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Regional Modeling of Weekday/Weekend Ozone Changes in the Midwestern US

Final Report

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COORDINATING RESEARCH COUNCIL, INC.
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Foreword

Under CRC Project A-69-1 "Regional Modeling of Weekday/Weekend Ozone Changes in the Midwestern US," ENVIRON International Corporation conducted research to evaluate a regional modeling system for simulating weekday/weekend ozone changes in the eastern US and understand how the weekday/weekend emission changes in urban cities affect ozone in downwind areas. Based on the research results, a draft journal manuscript entitled "Local and Regional Contributions to Weekday-Weekend Ozone Changes in the Midwest" was produced. It will be submitted to Atmospheric Environment for publication.

The draft manuscript is included in this report along with an Executive Summary and additional supporting materials not presented in the journal article.

Final Report

CRC PROJECT A-69-1

Regional Modeling of Weekday/Weekend Ozone Changes in the Midwestern US

Prepared for

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List of Abbreviations

AQS	Air Quality System (monitoring network)
CAMx	Comprehensive Air-quality Model with Extensions
CDC	Cincinnati/Dayton/Columbus
CENRAP	Central Regional Air Planning Association
CMAQ	Community Multiscale Air Quality Modeling System
CONCEPT	Consolidated Community Emissions Processing Tool
CRC	Coordinating Research Council
DDM	Decoupled Direct Method
EPA	Environmental Protection Agency
HC	Hydrocarbon
HDDV	Heavy Duty Diesel Vehicle
LADCO	Lake Michigan Air Directors Consortium
MANE-VU	Mid-Atlantic/Northeast Visibility Union
MEGAN	Model of Emissions of Gases and Aerosols from Nature
MM5	Mesoscale Model version 5
MNB	Mean Normalized Bias
MNE	Mean Normalized Error
MOVES	Motor Vehicle Emission Simulator
MSA	Metropolitan Statistical Area
NOx	Nitrogen Oxides (NO and NO2)
NREL	National Renewable Energy Laboratory
PAMS	Photochemical Assessment Monitoring Station
RPO	Regional Planning Organization
SIP	State Implementation Plan
SLM	Southern Lake Michigan
SoCAB	South Coast Air Basin
TNMOC	Total Nonmethane Organic Compound
VISTAS	Visibility Improvement State and Tribal Association of the Southeast
VOC	Volatile Organic Compound

Executive Summary

Summary/Conclusions

- Comprehensive Air-quality Model with Extensions (CAMx) was applied for a three-month long summer ozone episode to examine the weekend ozone effect in the Midwestern US at both urban and regional scales.
- The base case simulation is based on the Lake Michigan Air Directors Consortium (LADCO) 2005 modeling database which was improved by updating Heavy Duty Diesel Vehicle (HDDV) NOx emissions and weekday/weekend temporal adjustments for several non-road and area source emissions.
- The model generally reproduced the observed daily maximum 1-hour and 8-hour ozone and also correctly predicted weekend changes in the VOC-to-NOx ratio.
- So-called dynamic evaluation of the modeled weekend ozone changes throughout the summer revealed that meteorology had a bigger impact on the summer 2005 weekend ozone effect than anthropogenic emission changes.
- To avoid the confounding effect of meteorological changes, weekend ozone differences were determined by using a second simulation modeled with weekday emissions for all days of week (ozone differences between the base case and the second simulation isolated the effect of weekday/weekend emission changes).
- To further distinguish local effects of weekend emission changes from transported regional ozone differences, a third simulation applied weekend emission changes only within two urban areas with all weekday emissions for the remaining areas (ozone differences between the base case and the third simulations show the effect of regional weekend emission changes while the difference between the second and third simulations reveal the effect of local weekend emission changes).
- Regional emission reductions on weekends mostly lead to ozone decreases whereas for urban centers and immediate downwind areas weekend emission reductions increased ozone.
- The sign-change in the weekend ozone effect from urban centers to downwind areas is explained by a matching change in sign of ozone sensitivity to NOx emissions which was confirmed by computing ozone sensitivities to domain-wide NOx and VOC emissions.
- The sensitivity analysis also showed that weekday/weekend ozone differences in the Midwestern US are due primarily to weekend reductions in NOx emissions.

Recommendations

Based on this study, the following recommendations are made:

- The weekend ozone effect should be considered in regional ozone planning for the Midwestern US because the weekday/weekend ozone differences can be large enough to influence compliance with ozone air quality standards.
- Emission control strategies should take into account that local emission reductions may lead to both ozone increases and decreases.
- Dynamic evaluation of modeled ozone response to emission changes should include multiple ozone seasons (with consistent emission changes) to minimize the effect of meteorological variability.
- It may provide another insight in understanding the weekday/weekend ozone effects to examine long-term meteorological differences between the weekdays and weekend days (e.g., weekday/weekend analysis on LADCO's CART analysis data).

Overview of the Project

Introduction

Variation in human activity patterns between weekdays and weekends can cause ambient ozone levels to vary over the course of the week. Air quality modeling of weekday/weekend ozone can be used to (1) better understand the observed changes in ozone and precursors, and (2) test the model's ability to simulate the effects of emissions changes. Previous Coordinating Research Council (CRC) projects (CRC A-36 and A-56) studied weekday/weekend ozone changes for the Los Angeles area. However, formation of ozone has different characteristics in Southern California and the Eastern US because biogenic emissions and ozone transport tend to be significant in the Eastern US whereas local/urban ozone formation plays a major role in Southern California. A previous modeling study for the National Renewable Energy Laboratory (NREL) investigated weekday/weekend ozone changes in the Detroit area. CRC initiated project A-69-1 to perform a larger, regional scale modeling study to examine regional and local-scale contributions to weekday/weekend impacts in the Eastern US.

Specific objectives of the CRC A-69-1 project are to:

- Review weekday/weekend emission adjustments currently adopted for modeling in the Eastern US and recommend a consistent set of adjustments;
- Test an ozone model's ability to simulate weekday/weekend ozone changes for the regional scale; and
- Determine the extent that weekday/weekend emission changes in upwind urban areas affect downwind urban and rural areas.

Improvements to Emission Inventories

Mobile source emission inventories for the Eastern US were revised by updating heavy-duty diesel vehicle (HDDV) NOx emission rates and speed correction factors. Recent HDDV testing data for varying driving cycles that were not used in the development of MOBILE6 were reviewed and compared with MOBILE6 emission rates for hydrocarbon (HC) and NOx. Adjustment factors to MOBILE6 HDDV emissions were developed (Table ES-1).

Table ES-1. Average adjustment factors for HDDV to MOBILE6 for 2005.

Speed (mph)	HC	NOx
2	7.15	3.26
15	2.53	1.68
19	3.41	1.89
40	1.64	1.80
50	2.24	1.51

Updated HDDV emission rates were incorporated into link-based emissions inventories for six Upper Midwest States (IL, IN, MI, WI, OH, and MN) and county-level emissions modeling for other states. Mobile source emissions modeling used the Consolidated Community Emissions Processing Tool (CONCEPT) MV model. While the adjustment factors for hydrocarbons in Table ES-1 are large, the HDDV contribution to motor vehicle HC emissions is very small. HDDV NOx emissions, on the other hand, typically represent about half of the total on-road NOx emissions and the multipliers shown in Table ES-1 significantly increase that contribution. Figure ES-1 compares on-road NOx emissions by vehicle type in the unadjusted (base case emissions without the HDDV emission factor adjustments) and adjusted emission inventories and shows a 30-35% increase in overall on-road NOx emissions. For the HDDV sector, the increase in NOx emissions is 80 percent for Fridays and 70 percent for weekend days. The weekend increases are smaller because average speeds for HDDV are slightly higher on weekends, and the adjustments decrease with increasing speed. Recently EPA released a new emission factor model, called MOVES which replaced MOBILE6. MOVES has a completely different modeling approach than MOBILE6 and thus results in substantially different emissions (frequently higher NOx emissions) than MOBILE6. However, we believe our updated HDDV emissions should be comparable to those by MOVES as our updated emission factors are based on the same HDDV testing data that EPA used to develop MOVES. For more details on the HDDV NOx emission updates, see Appendix A.

Temporal profile adjustments to off-road mobile and area source emissions implemented by LADCO, other eastern Regional Planning Organizations (MANE-VU, CENRAP, and VISTAS) and EPA were reviewed and evaluated. Table ES-2 summarizes adjustments recommended by ENVIRON that were implemented in this study. For more details on the temporal profile adjustments, see Appendix B.

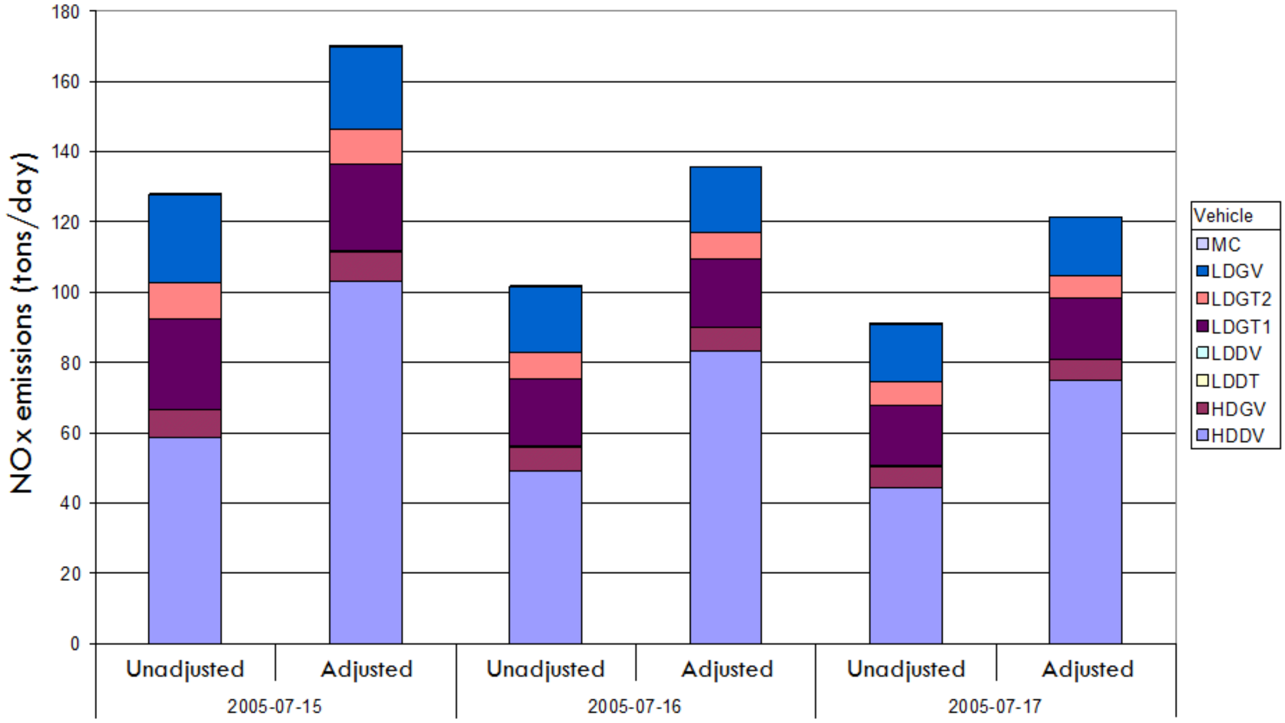

Figure ES-1. On-road NOx emissions (tons/day) by vehicle class for the Columbus, OH transportation network for a Friday (July 15)/Saturday (July 16)/Sunday (July 17), 2005. "Unadjusted" emissions are base case emissions without HDDV emission factor adjustments by speed; "Adjusted" emissions are with the adjustment factors.

Table ES-2. Temporal adjustments made to the temporal profiles for non-road and area sources.

Source Category	Recommendation	Comment
Surface Coating	Use LADCO adjustments	LADCO profiles generally show zero activities on weekends and during night reflecting that surface coating activity will likely have different patterns for weekdays and weekends.
		EPA default day of week profile is flat; EPA default diurnal profile shows non-zero activity during middle of night (unreasonable).
Stationary Source Fuel Combustion	Use EPA default	LADCO inventory assumes flat day of week and hour of day profiles.
		EPA default profile reflects that industrial fuel combustion will likely show lower activity during weekends; more reasonable to assume lower activity during middle of night (less heating).
Gasoline Service Station	Use LADCO adjustments	LADCO profile reflects that less traffic will likely result in less fueling activity during weekends.
		EPA default day of week profile is flat.
Consumer Solvent (e.g., automotive aftermarket products)	Use LADCO adjustments	LADCO profile reflects that people tend to perform auto service during weekends.
		EPA default day of week profile is flat; EPA default diurnal profile shows non-zero activity during middle of night (unreasonable).
Commercial Solvent – Pesticide Application	Use LADCO adjustments	LADCO profile reflects that commercial solvent/pesticide application will likely be reduced on Sunday.
		EPA default day of week profile is flat; EPA default diurnal profile shows non-zero activity during middle of night (unreasonable).
Lawn & Garden Equipment	Use SoCAB daily profile & LADCO adjustments for hourly profile	SoCAB profile shows sharply reduced commercial lawn & garden activity during weekends which is more reasonable.
		LADCO diurnal profile shows zero activity during night.
		EPA default diurnal profile shows non-zero activity during middle of night (unreasonable).
Construction Equipment	Use LADCO adjustments	LADCO adjustments and EPA default show similar day of week profiles, but LADCO profile is based on later data.
		EPA default diurnal profile shows non-zero activity at midnight (unreasonable).
Recreational Boating	Use CENRAP adjustments	LADCO profile reflects that recreational boating activity will likely increase during weekends; sport fishing which starts in the early morning will likely dominate the recreational boating activity in the morning.
		EPA default day of week profile is flat.

Base Case Model Performance Evaluation

The base case simulates ozone for the three month summer episode of June-August, 2005 with a 10-day spin-up period. The modeling domain consists of 36-km and 12-km grids over the eastern US and the Midwest, respectively. We added 4-km grids in two extended urban regions over Southern Lake Michigan (SLM) and Cincinnati/Dayton/Columbus (CDC).

Base case model performance was evaluated using EPA's Air Quality System (AQS) hourly ozone measurement database. Figure ES-2 shows mean normalized bias (MNB) and mean normalized error (MNE) of the modeled daily maximum 8-hour average ozone concentrations for each day over the 12-km Midwest domain. MNB and MNE are defined as follows:

$$\text{MNB} = \sum_i \frac{P_i - O_i}{O_i} \qquad \text{MNE} = \sum_i \left|\frac{P_i - O_i}{O_i}\right|$$

where P_i and O_i represent model predicted and observed ozone concentrations, respectively The model generally meets performance goals of ±15% for MNB and 35% for MNE on high ozone days. The model tends to over-predict peak 8-hour ozone on low ozone days (e.g., 10-11 June, 13-18 July, and 14-20 August where observed average peak 8-hour ozone concentrations are less than ~50 ppb). Ozone model performance for the 4-km grids is similar to the 12-km result.

Ozone formation occurs via reactions of radicals and is sensitive to the ratio of VOC to NOx concentrations because, in general, VOCs contribute to radical initiation and propagation whereas NOx contributes to radical termination and propagation. The VOC-to-NOx ratio influences how ozone formation responds to changing NOx and/or VOC emissions, thus model performance for the VOC-to-NOx ratio is one indicator of the model's ability to predict ozone response to emission changes. Modeled VOC-to-NOx ratios were evaluated at three Photochemical Assessment Monitoring Station (PAMS) sites in the SLM domain: Two sites in Chicago, Illinois and one in Milwaukee, Wisconsin. Figure ES-3 compares observed and modeled ratios of total nonmethane organic compounds (TNMOC) to NOx in the morning (06:00-09:00). Observed TNMOC-to-NOx ratios at the two Chicago sites range from 1.3 to 2.4 ppbC/ppb indicating ozone formation will be VOC-limited. The ratios at the Milwaukee site are slightly higher ranging from 3.4 to 5.1 ppbC/ppb. The model over-predicted the ratios at the two Chicago sites while under-predicting at Milwaukee. At all three sites, however, both observation and model show increases in weekend TNMOC-to-NOx ratios with the Milwaukee site having greater weekend increases than the Chicago sites.

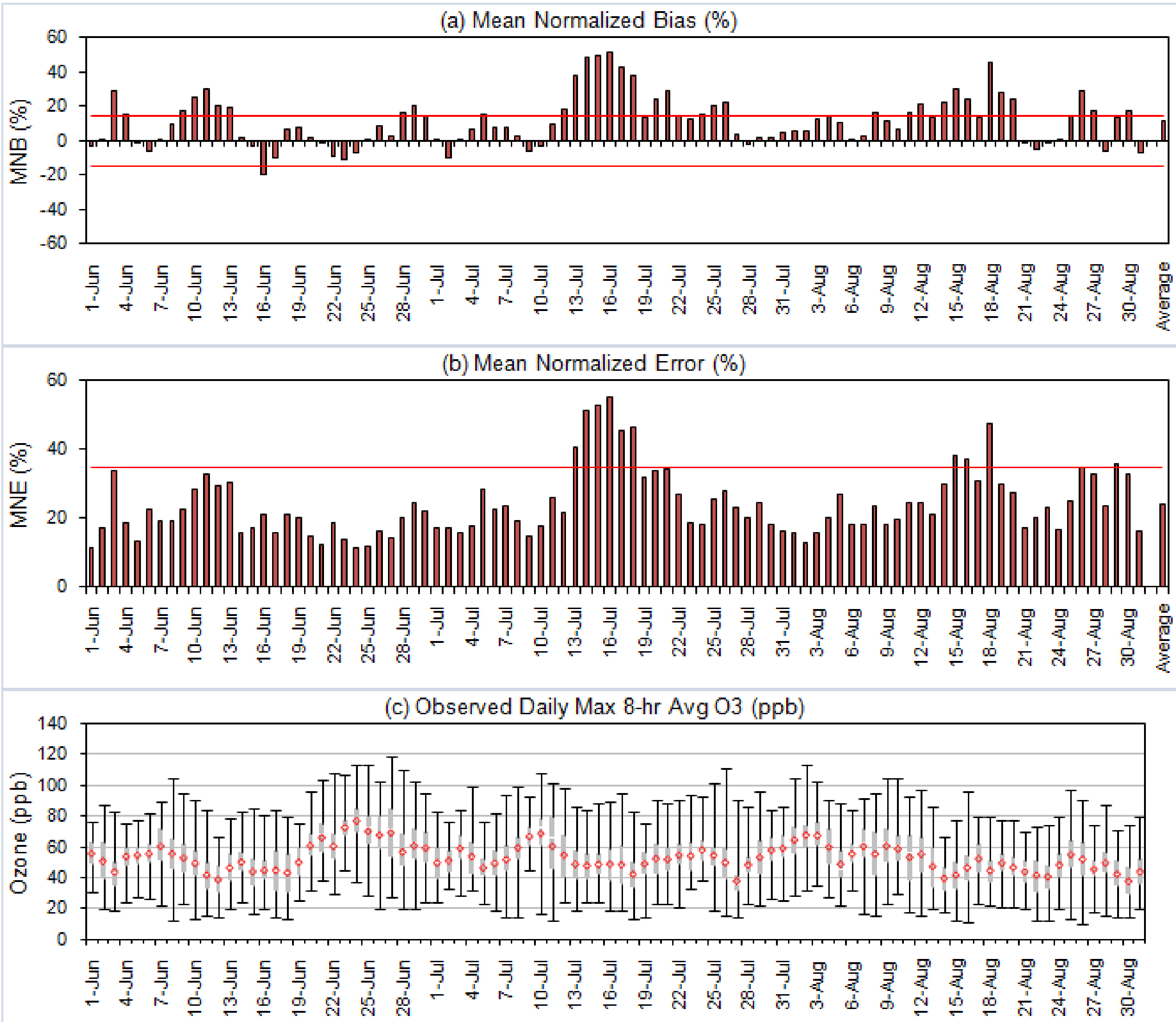

Figure ES-2. Statistical metrics for daily maximum 8-hour ozone concentrations over the 12-km Midwest domain: (a) Model mean normalized bias (MNB); (b) model mean normalized error (MNE); (c) box and whisker plot for observations: The inner quartiles (the 25th to 75th percentiles) are represented by gray boxes, separated at the median by a horizontal line; the lower and upper quartiles are represented by whiskers; the means are represented by diamond markers.

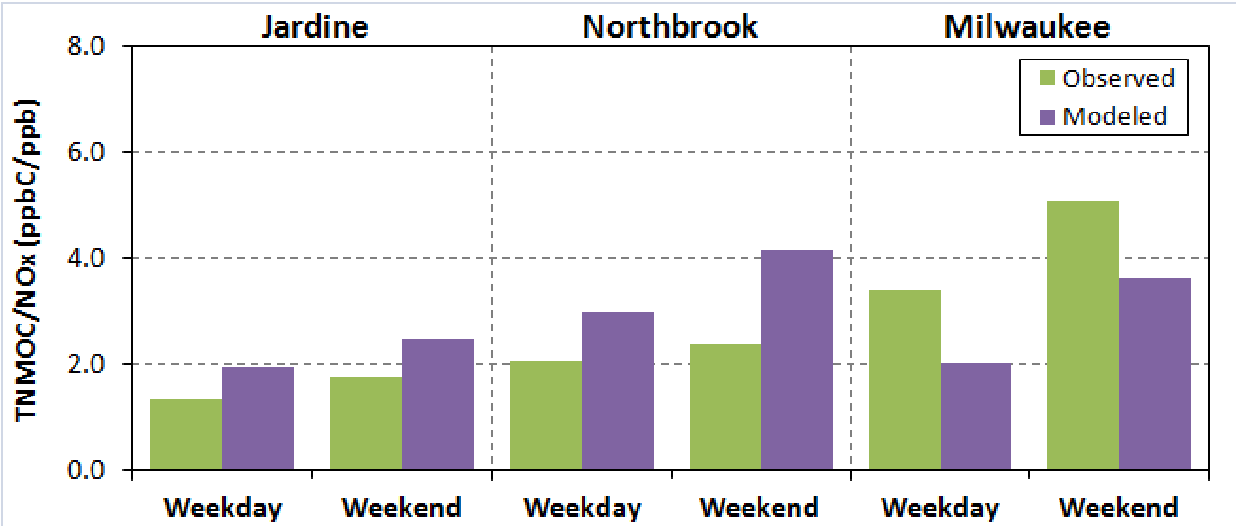

Figure ES-3. Median morning (06:00-09:00) TNMOC-to-NOx ratios for June-August, 2005. Weekday averages Monday through Friday during the three-month period and weekend averages Saturday and Sunday.

Spatial patterns of modeled and observed weekday/weekend ozone differences were compared at AQS monitoring sites focusing on high ozone conditions (60 ppb threshold) that are relevant to compliance with ozone standards. The observed difference in weekday/weekend daily maximum 8-hour ozone at the *i*-th monitoring site (D_i) was calculated as

$$D_i = (S_i - W_i)$$

where W_i and S_i represent averages of daily maximum 8-hour ozone on Wednesday and Saturday or Sunday, respectively. W_i is a simple average of Wednesdays with 8-hour ozone ≥ 60 ppb. S_i is the average of weekend days exceeding a threshold that yields the same percentile of selected weekend days as the selected Wednesdays at the *i*-th site.

Spatial plots of weekday/weekend ozone differences (Figure ES-4) were prepared by interpolating (Kriging) the observed and modeled D_i at sites with at least four Wednesdays with 8-hour ozone ≥ 60 ppb during the three-month episode (Figure ES-4 (a) shows the observations). Two different methods were used to calculate the modeled weekday/weekend ozone differences. In the first method a second model simulation (S1) was performed with weekday emissions on all days and the differences in modeled ozone (base case minus S1) result from weekday/weekend emission changes. This result is displayed in Figure ES-4 (b) using the Kriging interpolation method to place the observed and modeled ozone differences on a common basis. The modeled ozone differences agree poorly with the observed differences with observations showing much wider areas of ozone increase than modeled. Figure ES-4 (c) shows modeled ozone differences calculated using the same approach as the observed ozone differences (i.e., ozone differences between high ozone Wednesdays and weekend days predicted by the base case simulation), which gives better agreement with the observed weekday/weekend differences. The weekday/weekend ozone differences shown in Figures ES-4 (a) and (c) are affected both by weekday/weekend emissions changes and meteorological differences (e.g., temperature). Therefore, the above results demonstrate that, for this region and modeling period, meteorological differences between the weekdays and weekends had more influence than emission differences on ozone. Several ozone seasons may be averaged to minimize the effect of meteorological variability. However, averaging several years has the disadvantage that emissions change as new control programs are introduced and we cannot tell the effect of the change. The modeling approach shown in Figure ES-4 (b) has an important advantage in investigating how weekday/weekend emission changes affect ozone when strong meteorological influence exists during the study period.

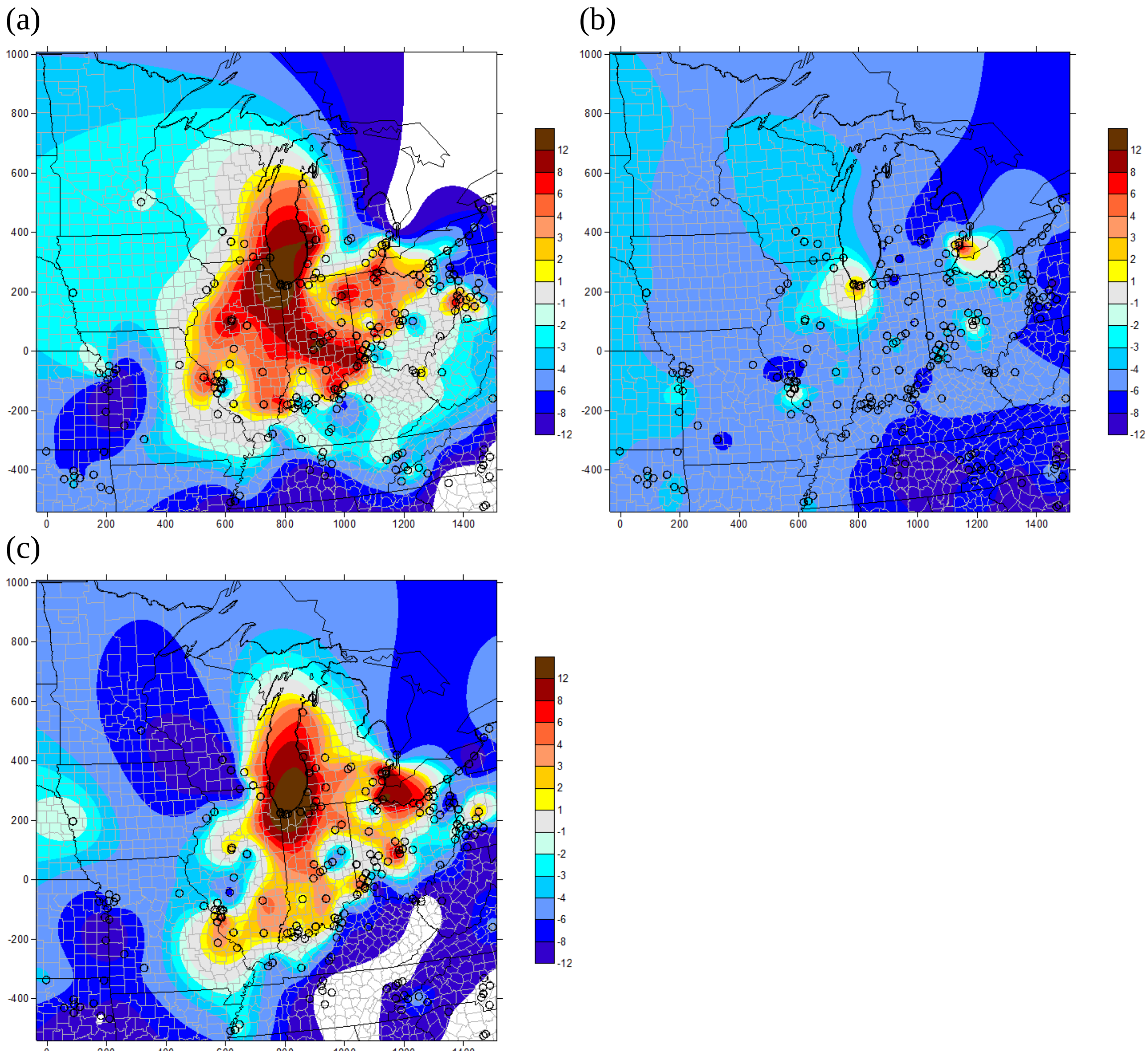

Figure ES-4. Weekend minus weekday differences in daily maximum 8-hour ozone concentrations (ppb) using Kriging interpolation of values at the AQS monitoring sites (circle markers). (a) Observed ozone differences of average high-ozone Wednesday minus average high-ozone Sunday. (b) Modeled ozone differences of the base case minus S1 simulation on average high-ozone Sunday. (c) Modeled ozone differences of average high-ozone Wednesday minus average high-ozone Sunday.

Local and Regional Effects of Weekend Emission Changes

In the following discussion, we will use the term “regional” to describe changes over the entire modeling domain outside the 4-km grids. Many urban areas are in close proximity in the Midwest such that effects of weekend emission changes may be transported from one urban area to another or from rural areas to urban areas. We performed another sensitivity case (S2) where the base case (both weekday and weekend) emissions were retained for the two 4-km urban modeling domains but all weekday- emissions (as in S1) were applied outside of the 4-km domains. Ozone differences between the base case and S2 (Figure ES-5 (a)) reveal that regional weekend emission changes mostly lower peak 8-hour ozone on weekend days indicating that regional ozone formation is NOx-limited. Conversely, ozone differences between S1 and S2 (Figure ES-5 (b)) reveal that local (urban) weekend emission changes lead to ozone increases as well as decreases. The weekend ozone increases at the urban centers and immediate downwind areas reach up to ~9 ppb in modeled daily maximum 8-hour ozone. Areas further downwind show weekend ozone decreases of up to ~7 ppb. Because some Midwest urban areas were found to be strongly VOC-limited (including Chicago and Detroit), the effect of weekday-weekend changes in both NOx and VOC emissions should be taken into account in developing control strategies for these areas.

Figure ES-6 shows time-series of local and regional contributions to weekend ozone changes for two urban centers (Chicago and Columbus). On average, ozone increases due to local weekday/weekend emission changes are lower at Chicago than Columbus on Saturday, but slightly higher on Sunday. Weekend ozone decreases due to regional emission changes are similar at the two locations. The overall weekend ozone change is the sum of the regional and local contributions using this methodology. On most days and on average the local contribution outweighs the transported contribution. The local contribution is greatest on the days when emissions change (Saturday and Sunday) whereas the regional contribution lags by a day (peaking on Sunday and Monday) and sometimes persists for several days because of the time required for ozone transport from rural areas to the urban areas.

Ozone Sensitivity to NOx and VOC Emissions

The ozone impacts of weekend emission changes for VOC and NOx can be understood by calculating ozone sensitivity to VOC and NOx emissions. The Decoupled Direct Method (DDM), an efficient sensitivity analysis tool, was applied to calculate the first-order sensitivities of daily maximum 8-hour ozone to anthropogenic NOx and VOC emissions (Figure ES-7). On weekends, the modeled ozone shows positive sensitivity to NOx emissions in most areas except for several urban centers where the sensitivity turns negative clearly showing a regional-to-urban shift from NOx-limited to VOC-limited conditions. Correspondingly, the weekend ozone consistently shows positive sensitivity to VOC emissions at the urban centers (the most VOC-limited are Chicago and Detroit). Ozone responses to anthropogenic NOx emissions (Figure ES-7 (a)) show similar spatial patterns to Figure ES-5 (c) indicating that modeled weekend ozone increases and decreases are mostly due to the weekend NOx reductions.

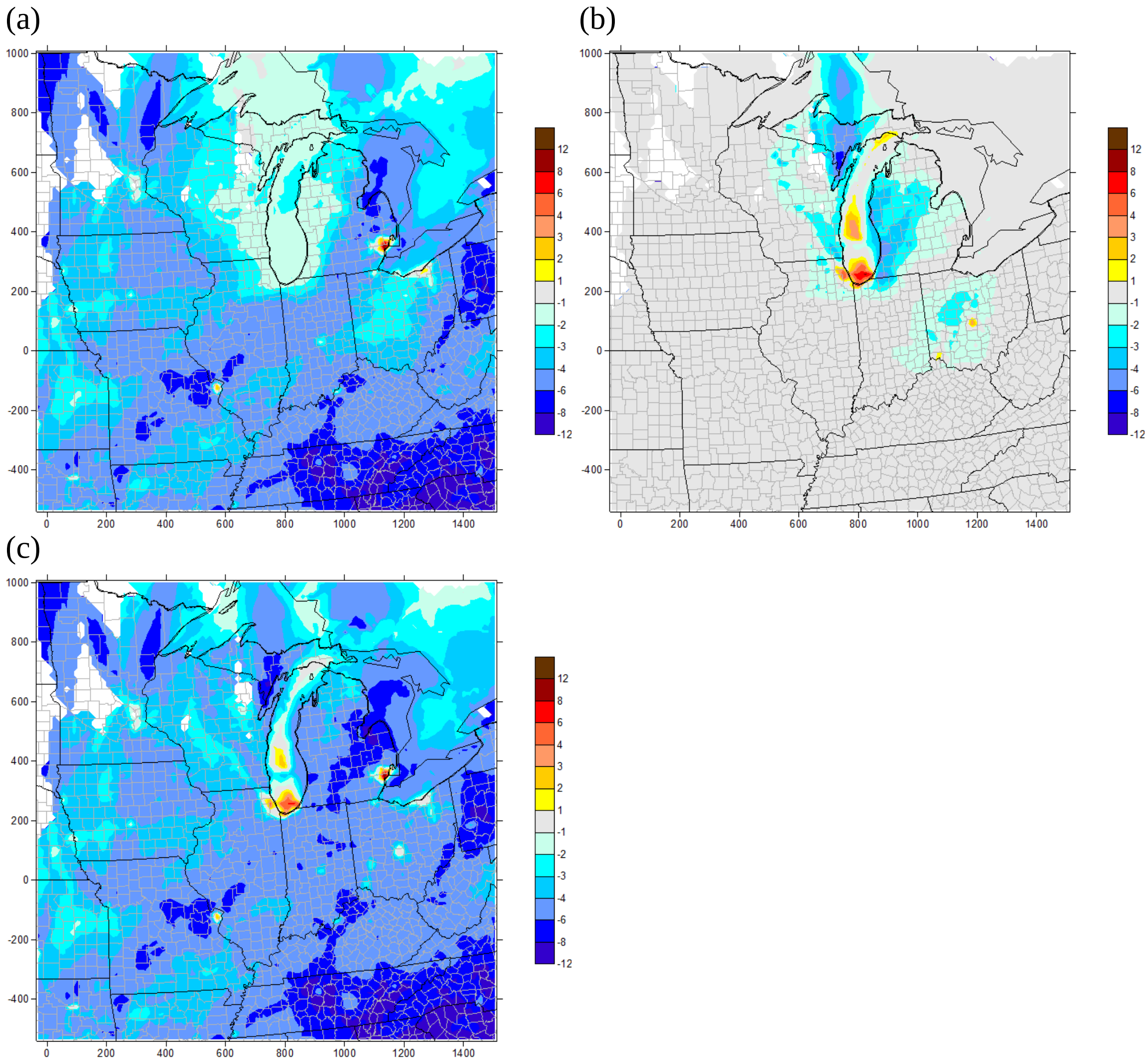

Figure ES-5. Weekend minus weekday differences in daily maximum 8-hour ozone concentrations (ppb). (a) Modeled ozone differences of the base case minus S2 simulation on Sundays. (b) Modeled ozone differences of S2 minus S1 simulations on Sundays. (c) Modeled ozone differences of the base case minus S1 simulation on Sundays (same as Figure ES-4 (b) but without Kriging interpolation).

(a) Chicago

(b) Columbus

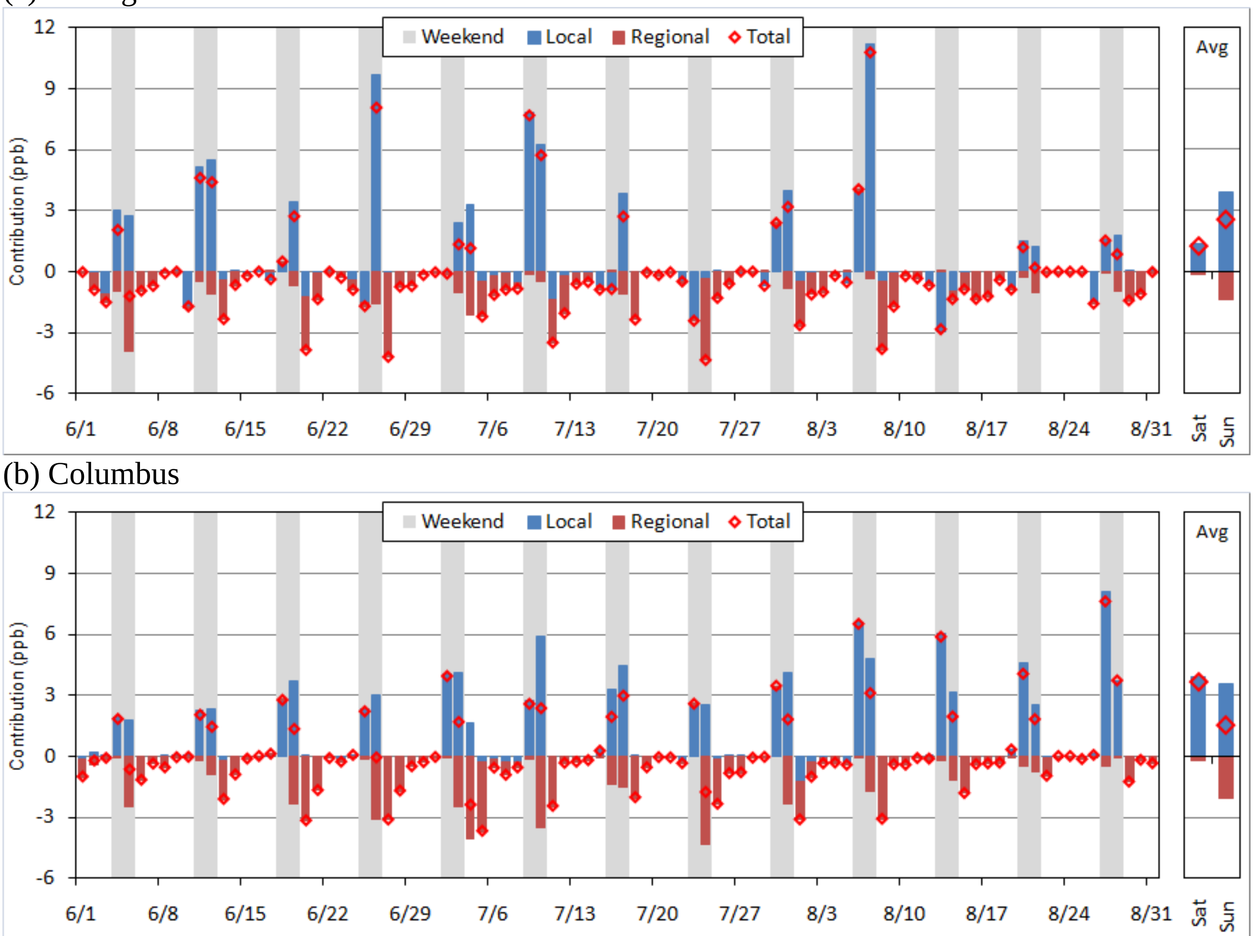

Figure ES-6. Time-series of local (S2 – S1) and regional (base case – S2) contributions to the weekend ozone changes at two urban centers. The total contribution (base case – S1) is the sum of the local and regional contributions shown by diamond markers.

(a) (b)

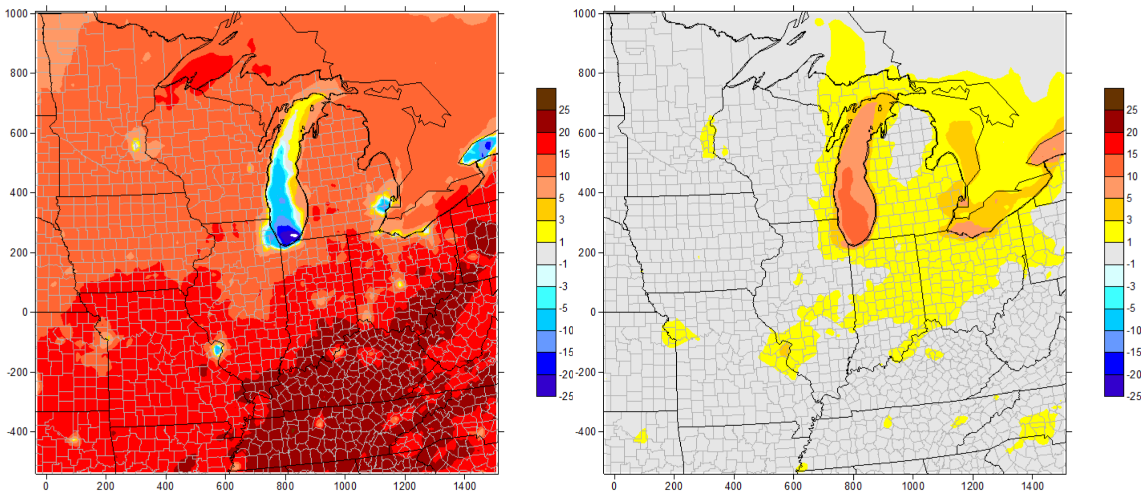

Figure ES-7. First-order DDM sensitivities of daily maximum 8-hour ozone (ppb) on average Sunday to domain-wide anthropogenic (a) NOx and (b) VOC emissions.

Draft Journal Manuscript

Local and Regional Contributions to Weekday-Weekend Ozone Changes in the Midwest

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Abstract

The weekend ozone effect refers to changes in ground-level ozone concentrations on weekends resulting from anthropogenic emission changes from weekdays and weekends. This study applied a three-dimensional photochemical grid model for a three-month summer period to examine the weekend ozone effect in the Midwestern US at both urban and regional scales. The model generally reproduced the observed daily maximum 1-hour and 8-hour ozone and also correctly predicted weekend changes in the VOC-to-NOx ratio. So-called dynamic evaluation of the modeled weekend ozone changes throughout the summer revealed that meteorology had a bigger impact on the summer 2005 weekend ozone effect than anthropogenic emission changes partly because meteorology strongly influences biogenic emissions. To avoid the confounding effect of meteorological changes, weekend ozone differences were determined by using a second simulation modeled with weekday emissions for all days of week. Ozone differences between the base case and the second simulation isolated the effect of weekday/weekend emission changes. To further distinguish local effects of weekend emission changes from transported regional ozone differences, a third simulation applied weekend emission changes only within two urban areas with all weekday emissions for the remaining areas. The ozone differences between the base case and the third simulations revealed that the effect of regional weekend emission differences is projected to be mostly lowered ozone on weekends. On the other hand, the difference between the second and third simulations revealed that weekend emission changes in two urban areas increased ozone locally in the urban centers and immediately downwind areas but lowered ozone further downwind. The sign-change in the weekend ozone effect from urban centers to downwind areas is explained by a matching change in sign of ozone sensitivity to NOx emissions which was confirmed by computing ozone sensitivities to domain-wide NOx and VOC emissions. The sensitivity analysis also showed that weekday/weekend ozone differences in the Midwestern US are due primarily to weekend reductions in NOx emissions.

Introduction

Nitrogen oxides (NOx) and volatile organic compounds (VOCs), emitted from anthropogenic and biogenic sources, are two main precursors that lead to ground level ozone formation (Seinfeld and Pandis, 1998). It is expected that different human activity patterns between weekdays and weekends would lead to variability in the emissions of ozone precursors over the course of the week. If the weekday/weekend differences in the precursor emissions are large enough to influence ground-level ozone concentrations, the weekday/weekend ozone changes may influence compliance with air quality standards and provide useful information about ozone response to precursor emission changes for designing effective air quality management plans.

The weekend ozone effect has been studied most extensively for the Los Angeles (LA) area (Levitt and Chock, 1976; Elkus and Wilson, 1976; Fujita et al., 2003; Blanchard and Tanenbaum, 2003; Lawson, 2003; Yarwood et al., 2003 and 2008) finding both widespread and large ozone increases and only limited and minor ozone decreases on weekends compared to weekdays depending upon location. Modeling and data analysis studies for Los Angeles show that reduced weekend NOx emissions result in less ozone titration, less inhibition of ozone formation and higher weekend ozone in urban areas where ozone formation is considered to be VOC-limited. For other parts of the US, the weekday/weekend changes in ozone precursors resulted in either weekend ozone increases or no significant weekly ozone variations (Graedel et al., 1977; Heuss et al., 2003; Torres-Jardon and Keener, 2006; Blanchard and Tanenbaum, 2006; Blanchard et al., 2008). Graedel et al. (1977) analyzed the weekend ozone effect in Hudson County, NJ where peak ozone concentrations on Sundays were virtually equivalent to those on weekdays despite of significant reduction in ozone precursors on Sundays. Ozone measurements at monitoring sites located at and near Atlanta, GA (Blanchard and Tanenbaum, 2006) and at Cincinnati, OH (Torres-Jardon and Keener, 2006) also showed similar level of peak ozone concentrations between Sundays and Wednesdays. Heuss et al. (2003) examined ozone monitoring sites across the US and reported weekend ozone increases in large cities in California, Midwest and Northeast Corridor. Blanchard et al. (2008) analyzed ozone measurement data in 23 US States focusing on the Northeast Corridor, the southern Lake Michigan area, the Atlanta Metropolitan Statistical Area (MSA), the Gulf of Mexico coast, Dallas-Fort Worth Consolidated MSA, the Phoenix MSA and the Colorado Front Range area, and concluded that no statistically significant weekend ozone increases occurred at most monitoring sites. The purpose of this study is to systematically investigate the weekend emissions and ozone changes in the Midwestern US at both urban and regional scales.

Weekday/weekend changes in ozone and its precursors provide a useful opportunity for dynamic evaluation of air quality models. A dynamic evaluation, which evaluates how accurately a model can predict air quality changes resulting from changes in model inputs such as emissions and meteorology, requires a time period with substantial and clearly-defined changes in emissions and/or meteorology. For example, Gilliland et al. (2008) selected summer episodes before and after extensive regional NOx emission reductions in the Eastern US (NOx SIP Call) for evaluation of the Community Multiscale Air Quality (CMAQ) model and reported that the model under-predicted the observed ozone reductions resulting from the NOx SIP Call. Pierce et al. (2010) evaluated CMAQ's ability to accurately predict the weekend ozone effect using summer ozone seasons between 1988 and 2005 and reported that the modeled weekend ozone changes are smaller than observed.

Base Case Modeling

The ozone modeling episode used for this study is based on the Lake Michigan Air Directors Consortium (LADCO) 2005 modeling database for the Midwestern US. Meteorological inputs were developed using the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model version 5 (MM5). Emission inventories were developed using a combination of data from States, Regional Planning Organizations (RPOs) and EPA (LADCO, 2008). Our base case simulation models ozone for the three month summer episode of June-August, 2005 with a 10-day spin-up period. The modeling was performed using version 5.20 of CAMx (ENVIRON, 2010) with the Carbon Bond 05 chemical mechanism (Yarwood et al., 2005). The LADCO modeling domain consists of 36-km and 12-km grids over the eastern US and the Midwest, respectively (Figure 1). We added 4-km grids in two extended urban regions over Southern Lake Michigan (SLM) and Cincinnati/Dayton/Columbus (CDC). Meteorological data for the 4-km grids were interpolated from the 12-km grid data while emissions data were prepared at 4-km resolution. The 36-/12-/4-km domains were run together efficiently using 2-way grid nesting in CAMx. Diurnally varying boundary conditions for the 36-km grid were developed based on monthly averaged 2002 GEOS-CHEM global model simulation outputs.

Improvements to the emission inventory were made for mobile source emissions, temporal allocation profiles, and biogenic emissions. The on-road mobile source emission inventory was revised by updating heavy-duty diesel vehicle (HDDV) NOx emission rates and speed correction factors with more recent testing data (ENVIRON, 2009). The updated emission rates were combined with roadway link-level activity data for six Upper Midwest States (Illinois, Indiana, Michigan, Wisconsin, Ohio, and Minnesota) and county-level activity data for the remainder of the 12-km modeling domain, using the Consolidated Community Emissions Processing Tool (CONCEPT) MV emissions model (Jimenez et al., 2008). More details on the HDDV NOx emission updates are in Supplementary Materials. Day of week and hour of day temporal profiles for off-road mobile and area source emissions were reviewed and updated (Table S2). Temporal profiles for gasoline distribution, solvent application, and surface coating as well as small stationary source emissions were revised based on information collected from various sources including published reports and telephone surveys (Jones, 2005). Temporal profiles for construction equipment were updated using equipment usage data collected by telephone survey of construction equipment owners and operators (Thesing and Bollman, 2004). Weekly profiles for lawn and garden equipment were revised based on emission activity data collected by Chinkin et al. (2003). Recreational boating activity data was updated based on a bottom-up survey conducted by Reid et al. (2004). Finally, biogenic emissions were updated using version 2.03a of Model of Emissions of Gases and Aerosols from Nature (MEGAN) (Guenther et al., 2006).

Table 1 summarizes weekday and weekend anthropogenic NOx and VOC emissions for source categories in the 12-km modeling domain. Total NOx emissions are reduced by 24% on Saturday and by 33% on Sunday relative to weekdays with the largest reductions occurring for on-road diesel vehicles. Average daytime (06:00-15:00) ambient NOx concentrations on Wednesdays and Sundays from EPA’s Air Quality System (AQS) observation during July 2005 over the 12-km domain were 13.9 and 8.6 ppb, respectively. It translates to 38% reduction of NOx on Sundays compared to Wednesdays, which agrees well with the inventory’s reduction. Total anthropogenic VOC emissions also decrease on both Saturday (7%) and Sunday (19%) with the largest reductions occurring for on-road gasoline vehicles. Combined, mobile sources (both on- and off-road) account for 99% of the weekday-to-Sunday NOx reduction and 52% of the VOC reduction.

Model Performance Evaluation

Base case model performance was evaluated using EPA's AQS hourly ozone measurement database. Figure 2 shows mean normalized bias (MNB) and mean normalized error (MNE) of the modeled daily maximum 8-hour average ozone concentrations for each day over the 12-km Midwest domain. MNB and MNE are defined as follows:

$$\text{MNB}=\sum_i \frac{P_i-O_i}{O_i} \qquad\qquad \text{MNE}=\sum_i \left|\frac{P_i-O_i}{O_i}\right|$$

where P_i and O_i represent model predicted and observed ozone concentrations, respectively The model generally meets performance goals of ±15% for MNB and 35% for MNE on high ozone days. The model tends to over-predict peak 8-hour ozone on low ozone days (e.g., 10-11 June, 13-18 July, and 14-20 August where observed average peak 8-hour ozone concentrations are less than ~50 ppb). Ozone model performance for the 4-km grids is similar to the 12-km result (Figures S2 and S3 in Supplementary Materials). Table 2 presents the performance metrics for 1-hour ozone concentrations over the three-month period applying a threshold (40 or 60 ppb) to the observed ozone. With either 40 or 60 ppb threshold, the model meets the performance goals for all modeling grids. The model generally over-predicts morning (06:00-09:00) NOx concentrations (Figures S4 and S5).

Ozone formation occurs via reactions of radicals and is sensitive to the ratio of VOC to NOx concentrations because, in general, VOCs contribute to radical initiation and propagation whereas NOx contributes to radical termination and propagation (Seinfeld and Pandis, 1998). The VOC-to-NOx ratio influences how ozone formation responds to changing NOx and/or VOC emissions, thus model performance for the VOC-to-NOx ratio is one indicator of the model's ability to predict ozone response to emission changes. Modeled VOC-to-NOx ratios were evaluated at three Photochemical Assessment Monitoring Station (PAMS) sites in the SLM domain: Two sites in Chicago, Illinois and one in Milwaukee, Wisconsin (Figure S6). In the morning (06:00-09:00), observed total nonmethane organic compounds (TNMOC) and NOx concentrations decreased on weekends by 7.3-29% and 35-49%, respectively, compared to weekdays at these sites (Figure S7). Figure 3 compares observed and modeled ratios of TNMOC to NOx in the morning (06:00-09:00). Observed TNMOC-to-NOx ratios at the two Chicago sites range from 1.3 to 2.4 ppbC/ppb indicating ozone formation will be VOC-limited. The ratios at the Milwaukee site are slightly higher ranging from 3.4 to 5.1 ppbC/ppb. The model over-predicted the ratios at the two Chicago sites while under-predicting at Milwaukee. At all three sites, however, both observation and model show increases in weekend TNMOC-to-NOx ratios with the Milwaukee site having greater weekend increases than the Chicago sites.

Spatial patterns of modeled and observed weekday/weekend ozone differences were compared at AQS monitoring sites focusing on high ozone conditions (60 ppb threshold) that are relevant to compliance with ozone standards. The observed difference in weekday/weekend daily maximum 8-hour ozone at the *i*-th monitoring site (D_i) was calculated as

$$D_i = (S_i - W_i)$$

where W_i and S_i represent averages of daily maximum 8-hour ozone on Wednesday and Saturday or Sunday, respectively. W_i is a simple average of Wednesdays with 8-hour ozone ≥ 60 ppb. S_i is the average of weekend days exceeding a threshold that yields the same percentile of selected weekend days as the selected Wednesdays at the *i*-th site.

Spatial plots of weekday/weekend ozone differences (Figure 4) were prepared by interpolating (Kriging) the observed and modeled D_i at sites with at least four Wednesdays with 8-hour ozone ≥ 60 ppb during the three-month episode (Figure 4 (a) shows the observations). Two different methods were used to calculate the modeled weekday/weekend ozone differences. In the first method (Yarwood et al., 2003), in addition to the base case, a second model simulation (S1) was performed with weekday emissions on all days and the differences in modeled ozone (base case minus S1) result from weekday/weekend emission changes (see Table 3 for weekday/weekend emission configurations). This result is displayed in Figure 4 (b) using the Kriging interpolation method to place the observed and modeled ozone differences on a common basis. The modeled ozone differences agree poorly with the observed differences with observations showing much wider areas of ozone increase than modeled. Figure 4 (c) shows modeled ozone differences calculated using the same approach as the observed ozone differences (i.e., ozone differences between high ozone Wednesdays and weekend days predicted by the base case simulation), which gives better agreement with the observed weekday/weekend differences. The weekday/weekend ozone differences shown in Figures 4 (a) and (c) are affected both by weekday/weekend emissions changes and meteorological differences (e.g., temperature). Therefore, the above results demonstrate that, for this region and modeling period, meteorological differences between the weekdays and weekends had more influence than emission differences on ozone. Weekday/weekend changes in biogenic VOC emissions generally reflect the meteorological differences, and in most areas biogenic VOC emissions are higher on average Sunday than on average Wednesday (Figure S8). Pierce et al. (2010) similarly concluded that several ozone seasons must be averaged to minimize the effect of meteorological variability. However, averaging several years has the disadvantage that emissions change as new control programs are introduced and we cannot tell the effect of the change. The modeling approach shown in Figure 4 (b) has an important advantage in investigating how weekday/weekend emission changes affect ozone when strong meteorological influence exists during the study period.

Local and Regional Effects of Weekend Emission Changes

In the following discussion, we will use the term "regional" to describe changes over the entire modeling domain outside the 4-km grids. Many urban areas are in close proximity in the Midwest such that effects of weekend emission changes may be transported from one urban area to another or from rural areas to urban areas. We performed another sensitivity case (S2) where the base case (both weekday and weekend) emissions were retained for the two 4-km urban modeling domains but all weekday- emissions (as in S1) were applied outside of the 4-km domains (see Table 3). Ozone differences between the base case and S2 (Figure 5 (a)) reveal that regional weekend emission changes mostly lower peak 8-hour ozone on weekend days indicating that regional ozone formation is NOx-limited. Conversely, ozone differences between S1 and S2 (Figure 5 (b)) reveal that local (urban) weekend emission changes lead to ozone increases as well as decreases. The weekend ozone increases at the urban centers and immediate downwind areas reach up to ~9 ppb in modeled daily maximum 8-hour ozone. Areas further downwind show weekend ozone decreases of up to ~7 ppb. Because some Midwest urban areas were found to be strongly VOC-limited (including Chicago and Detroit), the effect of weekday-weekend changes in both NOx and VOC emissions should be taken into account in developing control strategies for these areas.

Figure 6 shows time-series of local and regional contributions to weekend ozone changes for two urban centers (Chicago and Columbus). On average, ozone increases due to local weekday/weekend emission changes are lower at Chicago than Columbus on Saturday, but slightly higher on Sunday. Weekend ozone decreases due to regional emission changes are similar at the two locations. The overall weekend ozone change is the sum of the regional and local contributions using this methodology. On most days and on average the local contribution outweighs the transported contribution. The local contribution is greatest on the days when emissions change (Saturday and Sunday) whereas the regional contribution lags by a day (peaking on Sunday and Monday) and sometimes persists for several days because of the time required for ozone transport from rural areas to the urban areas.

Ozone Sensitivity to NOx and VOC Emissions

The ozone impacts of weekend emission changes for VOC and NOx can be understood by calculating ozone sensitivity to VOC and NOx emissions. The Decoupled Direct Method (DDM) is an efficient and accurate method to calculate model responses to changes in model inputs such as emissions, initial and boundary conditions, etc. (Dunker et al., 2002; Koo et al., 2007 and 2008). Using DDM, we calculated the first-order sensitivities of daily maximum 8-hour ozone to anthropogenic NOx and VOC emissions (Figure 7). On weekends, the modeled ozone shows positive sensitivity to NOx emissions in most areas except for several urban centers where the sensitivity turns negative clearly showing a regional-to-urban shift from NOx-limited to VOC-limited conditions. Correspondingly, the weekend ozone consistently shows positive sensitivity to VOC emissions at the urban centers (the most VOC-limited are Chicago and Detroit). Spatial distributions in Figure 7 (a) and Figure 5 (c) are similar indicating that modeled weekend ozone increases and decreases are mostly due to the weekend NOx reductions.

Summary

CAMx was applied to simulate a three-month long summer ozone episode in the Midwestern US based on the LADCO 2005 modeling database. The existing emission inventory was improved by updating HDDV NOx emissions and weekday/weekend temporal adjustments for several non-road and area source emissions. Model performances for 1-hour and daily maximum 8-hour ozone concentrations were satisfactory on high ozone days while displaying tendency toward over-prediction on low ozone days. The model correctly predicted weekend increases in TNMOC-to-NOx ratios at PAMS sites in the Southern Lake Michigan region although the magnitudes of the ratios were either over-predicted or under-predicted. Dynamic evaluation of the modeled weekend ozone changes was attempted but proved to be not useful because a single ozone season was insufficient due to meteorological variability dominated the emissions change.

To avoid a meteorological influence, additional simulations with the same meteorology but alternate emissions were conducted. Ozone differences between the base case and sensitivity simulations separated regional from local effects of weekday/weekend emission changes. Regional emission reductions on weekends mostly lead to ozone decreases whereas for urban centers and immediate downwind areas weekend emission reductions increased ozone. In the urban areas, the local contribution outweighs the transported contribution on most days and is greatest on weekend days when emissions change. On the other hand, the regional contribution lags by a day and sometimes persists for several days because of the time required for ozone transport from rural areas to the urban areas. Further downwind of urban centers weekend ozone increases turned to ozone decreases as the chemical regime changed from VOC-limited to NOx-limited ozone formation. Ozone sensitivities to NOx and VOC emissions (calculated using DDM) also showed VOC-sensitive conditions at urban centers and immediate downwind areas whereas rural areas displayed NOx-sensitive conditions.

Acknowledgements

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Tables and Figures

Table 1. Day-of-week anthropogenic NOx and VOC emissions over the Midwest 12-km modeling domain for July 2005.

	NOx (tons/day)				VOC (tons/day)			
	Weekday	**Friday**	**Saturday**	**Sunday**	**Weekday**	**Friday**	**Saturday**	**Sunday**
On-road gasoline	3552.2	3841.3	3068.0	2744.1	4224.9	4593.0	3585.0	3193.9
On-road diesel	6785.6	6680.1	3897.2	3252.5	426.1	418.3	237.6	191.9
Off-road	3331.2	3331.2	2747.1	2344.6	2299.4	2299.4	2316.3	2066.1
Marine/aircraft/railroad	1715.3	1715.3	1708.4	1708.5	71.7	71.7	68.0	68.1
Area sources	353.2	353.2	515.5	351.0	6612.4	6612.4	6663.3	5714.5
Low-level point sources	438.8	438.8	398.3	391.0	1614.9	1614.9	1318.8	1143.8
Total	**16176.3**	**16360.0**	**12334.5**	**10791.7**	**15249.4**	**15609.7**	**14189.0**	**12378.3**

Table 2. Mean normalized biases and errors for 1-hour ozone over the full episode with a threshold[1] of 40 or 60 ppb.

Modeling domain	**MNB (%)**		**MNE (%)**	
	40 ppb	**60 ppb**	**40 ppb**	**60 ppb**
Midwest 12-km	-0.2	-5.8	21.6	16.2
SLM 4-km	-9.9	-11.4	23.7	19.7
CDC 4-km	-1.4	-9.0	24.3	17.9

[1]Model/observation pairs with observed 1-hour ozone less than the threshold are excluded in calculating the performance metrics.

Table 3. Weekday/weekend emission[1] configurations for base case, S1 and S2 simulations.

	Modeling grid	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**	**Sat**	**Sun**
Base case	4-km grids	Wkd[2]	Wkd	Wkd	Wkd	Wkd	Sat	Sun
	Outside 4-km grids	Wkd	Wkd	Wkd	Wkd	Wkd	Sat	Sun
S1	4-km grids	Wkd	Wkd	Wkd	Wkd	Wkd	Wkd	Wkd
	Outside 4-km grids	Wkd	Wkd	Wkd	Wkd	Wkd	Wkd	Wkd
S2	4-km grids	Wkd	Wkd	Wkd	Wkd	Wkd	Sat	Sun
	Outside 4-km grids	Wkd	Wkd	Wkd	Wkd	Wkd	Wkd	Wkd

[1] Anthropogenic emissions were prepared for a Friday, a Saturday, and a Sunday for each month except for on-road mobile source emissions which additionally include a Thursday. The Friday, Saturday, and Sunday emissions represent all weekdays (Monday through Friday), Saturdays, and Sundays in each month, respectively, except for on-road mobile. For on-road mobile source emissions, the Thursday emissions represent all weekdays (Monday through Thursday) and the Friday emissions all Fridays in each month.
[2] Representative weekday emissions (Friday emissions for all anthropogenic emissions except for on-road mobile; Thursday emissions for on-road mobile source emissions)

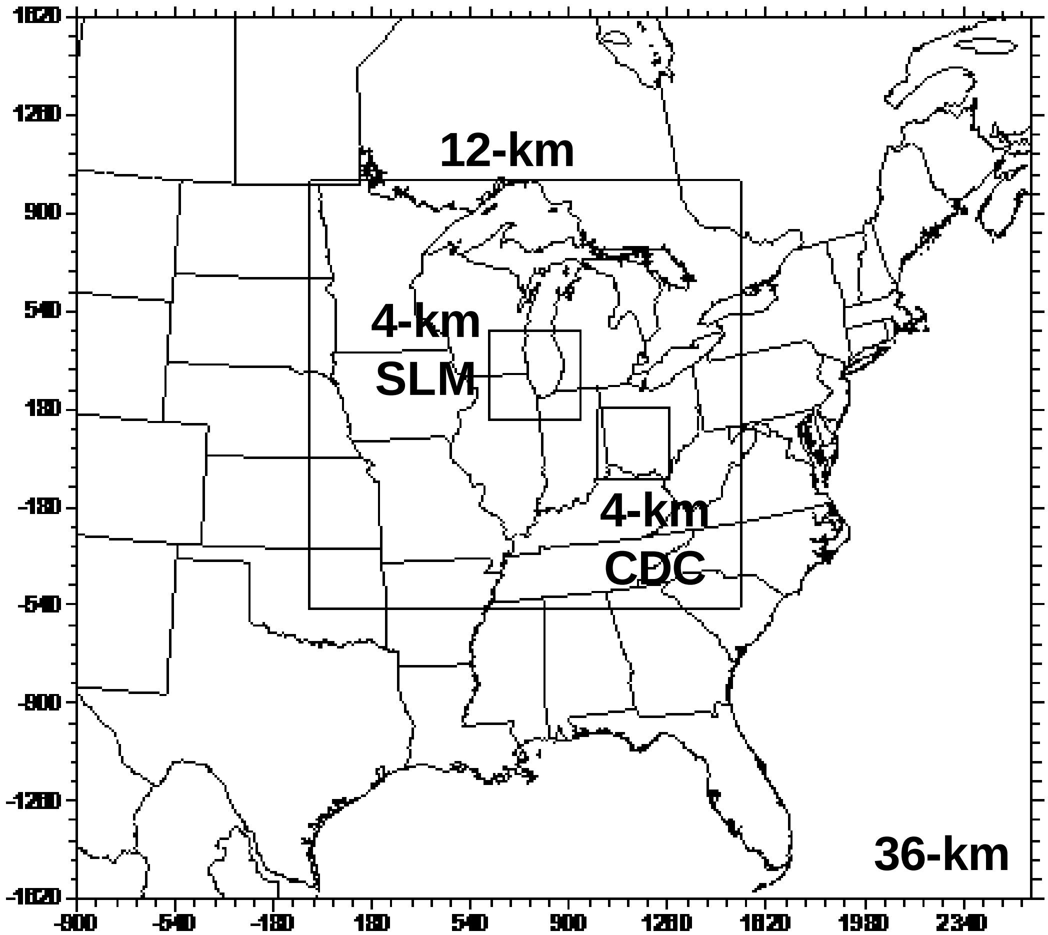

Figure 1. The LADCO 36-km modeling domain for the eastern US showing the nested 12-km domain for the Midwest and two 4-km domains for Southern Lake Michigan (SLM) and Cincinnati/Dayton/Columbus (CDC) in Ohio.

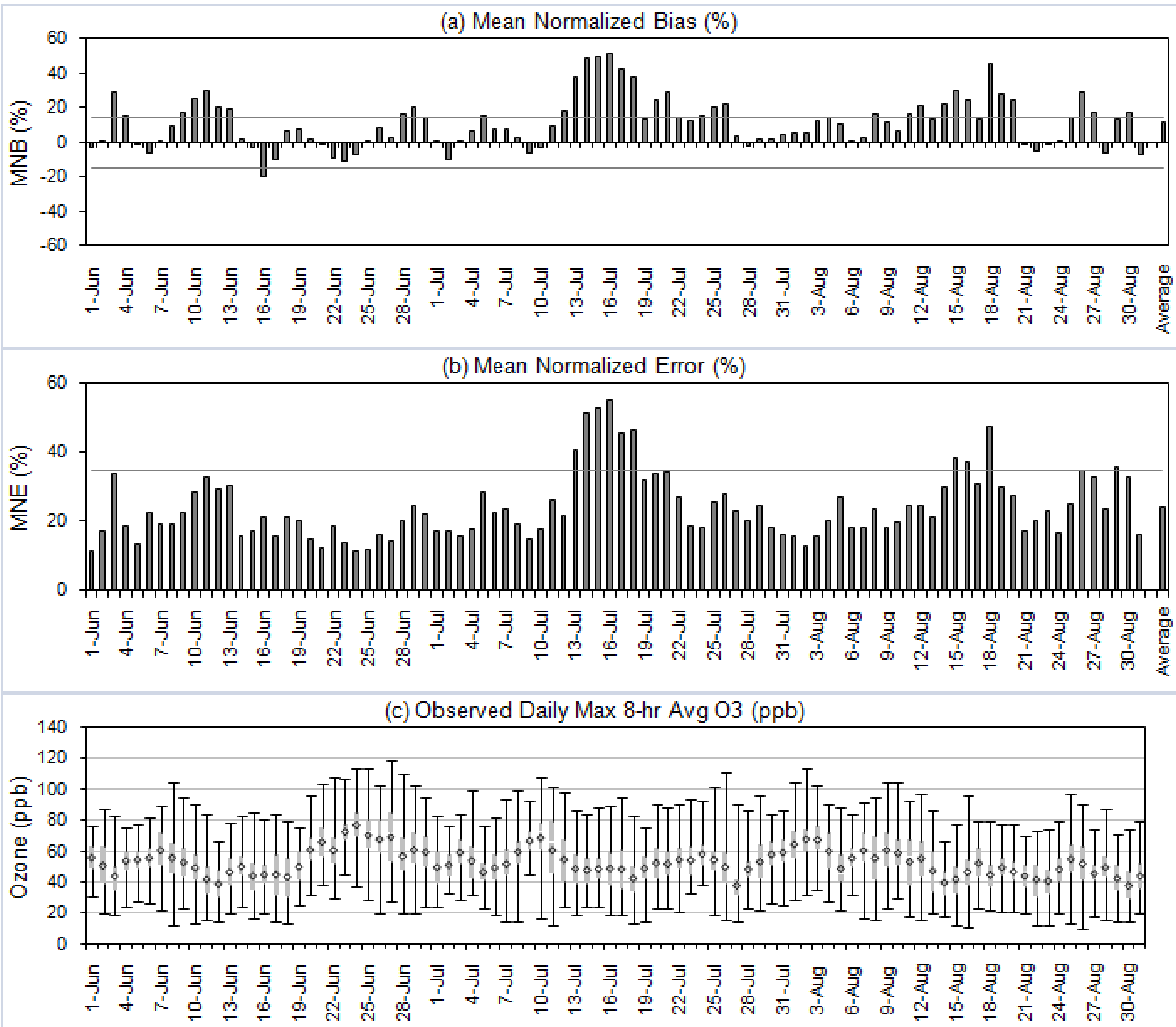

Figure 2. Statistical metrics for daily maximum 8-hour ozone concentrations over the 12-km Midwest domain: (a) Model mean normalized bias (MNB); (b) model mean normalized error (MNE); (c) box and whisker plot for observations: The inner quartiles (the 25th to 75th percentiles) are represented by gray boxes, separated at the median by a horizontal line; the lower and upper quartiles are represented by whiskers; the means are represented by diamond markers.

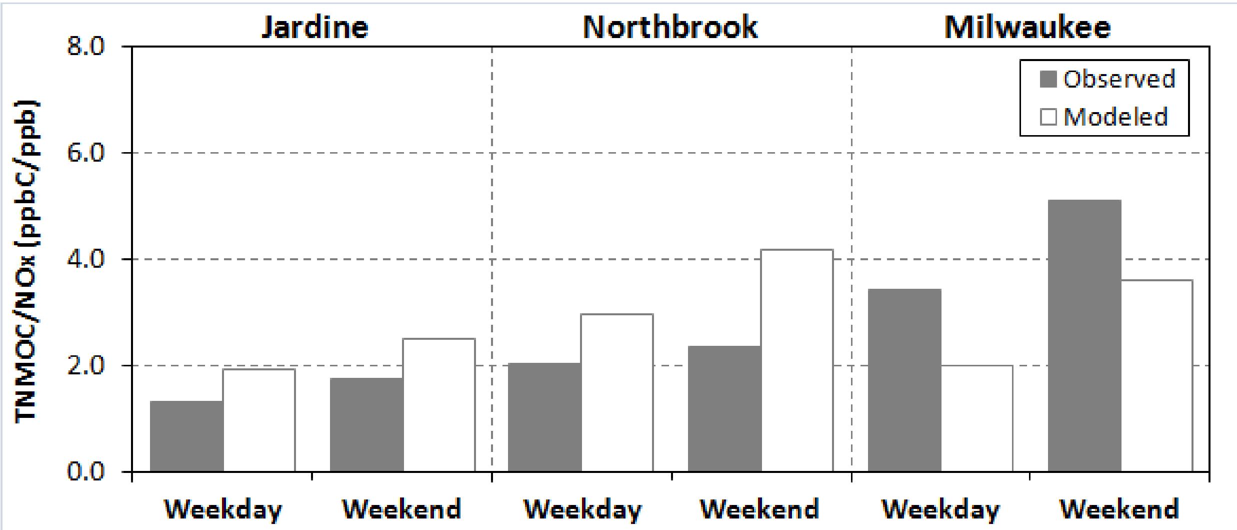

Figure 3. Median morning (06:00-09:00) TNMOC-to-NOx ratios for June-August, 2005. Weekday averages Monday through Friday during the three-month period and weekend averages Saturday and Sunday.

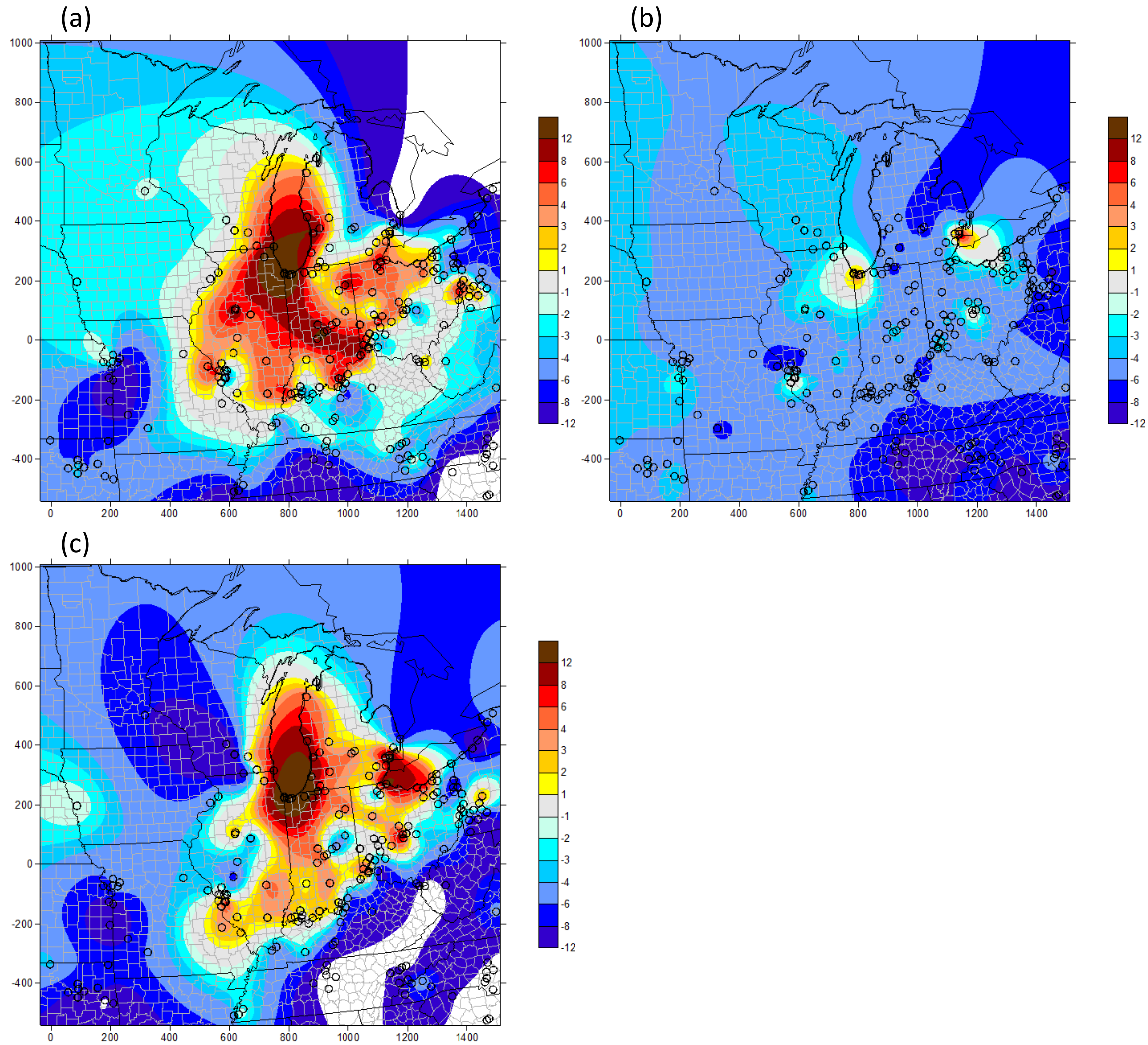

Figure 4. Weekend minus weekday differences in daily maximum 8-hour ozone concentrations (ppb) using Kriging interpolation of values at the AQS monitoring sites (circle markers). (a) Observed ozone differences of average high-ozone Wednesday minus average high-ozone Sunday. (b) Modeled ozone differences of the base case minus S1 simulation on average high-ozone Sunday. (c) Modeled ozone differences of average high-ozone Wednesday minus average high-ozone Sunday. Same plots for Saturday are presented in Supplementary Materials (Figure S9).

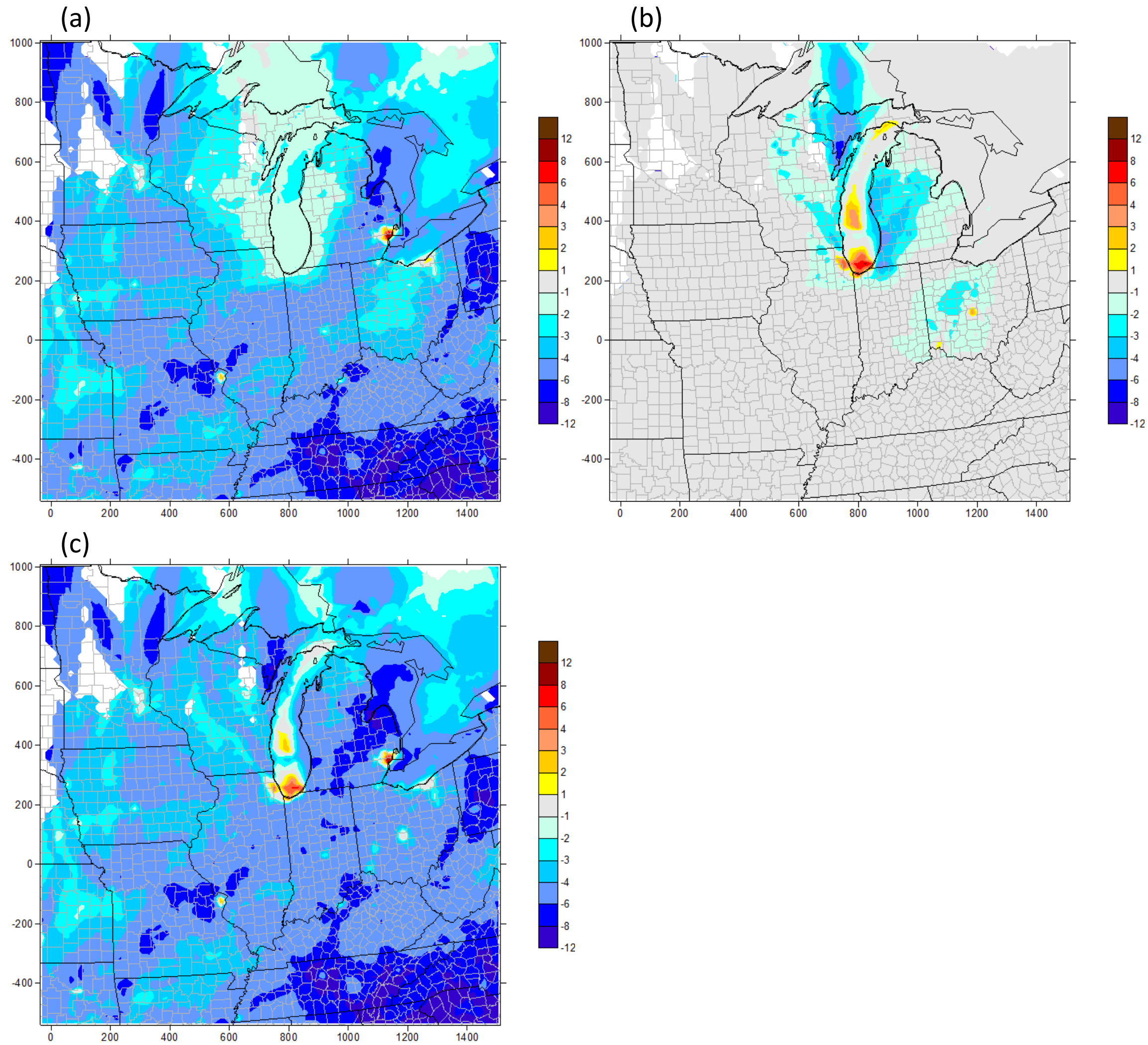

Figure 5. Weekend minus weekday differences in daily maximum 8-hour ozone concentrations (ppb). (a) Modeled ozone differences of the base case minus S2 simulation on high-ozone Sunday. (b) Modeled ozone differences of S2 minus S1 simulations on high-ozone Sunday. (c) Modeled ozone differences of the base case minus S1 simulation on high-ozone Sunday (same as Figure 4 (b) but without Kriging interpolation). Same plots for Saturday are presented in Supplementary Materials (Figure S10).

(a) Chicago

(b) Columbus

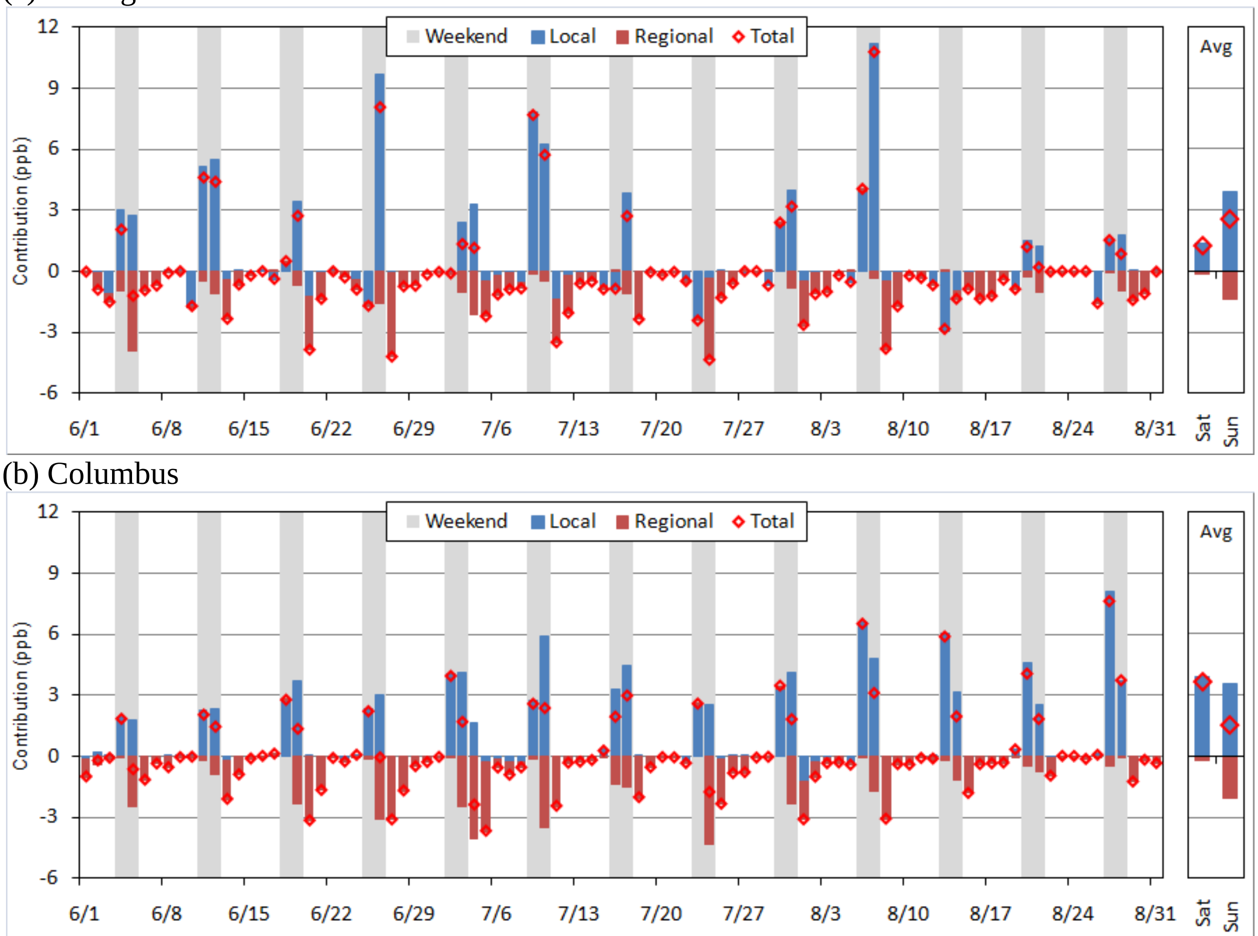

Figure 6. Time-series of local (S2 – S1) and regional (base case – S2) contributions to the weekend ozone changes at two urban centers. The total contribution (base case – S1) is the sum of the local and regional contributions shown by diamond markers.

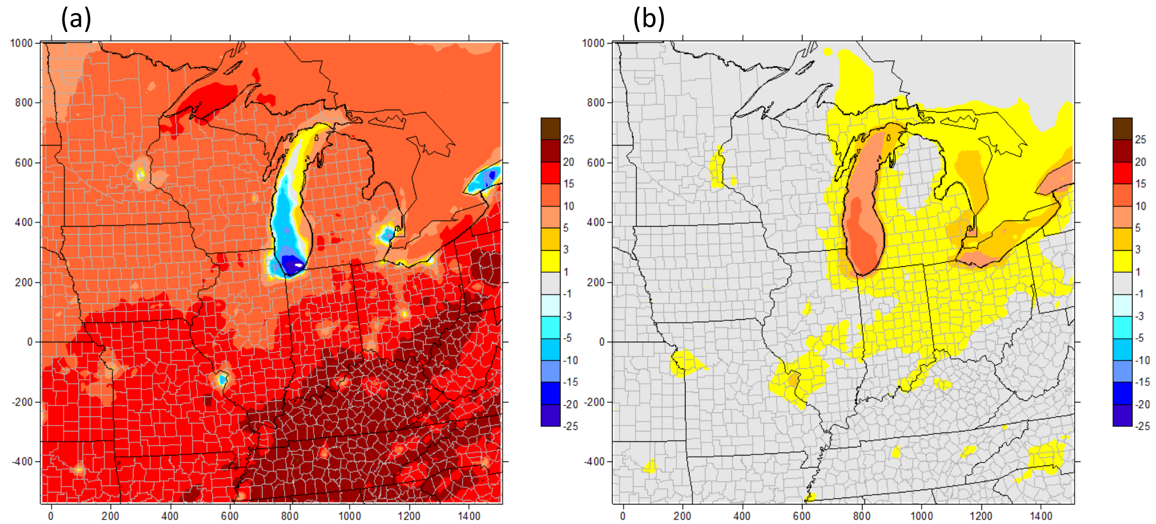

Figure 7. First-order DDM sensitivities of daily maximum 8-hour ozone (ppb) on average Sunday to domain-wide anthropogenic (a) NOx and (b) VOC emissions. Same plots for Saturday are presented in Supplementary Materials (Figure S11).

Supplementary Materials to Journal Manuscript

Heavy-Duty Diesel Vehicle NOx Emission Updates

Mobile source emission inventories for the Eastern US were revised by updating heavy-duty diesel vehicle (HDDV) NOx emission rates and speed correction factors. Recent HDDV testing data for varying driving cycles that were not used in the development of MOBILE6 were reviewed and compared with MOBILE6 emission rates for hydrocarbon (HC) and NOx. Adjustment factors to MOBILE6 HDDV emissions were developed (Table S1).

Table S1. Average adjustment factors for HDDV to MOBILE6 for 2005.

Speed (mph)	HC	NOx
2	7.15	3.26
15	2.53	1.68
19	3.41	1.89
40	1.64	1.80
50	2.24	1.51

Updated HDDV emission rates were incorporated into link-based emissions inventories for six Upper Midwest States (IL, IN, MI, WI, OH, and MN) and county-level emissions modeling for other states. Mobile source emissions modeling used the Consolidated Community Emissions Processing Tool (CONCEPT) MV model. While the adjustment factors for hydrocarbons in Table S1 are large, the HDDV contribution to motor vehicle HC emissions is very small. HDDV NOx emissions, on the other hand, typically represent about half of the total on-road NOx emissions and the multipliers shown in Table S1 significantly increase that contribution. Figure S1 compares on-road NOx emissions by vehicle type in the unadjusted (base case emissions without the HDDV emission factor adjustments) and adjusted emission inventories and shows a 30-35% increase in overall on-road NOx emissions. For the HDDV sector, the increase in NOx emissions is 80 percent for Fridays and 70 percent for weekend days. The weekend increases are smaller because average speeds for HDDV are slightly higher on weekends, and the adjustments decrease with increasing speed. Recently EPA released a new emission factor model, called MOVES which replaced MOBILE6. MOVES has a completely different modeling approach than MOBILE6 and thus results in substantially different emissions (frequently higher NOx emissions) than MOBILE6. However, we believe our updated HDDV emissions should be comparable to those by MOVES as our updated emission factors are based on the same HDDV testing data that EPA used to develop MOVES.

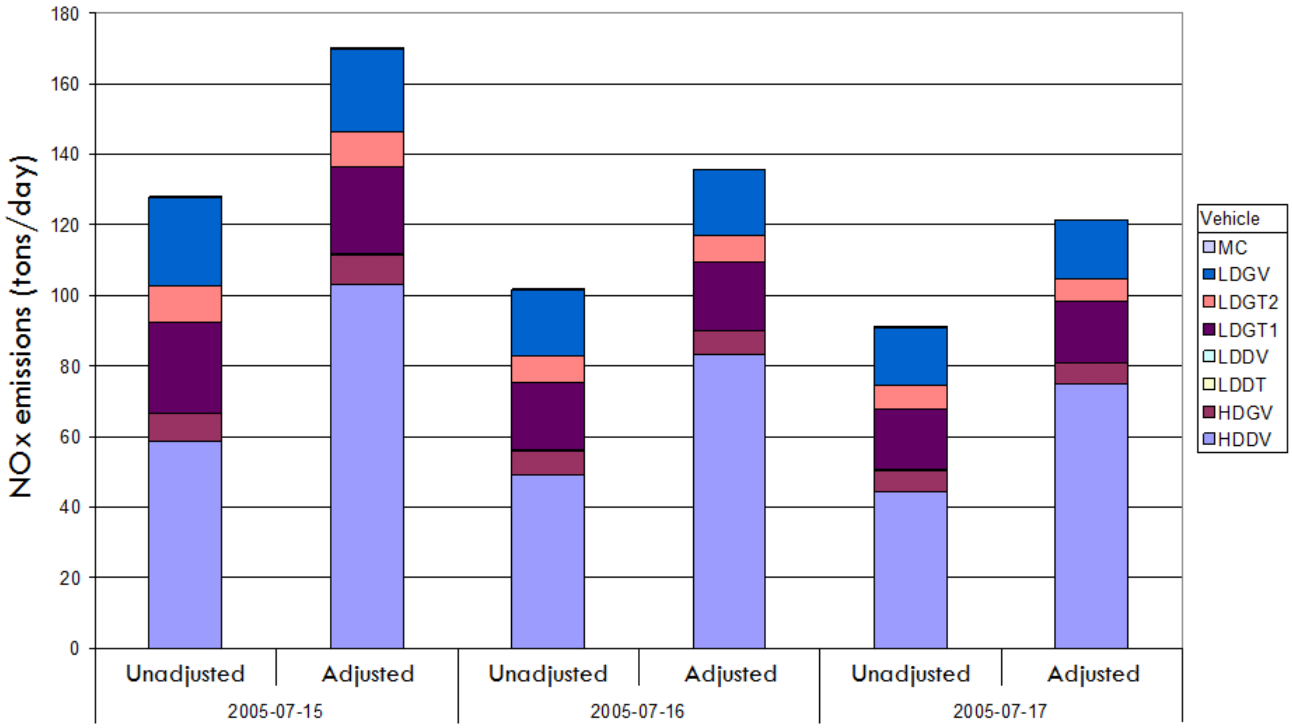

Figure S1. On-road NOx emissions (tons/day) by vehicle class for the Columbus, OH transportation network for a Friday (July 15)/Saturday (July 16)/Sunday (July 17), 2005. "Unadjusted" emissions are base case emissions without HDDV emission factor adjustments by speed; "Adjusted" emissions are with the adjustment factors.

Table S2. Temporal adjustments made to the temporal profiles for non-road and area sources.

Source Category	Recommendation	Comment
Surface Coating	Use LADCO adjustments	LADCO profiles generally show zero activities on weekends and during night reflecting that surface coating activity will likely have different patterns for weekdays and weekends.
		EPA default day of week profile is flat; EPA default diurnal profile shows non-zero activity during middle of night (unreasonable).
Stationary Source Fuel Combustion	Use EPA default	LADCO inventory assumes flat day of week and hour of day profiles.
		EPA default profile reflects that industrial fuel combustion will likely show lower activity during weekends; more reasonable to assume lower activity during middle of night (less heating).
Gasoline Service Station	Use LADCO adjustments	LADCO profile reflects that less traffic will likely result in less fueling activity during weekends.
		EPA default day of week profile is flat.
Consumer Solvent (e.g., automotive aftermarket products)	Use LADCO adjustments	LADCO profile reflects that people tend to perform auto service during weekends.
		EPA default day of week profile is flat; EPA default diurnal profile shows non-zero activity during middle of night (unreasonable).
Commercial Solvent – Pesticide Application	Use LADCO adjustments	LADCO profile reflects that commercial solvent/pesticide application will likely be reduced on Sunday.
		EPA default day of week profile is flat; EPA default diurnal profile shows non-zero activity during middle of night (unreasonable).
Lawn & Garden Equipment	Use SoCAB daily profile & LADCO adjustments for hourly profile	SoCAB profile shows sharply reduced commercial lawn & garden activity during weekends which is more reasonable.
		LADCO diurnal profile shows zero activity during night.
		EPA default diurnal profile shows non-zero activity during middle of night (unreasonable).
Construction Equipment	Use LADCO adjustments	LADCO adjustments and EPA default show similar day of week profiles, but LADCO profile is based on later data.
		EPA default diurnal profile shows non-zero activity at midnight (unreasonable).
Recreational Boating	Use CENRAP adjustments	LADCO profile reflects that recreational boating activity will likely increase during weekends; sport fishing which starts in the early morning will likely dominate the recreational boating activity in the morning.
		EPA default day of week profile is flat.

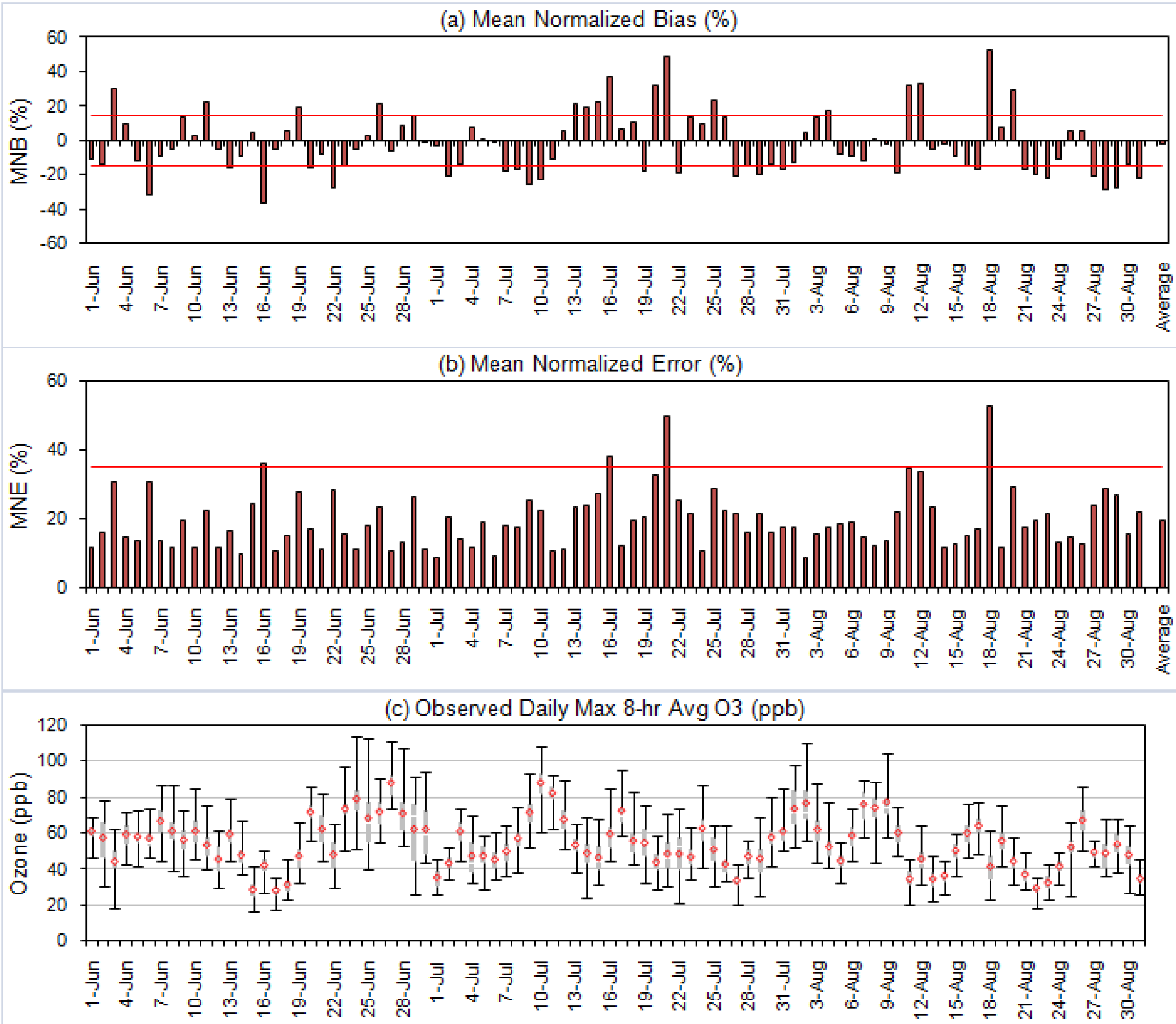

Figure S2. Statistical metrics for daily maximum 8-hour ozone concentrations over the SLM 4-km domain: (a) Model mean normalized bias (MNB); (b) model mean normalized error (MNE); (c) box and whisker plot for observations: The inner quartiles (the 25th to 75th percentiles) are represented by gray boxes, separated at the median by a horizontal line; the lower and upper quartiles are represented by whiskers; the means are represented by diamond markers.

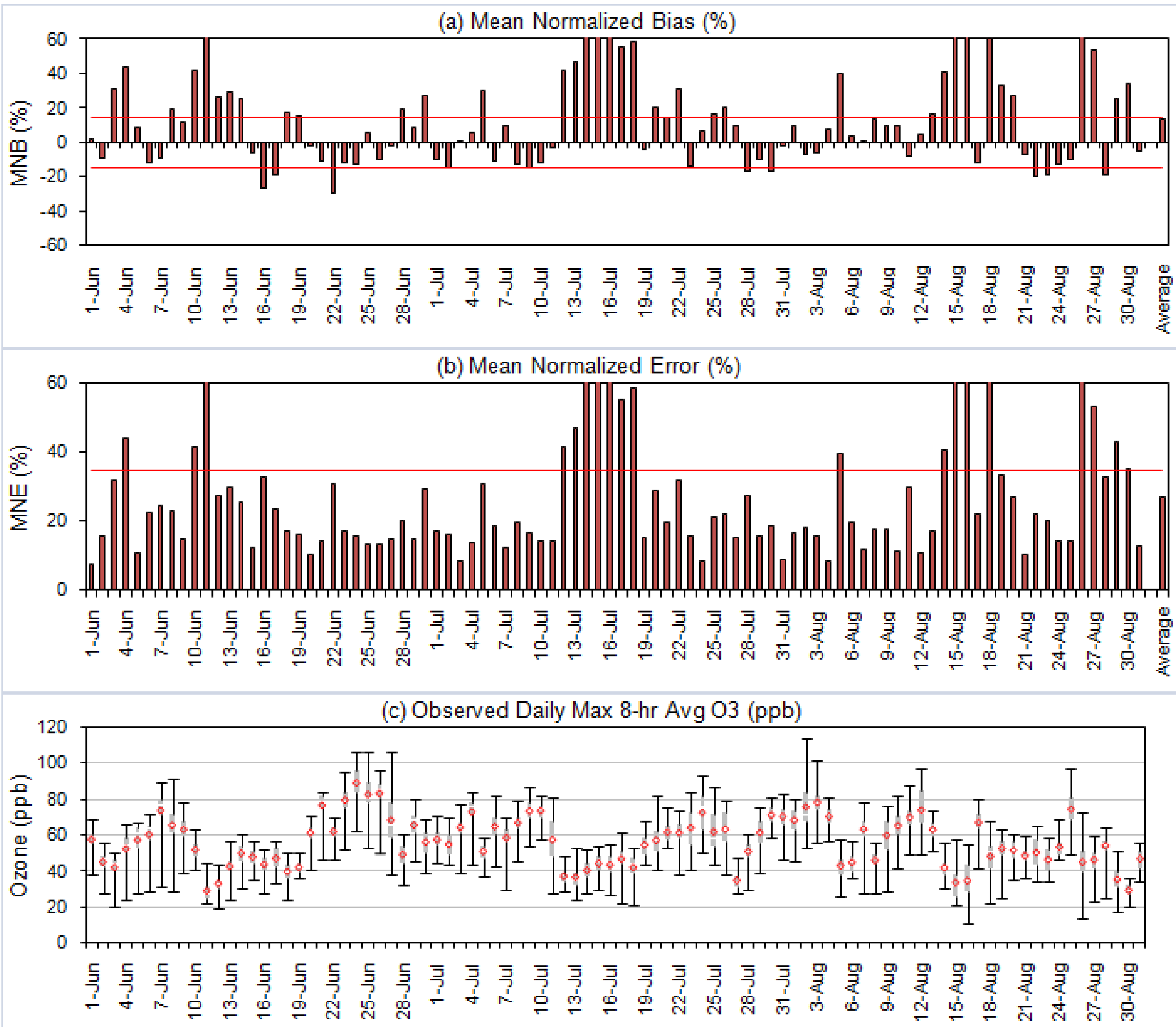

Figure S3. Statistical metrics for daily maximum 8-hour ozone concentrations over the CDC 4-km domain: (a) Model mean normalized bias (MNB); (b) model mean normalized error (MNE); (c) box and whisker plot for observations: The inner quartiles (the 25th to 75th percentiles) are represented by gray boxes, separated at the median by a horizontal line; the lower and upper quartiles are represented by whiskers; the means are represented by diamond markers.

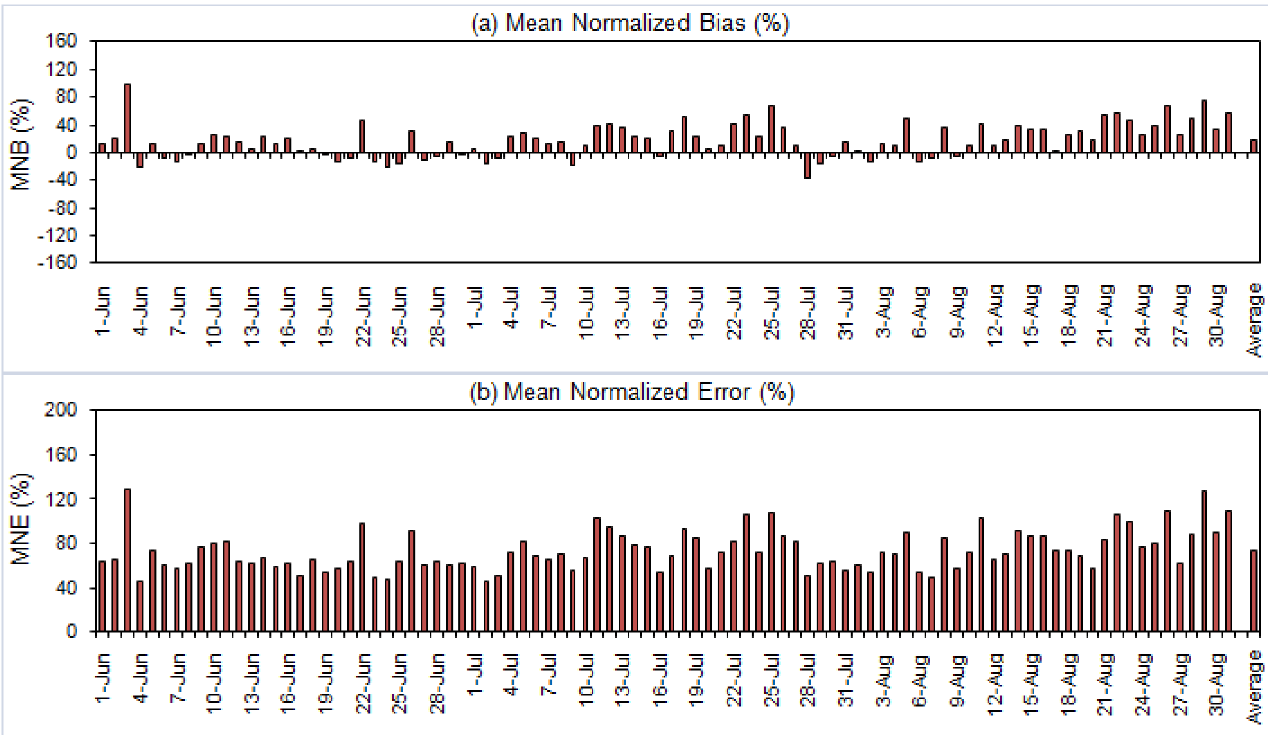

Figure S4. Statistical metrics for NOx concentrations in the morning (06:00-09:00) over the 12-km Midwest domain: (a) Model mean normalized bias (MNB); (b) model mean normalized error (MNE).

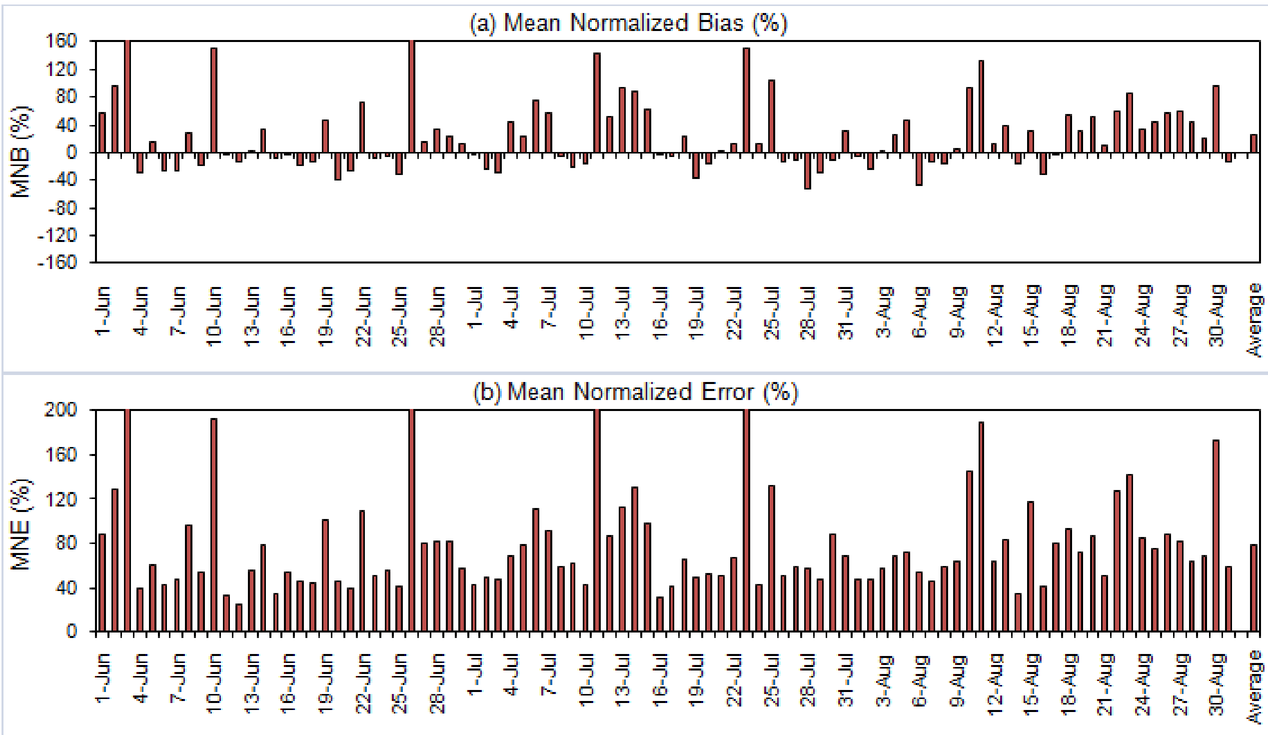

Figure S5. Statistical metrics for NOx concentrations in the morning (06:00-09:00) over the SLM 4-km domain: (a) Model mean normalized bias (MNB); (b) model mean normalized error (MNE).

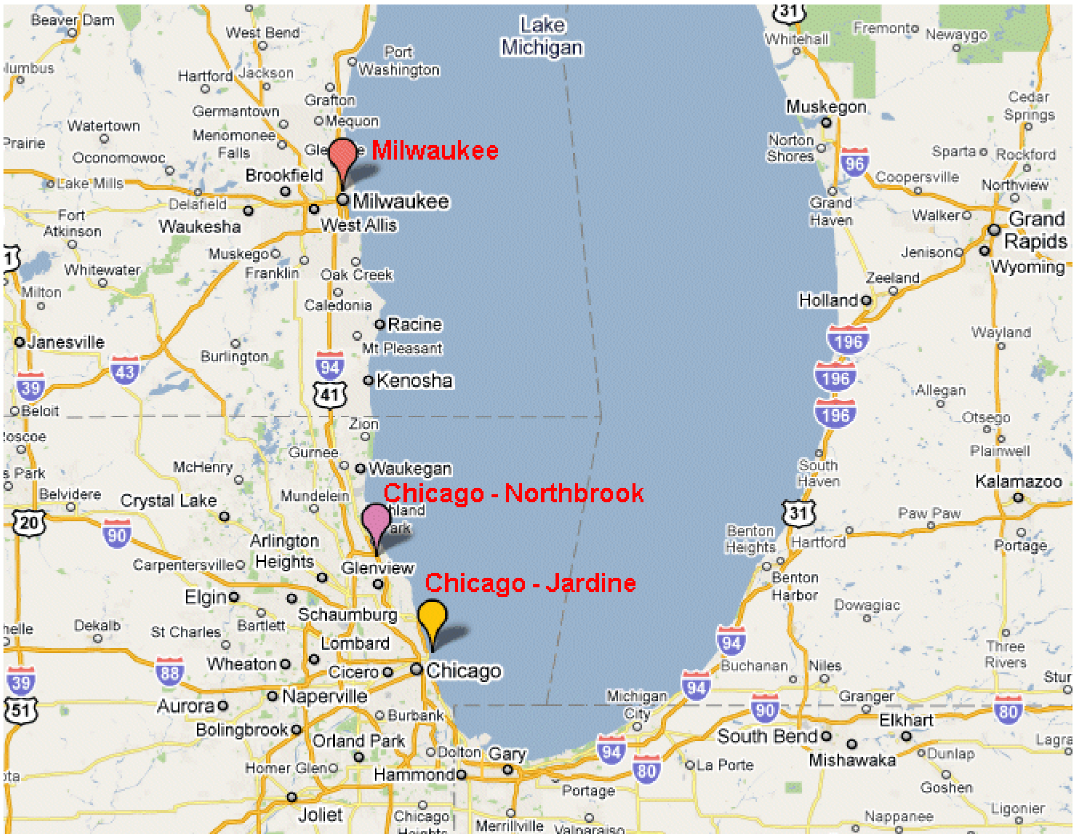

Figure S6. Locations of the three PAMS monitoring sites in the SLM 4-km domain.

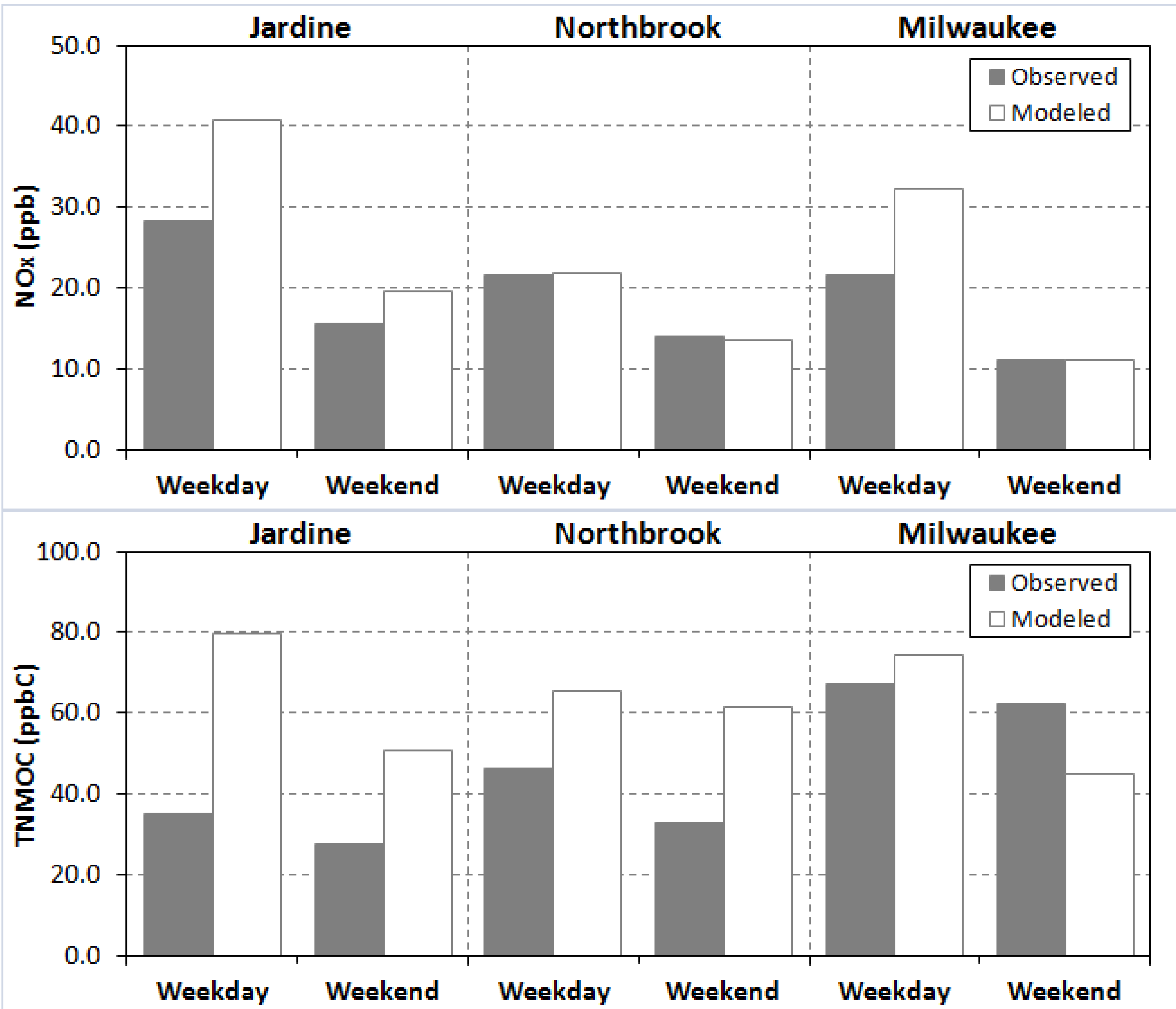

Figure S7. Median morning (06:00-09:00) NOx (top) and TNMOC (bottom) for June-August, 2005. Weekday averages Monday through Friday during the three-month period and weekend averages Saturday and Sunday.

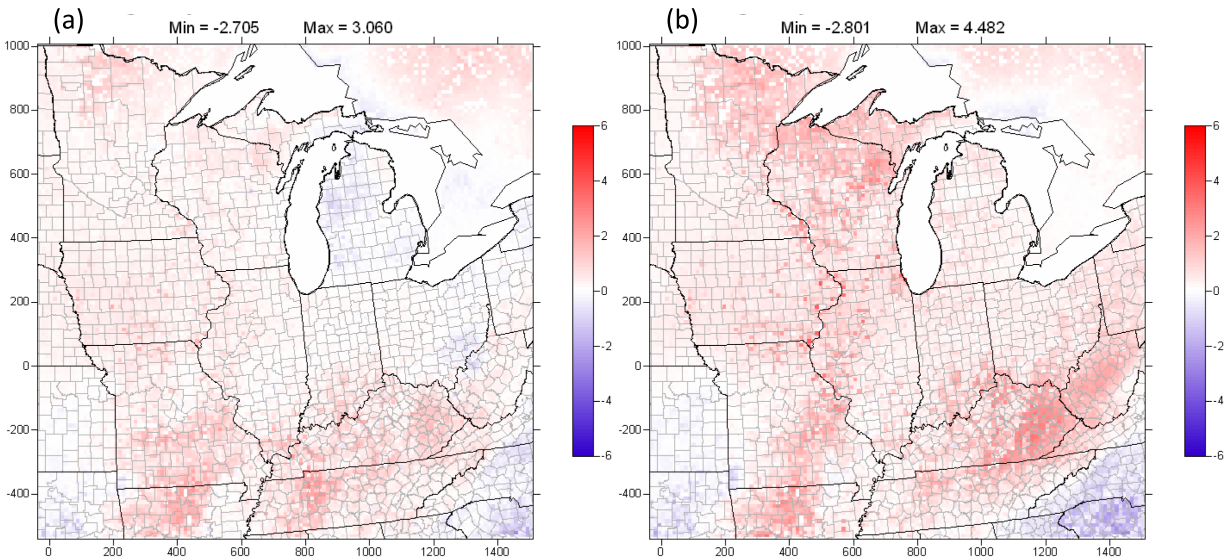

Figure S8. Weekend minus weekday differences in daily total biogenic VOC emissions (tons/day): (a) Biogenic VOC differences of average Saturday minus average Wednesday; (b) biogenic VOC differences of average Sunday minus average Wednesday.

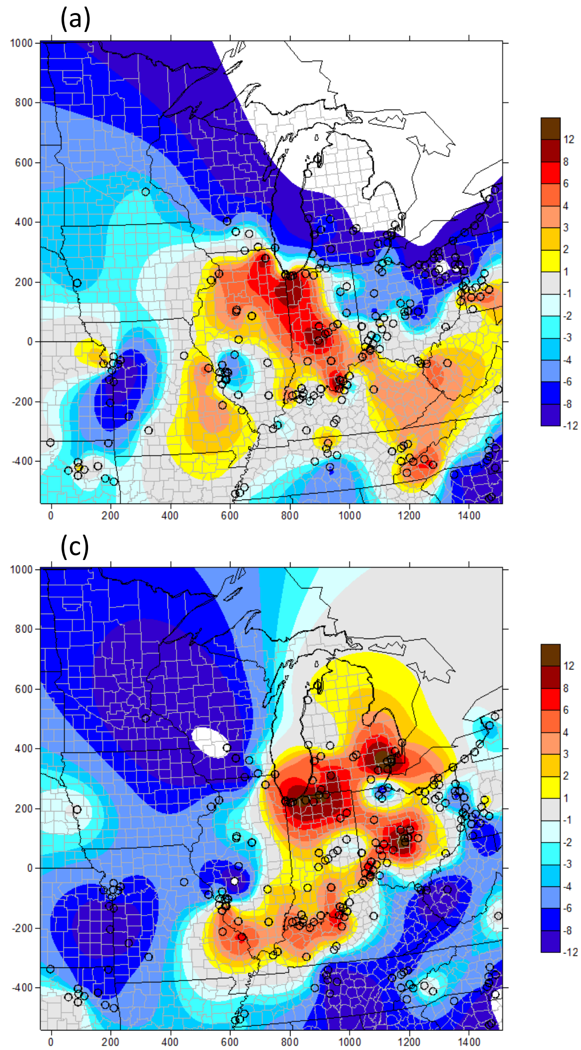

Figure S9. Weekend minus weekday differences in daily maximum 8-hour ozone concentrations (ppb) using Kriging interpolation of values at the AQS monitoring sites (circle markers). (a) Observed ozone differences of average high-ozone Wednesday minus average high-ozone Saturday. (b) Modeled ozone differences of the base case minus S1 simulation on average high-ozone Saturday. (c) Modeled ozone differences of average high-ozone Wednesday minus average high-ozone Saturday.

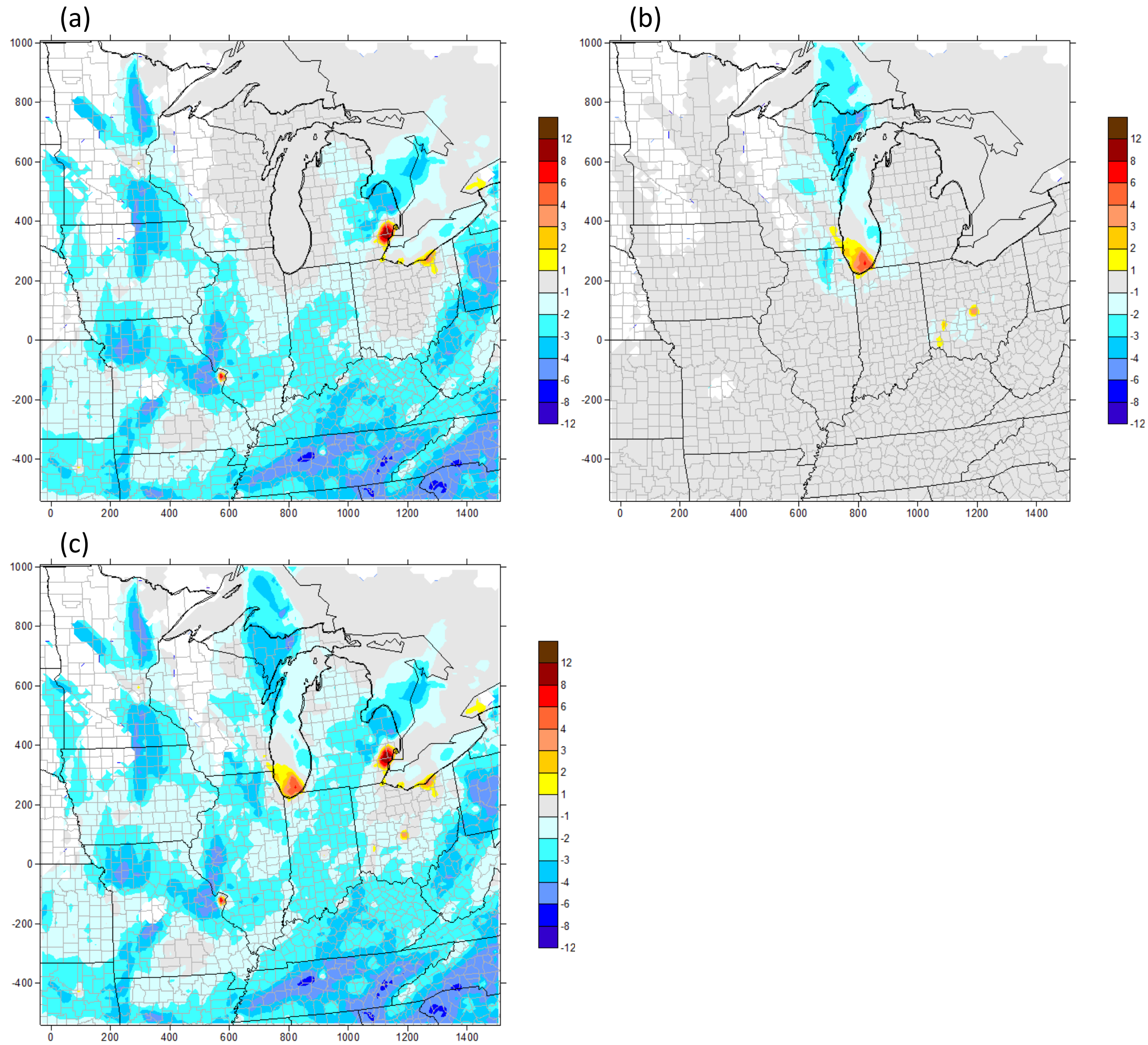

Figure S10. Weekend minus weekday differences in daily maximum 8-hour ozone concentrations (ppb). (a) Modeled ozone differences of the base case minus S2 simulation on high-ozone Saturday. (b) Modeled ozone differences of S2 minus S1 simulations on high-ozone Saturday. (c) Modeled ozone differences of the base case minus S1 simulation on high-ozone Saturday (same as Figure S9 (b) but without Kriging interpolation).

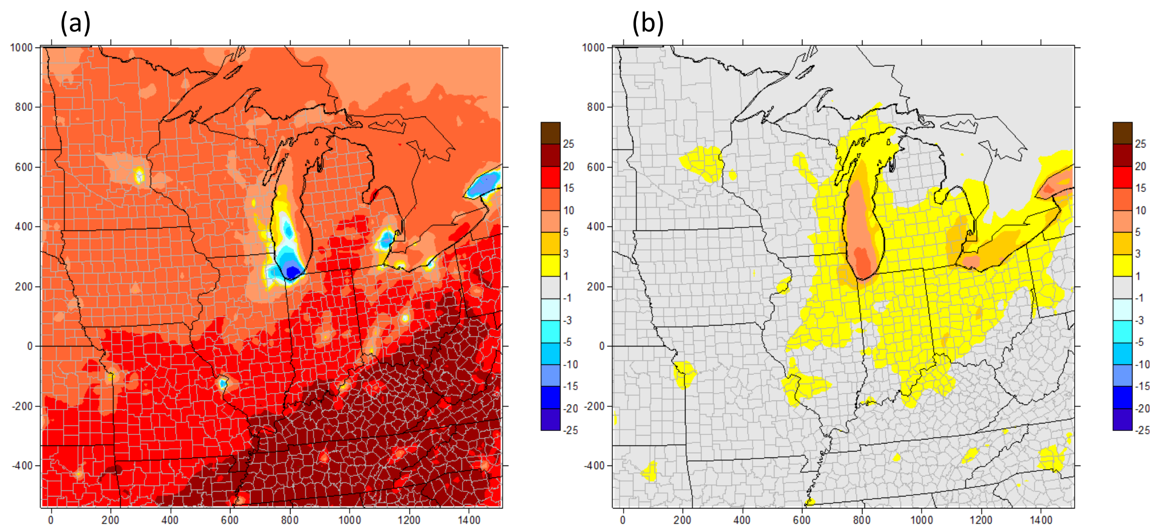

Figure S11. First-order DDM sensitivities of daily maximum 8-hour ozone (ppb) on average Saturday to domain-wide anthropogenic (a) NOx and (b) VOC emissions.

APPENDIX A

Technical Memorandum – Task 1A

1. Introduction

Variation in human activity patterns between weekdays and weekends can cause ambient ozone levels to vary over the course of the week. Air quality modeling of weekday/weekend ozone can be used to (1) better understand the observed changes in ozone and precursors, and (2) test the model's ability to simulate the effects of emissions changes. The Coordinating Research Council (CRC) has sponsored two projects (CRC A-36 and A-56) where ENVIRON studied weekday/weekend ozone changes for the Los Angeles area. ENVIRON also performed a modeling study for the National Renewable Energy Laboratory (NREL) to investigate weekday/weekend ozone changes in the Detroit area. These projects have prompted a need for a larger, regional scale modeling study to examine the weekday/weekend impacts on ozone concentrations at both upwind and downwind areas.

The objectives of the current CRC A-69 project are:

- To review weekday/weekend emission adjustments currently adopted for modeling in the eastern US and recommend a consistent set of adjustments for the modeling domain;
- To test the model's ability to simulate weekday/weekend ozone changes in the regional scale; and
- To determine the extent that weekday/weekend emission changes in upwind urban areas affect downwind urban and rural areas in the modeling domain.

Under Task 1a of this project, ENVIRON revised mobile source emission inventories for the Eastern U.S. by updating heavy-duty diesel vehicle (HDDV) NOx emission rates and speed correction factors. These updated emission rates were incorporated into link-based emissions modeling for the six Upper Midwest States, and into county-level emissions modeling for all other states in the 12k modeling domain of the Lake Michigan Air Directors Consortium (LADCO). The mobile source emissions were modeled using ENVIRON's CONCEPT MV model for the entire 12k modeling domain, with two nested 4k grids covering (a) the Southern Lake Michigan area, and (b) the Cincinnati/Dayton/Columbus area, as shown in Figure A-1.

2. Task 1a - Update Heavy-Duty Diesel Vehicle NOx Emission Rates and Speed Correction Factors

2.1. Base Emission Inventory Modeling

LADCO States

On-road mobile source emissions in the five LADCO states (Illinois, Indiana, Michigan, Wisconsin, and Ohio) plus Minnesota were developed by ENVIRON using the Consolidated Community Emissions Processing Tool (CONCEPT) MV emissions model (Jimenez et al., 2008). CONCEPT MV produces highly-resolved (temporally and spatially) emissions using link-based transportation demand modeling (TDM) data from 15 urban area networks and six statewide networks, with a total of about 850,000 links, as shown in Figure A-2.

The vehicle miles traveled (VMT) data provided by each TDM were disaggregated by roadway type, hour of day/day of week/month of year, using total volume temporal profiles. The hourly total volumes were then disaggregated into eight vehicle classes using vehicle mix temporal profiles. Figure A-3 shows an example of hourly temporal profiles for total VMT, and Figure A-4 shows and example of hourly temporal profiles for VMT mix. These temporal profiles were developed in previous ENVIRON work for LADCO by analyzing very large databases of hourly traffic counter and classification data supplied from Departments of Transportation in Illinois, Michigan, Minnesota, and Wisconsin (Lindhjem et al., 2004). SEMCOG and the Ohio DOT provided their own temporal profiles, and the Illinois profiles were used for Indiana (Jimenez et al., 2008).

It is important to understand that the total volume and vehicle mix temporal profiles developed for the LADCO states were applied to VMT, to properly allocate VMT by vehicle class, hour of day, and day of week. This is in contrast to the standard emissions modeling approach where the temporal profiles are applied to the estimated emissions. This is an important difference, and the two approaches will give different results, because the emission factors for heavy-duty vehicles are so much larger than those for light-duty vehicles.

Non-LADCO States

For all other states in the LADCO 2005 inventory, ENVIRON estimated emissions using county-level VMT and MOBILE6 inputs provided by the RPOs. In 2004, ENVIRON analyzed national databases of the Traffic Volume Trends and the Vehicle Travel Information System maintained by the Federal Highway Administration (FHWA), with the goal of assessing differences from state to state (Lindhjem and Shepard, 2004). From the database analyzed for that project, ENVIRON developed national average day of week and hour of day profiles, separately for light-duty and heavy-duty vehicles, as shown in Figures A-5 and A-6, that were used in all non-LADCO states.

For both the LADCO States and non-LADCO States modeling, ENVIRON generated motor vehicle emissions modeling using CONCEPT-MV for four July days (Thursday, Friday, Saturday, and Sunday), using average July meteorology. The Thursday values were used to represent all Mondays through Thursdays. Emissions estimates for June and August were estimated by scaling from the July emission inventories using factors provided by LADCO.

2.2. Heavy-Duty Diesel Vehicle Emissions Adjustment Factors

Unlike emission factors for light-duty vehicles, the MOBILE6 emission factors for heavy-duty vehicles were not produced from test data of in-use vehicles driven over representative duty cycles. Rather, heavy-duty vehicle emission rates in MOBILE6 are based on certification data tested on engines with optimal maintenance, generic miles per gallon average fuel consumption provided by the Truck In-Use Survey (TIUS) and an engineering analysis of typical fuel efficiency of engines. The MOBILE6 HDDV speed adjustments relied on an untested historic engineering assessment that was not documented when conducted in 1980s.

As part of another study, ENVIRON(2009) reviewed recent heavy-duty vehicle whole vehicle chassis dynamometer testing data at varying driving cycles that were not used in the development of MOBILE6, and compared those test data average emission rates with the speed-adjusted MOBILE6 emission rates for HC and NOx. The test data reviewed included data largely from the Coordinating Research Council (CRC) Report E-55/59 (West Virginia

University [Clark et al.], 2007), other West Virginia studies, the Colorado School of Mines Institute for Fuels and Engine Research (McCormack et al., 2003 and Yanowitz et al., 1999), and the University of California Riverside (Shah and Crocker, 2004). The CRC study provided detailed engine testing data for seventy-five trucks; the Riverside study provided test results for eleven trucks; and the Colorado studies provided test results for twenty-six trucks. Most of the data in these studies are for heavy-duty vehicles of Class 8a, 33,000 to 60,000 pounds gross vehicle weight rating.

ENVIRON prepared emission factor adjustments to MOBILE6 that represented the more recent data available for heavy-duty vehicles. These adjustments were reviewed with EPA MOVES modeling staff, who agreed that these adjustments are similar to what is in the upcoming MOVES model and thus would be appropriate to use for a sensitivity study. The heavy-duty vehicle emissions adjustments developed in this study were estimated from an average of the adjustments using four conditions: 10 and 25% failure rates for pre-1994 and 1994 and later model year diesel class 8a heavy heavy-duty trucks. The adjustments to the MOBILE6 heavy-duty vehicle emission rates are shown in Table A-1; Figure A-7 shows the NOx emission rates from the results of this study along with the MOBILE6 and California EMFAC model estimates for comparison.

Table A-1. Average adjustment factors for HDDV to MOBILE6 for 2005.

Speed (mph)	HC	NOx	PM
2	7.15	3.26	7.53
15	2.53	1.68	3.79
19	3.41	1.89	3.35
40	1.64	1.80	1.10
50	2.24	1.51	1.77

3. Task Deliverables and Results

The product of this task was CAMx model-ready mobile source emissions for the 12k region and the two nested 4k regions shown in Figure A-1; these emissions will be used in the air quality modeling to be performed as part of the overall A-69 study. HDDV adjustment factors in Table A-1 for hydrocarbons are large, but the HDDV contribution to motor vehicle HC is very small. HDDV NOx emissions, on the other hand, typically represent about half of the total on-road NOx emissions, so the multipliers shown in Table A-1 will significantly increase that contribution. HDDV VMT is accumulated mostly on freeways, interstates, and major arterials, and the average HDDV speeds in urban scale modeling is typically in the low 40’s mph.

Figure A-8 shows gridded NOx Emissions for the entire 12k grid and for the two nested 4k grids during the morning rush hour for a July Friday. The urban areas can be seen clearly, as can the interstates and major freeways between urban areas.

Figure A-9 compares the emissions by vehicle class for one of the local transportation networks in the Cincinnati/Dayton/Columbus 4k nested grid with and without the speed-based HDDV adjustment factors; the emissions shown are for July Friday/Saturday/Sunday. The chart shows that applying the adjustment factors results in a 30-35% increase in overall vehicle emissions. For HDDV emissions alone, the increase in NOx emissions is 80 percent for Fridays and 70 percent for weekend days. The weekend increases are smaller because average speeds for HDDV are slightly higher on weekends, and the adjustments decrease with increasing speed. In the morning rush hour, the increase will be even larger on a percentage basis, because the congested speeds are lower. Without the adjustments, HDDV accounted for about 40 to 50 percent of total daily vehicle emissions; with the speed adjustments their contribution increases to 60 to 70 percent in Columbus. Other local networks modeled have similar effects.

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Yanowitz, J., Graboski, M.S., Ryan, L.B.A., Daniels, T.L., McCormick, R.L. 1999, Chassis dynamometer study of emissions from 21 in-use heavy-duty diesel vehicles. *Environ. Sci. Technol.* 1999, **33**:209-216.

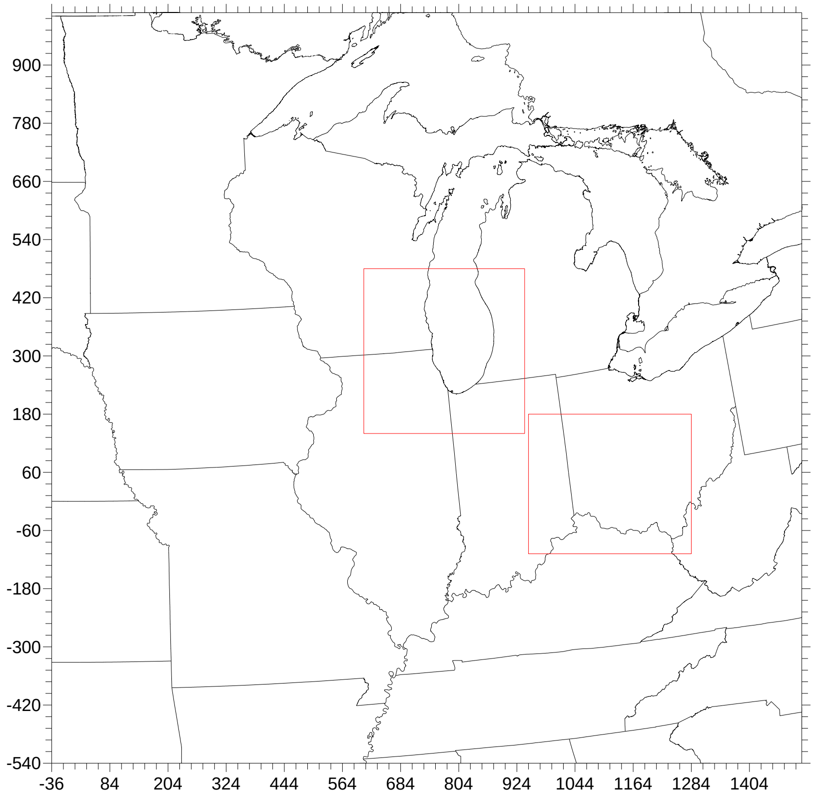


Figure A-1. LADCO 12k modeling domain, with two nested 4k grids covering (a) the Southern Lake Michigan area, and (b) the Cincinnati/Dayton/Columbus area.

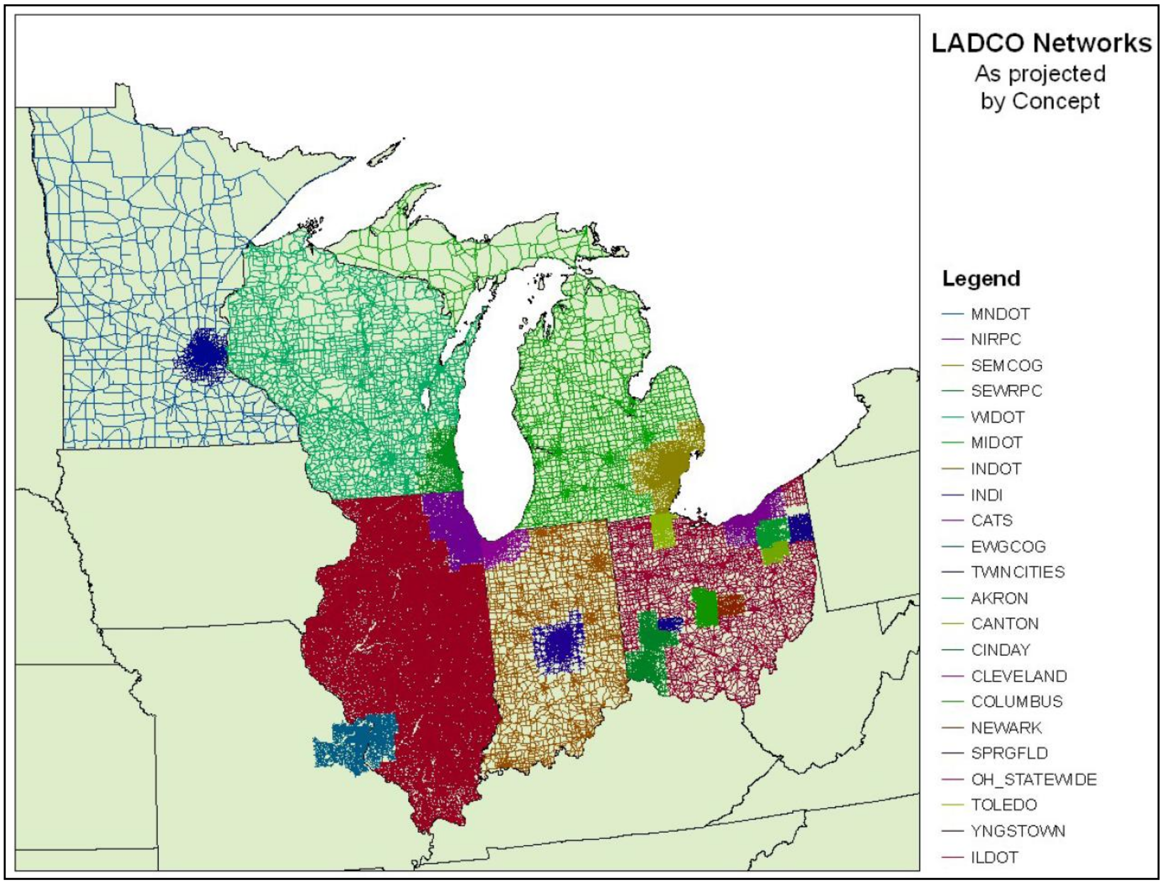


Figure A-2. LADCO region urban and statewide transportation network links.

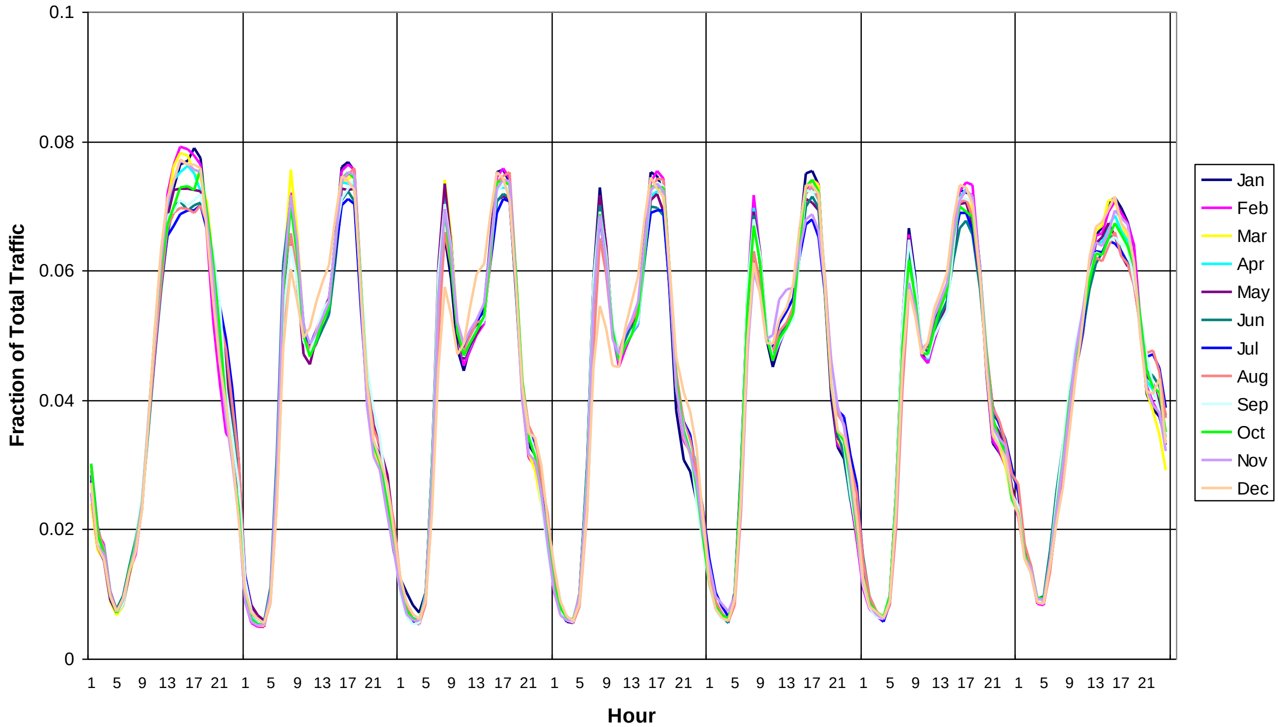


Figure A-3. Hourly temporal profiles by day of week (Sunday through Saturday) for total VMT on Michigan urban interstates.

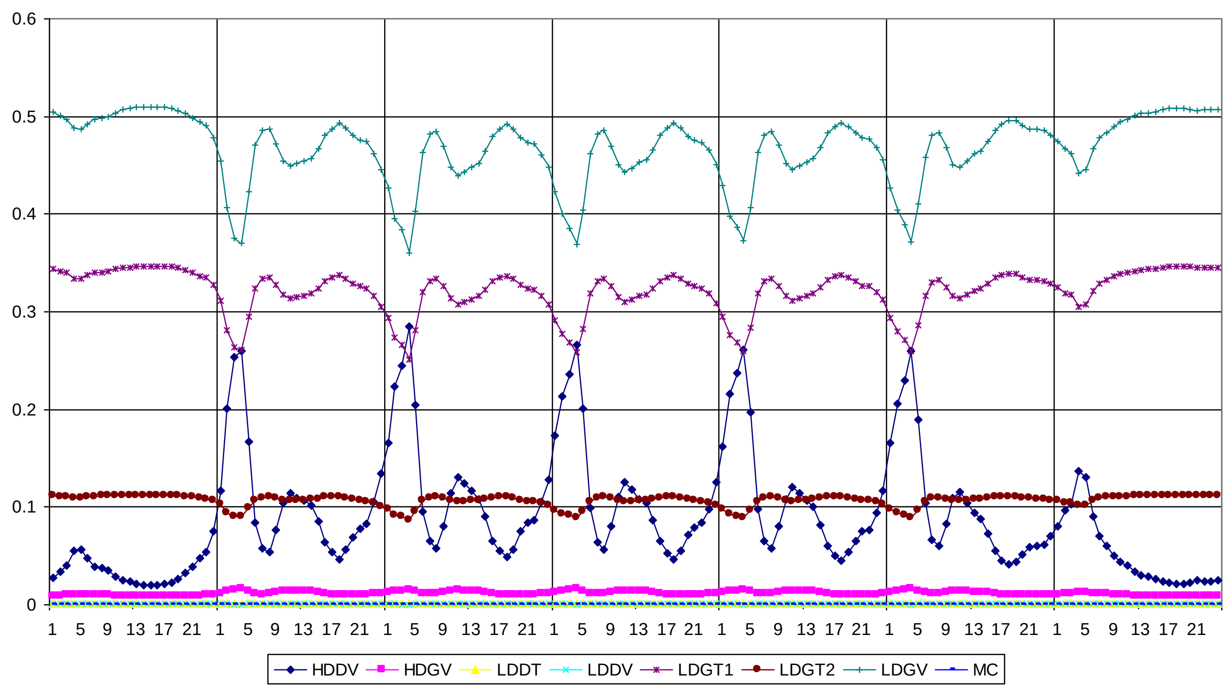


Figure A-4. Hourly temporal profiles for vehicle mix (i.e., VMT fraction) for Sunday through Saturday on Michigan urban interstates.

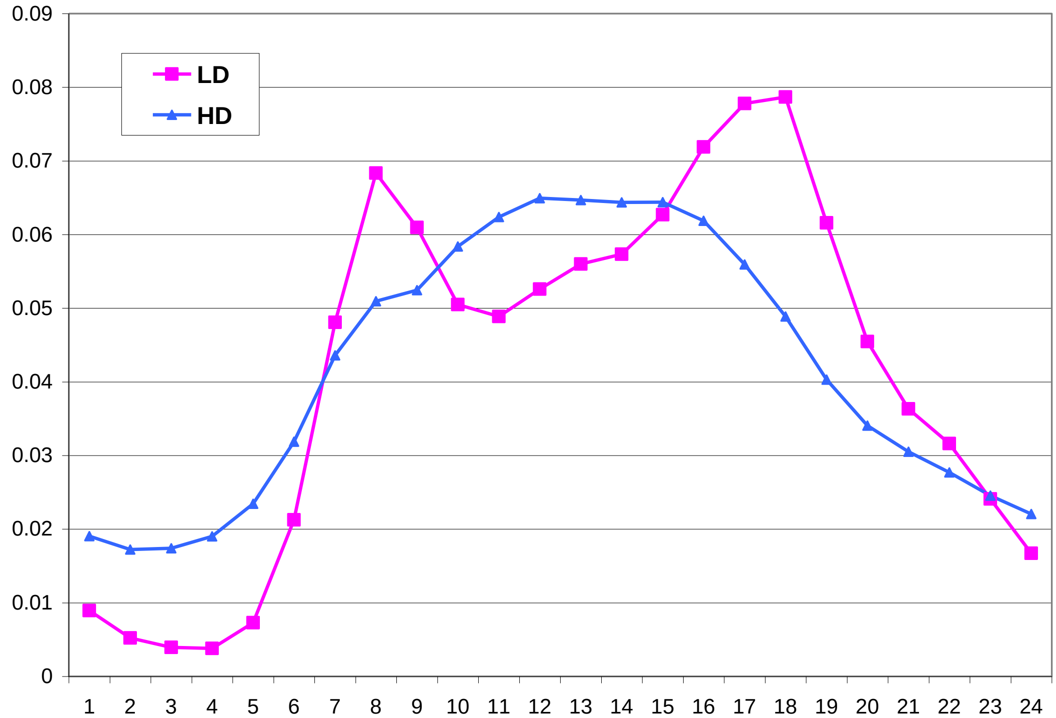


Figure A-5. Weekday hour of day profiles for on-road mobile source emissions in non-LADCO states.

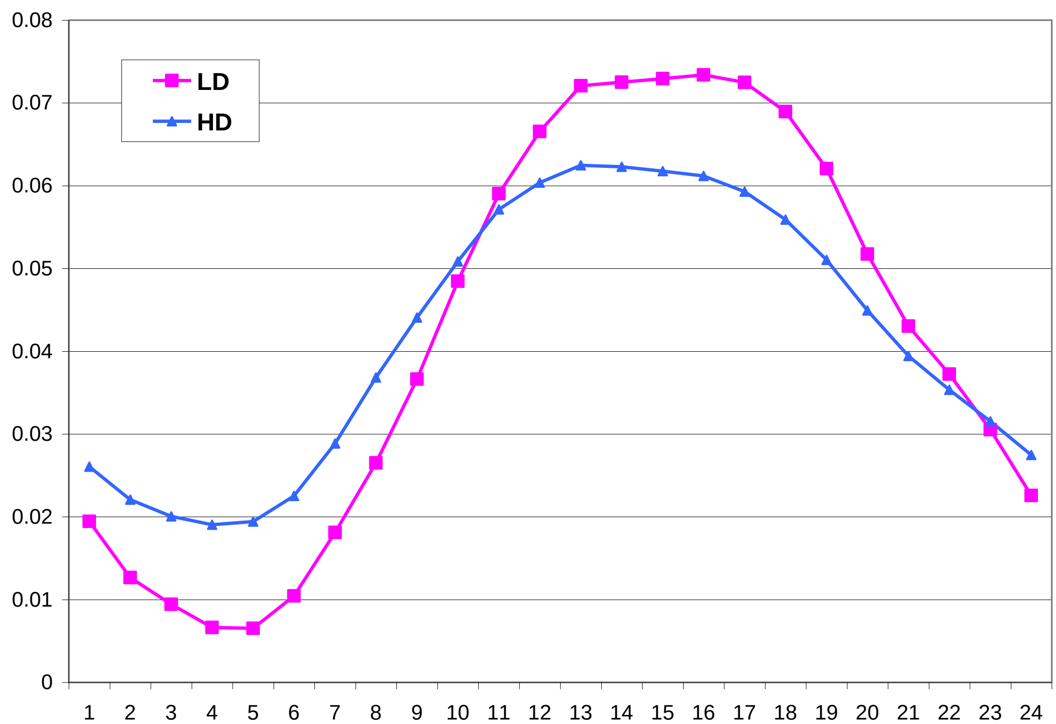


Figure A-6. Weekend hour of day profiles for on-road mobile source emissions in non-LADCO states.

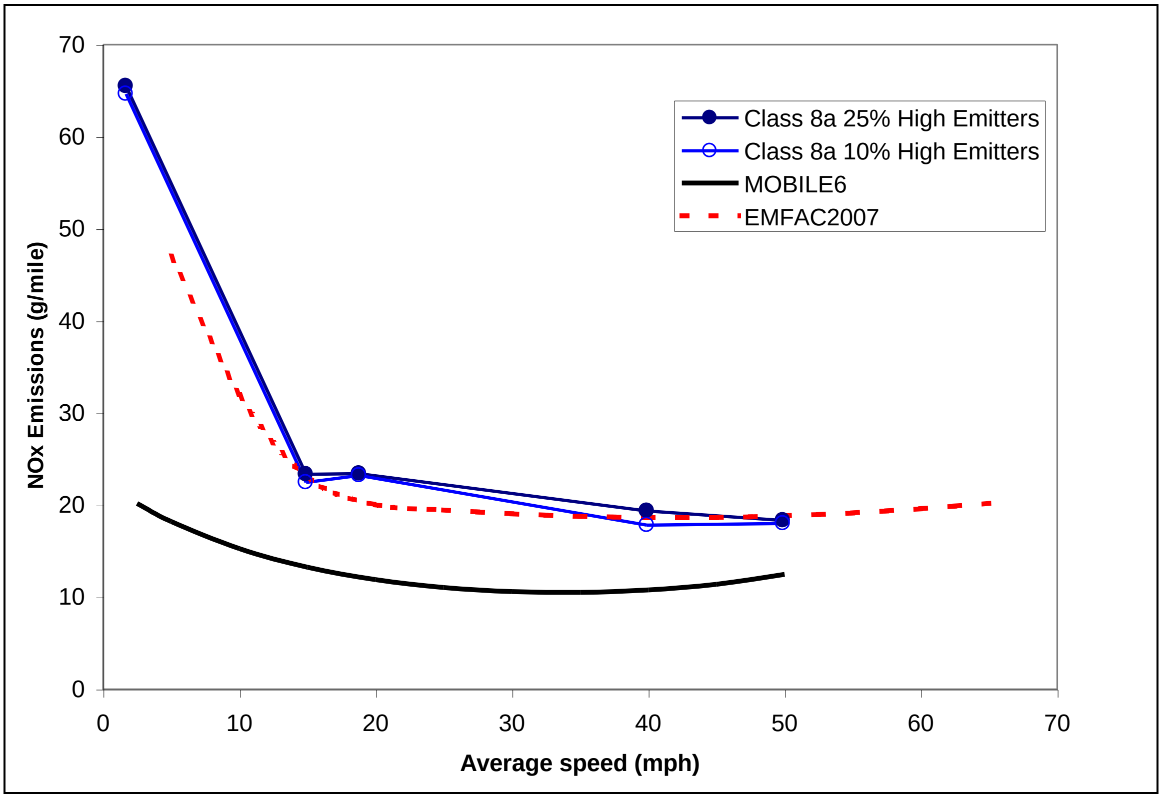
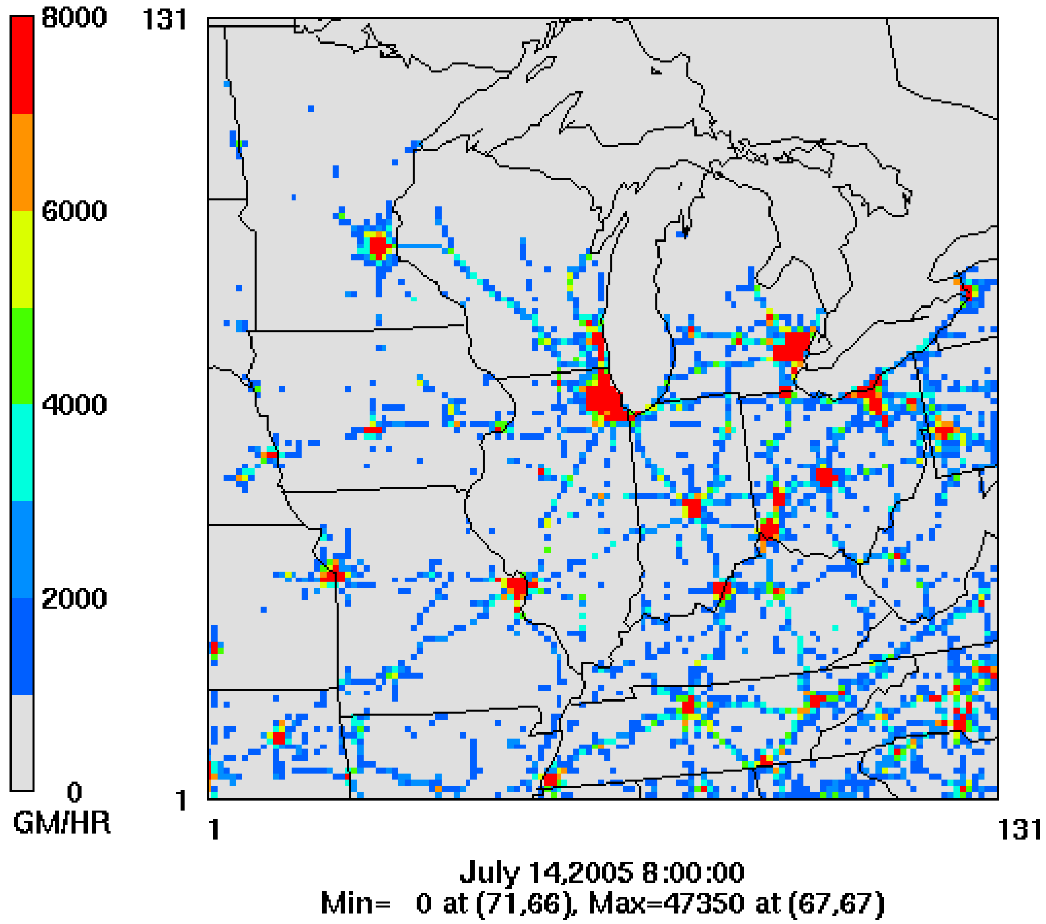
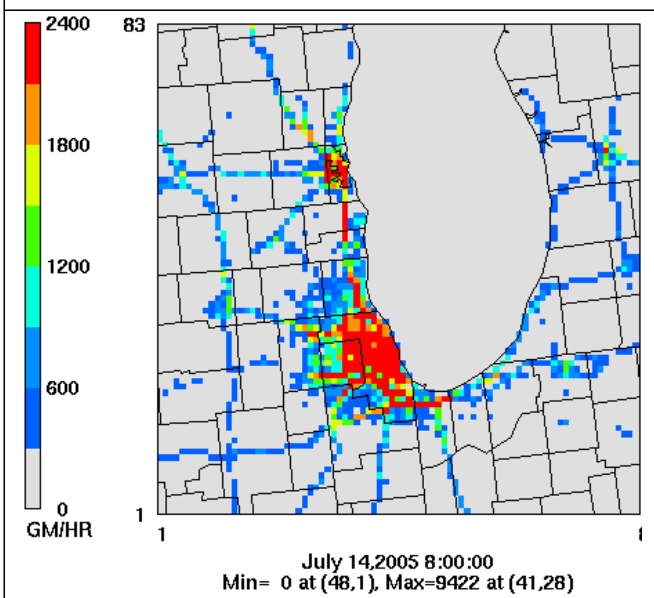


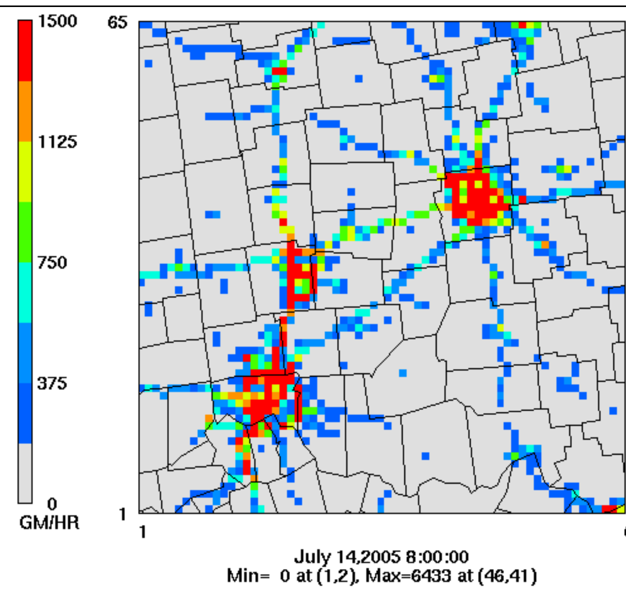
Figure A-7. Average NOx emissions for Class 8a vehicles in 2005.



(a) LADCO 12k modeling domain



(b) Southern Lake Michigan 4k nested grid



(c) Cincinnati/Dayton/Columbus 4k nested grid

Figure A-8. Gridded NOx Emissions for the 12k grid and two nested 4k grids, 8am-9am, July Friday.

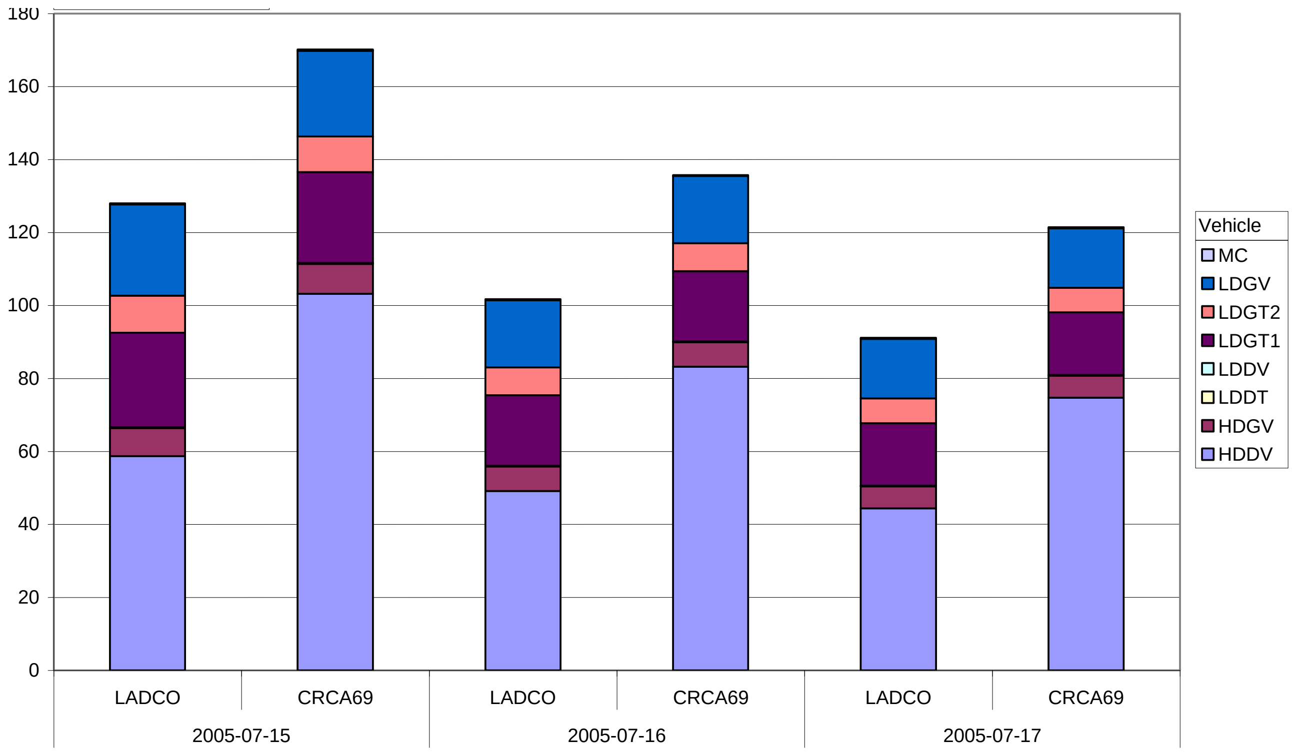


Figure A-9. NOx emissions by vehicle class for the Columbus, OH transportation network for a July Friday/Saturday/Sunday, 2005. “LADCO” emissions are base case emissions without HDDV emission factor adjustments by speed; “CRCA69” emissions are with the adjustment factors.

APPENDIX B

Technical Memorandum – Task 1

1. Introduction

It is expected that different human activity patterns between weekdays and weekends would cause ambient ozone levels to vary over the course of the week. Modeling of weekday/weekend ozone can be used to (1) better understand the observed changes in ozone and precursors, and (2) test the model's ability to simulate the effects of emissions changes. The Coordinating Research Council (CRC) has sponsored two projects (CRC A-36 and A-56) where ENVIRON studied weekday/weekend ozone changes for the Los Angeles area. ENVIRON also performed a modeling study for the National Renewable Energy Laboratory (NREL) to investigate weekday/weekend ozone changes in the Detroit area. These projects have prompted a need for a larger, regional scale modeling study to examine the weekday/weekend impacts on ozone concentrations at both upwind and downwind areas.

The objectives of the current CRC project (A-69) are:

- To review weekday/weekend emission adjustments currently adopted for modeling in the eastern US and recommend a consistent set of adjustments for the modeling domain;
- To test the model's ability to simulate weekday/weekend ozone changes in the regional scale; and
- To determine the extent that weekday/weekend emission changes in upwind urban areas affect downwind urban and rural areas in the modeling domain.

Under Task 1 of this project, ENVIRON has reviewed temporal profiles (day of week and diurnal profiles) in the current Lake Michigan Air Directors Consortium (LADCO) 2005 inventory and inventories developed by the other Regional Planning Organizations (RPOs). In many cases the RPOs are using default temporal profiles developed by EPA so our review focuses on where RPOs made adjustments to temporal profiles. We recommend temporal profile adjustments to be made to the regional inventory which will be used for the subsequent tasks of project A-69.

2. Task 1 – Review and Improve Weekend Emission Inventories for the Eastern US

In this task, we have reviewed the temporal profile adjustments implemented by LADCO in their 2005 inventory as well as other temporal profile adjustments developed by other eastern RPOs (MANE-VU, CENRAP, and VISTAS) that were not applied in the LADCO 2005 inventory. While other source categories may also show different temporal profiles between weekdays and weekends, we focused on our efforts on mobile (both on-road and off-road) and area source emissions which are expected to be responsible for most of the weekday/weekend effects. Month of year temporal profiles were not reviewed.

2.1. On-road mobile source emissions

<u>LADCO States</u>
On-road mobile source emissions in the five LADCO states (Illinois, Indiana, Michigan, Wisconsin, and Ohio) plus Minnesota were developed by ENVIRON using the Consolidated Community Emissions Processing Tool (CONCEPT) MV emissions model (Jimenez et al., 2008). CONCEPT MV produced highly-resolved (temporally and spatially) emissions using

link-based transportation demand modeling (TDM) data from 15 urban area networks and 6 statewide networks, with a total of about 850,000 links. The vehicle miles traveled (VMT) data provided by each TDM were disaggregated by roadway type, hour of day/day of week/month of year, using total volume temporal profiles (see Figure B-1 for an example of hourly temporal profiles for VMT). The hourly total volumes were then disaggregated into eight vehicle classes using vehicle mix temporal profiles (see Figure B-2 for an example of hourly temporal profiles for vehicle mix). These temporal profiles were developed in previous ENVIRON work for LADCO from traffic counter data supplied from the Illinois, Michigan, Minnesota, and Wisconsin DOT (Lindhjem et al., 2004). SEMCOG and the Ohio DOT provided their own temporal profiles, and the Illinois profiles were used for Indiana (Jimenez et al., 2008).

It is important to understand that the total volume and vehicle mix temporal profiles developed for the LADCO states were applied to VMT, to properly allocate VMT by vehicle class, hour of day, and day of week. This is in contrast to the standard emissions modeling approach where the temporal profiles are applied to the estimated emissions. This is an important difference, and the two approaches will give different results, because the emission factors for heavy-duty vehicles are so different from those for light-duty vehicles.

Non-LADCO States

For all other states in the LADCO 2005 inventory, ENVIRON estimated emissions using county-level VMT and MOBILE6 inputs provided by the RPOs. In 2004, ENVIRON analyzed national databases of the Traffic Volume Trends and the Vehicle Travel Information System maintained by the Federal Highway Administration (FHWA), with the goal of assessing differences from state to state (Lindhjem, 2004). From the database analyzed for that project, ENVIRON developed national average day of week and hour of day profiles, separately for light-duty and heavy-duty vehicles, as shown in Figures B-3 to B-5, that were used in all non-LADCO states.

2.2. Off-road and area source emissions

Adjustments to temporal profiles in the LADCO 2005 emission inventory and inventories developed by other RPOs are discussed below. We have focused on cases where RPOs changed the default temporal profile from EPA because these are the cases where (1) improved information may be available, and (2) RPOs are using different assumptions. We reviewed several contractor reports that documented methodologies for estimating temporal profiles used in the emission inventories for LADCO and other eastern RPOs. We examined day of week and hour of day profiles for various source categories discussed in these reports and compared them with the current EPA default profiles. For off-road mobile source and area source emissions, we have focused on major NOx and VOC sources (stationary source fuel combustion, gasoline distribution, consumer products, surface coating, etc.).

LADCO 2005 Inventory

For most off-road and area source emissions, EPA's default temporal profiles were used for the five LADCO states plus MN and IA. Temporal profiles for residential and commercial lawn and garden, construction equipment, and agricultural equipment emissions as well as small stationary source emissions were revised based on reviews funded by LADCO (Jones, 2005; Thesing and Bollman, 2004). Jones (2005) collected information from various sources including published reports and telephone surveys. For example, temporal profiles estimated for surface coating emission category were based on data from Emission Inventory Improvement Program (EIIP) report issued by EPA while telephone surveys of Midwest Equipment Dealers Association and

Home Depot stores were used to improve monthly profiles for emissions from lawn and garden equipments. We have discovered an error in the daily profiles for commercial lawn & garden activity reported by Jones (2005) and fixed it using the original data cited (Causley et al., 1995). To develop temporal profiles for construction equipment, Thesing and Bollman (2004) conducted telephone survey of construction equipment owners and operators and analyzed the equipment usage data. For the adjustments and our recommendations, see Table B-1. For the remaining states of the modeling domain, the off-road emissions were obtained from the RPOs.

<u>MANE-VU 2002 Inventory</u>
The off-road and area source emissions of the MANE-VU inventory are based on the EPA default temporal profiles and SCC cross-reference file (Mullen and Thesing, 2005; Pechan et al., 2005). Improvements to the default temporal allocations include: (1) updates to the default temporal cross-references to assign different existing profiles that are more reasonable; (2) new cross-references to assign existing profiles for the MANE-VU sources that didn't have default cross-references; and (3) new cross-references that assign new profiles for the MANE-VU sources that were missing in the default cross-reference file. The most commonly assigned day of week profiles were 7 (uniform 7 days) and 5 (weekday only) and the most common diurnal profiles were 12 (7am-6pm uniform) and 26 (maximum middle of the day & minimum early in morning). These updates were performed by Carolina Environmental Program.

<u>CENRAP 2002 Inventory</u>
Off-road and area source temporal profiles for the CENRAP emission inventory were based on those used for MANE-VU inventory with some new temporal profile assignments to include missing SCCs and/or cross-references (Pechan and CEP, 2005). STI conducted a bottom-up activity data survey for recreational boats, locomotive, and commercial marine vessels, and revised these temporal profiles (Reid et al., 2004).

<u>VISTAS 2002 Inventory</u>

For off-road and area sources, VISTAS used EPA-default temporal profiles as implemented in the EPA CAIR/CAMR/CAVR modeling platform (Morris et al., 2009).

<u>Activity Data for SoCAB</u>

STI has collected weekday/weekend emission activity data for various mobile, area, and point sources (Chinkin et al., 2003). Although this study was done for California's South Coast Air Basin, we have reviewed some of the source categories that may be applicable to other regions (e.g., lawn & garden equipments).

3. Summary and Recommendations

- <u>On-road mobile sources</u>. The LADCO 2005 modeling database has the most advanced, highly detailed on-road mobile source emission inventory for the Midwest. For the five LADCO states and Minnesota, we recommend using the emissions generated using LADCO 2005 CONCEPT MV emissions that were developed using the detailed temporal profiles for total VMT and VMT mix. For all other states in the modeling domain, we recommend applying the national average hour-of-day and day-of week temporal profiles for light-duty and heavy-duty vehicles based on traffic counter data (Figures B-3 to B-5).

Although on-road mobile emissions were not modeled consistently across the whole modeling domain (greater detail for the LADCO states), the modeling has used the best available data and the weekday/weekend temporal profiles used for the LADCO states and non-LADCO states are pretty similar.

- Off-road and area sources. We have reviewed adjustments made by other RPOs (VISTAS, CENRAP and MANE-VU) to the temporal profiles for major off-road and area sources. Our recommendations are based on reasonableness of the adjusted profiles. Figures B-6 to B-13 show day of week and hour of day profiles used for the various RPOs as well as EPA defaults. Table B-1 summarizes our recommendations and rationale for them.

Table B-1. Adjustments made to the temporal profiles for off-road mobile and area sources and our recommendations.

Source Category	Temporal Profiles	Recommendations	Rationale
Surface Coating	Figure B-6	LADCO adjustments	Surface coating activity will likely have different patterns for weekdays and weekends while the EPA default profile is flat; the EPA default diurnal profile shows non-zero activity during middle of night (unreasonable).
Stationary Source Fuel Combustion	Figure B-7	EPA default	Industrial fuel combustion will likely show lower activity during weekends; more reasonable to assume lower activity during middle of night (less heating).
Gasoline Service Station	Figure B-8	LADCO adjustments	Less traffic will likely result in less fueling activity during weekends.
Consumer Solvent	Figure B-9	LADCO adjustments	People tend to perform auto service during weekends; Commercial application of pesticide will likely be reduced on Sunday; the EPA default diurnal profile shows non-zero activity during middle of night (unreasonable).

Source Category	Temporal Profiles	Recommendations	Rationale
Commercial Solvent – Pesticide Application	Figure B-10	LADCO adjustments	Commercial solvent/pesticide application will likely be reduced on Sunday; the EPA default diurnal profile shows non-zero activity during middle of night (unreasonable).
Lawn & Garden Equipment	Figure B-11	SoCAB daily profile; LADCO adjustments for hourly profile	Commercial lawn & garden activity will likely decrease sharply during weekends; the EPA default diurnal profile shows non-zero activity during middle of night (unreasonable).
Construction Equipment	Figure B-12	LADCO adjustments	Similar day of week profiles, but LADCO profile is based on later data; the EPA default diurnal profile shows non-zero activity at midnight (unreasonable).
Recreational Boating	Figure B-13	CENRAP adjustments	Recreational boating activity will likely increase during weekends; sport fishing will likely dominate the recreational boating activity in the morning.

4. References

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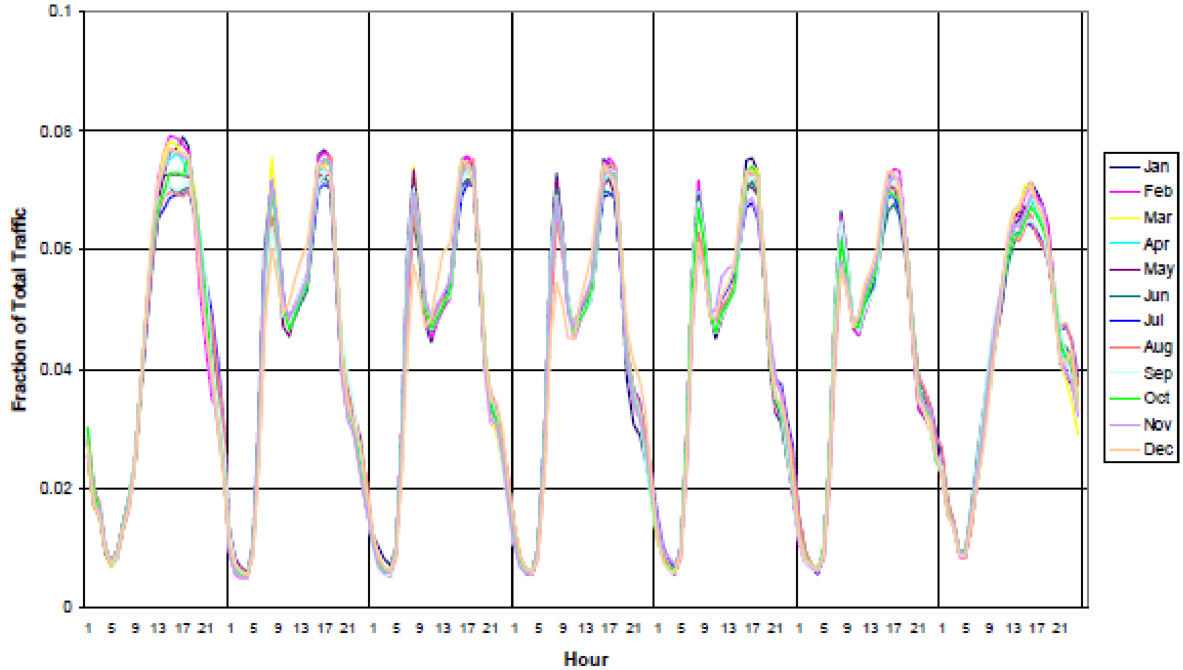


Figure B-1. Hourly temporal profiles by day of week (Sunday through Saturday) for total VMT on Michigan urban interstates.

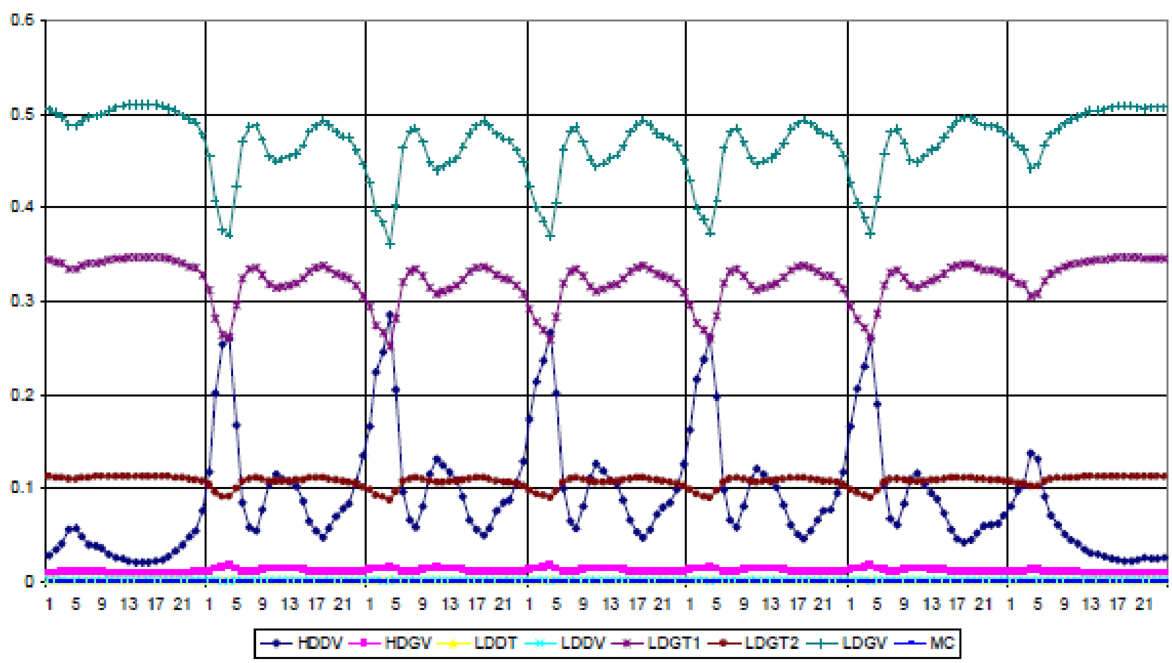


Figure B-2. Hourly temporal profiles for vehicle mix (i.e., VMT fraction) for Sunday through Saturday on Michigan urban interstates.

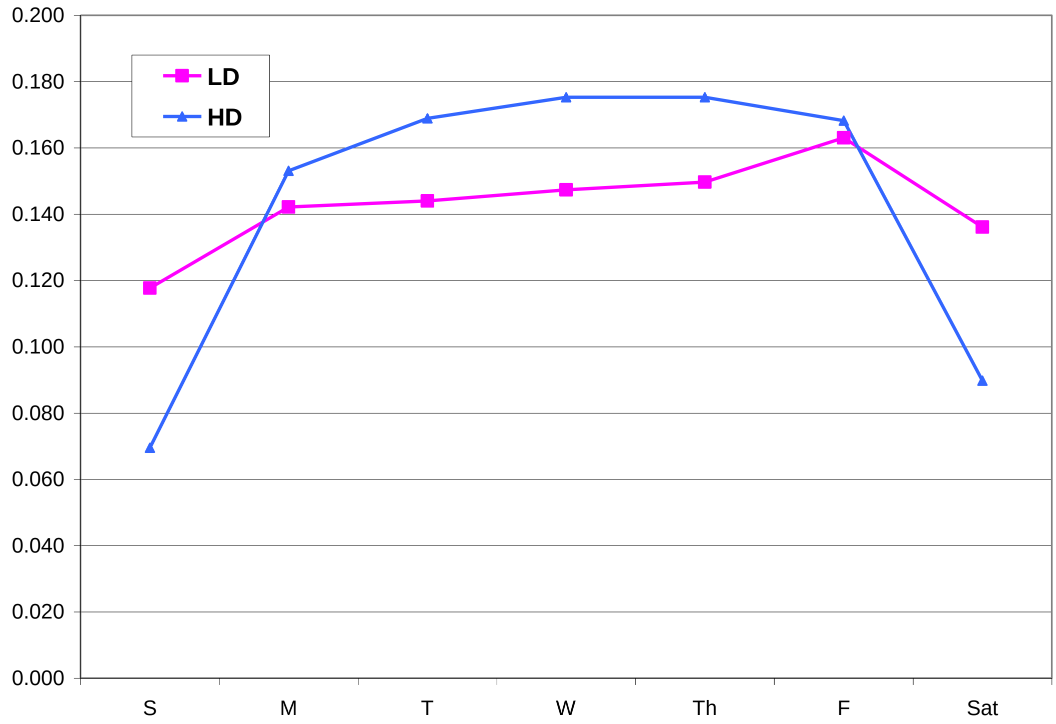


Figure B-3. Day of week profiles for on-road mobile source emissions of the non-LADCO states.

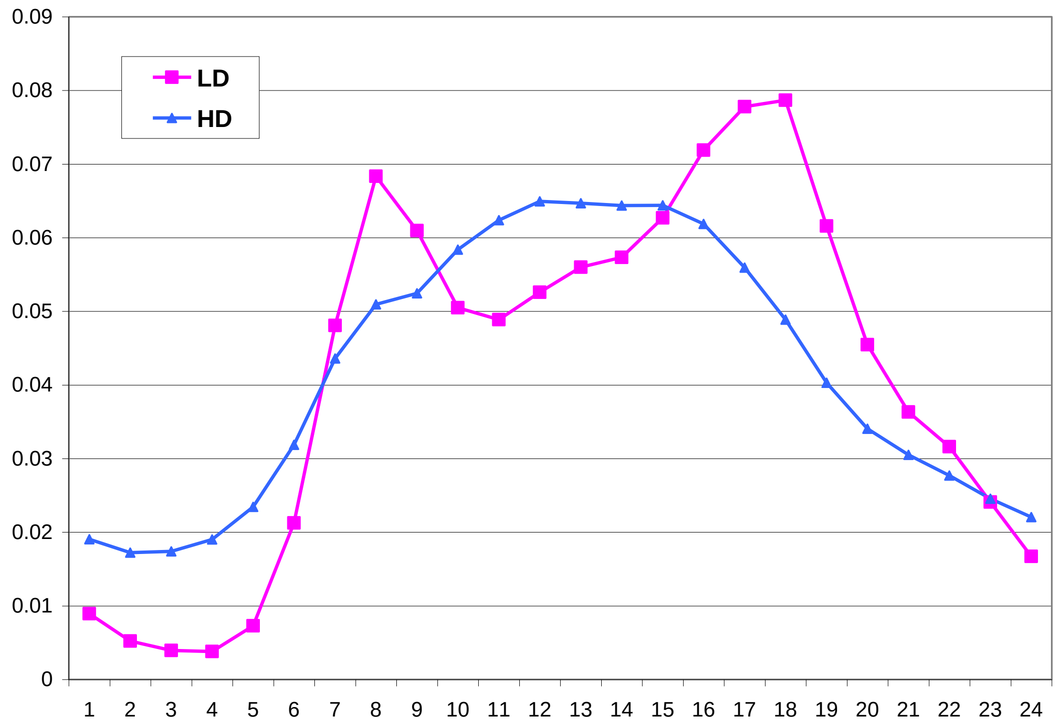


Figure B-4. Hour of day (weekday) profiles for on-road mobile source emissions of the non-LADCO states.

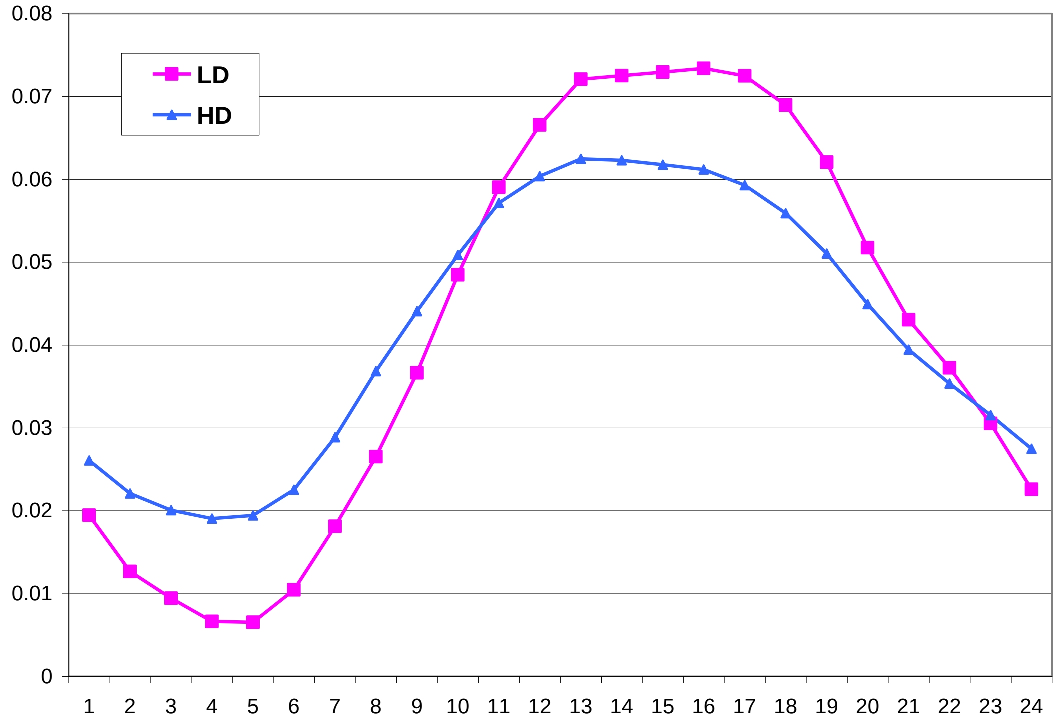
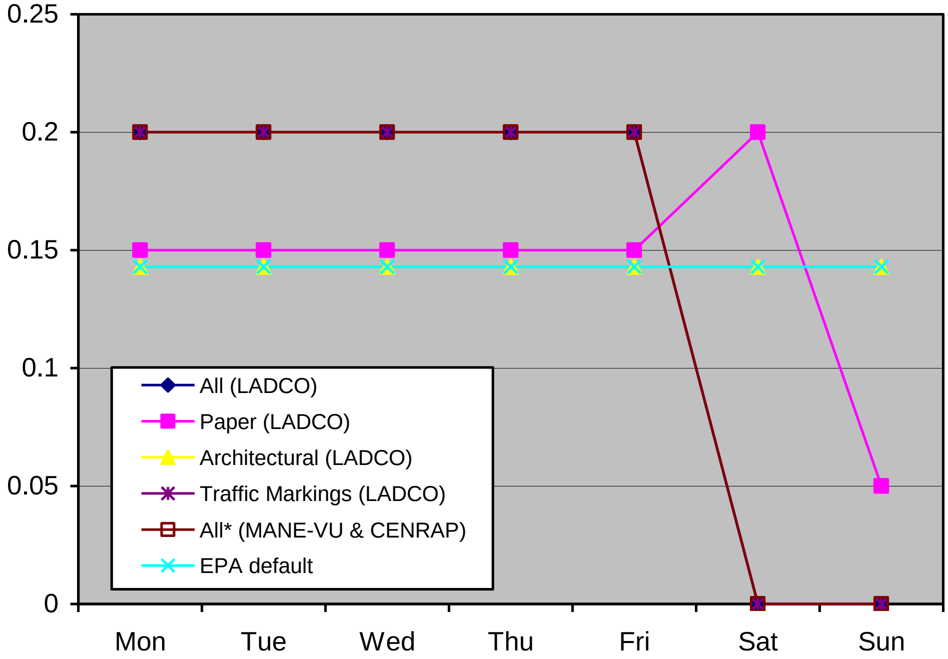


Figure B-5. Hour of day (weekend) profiles for on-road mobile source emissions of the non-LADCO states.

(a) Day of week profile



*Except for architectural coatings and traffic markings

(b) Hour of day profile

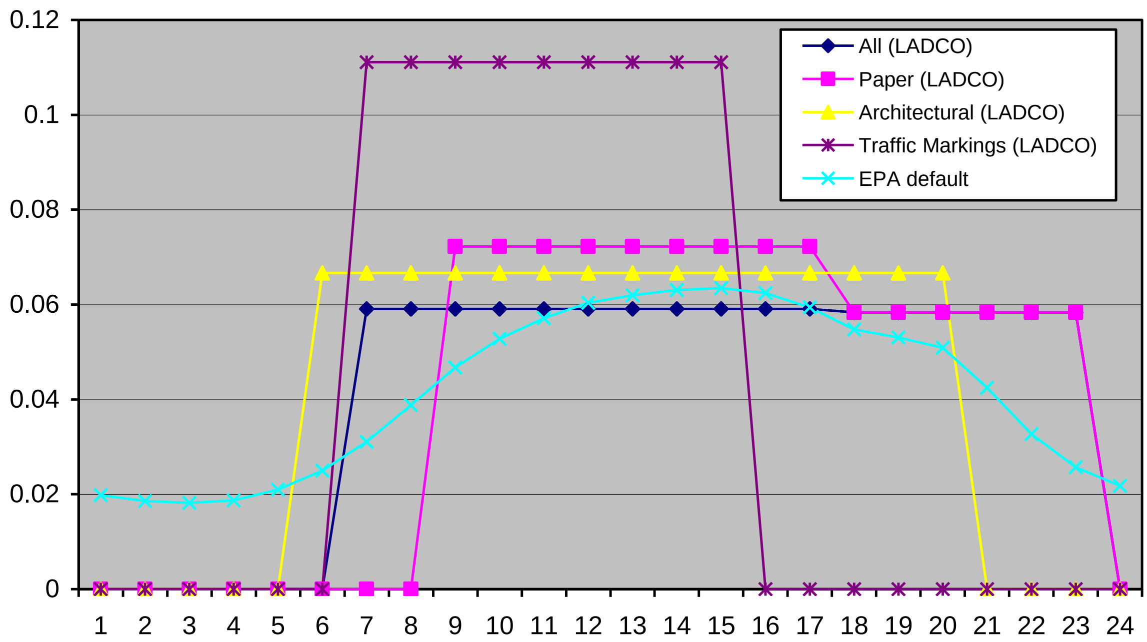
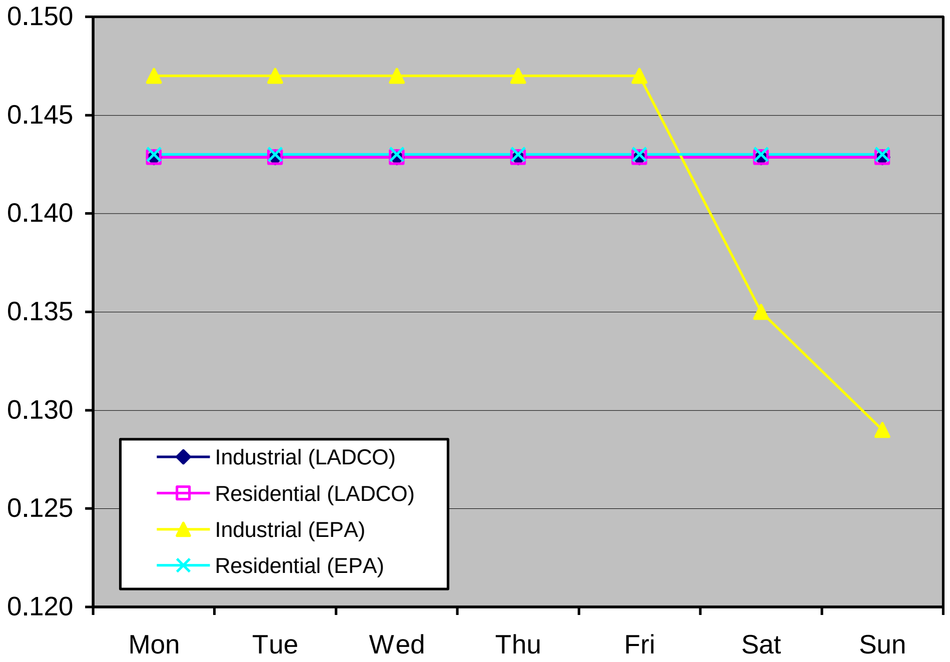


Figure B-6. Temporal profiles for the emissions from surface coating.

(a) Day of week profile



(b) Hour of day profile

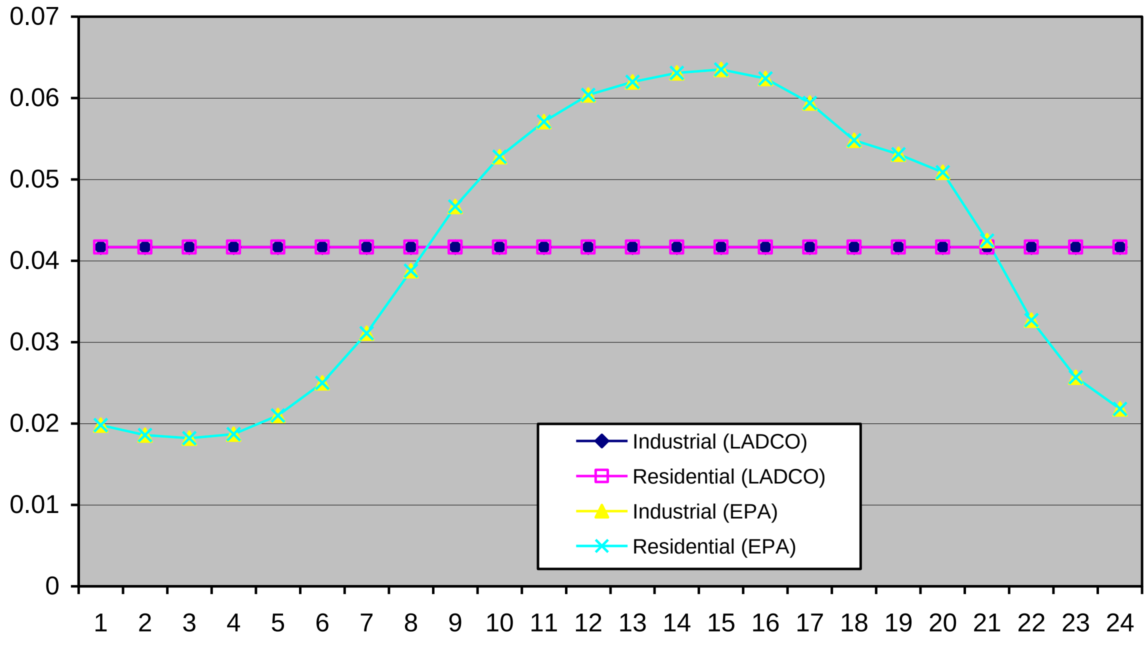
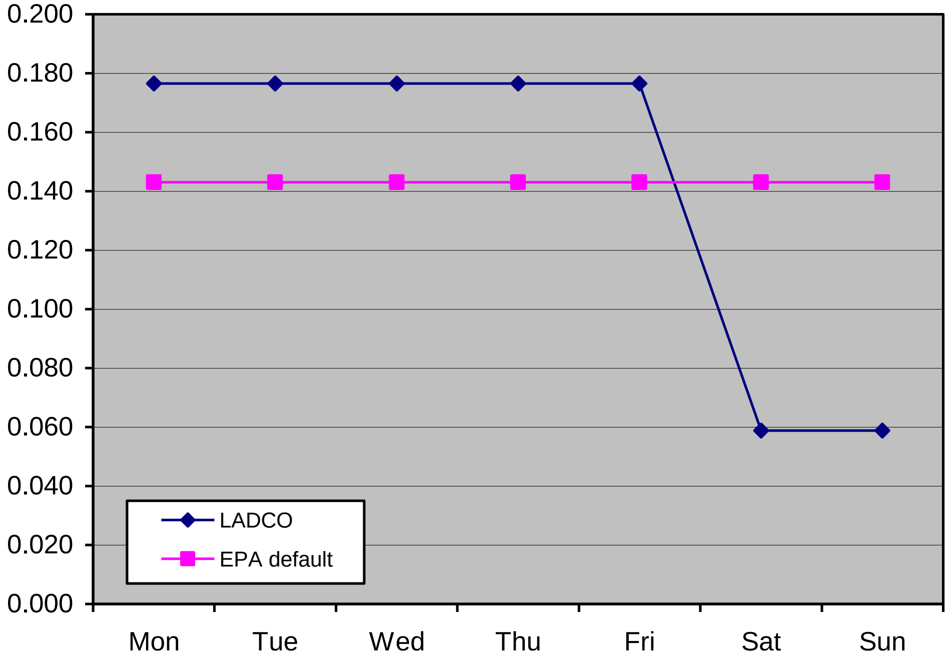


Figure B-7. Temporal profiles for the emissions from stationary source fuel combustion.

(a) Day of week profile



(b) Hour of day profile

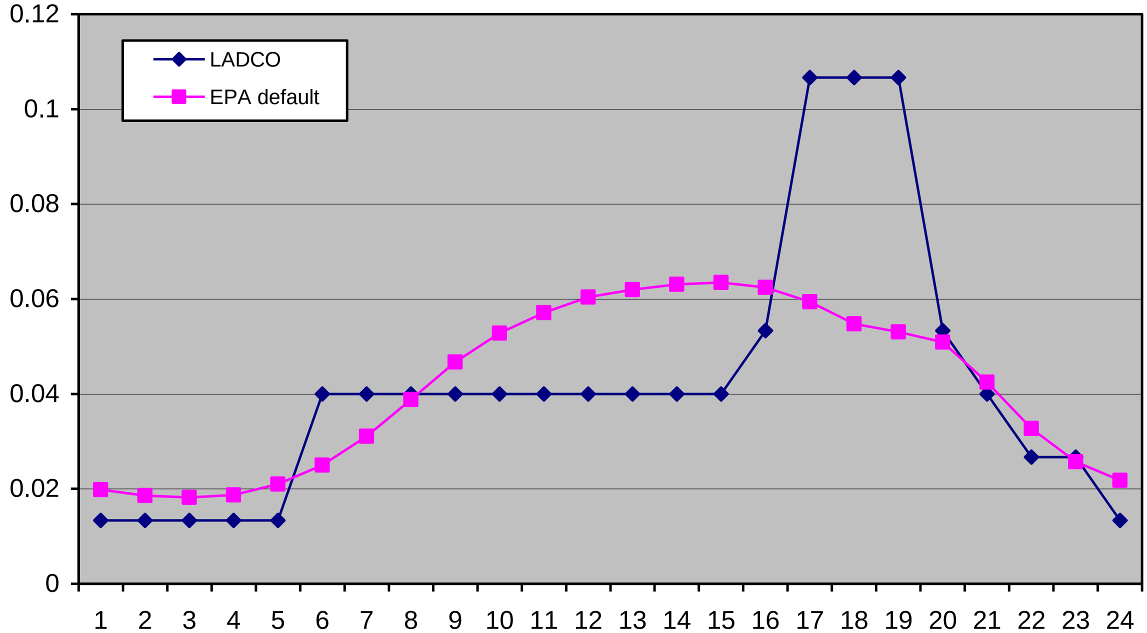
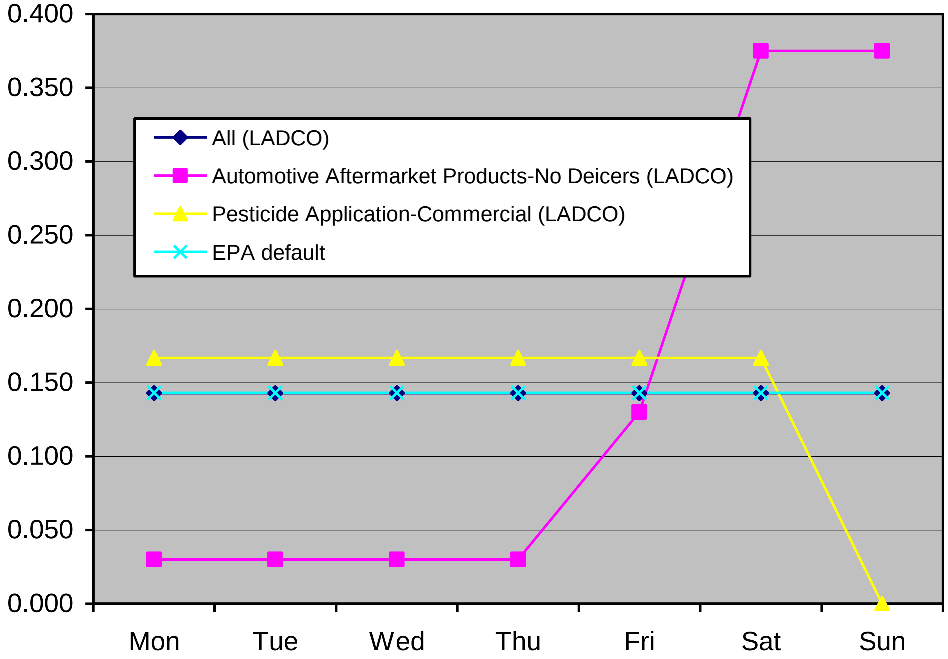


Figure B-8. Temporal profiles for the emissions from gasoline service stations.

(a) Day of week profile



(b) Hour of day profile

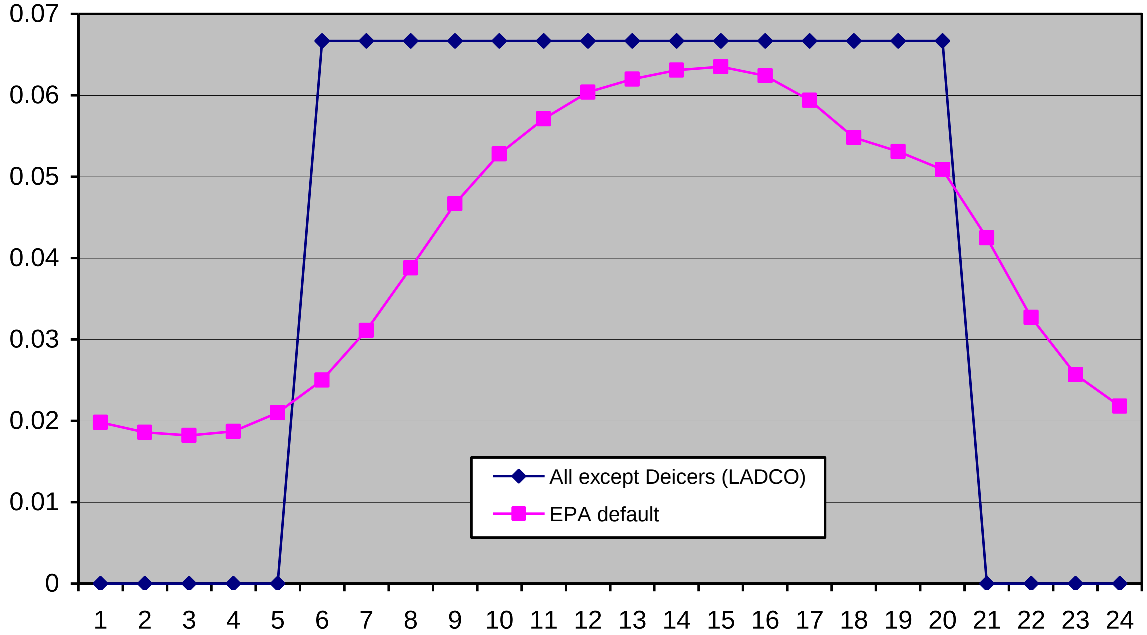
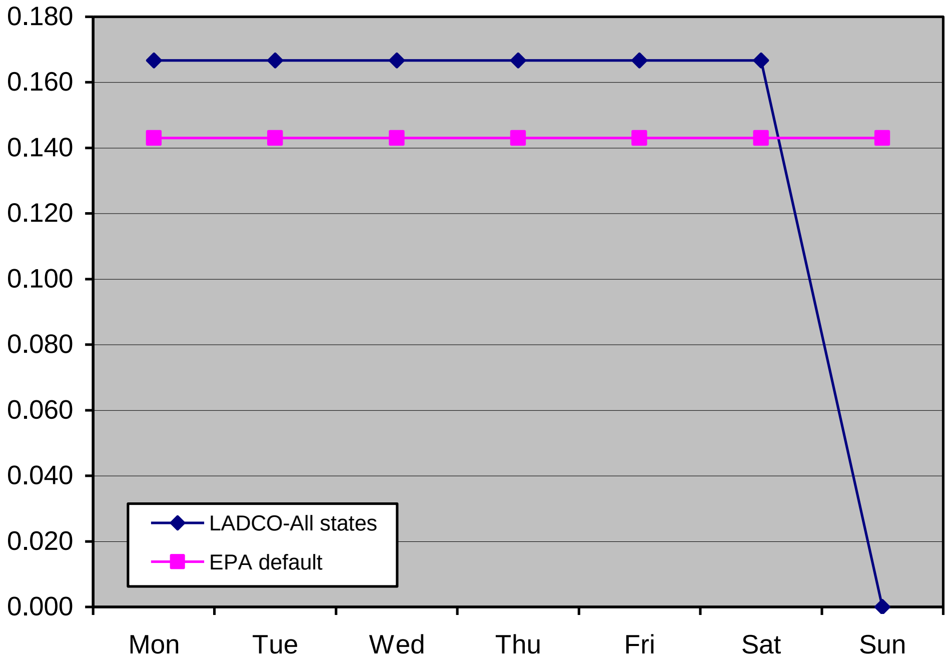


Figure B-9. Temporal profiles for the emissions from consumer solvent.

(a) Day of week profile



(b) Hour of day profile

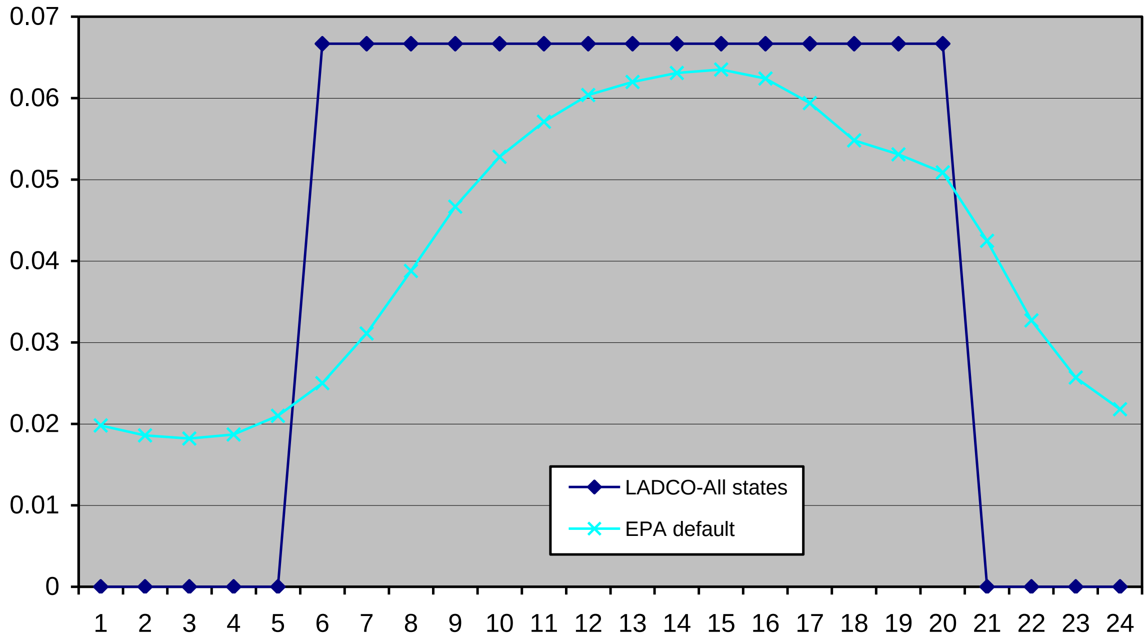
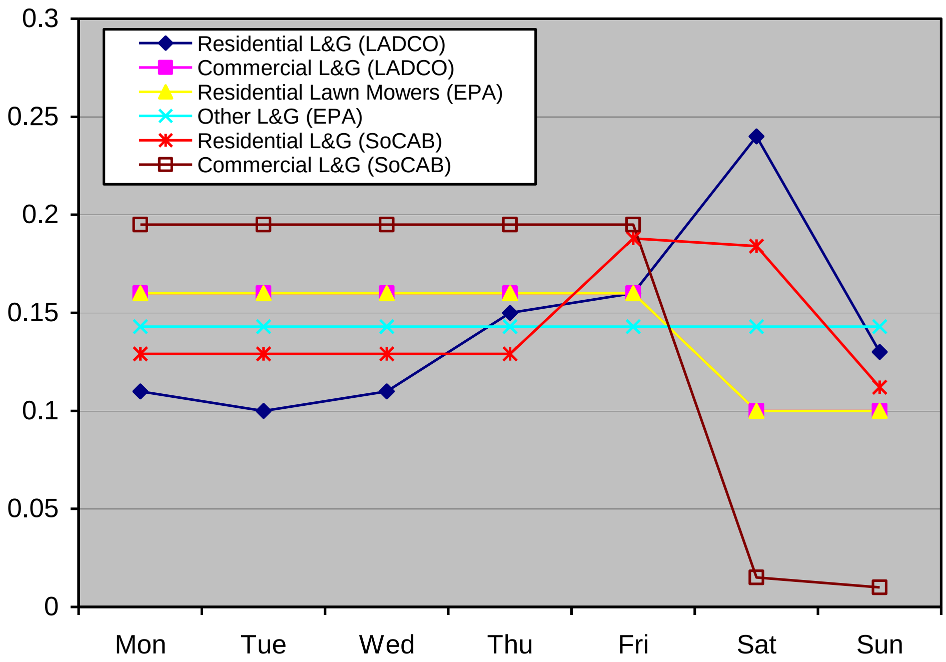


Figure B-10. Temporal profiles for the emissions from commercial solvent – pesticide application.

(a) Day of week profile



(b) Hour of day profile

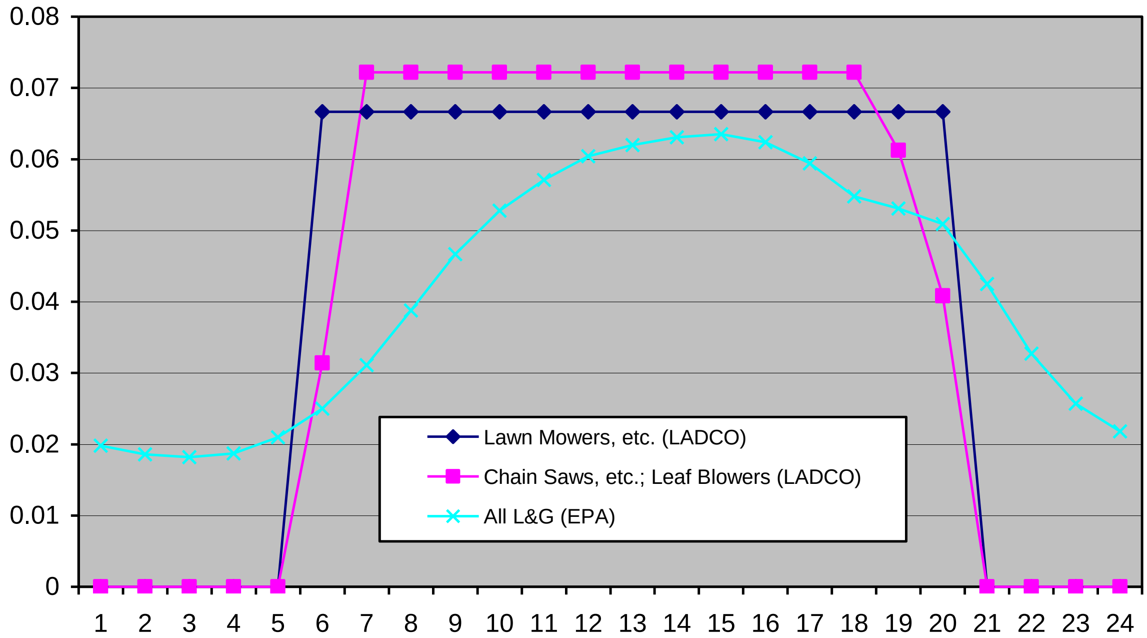
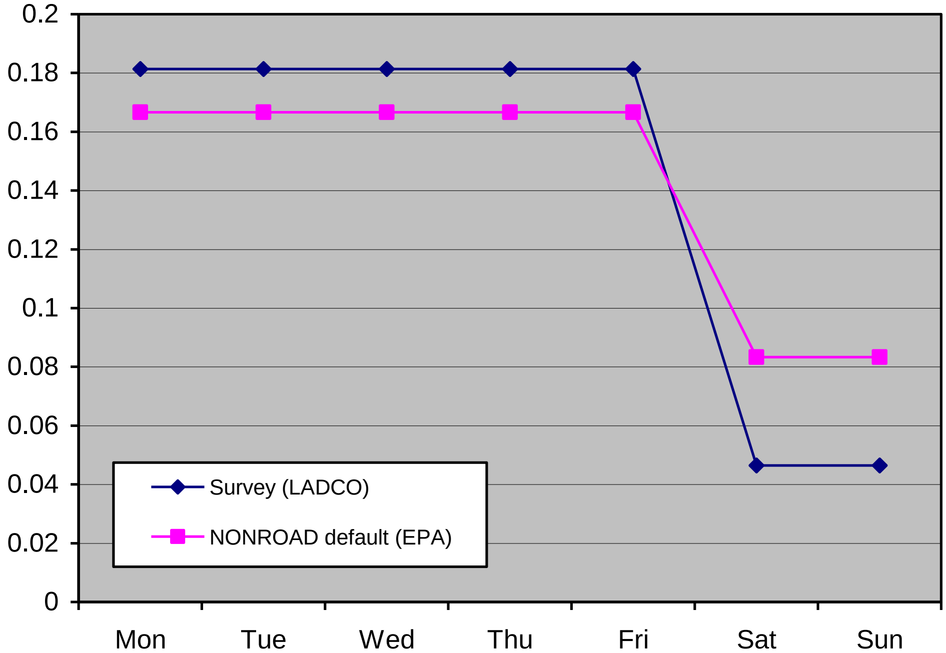


Figure B-11. Temporal profiles for the emissions from lawn & garden equipment.

(a) Day of week profile



(b) Hour of day profile

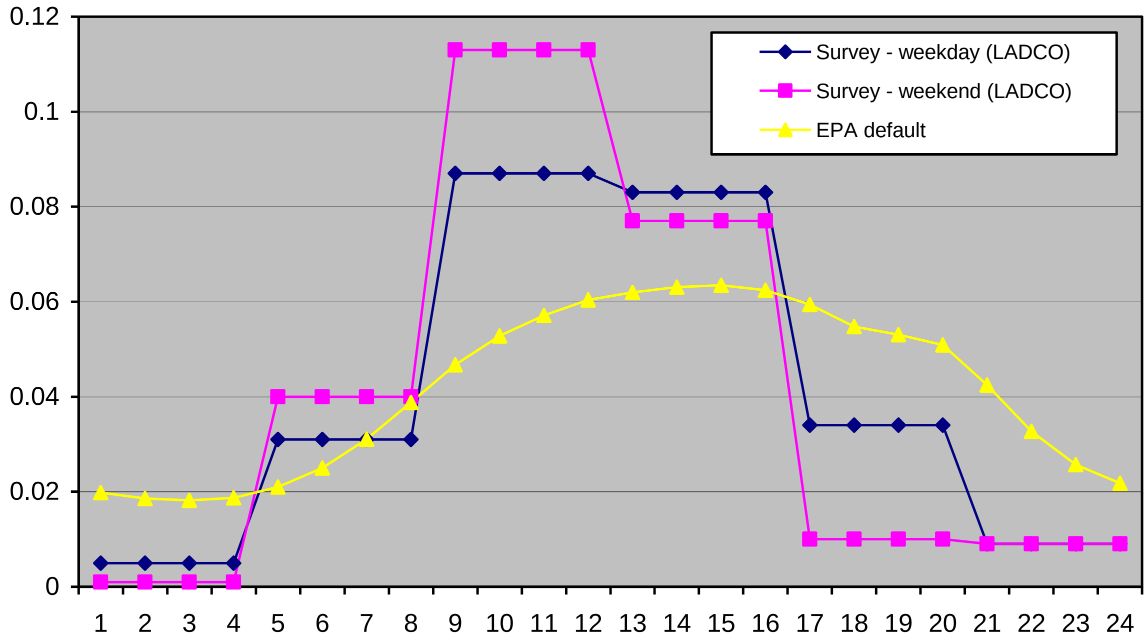
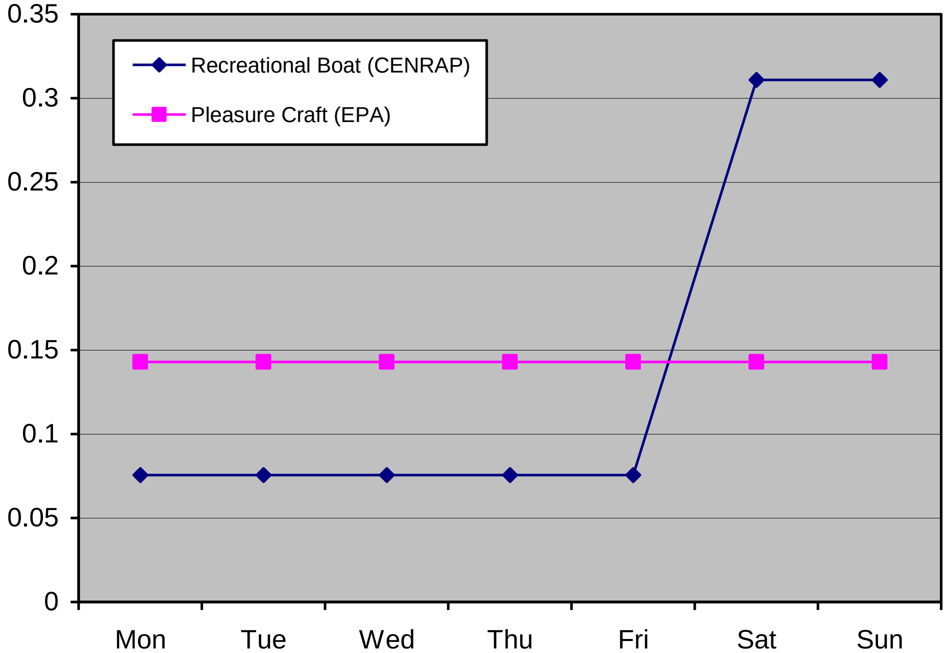


Figure B-12. Temporal profiles for the emissions from construction equipment.

(a) Day of week profile



(b) Hour of day profile

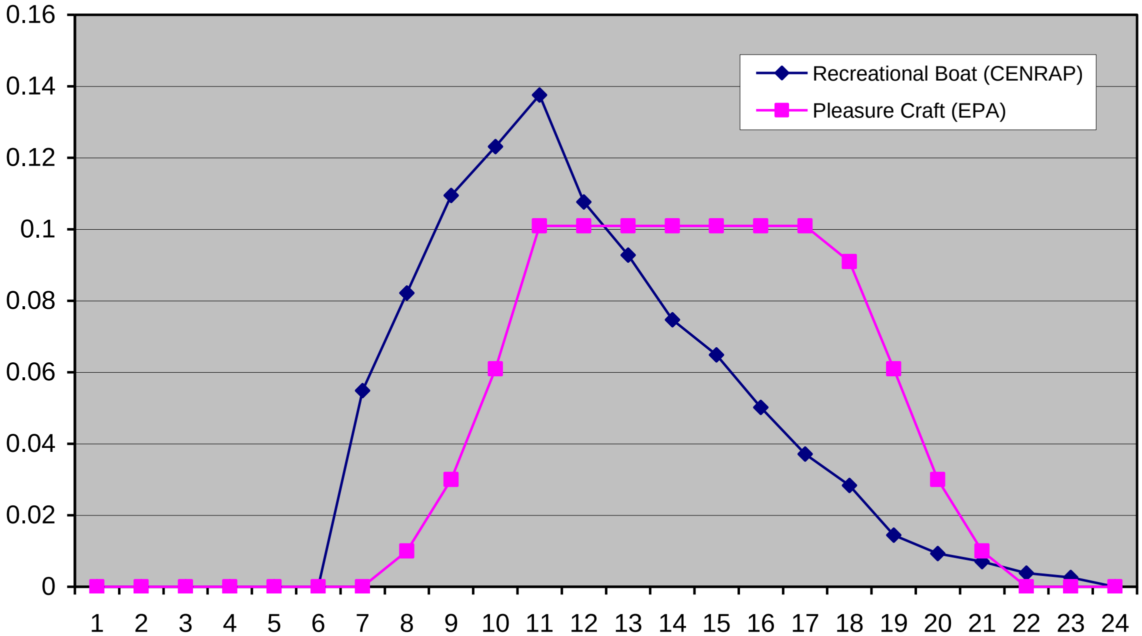


Figure B-13. Temporal profiles for the emissions from recreational boating.