Development of Emission Inventories of Recreational Boats and Commercial Marine Vessels for the Central States Regional Air Planning Association

Stephen B. Reid, Dana Coe Sullivan, Patricia S. Stiefer, and Lyle R. Chinkin
Sonoma Technology, Inc., 1360 Redwood Way, Suite C, Petaluma, CA 94954
sreid@sonomatech.com

ABSTRACT

In support of the Central States Regional Air Planning Association's (CENRAP) need to develop a regional haze plan, Sonoma Technology, Inc. developed a 2002 emission inventory of non-road mobile sources for the nine-state CENRAP region, which includes Texas, Oklahoma, Louisiana, Arkansas, Kansas, Missouri, Nebraska, Iowa, and Minnesota. Much of the project resources were devoted to estimating emissions from recreational boating activities and commercial marine vessels in this region because these sources are believed to be major contributors to primary and precursor particulate emissions near Class I areas in the CENRAP states.

Pleasure craft emission inventories were developed from bottom-up surveys of registered boat owners in each of the CENRAP states. Activity data gathered from these surveys were used to update default inputs to the EPA's NONROAD 2004 model. Recreational boat usage in the CENRAP region was estimated to be approximately twice that indicated by default inputs to the NONROAD model, and emission estimates for NO_x, VOC, SO_2, and $PM_{2.5}$ were 2-4 times higher than those included in the preliminary 2002 National Emissions Inventory (NEI). Also, the spatial distribution of emissions was significantly improved by replacing NONROAD spatial allocation surrogates with data developed from survey results.

Emission inventories for commercial marine vessels were developed from local activity data gathered directly from local agencies and EPA guidance for emissions estimation was followed. Emissions from commercial marine vessels in the CENRAP region were estimated to be approximately three times smaller than estimated for the preliminary 2002 NEI. In addition, the spatial distribution of emissions was significantly improved.

INTRODUCTION

The Central States Regional Air Planning Association (CENRAP) is responding to the U.S. Environmental Protection Agency's (EPA) mandate to protect visibility in Class I areas by researching visibility-related issues and developing a regional haze plan for the CENRAP region, which includes Texas, Oklahoma, Louisiana, Arkansas, Kansas, Missouri, Nebraska, Iowa, and Minnesota. Non-road mobile sources emit primary particulate matter (which is emitted directly to the atmosphere in particulate form) and precursors of secondary particulate matter (which is generated from chemical transformations in the atmosphere of gaseous precursor species such as ammonia, nitrogen oxides, sulfur oxides, and volatile organic compounds). Primary and secondary particulate matter contribute to regional haze in the CENRAP region. In recognition of these issues, the CENRAP sponsored the development of improved emission inventories of non-road mobile sources for each of the nine CENRAP states. In the preliminary 2002 NEI, emissions from these sources contributed 6% to 49% of the total inventories of nitrogen oxides (NO_x), volatile organic compounds (VOC), particulate matter of 2.5 microns aerodynamic diameter or less ($PM_{2.5}$), and sulfur dioxide (SO_2).

To assess the likely importance of non-road sources to visibility in Class I areas, STI and CENRAP's Emission Inventory Work Group reviewed NEI records for CENRAP counties containing or adjoining Class I areas. This review indicated that recreational boats and commercial marine vessels account for 57% to 74% of the non-road primary and precursor emissions in those counties. Therefore, these source categories were prioritized for "bottom-up" treatment, which involved gathering and using region-specific activity data to generate emission estimates.

TECHNICAL APPROACH

County-level pleasure craft emission estimates were prepared using the EPA's 2004 NONROAD model. However, the default activity data and spatial allocation factors used as inputs to the model were replaced with data derived from surveys of registered boat owners in each of the CENRAP states. Similarly, local activity data for commercial marine vessel operations were gathered from agencies such as the Tennessee Valley Authority, the U.S. Army Corps of Engineers, and local port operators. This information was used in conjunction with EPA guidance to develop emission inventories for commercial marine vessels.

Recreational Boats

Emissions from recreational boats were modeled with the latest version (2004) of the EPA's NONROAD model. NONROAD categorizes equipment types by SCC code. The codes pertaining to recreational boats are listed in Table 1.

Table 1. NONROAD source categories related to recreational boats.

SCC code[a]	Equipment Description
22-82-yyy-005	Pleasure Craft: Inboard Engine
22-82-yyy-010	Pleasure Craft: Outboard Engine
22-82-yyy-015	Pleasure Craft: Personal Watercraft
22-82-yyy-025	Pleasure Craft: Sailboat Auxiliary Engine

[a]In each code, the letters "yyy" refer to fuel type: 2-stroke gasoline (005), 4-stroke gasoline (010), or diesel (020).

For each of these source categories, the NONROAD model provides exhaust emission factors in units of grams of emissions per horsepower-hour (g/hp-hr) as a function of engine types and sizes. NONROAD also includes the following default databases of recreational boating activity, which may be updated with bottom-up or region-specific activity data, if available.

- NONROAD's default engine populations are based on 1998 Power Systems Research, Inc. (PSR) national surveys of engine manufacturer sales. The national population estimates are disaggregated to the state level by using a fuel consumption distribution developed by the Oak Ridge National Laboratory (ORNL). State-level populations are further disaggregated to the county level by using the total water surface area present in each county (U.S. Environmental Protection Agency, 2002a).
- NONROAD's default temporal profiles are based on two sources of information. Monthly allocation factors are derived from a boat usage survey performed for the National Marine Manufacturers Association (NMMA) (U.S. Environmental Protection Agency, 2002c). Weekday-weekend allocation factors were derived from a survey of recreational boaters conducted in California during 1993 and 1994 (U.S. Environmental Protection Agency, 1999b). These weekday-weekend factors are specific to equipment type only and do not vary geographically.

- NONROAD's annual equipment usages (hours of use) are based on a 1998 PSR equipment activity database. The application-specific estimates in this database are, in turn, based on several yearly surveys of equipment owners conducted by PSR (U.S. Environmental Protection Agency, 2002b).
- NONROAD's default engine load factors are based on a assumption that the EPA's recreational marine engine test cycle is representative of load factors for engines in use. Although PSR survey results for load factors exist, they are not represented in the NONROAD model because the EPA considered them to be insufficiently documented (U.S. Environmental Protection Agency, 2002b).

Because NONROAD relies primarily on national-level activity data, some regional and/or local equipment population and usage characteristics may not be represented well by the model. Moreover, the use of water surface area as a geographic allocation surrogate does not account for the navigability of a given body of water nor its popularity. Improving the various types of activity data used by NONROAD required gathering additional information about the ownership and use of recreational boats within the CENRAP region.

The activity data needed to update the NONROAD inputs for recreational boats were gathered through a bottom-up survey of representative groups of recreational boat owners. The survey was designed to gather data on vessel characteristics, hours of use, fuel consumptions, engine loads, and temporal and geographic usage patterns in each CENRAP state, and to control for reporting bias[1]. A representative pool of nearly 1,400 registered boat owners was recruited by telephone to participate in the study. A survey questionnaire and an incentive for participation were mailed to each participant, followed one week later by a reminder postcard. For the purposes of study design, a 50% return rate was anticipated for the mail survey; however, a significantly better response rate—more than 70%—was actually achieved. Geographic coverage and representativeness of the survey results were considered to be excellent for all states of the CENRAP region. Survey results were analyzed and used to estimate annual hours of use and engine load factors for each state and each type of boat.

To spatially allocate emissions, the counties where recreational boats are actually used must be determined rather than the counties where boats are registered because that data is not appropriate for spatial distribution. The survey questionnaire included one or more maps detailing the navigable waterways in the respondents' region, which allowed respondents to easily identify the counties in which they typically operate their boats. (Participants indicated their regions during telephone recruitment.) These responses were converted and used to calculate county-level activity for recreational boats.

The survey questionnaire also asked how recreational boat activity is distributed across the months of the year, the days of the week, and the hours of the day. Large variances in climate and boating habits throughout the CENRAP region, temporal patterns varied from state to state. Responses to these questions were analyzed and used to calculate seasonal, day-of-week, and diurnal temporal profiles for each state and type of boat.

Once appropriate NONROAD inputs were derived from the activity data, the model was run for each CENRAP state using state-specific temperature inputs and fuel characteristics (such as gasoline Reid vapor pressure and sulfur content).

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[1] Reporting bias frequently occurs when survey respondents have non-neutral attitudes about the behaviors they report. To account for the possibility that boat owners might mis-report their boat usage, respondents were asked about their specific usage pattern for the previous week—information that is much more likely to be reported accurately than "typical" usage. The specific usages were used to adjust reported "typical" usage patterns and reduce the effects of over-reporting.

Commercial Marine Vessels

Emissions estimates were prepared for commercial marine vessels operating in commercially active waterways in the CENRAP region. The inventory included river barges and other commercial vessels operating in inland waterways, as well as ocean-going ships, harbor tugboats, and other commercial vessels operating in the Gulf Intracoastal Waterway (GIWW).

Emission factors were taken from an EPA Regulatory Impact Analysis (RIA) of commercial marine vessel emissions (U.S. Environmental Protection Agency, 1999e). The RIA estimated emissions for the three categories of marine engines shown in Table 2. The EPA RIA also listed emission factors for Category 1 marine engines and cited emission factors for Category 2 and 3 marine engines from a previous EPA report (U.S. Environmental Protection Agency, 1998). Table 3 shows the work-based emission factors in grams per kilowatt-hour (g/kW-hr) for marine engines in each category. These emission factors were converted from a work basis to a fuel basis by using Equation 1 below.

Equation (1) $EF_{Fuel} = (EF_{Work} / \text{Fuel Consumption}) * \text{Conversion Factor}$

where

EF_{Fuel} = Fuel based emission factor (grams of pollutant per kilogram of fuel)
EF_{Work} = Work-based emission factor (g/kW-hr)
Fuel Consumption = Engine specific fuel consumption rate (g/kW-hr)
Conversion Factor = 1000 grams per kilogram

Table 2. EPA marine engine categories.

Category	Displacement (disp.) per Cylinder	Description[a]
1	disp. < 5 liters power ≥ 37 kW	Similar to land-based non-road engines. Used in smaller tugboats, ferries, fishing vessels, and dredges. Fueled by marine diesel oil.
2	5 ≤ disp. < 30 liters	Similar to engines used in locomotives. Used in smaller ocean-going vessels, as well as large tugboats, towboats, ferries, and fishing vessels. Fueled by marine diesel oil.
3	disp. ≥ 30 liters	Used primarily for propulsion in large, ocean-going vessels. Usually fueled by residual oil, which has a higher sulfur content than diesel oil.

[a]All three engine categories can also be used for "auxiliary" purposes (such as electrical generation) on larger vessels, though Category 2 engines are most often used in this way.

Emissions estimates were based primarily on bottom-up fuel usage data for inland river systems in the CENRAP region derived from the Tennessee Valley Authority (TVA) Barge Costing Model. This model was developed to estimate fuel usage by inland river segment for fuel tax purposes[2]. Inputs to the model include engine horsepower and trip characteristics for each vessel that travels on a given waterway segment in a given year. The model uses these data to estimate total fuel consumption, total cargo transported, and average vessel horsepower by waterway segment[3]. Each year, fuel consumption

[2] Some "segments" consist of an entire river, such as the Atchafalaya River in Louisiana. Longer rivers, such as the Mississippi, are broken up into multiple segments.
[3] The small rivers and tributaries not considered by the model account for only 1-3% of the total tonnage moved over inland waterways each year (Dager, 2004).

estimates are compared to actual tax receipts, and model errors have averaged only 1.5% per year since 1996.

Table 3. Marine engine emission factors.

Engine Category	Power (kW) or Engine Speed	Emission Factors (g/kW-hr)				
		HC	NO_x	CO	PM	SO_2[a]
1	37 – 75	0.27	11	2.0	0.9	1.29
	75 - 130	0.27	10	1.7	0.4	1.29
	130 - 225	0.27	10	1.5	0.4	1.29
	225 - 450	0.27	10	1.5	0.3	1.29
	450 - 560	0.27	10	1.5	0.3	1.29
	560 - 1000	0.27	10	1.5	0.3	1.29
	1000+	0.27	13	2.5	0.3	1.25
2 and 3	Medium[b]	0.5	12	1.6	0.25	1.25/13.46[c]
	Slow[b]	0.5	17	1.4	1.48	12.50

[a]Emission factors for SO_2 were calculated using an EPA algorithm based on fuel sulfur content (U.S. Environmental Protection Agency, 2000). Fuel sulfur contents for marine diesel oil and residual oil were assumed to be 0.25% and 2.70%, respectively (U.S. Environmental Protection Agency, 2003).
[b]Category 2 and smaller Category 3 engines are medium speed (2-stroke). Larger Category 3 engines are slow speed (4-stroke). Emission factors for Category 2 and 3 engines were converted from kilograms per ton of fuel consumed to grams per kilowatt-hour using fuel consumption estimates of 195 g/kW-hr for slow speed engines and 210g/kW-hr for medium speed engines (Pollack et al., 2004).
[c]The first value is for marine diesel oil, which is used in Category 2 engines, and the second value is for residual oil, which is used in Category 3 engines.

For the GIWW, the TVA model does not provide a complete picture of fuel consumption, as "deep-draft" (oceangoing), harbor tugs, and other vessels not bound for an inland river system are omitted. For these vessels, emission estimates were prepared with work-based emission factors and the following types of activity data (U.S. Environmental Protection Agency, 1999a):

- The number of total trips to and from each port
- The total number of trips passing (but not stopping at) each port
- Vessel characteristics for tugboats and transport ships operating in and through each port
- Speed and time-in-mode data for four operational modes (cruise, slow cruise, maneuvering, and hoteling or docking)
- Engine load factors for each of the four operational modes listed above

Much of the necessary data on vessel trips was obtained from the U.S. Army Corps of Engineers (USACE) Waterborne Commerce Statistics Center, which tracks vessel movements and characteristics, as well as barge trips and tonnage. Data were also obtained from the Maritime Administration of the Department of Transportation, which maintains a U.S. waterway database that includes vessel names and ports/waterways visited.

Vessel characteristics, speeds, times-in-mode, and engine load data have been modeled for deep sea, river, and Great Lake ports in the United States in a two-volume report produced by ARCADIS on behalf of the EPA (U.S. Environmental Protection Agency, 1999a, d). These documents provide a detailed analysis of selected ports, as well as a method for extrapolating activity data from these "known" ports to other ports with similar characteristics. Several of the ports chosen for detailed analysis are located within the CENRAP region, including St. Louis, Baton Rouge, New Orleans, Plaquemines, South Louisiana, and Corpus Christi. The techniques described in these reports were used to produce a profile of vessel characteristics and operations for all ports in the CENRAP states. Also, some bottom-up surveys of selected port authorities and/or vessel operators were performed to verify the assumptions made in creating these profiles.

Once emission factors were applied to fuel consumption or work-based activity data, the resulting emissions were spatially allocated using two methods. Emissions occurring in and around a deep sea or Great Lake port were assigned to the county in which the port was located. If a port spanned multiple counties, the number of port terminals in each county was used to allocate maneuvering and hoteling emissions, and the length of the port area in each county was used to allocate emissions from cruise mode. Data on port terminals and their waterway locations are available from the USACE (2003a).

However, for inland river systems, fuel consumption had to be disaggregated into "in-port" and "underway" components before emissions could be spatially allocated. To accomplish this, fuel consumption at river ports in the CENRAP states was estimated with fuel-based emission factors, and port-specific data on vessel trips and characteristics were obtained from USACE data, EPA guidance documents, and surveys of port authorities. Once in-port fuel consumption was estimated, the values were subtracted from Barge Costing Model fuel consumption estimates for the river segment in question. The remaining fuel consumption was considered "underway" and allocated to counties based on the fraction of a river segment's length passing through each county. These county-level river segment fractions were derived from the GIS-based National Waterway Network database produced by the Bureau of Transportation Statistics (BTS).

Emissions were temporally allocated using monthly activity patterns derived from Lock Performance Monitoring System (LPMS) data maintained by the USACE. This database provides USACE operators, planners, and managers with information on the use, performance, and characteristics of the USACE's national system of locks. The LPMS consists of data collected at most USACE-owned and/or -operated locks, including the number of vessels and barges locked, dates of lockages, and the type and tonnage of commodity carried (U.S. Army Corps of Engineers, 2003b). Statistics are published monthly for selected key locks, and these monthly data were used to generate a monthly activity profile for each inland river system, as well as the GIWW.

RESULTS

Recreational Boats

The CENRAP's emission inventory for recreational boating represents a significant improvement over existing inventories based on NONROAD default activity data. Surveys of representative groups of boat owners in each of the CENRAP states made possible the replacement of NONROAD default data with state-specific information that more accurately represents recreational boating activity in the CENRAP region. For example, Figures 1 and 2 compare the state-specific hours of operation and engine load factors for 2-stroke outboard motors[4] derived from survey data with corresponding NONROAD default figures (which do not vary by state). NONROAD indicates that these engines operate about 35 hours per year, while survey data indicate an annual usage of more than 50 hours for all states except Kansas, with a maximum of 85 hours per year in Missouri. Similarly, Figure 2 shows that NONROAD may also be underestimating engine load factors in the CENRAP states, as the values derived from survey data range from 0.24 to 0.38, while the NONROAD default value is 0.21.

[4] According to NONROAD population data, this engine type accounts for 73% of all recreational boat engines in the CENRAP region.

Figure 1. Comparison of state activity data with NONROAD model defaults for 2-stroke outboard engines.

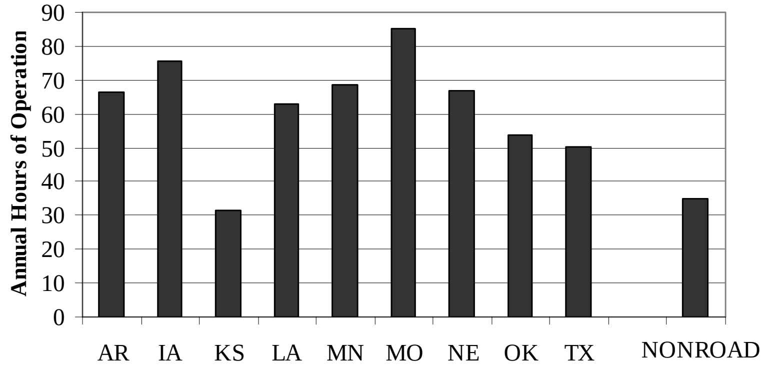
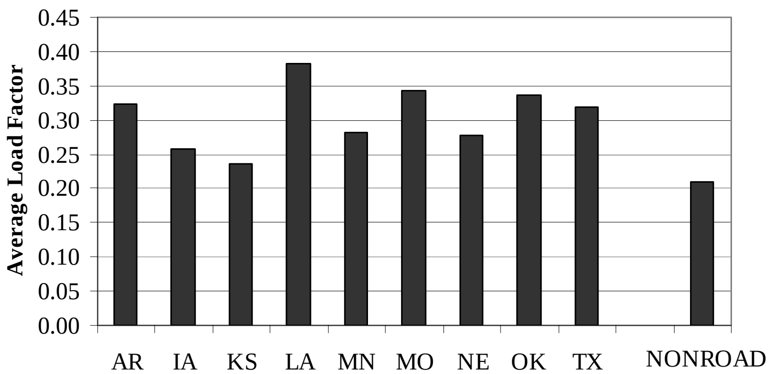


Figure 2. Comparison of state engine load factor data with NONROAD model defaults for 2-stroke outboard engines.



This improved activity data resulted in emission estimates 2 to 4 times[5] greater than estimates from the preliminary 2002 NEI (see Figure 5). Furthermore, emission estimates for recreational boating vary widely from state to state, as shown in Figures 3 and 4. Louisiana, Minnesota, Missouri, and Texas account for almost 80% of the annual NO_x and VOC emissions from recreational boating in the CENRAP region, while Nebraska and Kansas combined contribute less than 4% of the total NO_x and VOC emissions.

Figure 3. Annual recreational boating NO_x emissions by state and boat type.

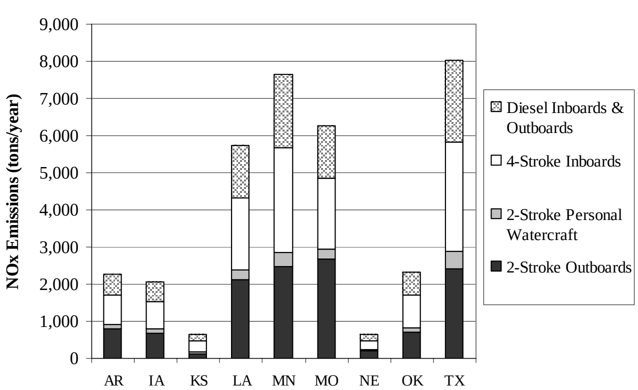
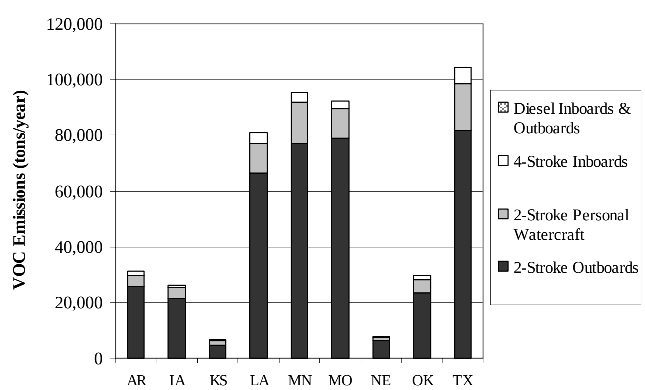
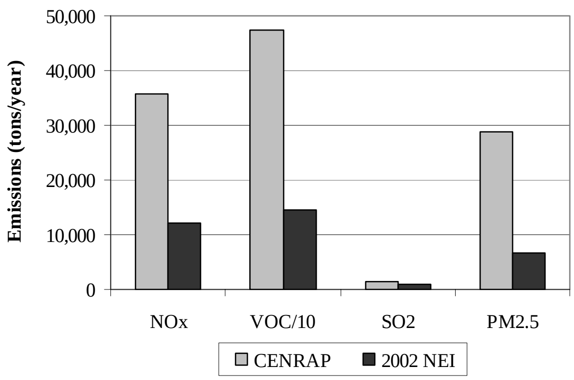


Figure 4. Annual recreational boating VOC emissions by state and boat type.



5 The scale of the differences may seem surprising; however, we believe that they are reasonably accurate and reliable because care was taken to control over-reporting bias and to ensure the representativeness of the survey results.

Figure 5. Comparison of recreational boating emission estimates with results from the preliminary 2002 NEI for the CENRAP region.



Temporally, emissions vary widely across the months of the year and days of the week, as shown in Figures 6 and 7. The monthly profiles shown in Figure 6 are virtually identical to NONROAD's default monthly allocation factors, which also show more pronounced seasonal activity variations for northern states such as Minnesota and Iowa[6]. On a weekly basis, recreational boating activity peaks on the weekends for each state, with weekend boating activities accounting for 56% to 69% of the total emissions in each state. By comparison, the NONROAD model assigns 70% of all recreational boating activity to weekend days.

Figure 6. Monthly variations in recreational boating emissions by state.

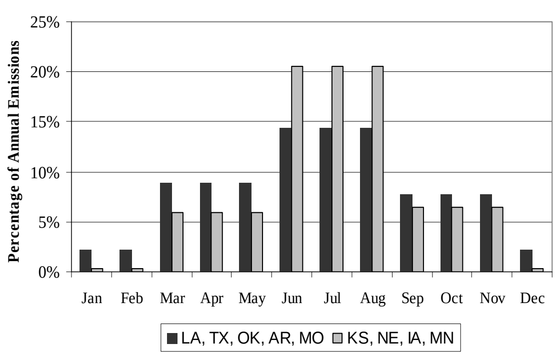


Figure 7. Day-of-week variations in recreational boating emissions by state.

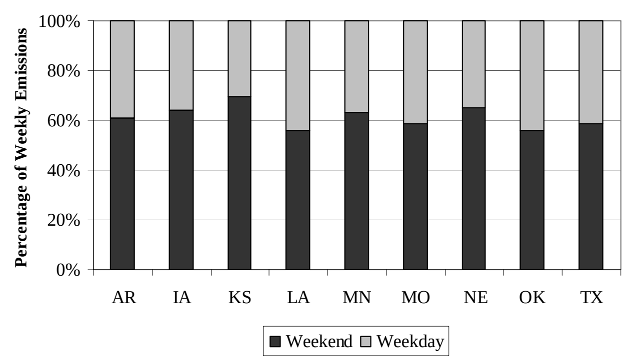
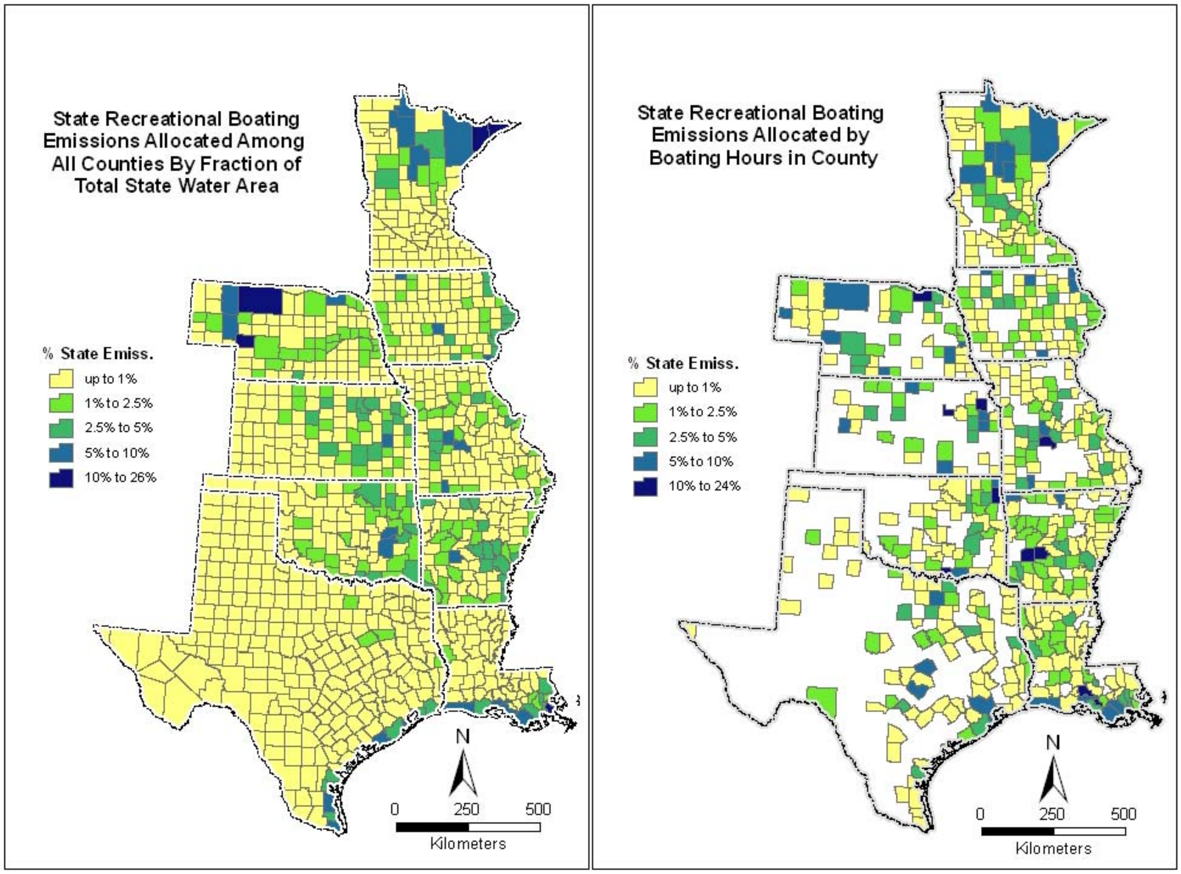


Figure 8 provides a side-by-side comparison of the spatial distributions that resulted from NONROAD 2004 defaults and from the CENRAP recreational boating survey results. The CENRAP spatial allocation represents the usage patterns reported by survey respondents and is, therefore, highly representative of real-world behavior. The NONROAD spatial allocation was achieved by allocating statewide emissions proportionally to each county's water surface area. This technique over-allocates emissions to areas that are unpopular with recreational boaters due to boating restrictions, remoteness from population centers, or other reasons.

[6] NONROAD monthly allocation factors for recreational boating vary by multi-state regions rather than by individual states. The state-specific monthly allocation factors produced for this study were grouped together for comparison purposes.

Figure 8. Comparison of county-level spatial allocation factors with NONROAD model defaults.



Commercial Marine Vessels

Emission estimates for commercial marine vessels were classified as either "in-port" or "underway" (see Figure 9). Emissions are highest in Louisiana and Texas—states which are home to several large GIWW ports. Figure 10 illustrates the monthly variability in commercial marine activity by state based on monthly summaries of freight movements through selected locks and ports for 2002. Greater seasonal variability occurred in northern states such as Minnesota, where wintertime commercial marine activity is comparatively low.

Figure 9. Annual commercial marine NOx emissions by state and source type.

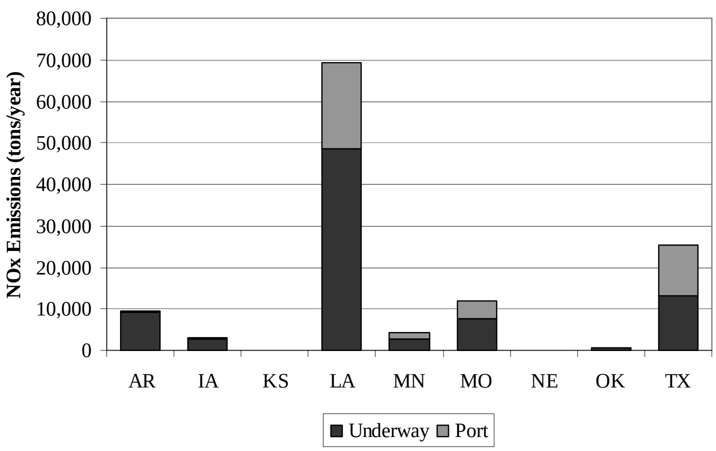
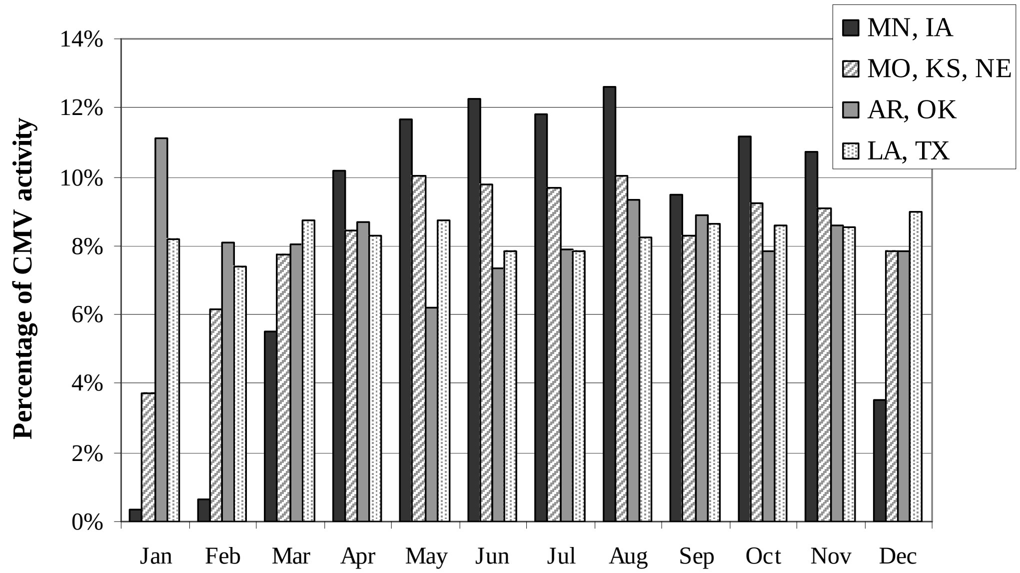


Figure 10. Monthly variability in commercial marine vessel activity by state.



As shown in Figure 11, emissions from commercial marine vessels in the CENRAP region were estimated to be approximately one-third of those included in the preliminary 2002 NEI. This difference is most likely due to the use of top-down methods to develop the NEI, which involved use of national-level data (annual hours of operation and fuel consumption) and the assumption that 75% of distillate fuel and 25% of residual fuel is consumed "in-port". National-scale, in-port emissions were assigned to the largest 150 ports in the country based on the amount of freight handled by each, and the remaining "underway" emissions were assigned to active shipping lanes based on traffic density patterns (U.S. Environmental Protection Agency, 1999c). Emissions in the preliminary 2002 NEI appear to be significantly overestimated at large ports. For example, Table 4 compares "in-port" emissions from the 2002 NEI for the counties of the Port of Baton Rouge and the Houston-Galveston Port with other inventories for these ports. CENRAP's emission inventories for these ports are similar to those prepared by Booz Allen Hamilton (1991), and Eastern Research Group and Starcrest (2003), both of which relied on bottom-up activity data. Also, Figure 12 shows that the NEI has much higher emissions in the Lake Superior region of Minnesota than the CENRAP inventory.

Figure 11. Comparison of commercial marine emission estimates with results from the preliminary 2002 NEI for the CENRAP region.

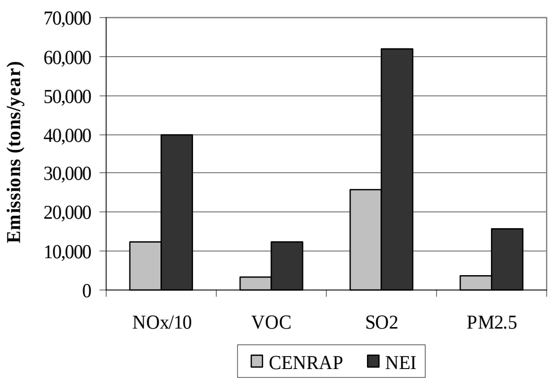
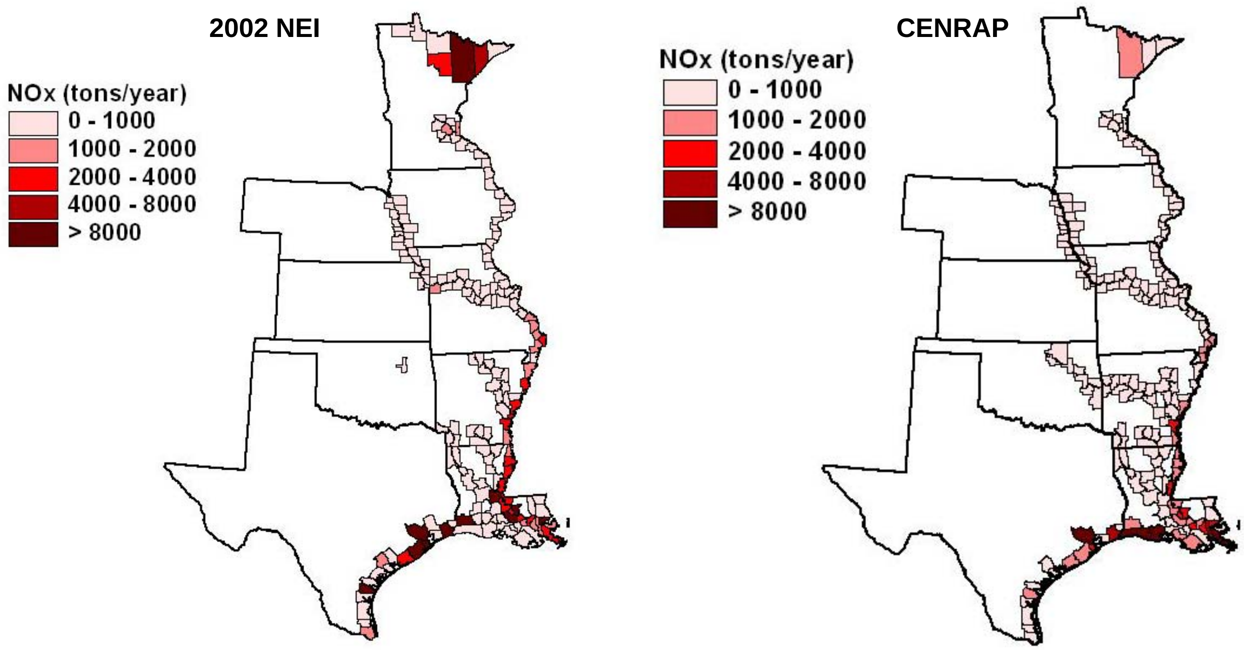


Table 4. Comparison of inventories for selected ports in the CENRAP region (emissions in tons/year).

Port	Inventory	$PM_{2.5}$	NO_x	CO	VOC	SO_2
Baton Rouge	1991 Booz-Allen Hamilton	129	2,187	449	203	928
	2002 CENRAP	196	5,355	737	170	1,562
	2002 NEI	1,407	36,088	4,756	1,128	5,291
Houston-Galveston	1991 Booz-Allen Hamilton	887	14,977	2,131	1,391	6,554
	2000 Starcrest	-----	7,336	1,022	219	-----
	2002 CENRAP	318	7,232	943	245	2,610
	2002 NEI	2,955	75,787	9,989	2,370	11,111

Figure 12. Comparison of the geographic distribution of CMV emissions in the 2002 CENRAP inventory with that of the preliminary 2002 NEI.



CONCLUSIONS

The emission inventories prepared for pleasure boats and commercial marine vessels in the nine-state CENRAP region represent significant improvements over existing inventories due to the use of local activity data gathered through surveys and other methods. The results of this work indicate that NO_x, VOC, SO_2, and $PM_{2.5}$ emissions from recreational boat usage in the CENRAP region is 2-4 times higher than estimates included in the preliminary 2002 National Emissions Inventory (NEI), while emissions from commercial marine vessel activity in the region are approximately three times lower than NEI estimates. Also, the spatial distribution of emissions from both pleasure boats and commercial marine vessels was significantly enhanced by replacing NONROAD allocation surrogates with data developed from survey results (pleasure boats) and by gathering port-specific vessel activity data (commercial marine vessels).

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