010 Base Case	-386.0	-42.2	-50.1	-10.2%	-5.3%	-5.6%	84.9	84.9				
b1-sns01	20% VOC On-Road NAA	0.0	-22.8	0.0	0.0%	-3.0%	0.0%	-0.2	-0.1	0.1	-0.2	0.1	-0.6
b1-sns02	Evap VOC On-Road in NAA (7 psi RVP)	-46.9	-9.8	-0.3	-1.4%	-1.3%	0.0%	-0.1	-0.1	0.1	-0.1	-0.2	-0.3
b1-sns03	0% Ethanol in NAA	323.3	-3.8	-2.0	9.5%	-0.5%	-0.2%	0.1	0.0	0.4	0.0	1.3	-0.2
b1-sns04	20% VOC O&G in NAA	0.0	-48.2	0.0	0.0%	-6.4%	0.0%	0.0	-0.1	0.0	-0.4	0.0	-0.8
b1-sns04b	20% VOC & NOx Ar, Pnt, Non-Rd and O&G in NAA	0.0	-72.5	-41.3	0.0%	-9.6%	-4.9%	-0.5	-1.1	1.8	-1.4	3.2	-3.3
b1-sns04c	20% VOC & 30% NOx Ar, Pnt, Non-Rd, O&G in NAA	0.0	-72.5	-62.0	0.0%	-9.6%	-7.4%	-0.7	-1.6	2.8	-2.0	5.1	-4.7
b1-sns04d	40% VOC O&G in NAA	0.0	-96.3	0.0	0.0%	-12.7%	0.0%	-0.1	-0.2	0.1	-0.7	0.1	-1.7
b1-sns05	20% NOx Pnt & O&G NAA	0.0	0.0	-20.6	0.0%	0.0%	-2.5%	-0.2	-0.5	0.3	-0.8	1.7	-2.0
b1-sns06	20% VOC Non-Rd in NAA	0.0	-12.7	0.0	0.0%	-1.7%	0.0%	-0.2	-0.1	0.0	-0.2	0.0	-0.8
b1-sns07	20% VOC Area in NAA	0.0	-7.5	0.0	0.0%	-1.0%	0.0%	-0.1	-0.1	0.0	-0.1	0.0	-0.2
b1-sns08	20% NOx Pnt & O&G CO	0.0	0.0	-78.0	0.0%	0.0%	-9.3%	-0.2	-0.6	1.1	-1.0	2.2	-2.2
b1-sns09	20% VOC O&G in CO	0.0	-67.2	0.0	0.0%	-8.9%	0.0%	0.0	-0.1	0.1	-0.3	0.1	-0.8
b1-sns10	20% VOC & NOx Point & O&G in CO	0.0	-77.5	-78.0	0.0%	-10.2%	-9.3%	-0.3	-0.6	0.9	-1.2	2.1	-2.7
b1-sns11	20% NOx Point & O&G in NAA + 20% NOx Pawnee	0.0	0.0	-23.0	0.0%	0.0%	-2.7%	-0.2	-0.5	0.3	-0.8	1.7	-2.0
b1-sns12a	Effects of increase in Bark Beetle 2006 to 2010	-8.4	-87.8	-0.3	-0.2%	-11.6%	0.0%	0.0	-0.1	0.1	-0.1	0.1	-0.1
b1-sns12b	Effects of 2010 Bark Beetle infestation	-21.1	-233.5	-0.8	-0.6%	-30.8%	-0.1%	-0.1	-0.1	0.1	-0.1	0.3	-0.3

2010 Base Case emission reductions from 2006 levels, all other emission reductions from 2010Base Cases
* Maximum difference in 2010 design value anywhere on the 4km grid.
**Maximum difference in daily maximum 8-hour ozone concentration anywhere on the 4km grid.

3.0 2010 APCA SOURCE APPORTIONMENT

3.1 INTRODUCTION

This section presents the 2010 ozone source apportionment modeling. This analysis is made using the CAMx modeling results for the 2010 base case emissions using the June-July 2006 episode (Morris et al., 2008b,c). This section begins with a technical description of the technique, followed by the application methodology and concluding with the analysis methodology and results.

3.2 TECHNICAL DESCRIPTION

Photochemical grid models are used to develop NO_x and/or VOC emission reduction strategies to attain ozone air quality objectives. Traditionally, the development of an ozone attainment strategy involves iteration through many photochemical grid model scenarios to identify which pollutants, source categories and source regions should be controlled. It is impractical to analyze every potential control strategy and so there is potential for implementing controls on sources that contribute little to the high ozone levels or, conversely, not controlling sources that do contribute.

3.2.1 Introduction to OSAT

ENVIRON developed an ozone source attribution approach that has become known as the "Ozone Source Apportionment Technology", or OSAT (Yarwood et al., 1996). This method was implemented in the CAMx photochemical grid model. OSAT provides a method for estimating the contributions of multiple source areas, categories, and pollutant types to ozone formation in a single model run.

The main challenges in developing and implementing a methodology to track the spatial and temporal relationships between separate groups of emission sources and ozone formation are:

- Accounting not only for the presence of ozone precursors from a given source region at a given receptor location, but also accurately estimating the cumulative contribution to ozone production of those precursors while they were en-route to the receptor.

- Insuring compatibility with the underlying air quality model formulation so that derived source-receptor relationships will be consistent with model response to emission changes.

- Providing sufficient spatial and temporal resolution while managing, within practical constraints, the computer resources required to run the software tool.

The methodology is designed so that all ozone and precursor concentrations are attributed among the selected source groupings at all times. Thus, for all receptor locations and times, the ozone (or ozone precursor concentrations) predicted by CAMx is attributed among the source groupings selected for OSAT. The methodology also estimates the fractions of ozone arriving at

the receptor that were formed en-route under VOC- or NO_X-limited conditions. This information indicates how ozone concentrations at the receptor will respond to reductions in VOC and NO_X precursor emissions.

The biggest limitation of this, or any other, ozone source apportionment approach likely results from the non-linear nature of the chemical interactions between emissions from different source groupings and their effect on ozone formation. This means that as soon as the emission inventory is perturbed, the source receptor relationships begin to change. Thus, OSAT can only estimate the contribution to ozone from a specific source grouping under the current emissions scenario. It cannot directly quantify the ozone reductions that will result from an emission control strategy because the CAMx response may well be non-linear with the magnitude of the control applied (e.g. 20 percent or 60 percent control) and the presence/absence of other simultaneous controls on other source groupings.

However, this fundamental truth of photochemical modeling does not limit the usefulness of OSAT: arguably it increases its usefulness. At any rate, it suggests the following approach to control strategy development with OSAT. For the base CAMx scenario, OSAT could be used to identify specific source groupings for which ozone reductions from emissions controls would be maximized. Just as important, OSAT will identify source groupings for which emissions controls are not effective at reducing ozone concentrations. The most effective and feasible control measures identified in this way can be applied to the emission inventory, leading to a revised CAMx scenario with different (lower) emissions. If additional controls are needed, OSAT could be applied again to identify the most effective control measures under the new conditions. Development of the control plan will still proceed by an iterative process, but OSAT can be used to guide the process to develop (and justify) more refined, better-targeted and more cost-effective ozone control strategies.

3.2.2 OSAT/APCA Technical Formulation

CAMx has been extended to accommodate extra tracer species needed to perform ozone source apportionment. For each user-specified source grouping (geographical area/emissions category) there are two distinct types of tracer species, "timing tracers"[1] and "ozone reaction tracers." The timing tracers are used to track the temporal relationships between precursor emissions and ozone formation. The ozone reaction tracers track the fate of ozone precursors (NO_X and VOC) emissions from each source grouping plus the ozone formation attributed to those emissions. The methodology requires that all ozone precursors be tracked so that all contributions to ozone can be accounted for, thus ozone and precursors originating from the model boundary and initial concentrations are also tracked as separate source groupings (however, no timing tracers are allocated to the initial or boundary conditions). The following sub-sections describe the methodologies employed for the timing and ozone reaction tracers.

OSAT tracks ozone formation from user defined source groups using reactive "ozone-tracers" that run in parallel to the CAMx host model. OSAT does not affect the host CAMX model calculations; rather it extracts information on ozone formation source-relationships from the model in a mass consistent fashion. There are four ozone-reaction tracers per source area to account for the contributions of emissions of separate source areas to the complex process of the

[1] Note that "timing tracers" were not used in the Denver ozone source apportionment modeling so are not discussed further.

ozone formation activity. It is important to recall that the mass of NO_X or VOC from a given source area that may be present at a given receptor at a selected hour is often not particularly relevant to the amount of ozone present there at that time. Rather, it is the contribution to ozone formation activity of source areas' NO_X and VOC emissions en-route to a receptor that must be determined. The ozone-reaction tracers are designed to integrate these en-route contributions to ozone production/destruction activity.

Ozone formation involves both NO_X and VOCs, and the NO_X and VOCs participating in ozone formation in any particular grid cell/time step may have originated from different source groupings. The ozone formation process can be controlled more by the availability of VOCs or NO_X, depending upon the relative abundance of both precursors, and ozone formation is described either as VOC-limited or NO_X-limited, respectively. When ozone production at a given location and time is NO_X-limited it makes sense to attribute ozone production to source groupings based on their contributions to the local NO_X and similarly to allocate based on VOC contributions when ozone formation is VOC-limited. Consequently, separate tracers are used to track ozone formation occurring under NO_X-and VOC-limited conditions.

The four types of ozone-reaction tracers that are tracked for each source grouping (i.e., geographic area/source category, boundary conditions or initial conditions) are explained below. The name of each tracer uniquely identifies the source grouping it represents:

N_i = NO_X tracer for source grouping *i*. Emitted with the same spatial and temporal distribution as NO_X emissions for source grouping *i*. Decays with local dNO_X/dt for each grid cell/time step.

V_i = VOC tracer for source grouping *i*. Emitted with the same spatial and temporal distribution as VOC emissions for source grouping *i*. Decays with local $dVOC/dt$ for each grid cell/time step. Note that VOC tracers are defined as single carbon species, so their concentrations are numerically equal in ppb and ppbC units.

$O3V_i$ = Tracer of ozone formation under VOC limited conditions attributed to source grouping *i*. If ozone formation is determined to be VOC-limited for a given grid cell/time step, $O3V_i$ is formed in proportion to local dO_3/dt in proportion weighted by the distribution of VOC precursors (V_i).

$O3N_i$ = Tracer of ozone formation under NO_X limited conditions attributed to source grouping *i*. If ozone formation is determined to be NO_X-limited for a given grid cell/time step, $O3N_i$ is formed in proportion to local dO_3/dt in proportion weighted by the distribution of NO_X precursors (N_i).

The ozone reaction tracer methodology was designed to be inherently mass consistent with CAMx. In other words, the sums of the NO_X, VOC and ozone tracers should remain consistent with their standard CAMx counterparts as follows:

$$\sum N_i = NO + NO_2$$

$$\sum V_i = \sum CB4\ VOCs$$

$$O3 = \sum O3V_i + \sum O3N_i$$

The tracer families, N_i and V_i, track NO_X and VOC emissions from each source grouping to allow attribution of ozone formation as it occurs throughout CAMx. The rates of emission of the N_i and V_i tracers are set equal to the total NO_X and VOC emissions in the inventory for a source grouping, respectively. For the V_i tracers, the emissions are set equal on a ppmC basis. For the initial condition (IC) source grouping, the N_{IC} and V_{IC} tracers are initialized from the CAMx initial concentration fields and receive no more mass input after the start of the simulation. For the boundary condition (BC) source grouping, the fluxes of NO_X and VOC entering CAMx from the boundaries are effectively interpreted as emissions of the N_{BC} and V_{BC} tracers at the model boundaries. Unlike emission source groupings, boundary and initial conditions also introduce ozone directly into CAMx. Since there is no way of determining whether the ozone in the boundary and initial conditions was formed under VOC or NO_X limited conditions, this ozone is divided equally between O3N and O3V tracers. However, subsequent ozone formation within CAMx from boundary and initial condition VOCs and NO_X is allocated to O3V and O3N tracers on the basis of whether ozone formation occurred under VOC or NO_X limited conditions.

The N_i, V_i, $O3N_i$ and $O3V_i$ tracers are deposited at rates determined by the standard CAMx deposition calculation on a surface grid cell by grid cell basis. For NO_X, the deposition velocity for each tracer N_i [$V_d(N_i)$] is set equal to the concentration weighted average of the deposition velocities for NO and NO_2:

$$V_d(N_i) = \frac{NO \times V_D(NO) + NO_2 \times V_D(NO_2)}{NO + NO_2}$$

Similarly, the deposition velocity for each tracer V_i is set equal to the concentration weighted average of the deposition velocities for the VOC species (the concentration weighting is performed on a ppmC basis). The deposition velocity for the O3N and O3V tracers is set equal to the ozone deposition velocity.

The N_i, V_i, $O3N_i$ and $O3V_i$ tracers are transported and diffused in the horizontal and vertical using the same transport and diffusion fluxes used in the host model for NOx, VOC and ozone, respectively.

The N_i tracer mass in each grid cell at each time step decays according to the chemical change in the CAMx predicted NO_X (ΔNO_X) weighted by the tracer contribution to the total of NO_X tracers from all source groupings:

$$N_i = N_i + \Delta NO_x \times \frac{N_i}{\sum N_i}$$

The V_i tracer mass in each grid cell at each time step decays according to the chemical change in the CAMx predicted VOC (ΔVOC) weighted by the tracer contribution to the total of VOC

tracers from all source groupings. However, because the reactivity of VOCs from different source groupings can be different, a weighting factor based on the OH-reactivity of each V tracer (kOH_i) is also introduced. The kOH_i for each source grouping is calculated at the start of each simulation period (typically one day) by averaging the OH rate constants of the speciated VOC emissions for each source grouping. The V tracer mass in each grid cell at each time step decays at a rate determined by the following equation:

$$V_i = V_i + \Delta VOC \times \frac{V_i \times kOH_i}{\sum (V_i \times kOH_i)}$$

The O3N and O3V tracers for each source grouping accumulate a weighted fraction of the ozone production activity (PO_3) and ozone destruction activity (DO_3) that occurs in each grid cell at each time step. The process of apportioning PO_3 and DO_3 across O3N and O3V tracers occurs as follows:

1. Determine whether the local (grid cell/time step) ozone production process is NO_X or VOC limited. As described in detail below, the determination is based on the ratio of the local HNO_3 and H_2O_2 production rates. If the H_2O_2/HNO_3 production ratio is greater than 1/3 during a time step, then ozone formation is NO_X limited. If this ratio is less than or equal to 1/3, then ozone formation is VOC limited.

2. For allocating ozone production under conditions determined to be:

   (a) NO_X limited: allocate PO_3 across O3N tracers

   $$O3N_i = O3N_i + PO_3 \times \frac{N_i}{\sum N_i}$$

   (b) VOC limited: allocate PO_3 across O3v tracers based on maximum incremental reactivity (MIR) factors

   $$O3V_i = O3V_i + PO_3 \times \frac{V_i \times MIR_i}{\sum V_i \times MIR_i}$$

3. For ozone destruction, allocate across all ozone tracers.

   $$O3X_i = O3X_i + DO_3 \times \frac{X_i}{\sum X_i}$$

   where X = N and V.

This is the algorithm used for OSAT ozone source apportionment. The Anthropogenic Precursor Culpability Assessment (APCA) method of ozone source apportionment in CAMx was used in the Denver 2010 modeling uses a different algorithm for allocating ozone production, as described below.

The MIRs used in equation (5) are the weighted average MIRs for the emissions in each source group. The MIR approach was developed by Carter (1994) to approximate the ozone forming potential of VOCs accounting for both kinetic and mechanistic reactivity effects. The MIR

represents the ozone formation potential of the VOC mixture accounting for the VOC reactions with OH as well as the effects of all of the VOC products that produce ozone formation. The VOC + OH reaction is the main VOC destruction mechanism so it is appropriate to weight the VOC destruction across the VOC reactive tracers by their composite reaction rate with OH (kOH).

The determination of whether the ozone produced is under more VOC-limited or NOx-limited conditions is based on the main radical termination reactions in the atmosphere. Under VOC-limited conditions the instantaneous production of HNO3 is higher, whereas under NOx-limited conditions the instantaneous production of H2O2 is higher. Thus a ratio of the production of these two species is used to determine whether ozone formation was more VOC-limited or NOx-limited, which was extensively tested in the development of OSAT (ENVIRON, 2008).

Anthropogenic Precursor Culpability Assessment (APCA). APCA differs from OSAT in recognizing that certain emission groups are not controllable (e.g., biogenic emissions) and that apportioning ozone production to these groups does not provide information that is relevant to control strategies. To address this, in situations where OSAT would attribute ozone production to non-controllable (i.e., biogenic) emissions, APCA re-allocates that ozone production to the controllable portion of precursors that participated in ozone formation with the non-controllable precursor. In the case where biogenic emissions are the uncontrollable source category, APCA would only attribute ozone production to biogenic emissions when ozone formation is due to the interaction of biogenic VOC with biogenic NO_X. When ozone formation is due to biogenic VOC and anthropogenic NO_X under VOC-limited conditions (a situation in which OSAT would attribute ozone production to biogenic VOC), APCA re-directs that attribution to the anthropogenic NO_X precursors present. The use of APCA instead of OSAT results in more ozone formation attributed to anthropogenic NO_X sources and less ozone formation attributed to biogenic sources. APCA is not really a "source apportionment" technique because it expresses biases as to which sources should be implicated (i.e., those that are controllable), hence it is referred to as a "culpability assessment." .

3.3 APPLICATION METHODOLOGY

The APCA version of the CAMx ozone source apportionment was applied using the 2010 base case inventory with the emissions segregated into 8 source categories and 11 source regions. The source categories are presented in Table 3-1. A list of the source regions is presented in a tabular form in Table 3-2 and in graphical form in Figures 3-1 and 3-2 for the 12 km and 4 km CAMx domains, respectively. Note that in some cases only small portions of states on the periphery of the 12 km grid are included in the analysis. Further note that source regions are defined on a grid cell basis, with each grid cell assigned to the region with the largest area. Thus, it is possible for sources on the border of a region to get assigned to an adjacent region.

Table 3-1. Source apportionment source groups for Denver SIP 2010 modeling.

Source Apportionment Source Groups
Biogenic/Fires
On-road Motor Vehicles
Non-road
Oil and Gas
Area Sources
Industrial Point Sources
Electric Generation Units
Boundary and Initial Conditions

Table 3-2. Source apportionment source regions for Denver SIP 2010 modeling.

Source Apportionment Source Regions
7-County Denver Metro
Larimer/Weld Counties
Northeastern Colorado
Southeastern Colorado
Southwestern Colorado
Northwestern Colorado
Wyoming, Idaho, Oregon
Utah, Nevada, California
Arizona, New Mexico
Kansas, Texas, Oklahoma, Missouri, Arkansas
Nebraska, South Dakota, Minnesota, Iowa

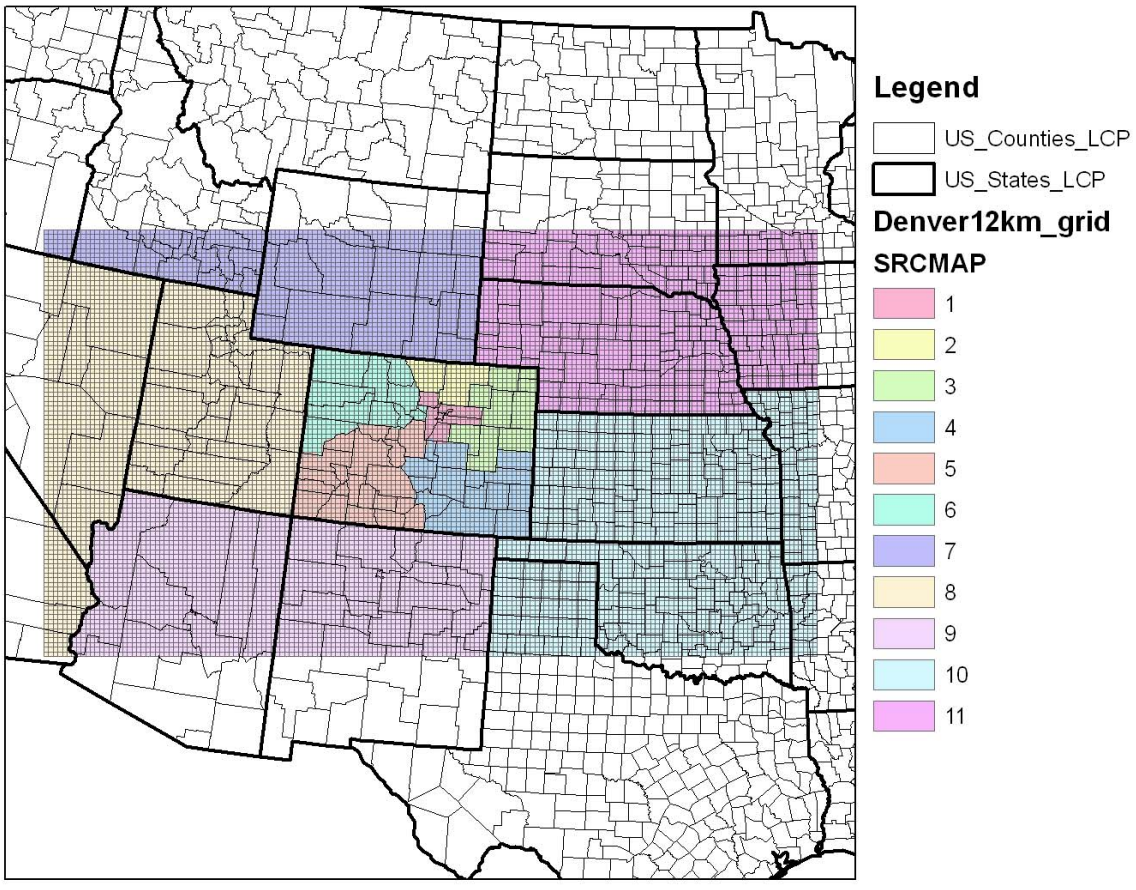

Figure 3-1. Source apportionment source regions in 12km CAMx domain.

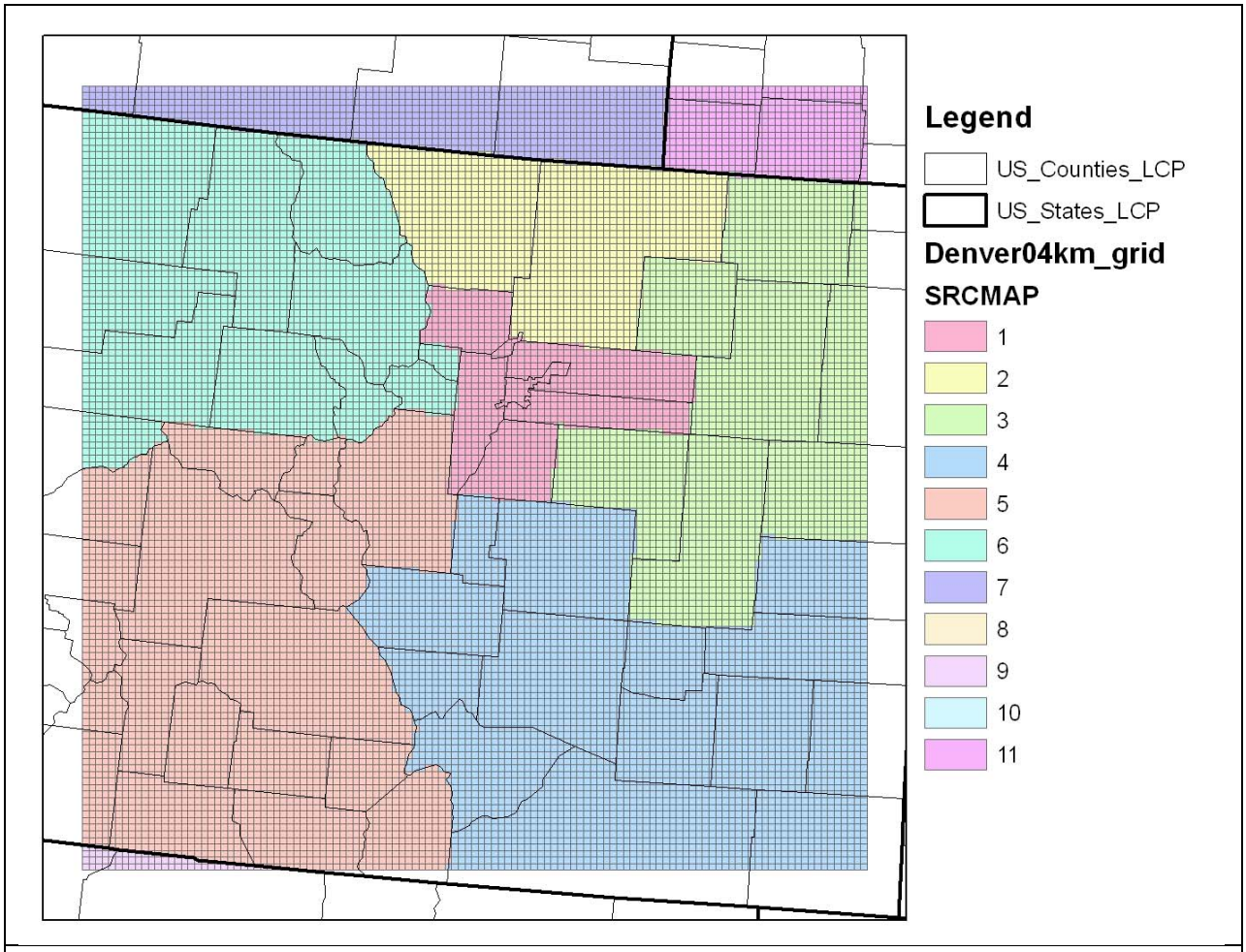

Figure 3-2. Source apportionment source regions in 4km CAMx domain.

3.4 ANALYSIS METHODOLOGY AND RESULTS

The source apportionment results were analyzed at the ozone monitor sites used in the ozone attainment test presented in Section 2 of this report. At each monitor location, for each day, the 8-hour average ozone results for each period over 70 ppb were averaged to develop a composite contribution.

Example displays for a high ozone day (July 29th) at the Rocky Flats North and Fort Collins West monitors, the two monitors with the highest future year design values are presented in this section. APCA ozone source apportionment modeling results for other days and other monitors are presented in Appendix C. The results show significant day-to-day and monitor-to-monitor variation. The Rocky Flats North results are presented in Figure 3-3. Figure 3-3a presents the ozone results including the boundary conditions, that is, the contribution from sources outside the 12 km domain. Of the 76.1 ppb of ozone estimated at the monitor, ~48 ppb was transported into the 12 km domain and ~18 ppb was attributed to sources in the seven-county Denver Metro area. Figure 3-3b presents the same results as 3-3a, but without the boundary conditions plotted and the vertical scale expanded to better resolve the source region contributions. This figure shows that of the ~18 ppb from Metro Denver sources ~10 ppb was from motor vehicles, ~5 ppb

was from non-road mobile sources with the balance from other sources. Figure 3-3c presents the ozone formed under anthropogenic NOx-limited conditions, that is, ozone formed under conditions where the model is responsive to NOx controls or since the APCA version of source apportionment was used, ozone formed under VOC-limited conditions due to the interaction of biogenic VOC with anthropogenic NOx. Figure 3-3d presents the ozone formed under anthropogenic VOC-limited conditions, that is, ozone formed under conditions where the model is responsive to VOC controls. These two figures suggest that emission reductions from NOx sources will be more effective at reducing ozone in the model than reductions from VOC sources, although both VOC and NOx controls will reduce ozone. Analogous plots for the Fort Collins West monitor are presented in Figure 3-4 that show similar contributions as the Rocky Flats North monitor, except the highest contributions are from sources in the Larimer/Weld County source region and oil and gas sources from Larimer/Weld County have a large contribution which they didn't at Rocky Flats North.

The source apportionment results vary by day and by location. However, several overall trends emerge, namely:

- Regional ozone transport into the 12 km domain is the largest contributor, often accounting for more than two-thirds of the total ozone;
- At the Denver Metropolitan monitors, the largest contributors are Denver Metropolitan area motor vehicle and non-road sources;
- At the Fort Collins and Greeley monitors the largest contributors tend to be Larimer and Weld County motor vehicles, non-road sources and oil and gas sources, and Denver Metropolitan sources;
- The majority of the ozone is attributable to anthropogenic NOx emissions.

In interpreting these results it is important to keep in mind that these source apportionment results are based on the Denver SIP 2006 modeling episode and are meteorologically dependent. For instance, the source apportionment modeling in support of the Denver Early Action Compact (Morris et. Al., 2004f,g) using the 2002 ozone episode showed more impact of sources in Larimer/Weld Counties into the Denver Metropolitan area.

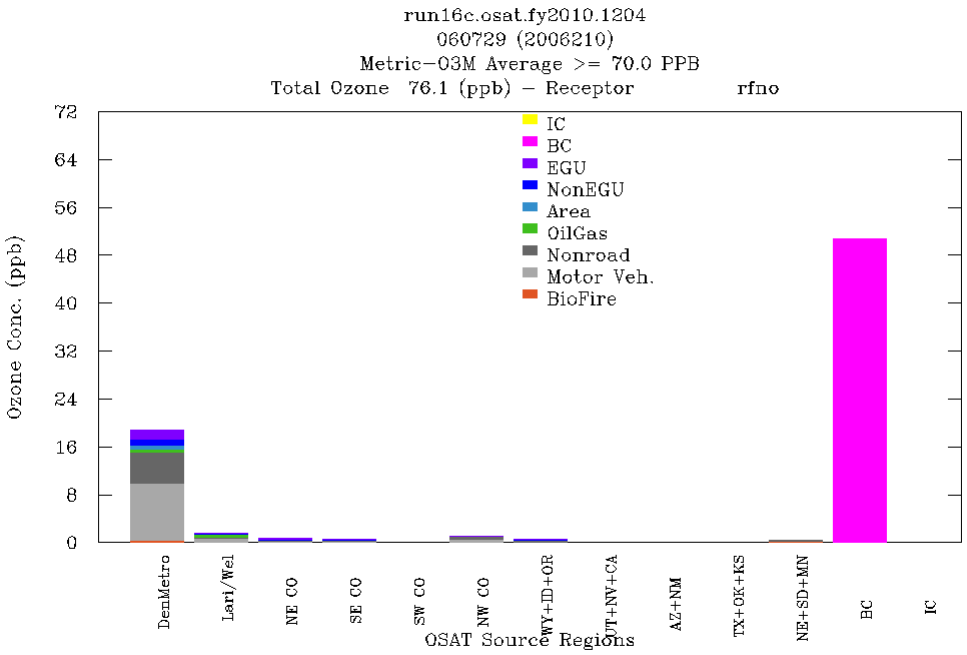

Figure 3-3a. Rocky Flats North source apportionment for 29 July including boundary conditions.

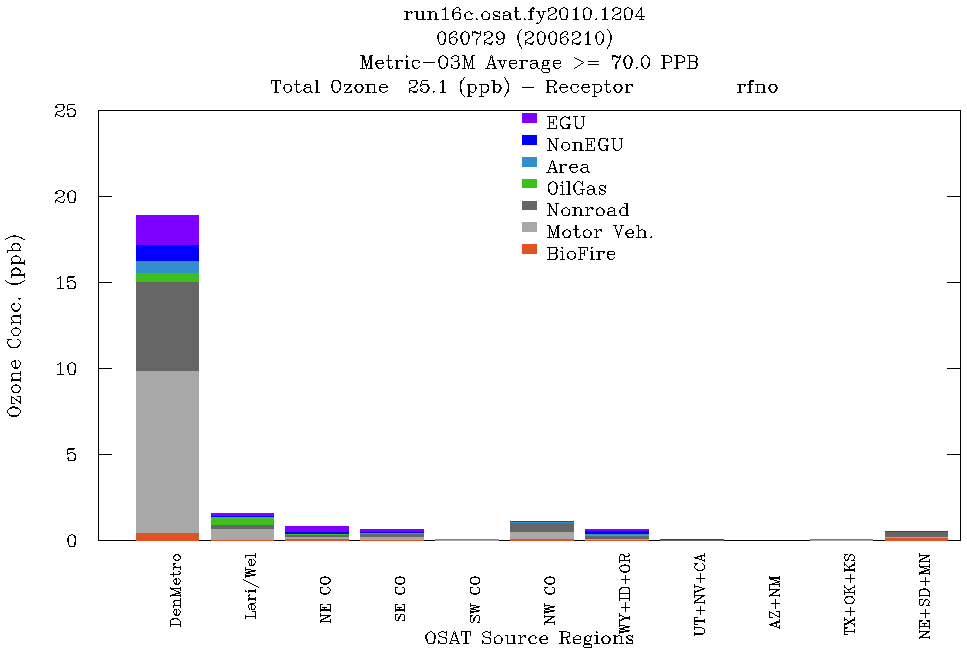

Figure 3-3b. Rocky Flats North source apportionment for 29 July excluding boundary conditions.

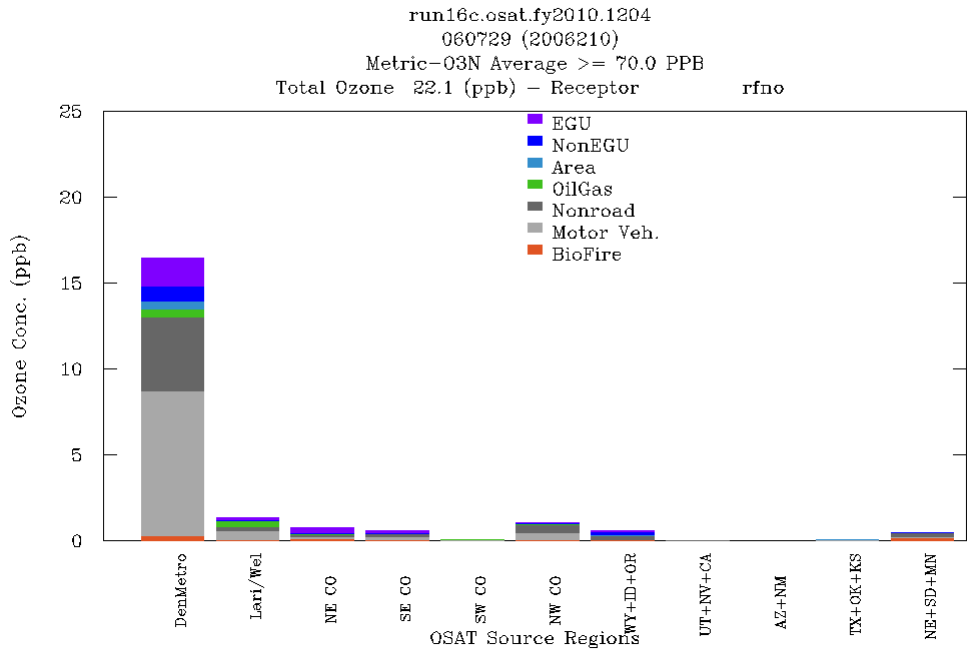

Figure 3-3c. Rocky Flats North source apportionment for 29 July attributable to anthropogenic NOx sources.

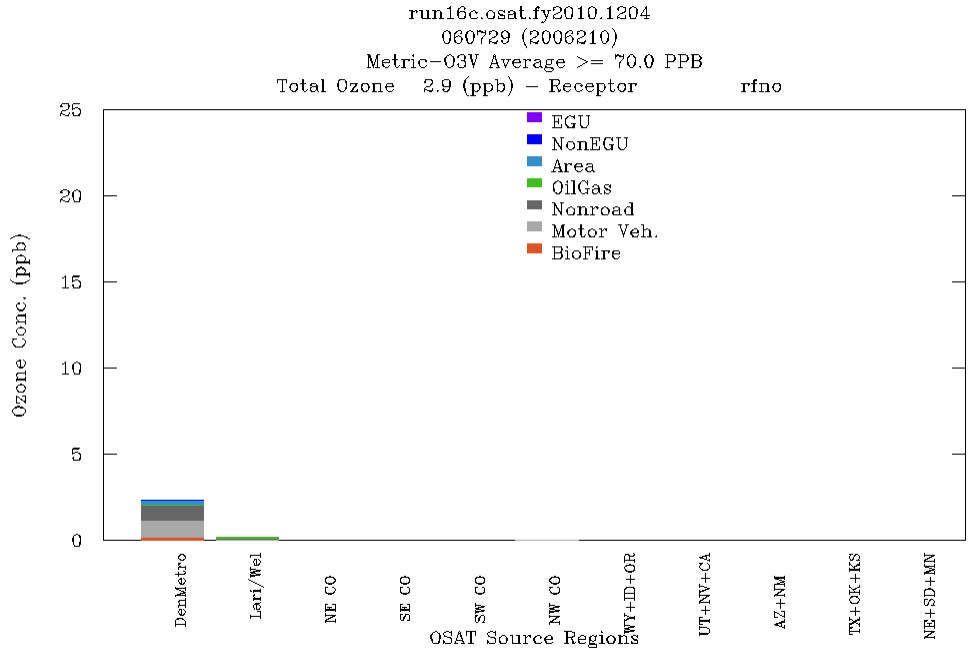

Figure 3-3d. Rocky Flats North source apportionment for 29 July attributable to anthropogenic VOC sources.

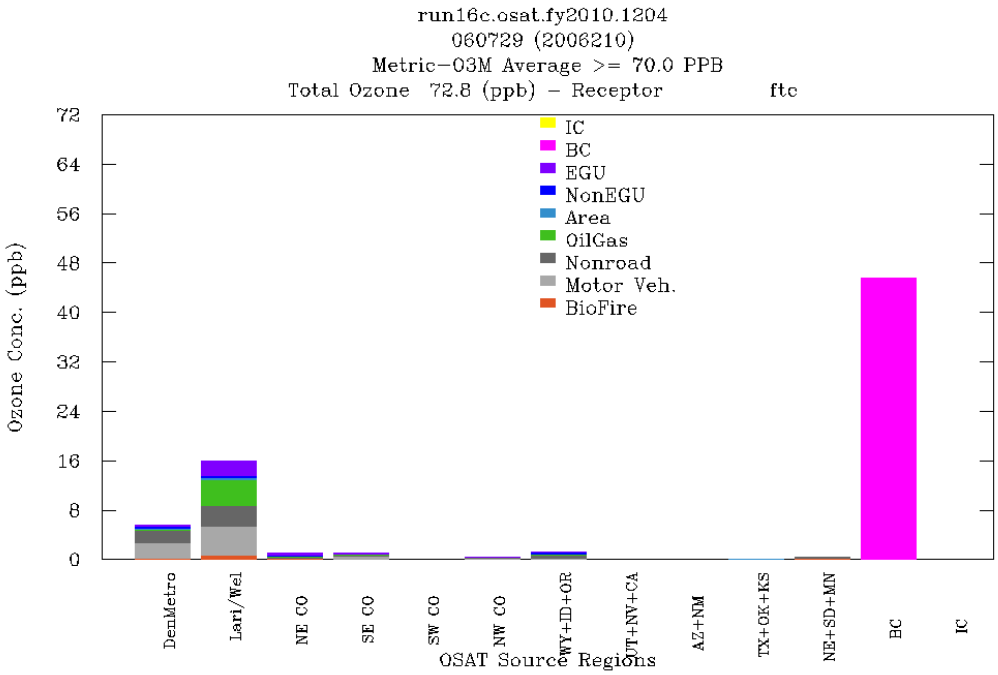

Figure 3-3a. Fort Collins West source apportionment for 29 July including boundary conditions.

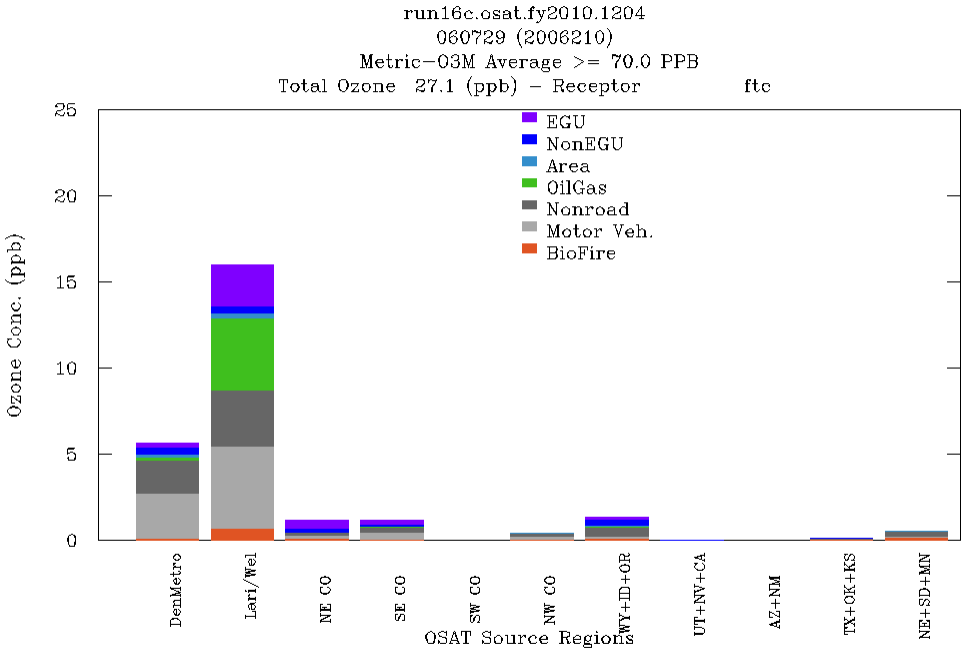

Figure 3-3b. Fort Collins West source apportionment for 29 July excluding boundary conditions.

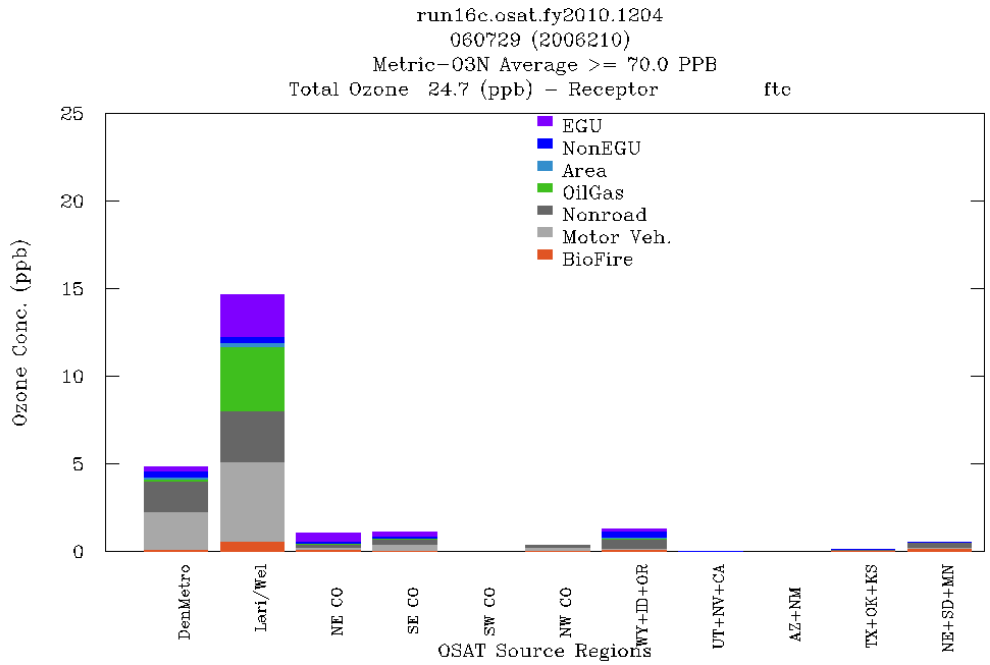

Figure 3-3c. Fort Collins West source apportionment for 29 July attributable to anthropogenic NOx sources.

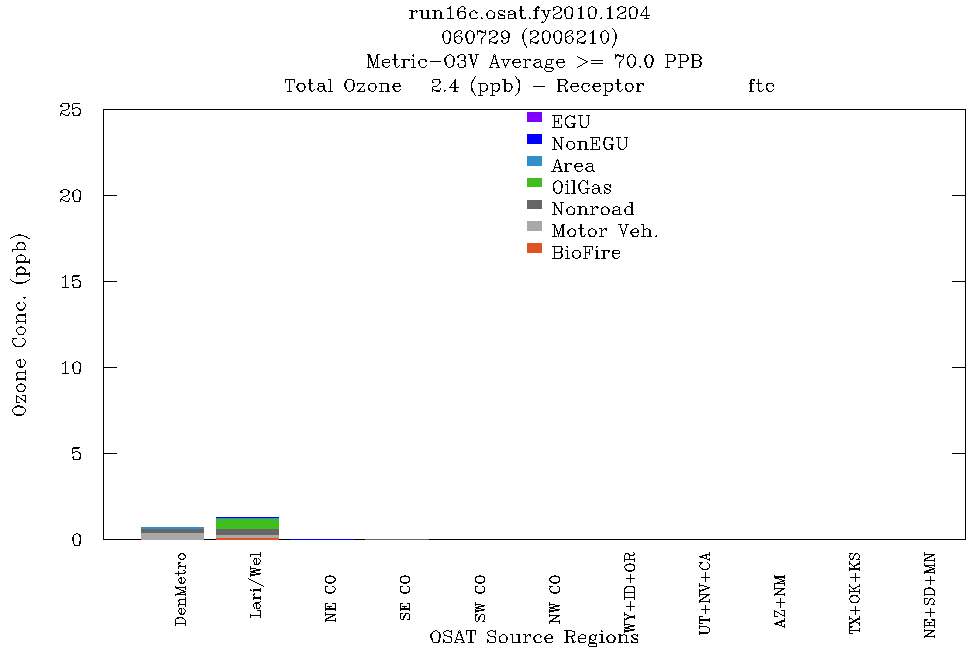

Figure 3-3d. Fort Collins West source apportionment for 29 July attributable to anthropogenic VOC sources.

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