Draft

LADCO 2005 COMMERCIAL MARINE EMISSIONS

Prepared for

Michael Koerber
Lake Michigan Air Director Consortium
2250 E. Devon Ave., Suite 250
Des Plaines, IL 60018

Prepared by

Christian E. Lindhjem
ENVIRON International Corporation
101 Rowland Way, Suite 220
Novato, CA 94945-5010

and

Louis Browning
ICF International
394 Pacific Avenue
San Francisco, CA 94111

March 2, 2007

EXECUTIVE SUMMARY

Commercial marine emissions comprise a wide variety of vessel types and uses. Table ES-1 describes the different types of commercial marine activity. This work determined emissions from these categories for 2005.

Table ES-1. Commercial vessel types. (All engine types are diesel except those marked).

Source Category Code (SCC)	Source Definition	Purpose	Geographic Area
2280002023	Push Boats	Barge Freight	River Traffic
			Lake Traffic
2280002021	Tugs	Vessel assist and support functions	Near port
2280003200	Deep draft	Laker and ocean-going large vessels	Mid-Great Lakes
2280003100			Near port
2280002022	Ferries	River or lake ferrying	Regular routes
2280002024	Other Commercial Vessels	Excursion boats primarily	Near dock
2280002025	Dredges	Dredging projects	Varies
2280002029	Support Vessels	General work boats	Near Port
2280002030, 2280004030[1]	Commercial Fishing	Market fishing	Great Lakes
2280002040, 2280004040[1]	Military	Coast Guard and Navy	Great Lakes

[1] Gasoline fueled.

The purpose of this work was to update the commercial marine emissions in the LADCO states for 2005 from previous ENVIRON work in 2004 that estimated emissions for 2002. Emission estimates were updated for all categories listed in Table ES-1. The most substantial change to the estimates from the previous work was to incorporate specific activity and emission rates for Great Lakes deep draft vessels based on recent port calls to the ports of Cleveland and Duluth-Superior, where more of the ships use smaller engines and lower sulfur fuels than estimated in the previous work. For other vessel types, ENVIRON used vessel population and push boat fuel consumption updated using 2004 (the most recent year available) data. Given the schedule for this project, ENVIRON updated the emission rates for commercial fishing and Coast Guard vessels, but did not gather new activity data estimating changes in activity. In general, ENVIRON did not change the 2004 activity rates to project 2005 emissions because activity of commercial marine vessels has not been growing over that last decade, and if anything has been declining.

Emission results are presented in Table ES-2 for all states. These include the emission totals by vessel category described in Table ES-1 and provided to LADCO in county-specific summary data files with this report.

Table ES-2. Five state 2005 emissions (metric tonnes/year) by vessel type for commercial marine emissions.

Vessel Type	HC[1]	CO	NOx	PM[1]	SO2
Deep Draft Vessels at Ports	69	122	1,400	82	651
Deep Draft Vessels (mid-Lake)	47	1,055	12,955	652	5,489
Push Boats on Rivers and Lakes	472	4,023	21,689	525	1,905
Tugs	98	857	4,575	110	397
Ferries	26	223	1,107	29	85
Other special (excursion) vessels	7	41	289	6	23
Support vessels	1	10	54	1	5
Dredges	2	22	122	3	66
Commercial Fishing	29	110	7	2	1
Military vessels (Coast Guard)	77	264	138	3	15

[1] HC converted to VOC and PM-total to PM10 and PM2.5 using EPA factors.

TABLE OF CONTENTS

Page

TABLES

FIGURES

INTRODUCTION

Commercial marine emissions comprise a wide variety of vessel types and uses. Table 1 describes the different types of data sources used to estimate commercial marine activity. In some cases, it was necessary to split the activity of similar vessels based on the available activity data. For instance, the Tennessee Valley Authority (TVA, 2006) provided accurate fuel consumption estimates for push boats only on river systems while the same types of vessels that operate in the Great Lakes (primarily Lake Michigan between Milwaukee or Burn Harbor and Chicago) were estimated from other freight data by link as provided by the US Army Corps of Engineers (USACE, 2006). Also, ENVIRON defined source category codes (SCC) that do not appear in the official EPA list of SCC to retain as much disaggregation as possible though all SCC 2280002021 through 2280002029 can be summed into 2280002020 that is an official code designation.

Table 1. Commercial vessel types. (All engine types are diesel except those marked).

Source Category Code (SCC)	Source Definition	Purpose	Geographic Area	Data Source
2280002023	Push Boats	Barge Freight	River Traffic	TVA and USACE Lock Statistics
			Lake Traffic	USACE Freight Links
2280002021	Tugs	Vessel assist and support functions	Near port	USACE Vessel Lists
2280003200	Deep draft	Laker and ocean-going large vessels	Mid-Great Lakes	USACE Freight Links This work
2280003100			Near port	This work
2280002022	Ferries	River or lake ferrying	Regular routes	USACE Vessel Lists
2280002024	Other Commercial Vessels	Excursion boats primarily	Near dock	USACE Vessel Lists
2280002025	Dredges	Dredging projects	Varies	USACE Dredging Contracts
2280002029	Support Vessels	General work boats	Near Port	USACE Vessel Lists
2280002030, 2280004030[1]	Commercial Fishing	Market fishing	Great Lakes	State registration and catch tonnage
2280002040, 2280004040[1]	Military	Coast Guard and Navy	Great Lakes	Coast Guard Fuel Purchases

[1] Gasoline fueled.

It is necessary to define our vessel type terms especially for potentially confusing types. Push boats and tugs are typically vessels of similar design except push boats are used exclusively to push barges, while tugs are self-propelled support vessels with a V-shaped bow designed for vessel assist and other general purposes usually near port rather than strictly in long-haul freight movements as are push boats. Deep draft vessels can be generally defined as those with drafts greater than 14 feet, and in the Great Lakes are described as ‘salty’ (ocean-going) and ‘laker’ (primarily freighters, such as bulk carriers or tankers dedicated to the large fresh water lakes) designed to tolerate storm conditions mid-lake. Push boats (tug and barge combinations) move other freight in the Great Lakes, but these are restricted to within 5 miles of shore. Other vessels include ferries, excursion boats (including such vessels that might be used for group day trips, dinner cruises, and casinos), dredges (of various types), and commercial fishing vessels. In other areas, such as in the U.S. gulf coast or near naval ports, supply vessels (for off-shore oil wells or cable-laying) and military vessels are often found in high numbers but both appear in limited numbers in the Great Lakes.

EMISSION FACTORS

EPA defines three categories of marine diesel engines in Table 2, those primarily used for commercial operations, by the cylinder displacement. The engines correspond primarily to those used for propulsion power on large deep draft vessels (Category 3), auxiliary engines on large vessels and propulsion power for mid-sized (larger ferries, tugs, and excursion) vessels (Category 2), and smaller vessels (Category 1).

Table 2. Marine engine categories.

Engine Category	Displacement (l/cylinder)
Category 1	< 5.0
Category 2	5.0 < disp. < 30
Category 3	>30

Category 1

EPA revised emission factor estimates in the Regulatory Impact Analysis (RIA) and published a rulemaking for commercial marine vessels. (EPA, 1999a &1999b) In the RIA (EPA, 1999b), EPA estimated the emission factors in accordance with the defined engine categories. In Tables 3 are the EPA-estimated base (precontrolled) emission factors for marine engines for each category of engine.

Table 3. Baseline emission factors for category 1 marine engines (taken from Table 5-3, EPA 1999B).

Power Range [kW]	HC [g/kW-hr]	NOx [g/kW-hr]	CO [g/kW-hr]	PM [g/kW-hr]
37-75	0.27	11	2.0	0.90
75-130	0.27	10	1.7	0.40
130-225	0.27	10	1.5	0.40
225-450	0.27	10	1.5	0.30
450-560	0.27	10	1.5	0.30
560-1000	0.27	10	1.5	0.30
1000+	0.27	13	2.5	0.30

The SO2 and NH3 emission rates were estimated from general input data of fuel sulfur level of 0.33% sulfur and 0.16 g NH3/gallon typically used for diesel engines. The sulfur was converted to SO2 using 7.1 lb/gallon and accounting for the direct conversion of sulfur to particulate sulfate (2.247%) resulting in a SO2 emission rate of 20.62 g/gallon.

Emissions standards for NOx have been instituted under international standards starting with model year 2000 though the emission standards do not result in much reduction from the levels shown in Table 3. EPA has finalized emission standards that will result in emission reductions from U.S flagged commercial marine vessels and those standards are shown in Table 4. However, this emission inventory was intended for 2005, so only two model years at most could be subject to the new emission standards, which represent about 1-2% of the fleet based on the latest available age distribution for 2004 (USACE, 2006). Because there was insufficient information about the engine displacement and the emission reduction would be insignificantly low, no emission reduction was credited for 2005 in this emission inventory effort for the new emission standards.

Table 4. EPA primary exhaust emission standards for US flagged vessels (g/kW-hr).

Subcategory Liters/cylinder	Model Year	THC + NOx g/kW-hr	CO g/kW-hr	PM g/kW-hr
Power < 37 kW And disp. <0.9	2005	7.5	5.0	0.40
0.9 < disp. < 1.2	2004	7.2	5.0	0.30
1.2 < disp. < 2.5	2004	7.2	5.0	0.20
2.5 < disp. < 5.0	2007	7.2	5.0	0.20
5.0 < disp. < 15	2007	7.8	5.0	0.27
15 < disp. < 20 Power <3300 kW	2007	8.7	5.0	0.50
15 < disp. < 20 Power >3300 kW	2007	9.8	5.0	0.50
20 < disp. < 25	2007	9.8	5.0	0.50
25 < disp. < 30	2007	11.0	5.0	0.50

Emission estimates were determined either by multiplying engine power, load factor, and hours per year of operation or on the basis of the number of gallons of fuel consumed. The technique needed to be made flexible because activity data is available in many formats.

Category 2 and 3

Category 2 engines are used in larger vessels for propulsion and auxiliary power, and category 3 engines almost exclusively for propulsion power. The emission factors for Category 2 and 3 engines used in this work were derived from an analysis of emission data that was published in 2002 by Entec (2002). The Entec analysis included emissions data from 142 propulsion engines and two of the most recent research programs: Lloyd's Register Engineering Services in 1995 and IVL Swedish Environmental Research Institute in 2002. The resulting Entec emission factors include individual factors for three speeds of diesel engines (slow-speed diesel (SSD), medium-speed diesel (MSD), and high-speed diesel (HSD)), steam turbines (ST), and three types of fuel (residual oil (RO), marine diesel oil (MDO), and marine gas oil (MGO)). Table 5 lists the propulsion engine emission factors used for port inventory development of Duluth-Superior and Cleveland based on the Entec study.

It should be noted that Entec does not list PM factors for either PM_{10} or $PM_{2.5}$. The PM_{10} to $PM_{2.5}$ conversion factor used here is 0.92. While the NONROAD model uses 0.97 for such conversion based upon low sulfur fuels, a value of 0.80 was suggested in a report from Lyyränen et al. (1999) for high sulfur fuels. A reasonable value seems to be closer to 0.92 because higher sulfur fuels in medium and slow speed engines would tend to produce larger particulates than high-speed engines on low sulfur fuels.

PM_{10} and SO_2 emission factors were based upon recommendations from ENVIRON and provided as Appendix A.

Table 5. Emission factors propulsion engines, g/kWh.

Cat.	Speed	Sulfur	NOx	CO	HC	PM_{10}	$PM_{2.5}$	SO_2	BSFC
3	SSD	2.7%	18.1	1.4	0.6	1.05	0.96	10.29	195
		2.5%	18.1	1.4	0.6	0.99	0.91	9.53	
	MSD	2.7%	14.0	1.1	0.5	1.11	1.02	11.09	210
		2.5%	14.0	1.1	0.5	1.04	0.96	10.26	
		1.5%	13.2	1.1	0.5	0.71	0.66	6.16	
2	MSD	2.5%	14.0	1.1	0.5	1.04	0.96	10.26	210
		1.5%	13.2	1.1	0.5	0.71	0.66	6.16	
		0.3%	13.2	1.1	0.5	0.32	0.29	1.23	
Steam	Steam	1.5%	2.0	0.2	0.1	0.92	0.85	8.94	305

The methodology to calculate PM_{10} emission factors uses the following equation:

$$PM_{10}\ EF(g/kWh) = PM_{10}\ EF_{(0\%\ sulfur)} + BSFC \times 7 \times 0.02247 \times \text{Fuel Sulfur Fraction}$$

The above equation is based upon the PM vs. sulfate relationship from EPA's (2004) NONROAD model (also described in the ENVIRON (2005) Port of San Francisco Shoreside Feasibility Study). This relationship holds that 2.247% of fuel sulfur converts to $H_2SO_4{:}7H_2O$ (molecular weight 7 times that of sulfur). Brake specific fuel consumption (BSFC) used for SSDs was 195 g/kWh, while BSFC used for MSDs was 210 g/kWh based upon Lloyds 1995. BSFC used for Steam was 305 g/kWh. The PM_{10} EF at 0% sulfur was taken from the ARB (2005) methodology at 0.25 g/kWh at 0.1% sulfur.

Emission factors for SO_2 emissions were calculated using the below formula assuming the remaining 97.753% of the fuel sulfur was converted to SO_2 (as described above, the remaining 2.247% is assumed to be emitted directly as particulate sulfate) and taking into account the molecular weight difference between SO_2 and sulfur (molecular weight 2 times sulfur).

$$SO2\ EF = BSFC \times 2 \times 0.97753 \times \text{Fuel Sulfur Fraction}$$

Emission factors are considered to be constant down to about 20 percent load. Below that threshold, emission factors tend to increase as the load decreases. This trend results because diesel engines are less efficient at low loads and the brake specific fuel consumption tends to increase. Thus, while mass emissions (grams per hour) decrease with low loads, the engine power tends to decrease more quickly, thereby increasing the emission factor (grams per engine power) as load decreases. Energy and Environmental Analysis Inc. (EEA, 2000) demonstrated this effect in a study prepared for EPA. EEA determined emission factor adjustments based on load factor. Table 6 presents these adjustment factors based upon engine load. These factors were multiplied by the emission factors given into determine emission factors at loads below 20 percent.

Table 6. Emission factor adjustment factors at low loads.

Load	NOx	CO	HC	PM	SO_2
1%	11.47	20.00	89.44	19.17	1.00
2%	4.63	10.00	31.62	7.29	1.00
3%	2.92	6.67	17.21	4.33	1.00
4%	2.21	5.00	11.18	3.09	1.00
5%	1.83	4.00	8.00	2.44	1.00
6%	1.60	3.33	6.09	2.04	1.00
7%	1.45	2.86	4.83	1.79	1.00
8%	1.35	2.50	3.95	1.61	1.00
9%	1.27	2.22	3.31	1.48	1.00
10%	1.22	2.00	2.83	1.38	1.00
11%	1.17	1.82	2.45	1.30	1.00
12%	1.14	1.67	2.15	1.24	1.00
13%	1.11	1.54	1.91	1.19	1.00
14%	1.08	1.43	1.71	1.15	1.00
15%	1.06	1.33	1.54	1.11	1.00
16%	1.05	1.25	1.40	1.08	1.00
17%	1.03	1.18	1.28	1.06	1.00
18%	1.02	1.11	1.17	1.04	1.00
19%	1.01	1.05	1.08	1.02	1.00
20%	1.00	1.00	1.00	1.00	1.00

As with propulsion engines, the most current set of auxiliary engine emission factors comes from Entec (2002). Table 7 provides these auxiliary engine emission factors used for development of the Cleveland and Duluth-Superior inventories. There was no need for a low load adjustment factor for auxiliary engines, because they are generally operated in banks meaning several engines are available for the auxiliary load. When only low loads are needed, one or more engines are shut off, allowing the remaining engines to operate at a more efficient level. All auxiliary engines are assumed to be MSD with a BSFC of 210 g/kWh.

Table 7. Auxiliary engine emission factors, g/kWh.

Fuel Sulfur	NOx	CO	HC	PM_{10}	$PM_{2.5}$	SOx
2.70%	14.7	1.1	0.4	1.11	1.02	11.09
2.50%	14.7	1.1	0.4	1.04	0.96	10.26
1.50%	13.9	1.1	0.4	0.71	0.66	6.16
1.50%	13.9	1.1	0.4	0.71	0.66	6.16
0.30%	13.9	1.1	0.4	0.32	0.29	1.23

Estimated Fuel Sulfur Levels

The fuel sulfur used by the marine engines has a dramatic effect on the PM and SOx emissions from vessels. In the previous inventory (ENVIRON, 2004) development for Category 3 rulemaking, an average sulfur level of 3% sulfur was used for propulsion engines, and an average fuel sulfur level of 0.33% was used for auxiliary engines. It was assumed that while at dock, auxiliary engines were fueled on EPA non-road diesel fuel. As part of the inventory provided by Mr. Harkins (2006), fuel types used in propulsion engines were provided. Estimates of sulfur levels for the various fuels are provided in Table 8. Because most ships use the same fuel for both propulsion and auxiliary engines, fuel specified for the propulsion engines was used in the calculation of emissions from auxiliary engines in this analysis.

Table 8. Assumed sulfur levels in marine diesel fuels.

Fuel Type	Fuel Sulfur Levels
RO	2.7%
IF 320	2.7%
IF 280	2.7%
IF 180	2.5%
IF 120	2.5%
IF 60	1.5%
IF 40	1.5%
#6	1.5%
#2	0.3%

GENERAL DUTY CYCLE

To estimate the engine load, there are two engine test cycles that EPA has used to represent engine duty cycles, the E-3 (and a similar cycle called E-2 for constant speed engines typically with variable pitch propellers) and E-5 cycles described by the ISO (1996) as for heavy-duty and diesel craft less than 24 meters in length roughly corresponding to commercial and recreational use. In Table 9 are the two potential test cycle load factors available; E5 for general-purpose smaller marine diesel engines and E3 for ship propulsion and other heavy-duty marine applications. The load for the E-3 and E-2 test cycle is 69% average in-use load, while the E-5 test cycle is 34% of propulsion load. If it could be determined that the vessels found in the Coast Guard list were used for commercial purposes including ferries or other commercial functions then the E-3 load factor was used. Else the lower E-5 load factor was used primarily for vessels that were obviously excursion vessels including casinos and other similar types.

Table 9. Marine engine test cycles time in mode.

Power	E5 Cycle	E3/E2 Cycle
100	0.08	0.2
75	0.13	0.5
50	0.17	0.15
25	0.32	0.15
0	0.3	0
Avg. Load	34%	69%

Often fuel consumption can be easier obtained which reflects the total activity (power, load factor, and hours) of a vessel or group of vessels. However, a fuel consumption estimate must be converted to the specific emission factors. The specific fuel consumption rate of 0.345 lb-fuel/gallon (and 7.1 lb/gallon diesel fuel density) was used for this work as taken from EPA (1997) used to convert locomotive specific emissions to gallons units.

PUSH BOATS

In the LADCO region, tugs pushing barge traffic is one of the primary emission sources of the categories covered by commercial marine emissions. Barges are usually pushed by tugs specifically designed for river movements, though in fair weather barges may be pushed near (within 5 miles) shore on the Great Lakes. The major river systems in the LADCO region are the Mississippi, Ohio, and Illinois rivers. The freight movements and lock statistics (USACE, 2006) are well documented through river lock systems down to the Mississippi – Ohio confluence.

The Tennessee Valley Authority (TVA, 2006) has been using freight movement data and lock performance data to estimate fuel consumption by river system in their ‘barge costing model’. There are many factors affecting the fuel consumption including the configuration of the barges (how many barges can be operated per tug, the numbers of empty barges, the wait (idle) time at each lock, and other factors used by TVA to estimate fuel consumption along each route. TVA provided fuel consumption estimates and efficiency (ton-mile per gallon of fuel consumed) along river systems in the LADCO area.

River Barge Traffic

The fuel consumption by barge traffic on river systems was provided by TVA (2006) and is shown in the Table 10. The estimates provided here reflect only the river freight transfers and show the relative magnitude of activity along each river segment. The Calumet-SAG Channel, Chicago Sanitary and Ship Canal, and the South Branch of the Chicago River are all found exclusively within Cook County, while the other river systems reflect activity through multiple counties.

Table 10. Fuel consumption (gallons of diesel) by river system.

Waterway	1998	1999	2000	2001	2002	2003	2004
Calumet-Sag Channel, Il	573,518	517,008	274,349	187,364	392,884	288,105	241,658
Chicago Sanitary & Ship Canal, Il	596,678	647,159	614,426	523,492	687,271	653,519	758,182
Chicago River, South Branch, Il	19,789	39,889	27,606	26,655	32,354	31,610	37,647
Illinois River, Il	35,554,221	36,849,299	28,564,949	28,890,213	28,006,409	28,732,724	30,268,732
Ohio River	84,238,537	83,085,263	94,373,783	93,529,533	91,697,677	83,027,511	89,820,545
Mississippi above the Missouri	34,264,628	40,760,732	35,507,994	36,180,816	35,641,058	34,602,029	31,901,668
Mississippi Between Missouri and Ohio	51,261,419	64,649,042	52,607,979	44,360,390	50,904,864	45,265,442	32,215,131

The geographic allocation of the fuel consumption was accomplished using lock freight statistics available from the Army Corp of Engineers (http://www.iwr.usace.army.mil/ndc/lpms/lpms.htm). Given the schedule for this work, ENVIRON relied on the previous spatial allocation (ENVIRON, 2004) that used the most recent lock statistics available for calendar year 1999. The freight statistics through each lock were used to estimate the ton-miles for river segments. The ton-miles between two locks were calculated using the average freight tonnage of two locks multiplied by the river mileage between the two locks as demonstrated for the Illinois River in Table 11. For river segments below or above the last available lock, the freight of the last lock was used if no other estimates were available. The ton-mile estimate for each river link, between each lock or at the end of the river system such as the Ohio-Mississippi confluence, was normalized across each river system to allocate the total fuel consumption by river system in Table 10. So while the spatial allocation was based on historic data, the overall activity along the river was based on the most recent data available.

Table 11. Example: activity apportionment along the Illinois River.

Illinois River				
Lock	**Miles**	**1999 kTon**	**KTon-mile**	**Apportioned**
Thomas J. O'Brien[1]	326.5	7,372		
Cook Co. Line[1]	298 est.			
			110,669	1.3%
Lockport	291.1	16,039		
			81,888	0.9%
Brandon Road	286	16,074		
			245,202	2.8%
Dresden Island	271.5	17,747		
			496,345	5.7%
Marseilles	244.6	19,156		
			275,672	3.2%
Starved Rock	231	21,384		
			1,924,601	22.2%
Peoria	157.7	31,129		
			2,585,671	29.8%
LaGrange	80.2	35,598		
			2,953,044	34.0%
Mississippi[2]	0	38,044 est.		
Totals			**8,673,094**	**100.0%**

[1] Lock above the SAG Channel confluence (confluence is roughly equivalent to the Cook Co. line shown here) so activity contained in Chicago – South Branch and Sanitary and Ship Canal activity estimates

[2-] Estimated based on added tonnage along Mississippi river

The procedure used here to apportion the fuel consumption was developed because the freight tonnage typically increases as the river flows. So the fuel consumption and therefore emissions are more appropriately apportioned to the lower reaches of the river using this method.

The fuel consumption for each between-lock river segment was apportioned to the county using the relative river mileage within each county for each segment. For the Illinois River, the fuel consumption and emissions were allocated to the county that encompassed or were split between two Illinois counties if they bordered the river. For the Mississippi and Ohio rivers, the fuel consumption and emissions were divided by two to reflect that these rivers form the borders of the LADCO states and states outside of the region of interest.

Once the fuel consumption was estimated the emissions were predicted based on the typical engines installed on push boats. The Army Corps of Engineers (USACE, Vessel Characteristics, 2006) provides vessel characteristics for push boats. Because the emission factors depend primarily upon the power of the engines (as Table 3 shows, Category 1 engines above 1000kW had similar emission factors to Category 2 engines shown in Table 5 for medium speed engines) the fraction of the power available in push boats registered in the LADCO states was divided into those with propulsion power above and below 2680 horsepower (assuming 2 engines with rated power of 1000 kW). Smaller engines provided only 20% of the push boat power and 80% by larger engines, so the average emission factor for push boats was determine using these fractions and the estimates in Table 3 for engines between 225 –1000 kW and those above 1000 kW. The emission factors in specific units (g/kW-hr or g/hp-hr) were converted gallon units using the specific fuel consumption estimate of 0.345 lb/hp-hr and fuel density of 7.1 lb/gallon as used to convert specific emissions to gallons units in the EPA's (1997) locomotive emissions estimates. The emission factors used in this work are shown in Table 12.

Table 12. Emission factors (g/gallon) used for push boats.

Engine\Pollutant	HC	NOx	CO	PM	SO2	NH3
<1000 kW	4.14	153.4	23.0	4.6		
>1000 kW	4.14	199.4	38.3	4.6		
Avg.	4.14	190.2	35.3	4.6	16.7	0.116

Great Lakes Barge Traffic

For freight transfers on the Great Lakes, the Coast Guard restricts barge traffic within 5 miles of shore (http://www.port.mil.wi.us/bargewebpage.html), so freight transfers within these limits were considered to be barge only. The links that are outlined by USACE (2006) and shown in Figure 1 where barge links roughly correspond to those blue links ringing the shore. Some freight transfers between the outlet of the Illinois River system (through the Chicago River, SAG Channel, or Chicago Sanitary and Ship Canal) to other Great Lakes ports such as Burns Harbor or Indiana Harbor may be more direct.

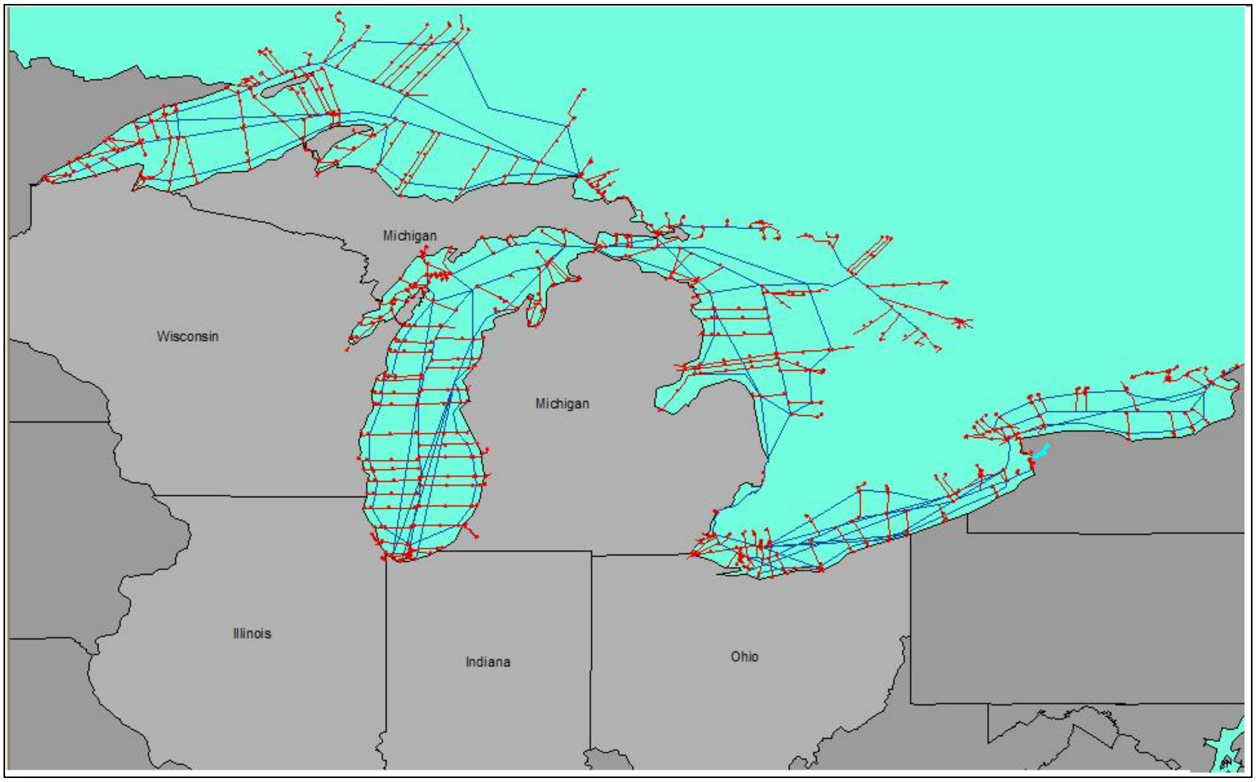

Figure 1. Great Lakes freight links.

The tonnage along each freight link was provided by USACE (2006) with spatial descriptions of each link. The links described as Lake "Spines," and those described as "Access" links coming from large ports serving deep draft vessels shown in red in Figure 1 were sorted out for barge traffic leaving only links around the lake rather than those in the middle of the lakes. The links described in this data include lengths and longitude and latitude where the links lengths and position are only approximate representations but the actual vessel movements may not be restricted to these specific positions but were used as such for the county spatial allocation.

The tonnage and link lengths were multiplied to estimate ton-miles of freight movements. The fuel consumption associated with these vessel movements was assumed to be 549 ton-miles per gallon from the previous work (ENVIRON, 2004), the same as the lower Mississippi between the Missouri and Ohio rivers and the most fuel efficient push boats freight transfers within the LADCO region. The best estimate of fuel consumption was used because the Lake transfers have no significant locks, turns, passing traffic, or current to contend with, as opposed to river movements, which reduce the fuel efficiency of these freight movements. The fuel consumption estimate was then used to convert the Table 12 emission rates to units useful for estimating emissions with ton-mile as the activity indicator and shown in Table 13.

Table 13. Emission rates (g/ton-mile) for push boats assuming 549 (ton-mile/gallon) fuel consumption rate.

HC	CO	NOx	PM – 10	SO2	NH3
0.0075	0.0643	0.3465	0.0084	0.0304	0.0002

OTHER TUGS

Tugs, as defined by USACE (2006) separate of push boats, are working vessels other than those push boats used to transport freight. These tugs could be used in a variety of other activities such as providing assist to larger deep draft vessels near ports, short movements of barges in and around ports, and as supply vessels or other sundry needs throughout the Great Lakes area or along the major river systems.

The Coast Guard provides through the Army Corps (USACE, Vessel Characteristics, 2006) the number of vessels and their characteristics, installed power and other data, for a wide variety of boats and distinguishes tugs from push boats. The vessels, identified as tugs, were associated with emissions in the county of the port of registry as provided through the Army Corps information. It is likely that some or all of the boats also operate outside the county of the port listed for a significant fraction of their time.

The activity of these vessels is unknown, so a small survey of vessel operators in the LADCO states was undertaken in the previous effort (ENVIRON, 2004) to identify a reasonable hour per year estimate. The survey response from five operators included activity estimates for a total of 35 tugs of which 6 were no longer in service but appeared in the vessel list. The average annual usage, including those no longer in service, was 1831 hours and used for these emissions estimates. It is possible that this was an underestimate because newer vessels may have replaced those tugs that are no longer in service and are not yet in the Army Corps data. The annual usage estimate of 2309 hours for eliminating the responses from those tugs no longer in service may be more appropriate but was not used. Because these vessels are workboats, the E3 test cycle load factor of 0.69 was used to estimate emissions.

DEEP DRAFT VESSELS

Estimates for deep draft vessels relied upon detailed port inventory information prepared for Cleveland and Duluth-Superior. Detailed ship calls for those two harbors were obtained from Richard Harkins, previously of the Lake Carriers Association. The port calls provided by Mr. Harkins included ship name, number of calls, maneuvering and hotelling times, tons of cargo carried and fuel used, along with other information. These data were matched with Lloyds Register Ship data to provide ship characteristics such as ship power, engine design and designation, ship type, service speed and ship dead weight tons. Ship calls were divided between Lakers and Salties. Lakers typically operate only within the Great Lake area and contain a combination of Category 2 and 3 ships. Salties are typically foreign ships that travel into the Great Lakes through the Saint Lawrence River out into the Atlantic and are usually Category 3. The U.S. Environmental Protection Agency defines engine categories by the displacement per cylinder of the engine as shown in Table 14. These categories relate to land-based engine equivalents.

Table 14. EPA marine compression-ignition engine categories.

Category	Specification	Use	Approximate Power Ratings
1	Gross Engine Power ≥ 37 kW[1] Displacement < 5 liters per cylinder	Small harbor craft and recreational propulsion	< 1,000 kW
2	Displacement ≥ 5 and < 30 liters per cylinder	OGV auxiliary engines, harbor craft, and smaller OGV propulsion	1,000 – 3,000 kW
3	Displacement ≥ 30 liters per cylinder	OGV propulsion	> 3,000 kW

[1] EPA assumes that all engines with a gross power below 37 kW are used for recreational applications and are treated separately from the commercial marine category.

Engine speed designations are shown in Table 15. Most ships have diesel engines, although some older ships are steamships.

Table 15. Marine engine speed designations.

Speed Category	Engine RPM[1]	Usual Engine Stroke Type
Slow	< 130 RPM	2
Medium	130 – 1,400 RPM	4
High	> 1,400 RPM	4

[1] RPM = revolutions per minute.

Ship Types

Deep draft vessels vary greatly in speed and generating capacity based on ship type. Various studies break out vessel types differently, but it makes most sense to break vessel types out by the cargo they carry. Table 16 lists various deep draft vessel types that are used in this study.

Table 16. Deep draft vessel ship types.

Ship Type	Description
Bulk Carrier	Self-propelled dry-cargo ship that carries loose cargo.
General Cargo	Self-propelled cargo vessel that carries a variety of dry cargo.
Passenger Ship	Self-propelled passenger ships.
Tanker	Self-propelled liquid-cargo vessels including chemical tankers, petroleum product tankers, etc.
ITB	Integrated Tug/Barge

Activity Determinations

The description of a vessel’s movements during a typical call is best accomplished by breaking down the call into modes that have similar speed characteristics. Vessel movements for each call are described by using four distinct time-in-mode calculations. Each time-in-mode is associated with a speed and, therefore, an engine load that has unique emission characteristics. While there will be variability in each vessel's movements within a call, these time-in-modes allow an average description of vessel movements at each port. Time-in-modes were estimated for each vessel call occurring in Duluth and Burns Harbor for the analysis year. The time-in-modes are described in Table 17.

Table 17. Vessel movements and time-in-mode descriptions.

Summary Table Field	Description
Call	A call is one entrance and one clearance from the MEPA[1] area. An entrance is defined as entering the breakwater (port entrance) of the port, while a clearance is defined as leaving the breakwater of a port.
Cruise (hr/call)	Time at service speed (also called sea speed or normal cruising speed) usually considered to be 94 percent of maximum speed and 83 percent of MCR[2]. Calculated for each MEPA area from the start of the RSZ and includes 7 nautical miles out into the Great Lakes.
Reduced Speed Zone (RSZ) (hr/call)	The RSZ is when the ship is traveling at less than service speed due to a mandated area or for navigational reasons. The RSZ are estimated here as the distance to slow from service speed to maneuvering speed and is estimated at 3 nautical miles. RSZ speeds are estimated as the average between service speed and maneuvering speed.
Maneuver (hr/call)	Time in the MEPA area between the breakwater and the pier/wharf/dock (PWD). Maneuvering within a port is estimated to occur at 4 knots on average.
Hotelling (hr/call)	Hotelling is the time at a PWD when the vessel is operating auxiliary engines only. Auxiliary engines are operating at some load conditions the entire time the vessel is manned, but peak loads will occur after the propulsion engines are shut down. The auxiliary engines are then responsible for all onboard power or are used to power off-loading equipment, or both.

1 MEPA = Marine Exchange/Port Authority.
2 MCR = maximum continuous rating.

Cruise speed listed in Lloyd's data is generally taken as 94 percent of the maximum service speed. Cruise distance is defined here as 7 nautical miles from where the ship begins to slow down to enter the port. The slowing from cruise speed to maneuvering speed occurs over the next 3 nautical miles and ends at the port entrance. The speed for this reduced speed zone is the average between the ship cruise speed and the maneuvering speed of 4 knots. Maneuvering is the time when the ship travels from the breakwater to the PWD. Hotelling time is estimated as the time when the ship is at the PWD with the auxiliary engines on. Both cruise and RSZ times were calculated based upon the individual ship speed and distance. Maneuvering and hotelling times were taken directly from the port call data provided by Mr. Harkins.

Propulsion Engine Load Factors

In the previous inventory (ENVIRON, 2004), propulsion engine load factors were estimated from a modification of the Propeller curve.

Load Factor = 0.1 + 0.7*(actual speed/cruise speed)^3

The 10% minimum for zero actual speed was considered to include auxiliary engines and could be used to estimate auxiliary power when hotelling. In newer methodologies, propulsion engine load factors are calculated directly from the propeller curve based upon the cube of actual speed divided by maximum speed (at 100% maximum continuous rating [MCR]) and auxiliary engine loads calculated separately.

Load Factor = (actual speed/maximum speed)^3

Since cruise speed is estimated at 94 percent of maximum speed, the load factor at cruise is calculated at 0.83 which is very close to the 0.8 used previously in the inventory development. The main difference is that in the new calculations, auxiliary engines are not included but addressed separately.

In Starcrest's (2003, 2004) two most recent inventories, they found that load factors as low as 2 percent were possible. These lower factors are possible, because ships often cycle their propulsion engine on and off during maneuvering to reduce speeds below the dead slow setting of approximately 5.8 knots. In fact, during its vessel boarding program at the Port of Los Angeles, Starcrest found container ships had engines stopped 25 to 50 percent of their time during maneuvering. While load factors were calculated using the above propeller law for each call, load factors below 2 percent were set to 2 percent as a minimum.

Treatment of Auxiliary Engines

As stated above, auxiliary engines were combined with propulsion engines in the previous inventory. In the methodology suggested here, auxiliary engine maximum continuous rating power and load factors should be calculated separately from propulsion engines and different emission factors applied. Most propulsion engines are considered slow speed or medium speed Category 2 or 3 engines, while most auxiliary engines are considered medium speed Category 2 engines. Since hotelling emissions are a large part of port inventories, it is important to distinguish propulsion engine emissions from auxiliary engine emissions.

In 2005, California Air Resources Board (ARB, 2005) conducted an Oceangoing Ship Survey of 327 ships in January 2005. Table 18 shows average auxiliary engine power compared to propulsion power obtained from the ARB survey. While it is important to determine proper ratios for each port because of differences in the types of ships calling on that port if possible, these ratios and engine speeds were used in the new typical port inventory development as a surrogate for auxiliary power.

Load factors for auxiliary engines vary by ship type and operating mode. It was previously thought that power generation was provided by propulsion engines in all modes but hotelling. Several recent studies have shown that auxiliary engines are on all of the time, with the largest loads during hotelling. Table 19 shows the auxiliary engine load factors determined by Starcrest, through interviews conducted with ship captains, chief engineers, and pilots during its vessel boarding programs. Auxiliary load factors should be used in conjunction with total auxiliary power. Auxiliary load factors listed in Table 19 are used together with the total auxiliary engine power from Table 18.

Table18. Auxiliary engine power ratios (ARB, 2005 Survey).

Ship Type	Average Propulsion Engine (kW)	Average Auxiliary Engines				Auxiliary to Propulsion Ratio
		Number	Power Each (kW)	Total Power (kW)	Engine Speed	
Bulk Carrier	8,000	2.9	612	1,776	Medium	0.222
Passenger Ship	39,600	4.7	2,340	11,000	Medium	0.278
General Cargo	9,300	2.9	612	1,776	Medium	0.191
Miscellaneous[1]	6,250	2.9	580	1,680	Medium	0.269
Tanker	9,400	2.7	735	1,985	Medium	0.211

[1] Miscellaneous ship types were not provided in the ARB methodology, so values from the Starcrest Vessel Boarding Program were used. This is used for ITBs.

Table 19. Auxiliary engine load factor assumptions.

Ship-Type	Cruise	RSZ	Maneuver	Hotel
Self-Unloader[1]	0.17	0.27	0.45	0.30
Bulk Carrier	0.17	0.27	0.45	0.22
Passenger Ship	0.80	0.80	0.80	0.64
General Cargo	0.17	0.27	0.45	0.22
Miscellaneous	0.17	0.27	0.45	0.22
Tanker	0.13	0.27	0.45	0.67

[1] Self-unloaders were assigned a higher hotelling load factor than bulk carriers due to the fact that auxiliary engines are used during unloading.

Cleveland Port Inventory

Using the methodology discussed above, emissions for ship calls in 2005 were calculated using the call information provided by Mr. Harkins (2006). Results are shown in Table 20 by mode for Lakers and compared against Harkins' results in Table 21.

The main difference is in the maneuvering mode due to the fact that Mr. Harkins did not apply the low load emission factor adjustment factors during maneuvering. Installed power is the ship propulsion power multiplied by calls.

Table 20. Cleveland Laker inventory by mode (this work).

Mode	Installed Power (MW)	Tonnes per year					
		NOx	PM_{10}	$PM_{2.5}$	HC	CO	SOx
Cruise	3,581	30.262	1.215	1.171	1.134	2.515	8.858
RSZ	3,581	6.988	0.281	0.258	0.249	0.575	1.934
Maneuver	3,581	29.987	1.062	0.977	3.996	3.838	2.677
Hotel	3,581	31.570	0.930	0.856	0.906	2.492	5.451
Total	3,581	98.806	3.488	3.262	6.285	9.420	18.920

Table 21. Cleveland Laker inventory by mode (Harkins, 2006).

Mode	Installed Power (MW)	Tonnes per year					
		NOx	PM_{10}	$PM_{2.5}$	HC	CO	SOx
Cruise	3,588	25.991	1.142	1.093	0.314	4.644	8.184
RSZ	3,588	6.433	0.283	0.271	0.078	1.149	2.025
Maneuver	3,588	17.654	0.543	0.516	0.189	3.167	3.176
Hotel	3,588	28.025	1.058	1.010	0.301	5.154	6.903
Total	3,588	78.104	3.026	2.889	0.883	14.114	20.288

Similar calculations for Salties are shown in Table 22 and compared against Harkins' inventory in Table 23. Again the major difference between the ICF results and Harkins' results is that Mr. Harkins did not apply the low load adjustment factors to the emission factors for maneuvering. In addition, this work assumed that auxiliaries used RO while Harkins assumed they used a lower sulfur fuel. And a higher auxiliary load was used based on a realistic power and typical load factors especially during hotel modes.

Table 22. Cleveland Salty inventory by mode (this work).

Mode	Installed Power (MW)	Tonnes per year					
		NOx	PM_{10}	$PM_{2.5}$	HC	CO	SOx
Cruise	518	7.771	0.469	0.431	0.258	0.601	4.621
RSZ	518	1.618	0.101	0.093	0.052	0.125	1.001
Maneuver	518	1.906	0.163	0.150	0.254	0.237	0.805
Hotel	518	22.507	1.698	1.562	0.612	1.684	16.972
Total	518	33.803	2.431	2.236	1.176	2.647	23.400

Table 23. Cleveland Salty inventory by mode (Harkins, 2006).

Mode	Installed Power (MW)	Tonnes per year					
		NOx	PM_{10}	$PM_{2.5}$	HC	CO	SOx
Cruise	509	5.688	0.348	0.336	0.196	0.477	3.210
RSZ	509	1.408	0.086	0.083	0.048	0.118	0.794
Maneuver	509	1.024	0.063	0.060	0.035	0.086	0.578
Hotel	509	8.247	0.228	0.216	0.083	1.531	1.154
Total	509	16.366	0.725	0.695	0.362	2.212	5.737

Duluth-Superior Port Inventory

A similar procedure to Cleveland was performed on the Lakers and Salties that called upon Duluth-Superior. Results are shown in Table 24 by mode for Lakers and compared against Harkins' (2006) results in Table 25. The main difference is in the maneuvering mode due to the fact that Mr. Harkins did not apply the low load emission factor adjustment factors during maneuvering. A higher auxiliary load was used based on a realistic power and typical load factors especially during hotel modes.

Table 24. Duluth-Superior Laker inventory by mode (this work).

Mode	Installed Power (MW)	Tonnes per year					
		NOx	PM_{10}	$PM_{2.5}$	HC	CO	SOx
Cruise	8,408	91.049	5.232	4.813	3.317	7.384	45.437
RSZ	8,408	20.215	1.127	1.037	0.703	1.624	9.766
Maneuver	8,408	36.180	2.572	2.367	4.536	4.378	10.554
Hotel	8,408	98.297	4.620	4.251	2.769	7.616	38.759
Total	8,408	245.741	13.552	12.467	11.326	21.003	104.516

Table 25. Harkins Duluth-Superior Laker inventory by mode.

Mode	Installed Power (MW)	Tonnes per year					
		NOx	PM_{10}	$PM_{2.5}$	HC	CO	SOx
Cruise	8,515	85.096	4.700	4.530	2.030	10.925	40.063
RSZ	8,515	21.061	1.163	1.121	0.502	2.704	9.916
Maneuver	8,515	20.741	1.286	1.241	0.507	2.633	11.245
Hotel	8,515	38.656	3.229	3.119	0.542	6.804	28.206
Total	8,515	165.554	10.379	10.010	3.581	23.066	89.431

Similar calculations for Salties are shown in Table 26 and compared against Harkins' inventory in Table 27. Again the major difference between the ICF results and Harkins' results is that Mr. Harkins did not apply the low load adjustment factors to the emission factors for maneuvering. In addition, ICF assumed that auxiliary engines used RO while Harkins assumed they used lower sulfur fuel. A higher auxiliary load was used based on a realistic power and typical load factors especially during hotel modes.

Table 26. Duluth-Superior Salty inventory by mode (this work).

Mode	Installed Power (MW)	Tonnes per year					
		NOx	PM_{10}	$PM_{2.5}$	HC	CO	SOx
Cruise	697	10.145	0.625	0.575	0.338	0.786	6.170
RSZ	697	2.107	0.134	0.123	0.068	0.162	1.328
Maneuver	697	2.538	0.220	0.202	0.341	0.316	1.072
Hotel	697	21.735	1.639	1.508	0.591	1.626	16.390
Total	697	36.524	2.619	2.409	1.339	2.890	24.960

Table 27. Harkins Duluth-Superior Salty inventory by mode.

Mode	Installed Power (MW)	Tonnes per year					
		NOx	PM_{10}	$PM_{2.5}$	HC	CO	SOx
Cruise	655	9.056	0.441	0.429	0.304	0.702	4.063
RSZ	655	3.736	0.182	0.177	0.125	0.290	1.676
Maneuver	655	1.358	0.066	0.064	0.046	0.105	0.609
Hotel	655	5.388	0.153	0.145	0.054	1.000	0.790
Total	655	19.539	0.841	0.815	0.529	2.097	7.139

Port Matching

The remaining ports were estimated from the detailed inventories prepared for Cleveland and Duluth-Superior discussed above. Ports were matched to the two ports based upon port size and the ship types that call on the port. The modeled ports that were matched are shown in Table 28, along with the total tons of cargo shipped in 2004 taken from the U.S. Army Corps of Engineers (2004) and the percent of cargo that was shipped on bulk carriers in 1996 (Arcadis, 1999). Foreign calls at each port obtained from U.S. Army Corps of Engineers (USACE, 2004) for 2004, the latest year available. Mr. Harkins indicated that traffic in 2005 was virtually identical to that in 2004. Emissions for foreign calls were determined from the matched port (Cleveland or Duluth-Superior) for identical ships of the same ship type, engine type and dead weight ton range as the modeled port. Cargo tonnage for foreign calls was estimated from the matched port data based upon the ratio of calls and dead weight tonnage of the ships calling on the modeled port. The portion of the cargo tonnage moved by foreign bulk carriers was compared against the total tonnage moved at the port times the percent of cargo moved by bulk carriers. The ratio of total Laker bulk carrier tonnage divided by the total foreign Laker bulk carrier tonnage was used to increase the number of calls of each ship type to account for domestic traffic.

Table 28. Port matching and cargo tonnage.

Port Name	Cargo (Tons)	Bulk Carrier % of total	Match Port[1]
Toledo Harbor, OH	9,861,562	89%	DS
Ashtabula Harbor, OH	10,938,476	99%	DS
Indiana Harbor, IN	18,228,291	75%	DS
Conneaut Harbor, OH	8,026,733	86%	DS
Duluth-Superior Harbor, MN and WI	45,392,619	95%	DS
Detroit Harbor, MI	16,858,179	87%	DS
Port of Chicago, IL	24,602,157	21%	DS
Sandusky Harbor, OH	3,404,447	95%	DS
Cleveland Harbor, OH	15,774,611	86%	CL
Charlevoix Harbor, MI	1,462,735	63%	CL
Milwaukee Harbor, WI	3,155,896	73%	CL
Burns Waterway Harbor, IN	9,801,740	80%	CL
Port Dolomite, MI	3,505,309	83%	CL
Fairport Harbor, OH	2,771,713	82%	CL
Marblehead, OH	3,826,771	91%	CL
Marysville, MI	1,361,797	98%	CL
Drummond Island, MI	1,715,826	75%	CL
Marquette Harbor, MI	1,537,556	63%	CL
Calcite, MI	8,949,167	91%	CL
Muskegon Harbor, MI	2,683,861	99%	CL
Presque Isle Harbor, MI	10,134,332	99%	CL
Lorain Harbor, OH	3,007,249	98%	CL
Monroe Harbor, MI	948,293	93%	CL
Alpena Harbor, MI	3,274,896	100%	CL
Gary Harbor, IN	8,531,123	79%	CL
Marine City, MI	4,077,289	100%	CL
Escanaba, MI	6,620,080	91%	CL
Buffington Harbor, IN	1,449,395	77%	CL
Stoneport, MI	7,753,812	95%	CL

Port Name	Cargo (Tons)	Bulk Carrier % of total	Match Port[1]
St. Clair, MI	5,280,623	98%	CL

[1] CL = Cleveland Harbor, DS = Duluth-Superior Harbor

Because the foreign Laker traffic use mostly bulk carriers that are Canadian ships transferring cargo to the U.S. or U.S. ships transferring cargo to Canada via the Lakes only, it is likely that the foreign cargo Lakers are similar in design to the domestic bulk carriers. Data from USACE on Salties had been used directly to represent foreign ships. However because the USACE data provided ship name and Lloyds number, the vessels could be matched directly with Lloyds data to determine engine type, ship power and service speed. This information was used to calculate average ship power and speed by ship type, engine type and dead weight ton range by grouping Canadian foreign vessel traffic with the domestic Laker vessels. The engine power was used directly to calculate total engine load with the load factor and time in mode for both cruise and RSZ zones in order to estimate emissions. Emissions from the matched port (Duluth-Superior or Cleveland) were adjusted for the modeled port based upon the difference in the time in mode, load factor, and propulsion power between the modeled and matched ports.

Emissions from deep draft vessels by port are given in Table 29. Emissions from 'Lakers' by port are given in Table 30. Emissions from 'Salties' by port are given in Table 31. The Duluth – Superior port activities span the Minnesota – Wisconsin border. So a crude assumption based on relative numbers of berths and likely activity of 1/3 the activity occurs in Wisconsin was used to apportion the emissions of this port.

Table 29. Deep draft vessel emissions by port.

Port Name	Installed Power (MW)	Tonnes per year					
		NOx	PM_{10}	$PM_{2.5}$	HC	CO	SOx
Duluth-Superior, MN & WI	9,105	282.27	16.17	14.88	12.66	23.89	129.48
Burns Waterway, IN	4,345	144.28	7.81	7.27	7.78	12.78	62.74
Indiana, IN	4,209	145.21	9.51	8.75	6.40	12.20	80.94
Cleveland, OH	4,098	132.61	5.92	5.50	7.46	12.07	42.32
Detroit, MI	3,169	125.78	7.52	6.92	5.34	10.48	64.17
Ashtabula, OH	2,514	80.93	4.90	4.51	3.92	6.97	40.68
Toledo, OH	2,442	30.05	2.09	1.93	1.09	2.38	19.77
Conneaut, OH	2,440	74.52	4.42	4.07	3.71	6.48	35.79
Calcite, MI	2,106	45.35	2.66	2.46	2.41	4.10	19.41
St. Clair, MI	1,869	46.20	2.32	2.12	2.60	4.22	15.84
Presque Isle, MI	1,854	20.25	2.60	2.50	0.79	1.73	22.94
Alpena, MI	1,728	35.31	2.71	2.49	1.56	3.08	22.03
Gary, IN	1,653	44.12	2.47	2.26	2.69	4.05	18.06
Chicago, IL	1,558	62.47	4.26	3.91	2.45	5.08	37.86
Stoneport, MI	1,552	26.68	1.85	1.77	1.29	2.39	14.40
Marine City, MI	1,446	37.41	1.79	1.63	2.07	3.41	11.94
Escabana, MI	1,305	25.32	1.44	1.36	1.46	2.34	10.36
Marblehead, OH	1,009	44.98	2.11	1.97	2.42	4.09	14.57
Milwaukee, WI	970	33.75	2.21	2.01	1.47	2.79	19.92
Muskegon, MI	912	22.98	1.00	0.93	1.22	2.08	6.76

Port Name	Installed Power (MW)	Tonnes per year					
		NOx	PM_{10}	$PM_{2.5}$	HC	CO	SOx
Dolomite, MI	835	17.12	1.10	1.01	0.91	1.55	8.22
Lorain, OH	832	21.11	0.94	0.86	1.25	1.95	6.05
Sandusky, OH	822	24.92	1.65	1.52	1.16	2.13	13.61
Fairport, OH	617	16.17	0.72	0.69	0.98	1.50	4.90
Drummond Island, MI	482	11.17	0.64	0.58	0.61	1.02	4.56
Charlevoix, MI	410	13.71	0.49	0.46	0.71	1.24	2.80
Buffington, IN	295	6.92	0.30	0.28	0.37	0.63	1.99
Marysville, MI	287	8.20	0.38	0.35	0.47	0.75	2.55
Marquette Harbor, MI	185	4.03	0.21	0.21	0.25	0.38	1.56
Monroe Harbor, MI	124	4.03	0.14	0.13	0.19	0.36	0.91

Table 30. Laker emissions by port.

Port Name	Installed Power (MW)	Tonnes per year					
		NOx	PM_{10}	$PM_{2.5}$	HC	CO	SOx
Duluth-Superior, MN & WI	8,408	245.74	13.55	12.47	11.33	21.00	104.52
Indiana, IN	4,155	141.97	9.29	8.54	6.29	11.94	78.74
Burns Waterway, IN	3,652	97.21	4.47	4.22	6.14	9.10	30.52
Cleveland, OH	3,581	98.81	3.49	3.26	6.29	9.42	18.92
Detroit, MI	2,694	98.80	5.61	5.16	4.36	8.35	45.92
Conneaut, OH	2,440	74.52	4.42	4.07	3.71	6.48	35.79
Ashtabula, OH	2,425	75.85	4.54	4.18	3.74	6.57	37.23
Calcite, MI	2,106	45.35	2.66	2.46	2.41	4.10	19.41
Toledo, OH	2,065	10.94	0.72	0.67	0.38	0.87	6.75
St. Clair, MI	1,869	46.20	2.32	2.12	2.60	4.22	15.84
Presque Isle, MI	1,854	20.25	2.60	2.50	0.79	1.73	22.94
Alpena, MI	1,728	35.31	2.71	2.49	1.56	3.08	22.03
Gary, IN	1,653	44.12	2.47	2.26	2.69	4.05	18.06
Stoneport, MI	1,552	26.68	1.85	1.77	1.29	2.39	14.40
Marine City, MI	1,446	37.41	1.79	1.63	2.07	3.41	11.94
Escabana, MI	1,305	25.32	1.44	1.36	1.46	2.34	10.36
Marblehead, OH	1,009	44.98	2.11	1.97	2.42	4.09	14.57
Chicago, IL	966	31.38	2.02	1.86	1.31	2.62	16.55
Muskegon, MI	877	20.71	0.83	0.77	1.14	1.91	5.06
Dolomite, MI	835	17.12	1.10	1.01	0.91	1.55	8.22
Lorain, OH	832	21.11	0.94	0.86	1.25	1.95	6.05
Sandusky, OH	822	24.92	1.65	1.52	1.16	2.13	13.61
Fairport, OH	617	16.17	0.72	0.69	0.98	1.50	4.90
Milwaukee, WI	614	10.47	0.55	0.50	0.66	0.97	3.90
Drummond Island, MI	482	11.17	0.64	0.58	0.61	1.02	4.56
Charlevoix, MI	410	13.71	0.49	0.46	0.71	1.24	2.80
Buffington, IN	295	6.92	0.30	0.28	0.37	0.63	1.99
Marysville, MI	287	8.20	0.38	0.35	0.47	0.75	2.55
Marquette Harbor, MI	175	3.70	0.19	0.18	0.23	0.35	1.32
Monroe Harbor, MI	124	4.03	0.14	0.13	0.19	0.36	0.91

Table 31. Salty emissions by port.

Port Name	Installed Power (MW)	Tonnes per year					
		NOx	PM_{10}	$PM_{2.5}$	HC	CO	SOx
Duluth-Superior, MN & WI	697	36.52	2.62	2.41	1.34	2.89	24.96
Burns Waterway, IN	693	47.07	3.34	3.04	1.63	3.68	32.22
Chicago, IL	592	31.09	2.24	2.06	1.14	2.46	21.30
Cleveland, OH	518	33.80	2.43	2.24	1.18	2.65	23.40
Detroit, MI	475	26.98	1.91	1.76	0.97	2.13	18.25
Toledo, OH	377	19.11	1.37	1.26	0.71	1.52	13.02
Milwaukee, WI	356	23.28	1.67	1.51	0.81	1.82	16.02
Ashtabula, OH	89	5.08	0.36	0.33	0.18	0.40	3.45
Indiana, IN	54	3.24	0.23	0.21	0.12	0.25	2.19
Muskegon, MI	35	2.27	0.18	0.16	0.08	0.18	1.69
Marquette Harbor, MI	11	0.33	0.03	0.02	0.01	0.03	0.24

Mid-Lake Traffic

To estimate the mid-lake deep draft vessel activity, USACE (2006) freight links (red links plus mid-Lake links shown in Figure 1) tonnage data was used to provide estimates of activity. The USACE uses text descriptions, and the links for the deep draft vessel in the middle of each lake are labeled “spines” with “access” links to each of those spines. The freight links along the “spine” of each lake and the “access” to each spine were defined as those associated with deep draft vessels because these shipping lanes are outside of the area designated as barge traffic. The port emission estimates extend out 10 nautical miles from port (7 miles for cruise plus 3 miles for reduced speed and maneuvering), so ENVIRON reduced the length of each access link by 10 miles. Multiplying the freight tonnage by the length of each link provides an activity indicator for deep draft vessels away from port.

In order to estimate emissions, the emission per ton-mile was estimated based on the cruise mode emission estimates for ports calls to Cleveland and Duluth described in this work. The cruise mode was defined as 7 miles each way (14 miles both ways) and together with the tonnage for each port in 2004 (the year for which the activity data was available) a ton-mile estimate for the cruise mode emission was made. The emissions in gram per ton-mile during the cruise mode were estimated and these estimates are shown in Table 32. The average of the two ports was used to estimate mid-Lake emissions using the 2002 freight tonnage data and link lengths from USACE (2006).

Table 32. Emission rate (gram per ton-mile) for deep draft vessels.

Port	Vessel Type	2004 Tonnage	HC	CO	NOx	PM	SO2
Cleveland	Laker	12,859,288	0.0063	0.0140	0.1681	0.0068	0.0492
	Salty	622,387	0.0296	0.0690	0.8919	0.0538	0.5304
	Sub Average		**0.0074**	**0.0165**	**0.2015**	**0.0089**	**0.0714**
Duluth	Laker	42,841,746	0.0055	0.0123	0.1518	0.0087	0.0758
	Salty	1,845,156	0.0131	0.0304	0.3927	0.0242	0.2388
	Sub Average		**0.0058**	**0.0131**	**0.1618**	**0.0094**	**0.0825**
Lakes Average			**0.0066**	**0.0148**	**0.1816**	**0.0091**	**0.0770**

FERRIES, EXCURSION CRAFT, AND OTHER VESSELS

Ferries, excursion craft, and other vessels (primarily identified as support vessels) were determined from a list of vessels provided by the Coast Guard to the USACE (2004). The list includes the push boats, tugs, and other self-propelled craft. The other self-propelled craft includes a wide variety of vessels registered in the U.S. including freight, passenger vessel of all types, and a very few support vessels. The freight vessels were excluded from review because the freight transfers were either covered under the categories of deep draft or push boats. The remaining vessels were primarily ferries and excursion vessels.

Ferries are used for either transportation or excursion and many are operated only seasonally. The ferries in the LADCO states are shown in Table 33 to confirm that the Coast Guard lists provided the operating ferries and to estimate operating times to estimate engine loads over the course of the year.

Table 33. Sample ferry runs in the LADCO area.

State	Port 1	Port 2	Other Ports & Comments
Wisconsin	Bayfield	La Point	Madeline Island
	Sauk	Columbia	Merrimac Free Ferry
	Cassfield	Iowa	
	Washington Island	Gills Rock	
	Milwaukee	Muskegon	New since 2002
Illinois	Golden Eagle	Iowa	
	Grafton	Calhoun Co.	
	Brussels		
Michigan	Ludington, MI	Manitowoc, WI	Badger Steamship
	Mackinac	St. Ignace	Mackinac City
	Beaver Island	Charlevoix	
	Manitou Islands	Leland	
	Algonac, MI	Canada	
	Munising	Grand Island	
Ohio	Port Clinton	Put-in-Bay \ Bass Islands	
	Sandusky	Pelee Island Canada	
	Marblehead	Kelley's Island	

In the previous work (ENVIRON, 2004) sample ferry runs were use to estimate the annual activity where the annual activity of a specific vessel could be estimated. These sample ferries shown in Table 34 produce a range of operating hours and are likely higher than typical for all vessels. Because these vessels are those operating at a higher rate than other ferry runs and excursion craft, and these schedules are likely maximum operating hours, an estimate of 1500 hours per year was used for all vessels in the USACE list. By contrast the survey data for tugs indicated an annual usage of 1831 hours per year, so the reduced estimate of 1500 hours is reasonable for these seasonal operators.

Table 34. Selected ferry-operating hours.

Ferry	Activity Description	Operating Hours (per crossing estimate)	Annual Activity Estimate (hours/year)
Badger (WI, MI) http://www.ssbadger.com/scheduleFares.asp	60 days 2 crossings 80 days of 4 crossings	4 hours running 1.5 hours at dock	1,840 running 690 at dock **2,530 total**
Beaver Island (MI) http://www.bibco.com/	706 crossings April –Dec.	2 hours running 1 hours at dock	1,412 running 706 at dock **2,118 total**
Jet Express (OH) (Maybe more than one boat) http://www.jet-express.com/schedules.html	5091 crossings May – Oct.	0.5 hours per crossing	**2,546 total**
Cassville (WI) http://www.cassville.org/ferry.html#Schedule	132 days	6 hours running per day	**789 total**

The load factor for ferries (labeled “Other Carriers (Specialized)” or “Other Carriers (Specialized)” in the USACE vessel lists) and other vessels including those labeled “Offshore Support” and “General cargo” were assumed to be workboats, so the 0.69 load factor was used to estimate emissions for these vessels. For “Passenger (Cruise)” and “Passenger (Other)” (which include excursion craft such as found at the Wisconsin Dells) vessels, a lower load factor of 0.34 was used to estimate emissions.

Dredging activity was derived from the total dredged material provided by USACE (2006). Emission rates were derived using results from another study (Starcrest, 2000), where emissions were estimated and associated with tonnage of material dredged of those emission estimates.

COMMERCIAL FISHING

Commercial fishing has a long tradition in the Great Lakes, but commercial fishing boats are a very small contribution to air emissions over the Great Lakes. Commercial fishing boats were provided in the State registration databases for Michigan and Wisconsin. As shown in Table 35, these two states have the most important commercial fisheries. The emission estimate for Ohio was determined from a ratio of the fish landings and emissions estimates for the other two States. There are relatively few commercial fishing vessels with 299 boats registered in Michigan and 74 in Wisconsin. But the Wisconsin data did not identify vessel types, so only the Michigan fleet was used.

Table 35. Fish landings in 2002 and 2005 (NMFS, 2007).

State	2002		2005	
	Landings (tonnes)	Value (million $)	Landings (tonnes)	Value (million $)
Illinois	0	0	0	0
Indiana	0	0	0	0
Ohio	1,555	3.1	1,769	3.3
Michigan	4,291	7.4	3,936	6.2
Wisconsin	2,019	4.8	1,718	2.7

The number of boats and operations are rather small compared with other commercial marine emission sources. However for completeness, commercial marine vessels were identified from the boat registrations in Michigan and associated with recreational boats powered by engines greater than 100 horsepower, an arbitrary lower power estimate of installed power among these 299 commercially operated boats.

In the previous work (ENVIRON, 2004) an approximate estimate of the annual usage for these boats was taken from information from an old commercial fishing vessel, the Barney Devine, purchased by the Wisconsin DNR (http://dnr.wi.gov/org/water/fhp/fish/lakemich/Barney%20Devine.htm) as a research vessel, which indicate that the engine had 10,000 hours on 1972 engine in 2004 averaging 476 hours per year. (The engine was a 1972, 235hp Cummins.)

The boat totals for 2005 (same as 2002), separated by diesel and gasoline inboard and outboard types based on the Michigan commercial fishing boats data, were used to create NONROAD commercial vessel NONROAD input files. The NONROAD activity file was modified to use the 476 hours per year estimate instead of the lower recreational hours estimate. With the modified NONROAD input files, the emissions were then estimated for these boats. The geographic allocation of the registration county was available for Michigan, and the Great Lakes counties inboard allocation for the Wisconsin information. No change in overall activity was assumed for 2005, which seems a reasonable assumption based on the catch in the two years, however the NONROAD model fleet turnover to 2005 was included in the emission calculations.

MILITARY VESSELS

The primary military vessels operating the Great Lakes are those of the Coast Guard 9th District. The Coast Guard vessels include both larger cutters using diesel fuel and gasoline-fueled inboard and outboard engines. The Coast Guard (2004) supplied fuel purchases for 2002 for the 9th District; 766,505 gallons of diesel and 209,216 gallons of gasoline. For 2005, no change in activity was assumed to meet the schedule for this work.

The larger cutters of 140 feet or longer, typically use Category 2 or larger Category 3 engines for propulsion (installed power typically 2500 hp; http://www.uscg.mil/d9/grumil/unit/sturgeonbay/cgcmobilebay/cgcmobilebay1.html) and other smaller engines for auxiliary power. So the large (>1000kW) Category 1 engine emission factors were used because they were approximately equivalent to the Category 2 emission factors. These emission factors were converted to emission in terms of grams per gallon using the fuel consumption assumption used by EPA in developing locomotive emission factors, where locomotive engines are similar to the reported make and model of the marine engines used in these cutters.

The gasoline-fueled engines used by the Coast Guard include both inboard and outboard engine types. The average emission factors in units of gram per gallon were developed using the average emissions and fuel consumption estimates from NONROAD model accounting for the fleet turnover to 2005.

The 9th District (http://www.uscg.mil/d9/uscgd9.html) encompasses the shores of the Great Lakes states of Minnesota, Wisconsin, Michigan, Illinois, Indiana, Ohio, Pennsylvania and New

York. The emissions for the 9th District activity were apportioned to each county using the shoreline length for the Great Lakes including parts of Minnesota, Pennsylvania, and New York. Therefore only part of the 9th District's activity occurs within the LADCO states.

EMISSION RESULTS

Emission results are presented in Table 36 for all states. These include the emission totals by vessel category described initially and provided as EPA NIF files with this report.

Table 36. Five state 2005 emissions (metric tonnes/year) by vessel type for commercial marine emissions.

Vessel Type	HC[1]	CO	NOx	PM[1]	SO2
Deep Draft Vessels at Ports	69	122	1,400	82	651
Deep Draft Vessels (mid-Lake)	47	1,055	12,955	652	5,489
Push Boats on Rivers and Lakes	472	4,023	21,689	525	1,905
Tugs	98	857	4,575	110	397
Ferries	26	223	1,107	29	85
Other special (excursion) vessels	7	41	289	6	23
Support vessels	1	10	54	1	5
Dredges	2	22	122	3	66
Commercial Fishing	29	110	7	2	1
Military vessels (Coast Guard)	77	264	138	3	15

[1] HC converted to VOC and PM-total to PM10 and PM2.5 using EPA factors.

REFERENCES

ARCADIS Geraghty & Miller. 1999. Commercial Marine Activity for Great Lake and Inland River Ports in the United States, EPA Report EPA420-R-99-019, September.

California Air Resources Board. 2005. "Emissions Estimation Methodology for Ocean-Going Vessels," Appendix D, October 17.

California Air Resources Board. 2005. "2005 Oceangoing Ship Survey, Summary of Results," September.

Coast Guard. 2004. Personal communication with Renee Sykora, May 24.

Energy and Environmental Analysis Inc. 2000. Analysis of Commercial Marine Vessels Emissions and Fuel Consumption Data, EPA420-R-00-002, February.

Entec UK Limited. 2002. "Quantification of Emissions from Ships Associated with Ship Movements between Ports in the European Community, prepared for the European Commission," July.

ENVIRON. 2005. "Shoreside Power Feasibility Study for Cruise Ships Berthed at Port of San Francisco," Prepared for the Port of San Francisco.

ENVIRON. 2004. "LADCO Nonroad Emission Inventory Project For Locomotive, Commercial Marine, And Recreational Marine Emission Sources," Prepared for LADCO, December.

EPA. 2004. "Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling—Compression Ignition Engines," EPA Report No. EPA420-P-04-009, April.

EPA. 1999a. "Control Of Air Pollution From Marine Compression-Ignition Engines." Part 94, Code of Federal Regulations, December, 1999. Published in the Federal Register December 29.

EPA. 1999. "Final Regulatory Impact Analysis: Control of Emissions from Compression-Ignition Marine Engines." EPA420-R-99-026, November.

EPA. 1997 "Emission Factor for Locomotives." Environmental Protection Agency, EPA420-F-97-051, December.

Harkins, R.W. 2006. "Great Lakes Marine Air Emissions – We're Different Up Here!," September 2006. And personal communication with Richard Harkins of Lake Carriers Association, November 30.

ISO. 1996. "Reciprocating Internal Combustion Engines – Exhaust Emission Measurement" Part 4 Test Cycles for Different Engine Applications." International Standards Organization Regulations 8178, 1996 Edition.

Lyyränen, J., J. Jokiniemi, E. Kauppinen, and J. Joutsensaari. 1999. "Aerosol characterization in medium-speed diesel engines operating with heavy fuel oils," Journal of Aerosol Science, Vol. 30., No. 6. pp. 771-784.

NMFS. 2007. "Annual Landings." National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Department of Commerce, Available Online at: http://www.st.nmfs.gov/st1/commercial/landings/annual_landings.html last updated January.

Starcrest Consulting Group, LLC. 2004. "Port-Wide Baseline Air Emissions Inventory," prepared for the Port of Los Angeles, June.

Starcrest Consulting Group, LLC. 2003. "The New York, Northern New Jersey, Long Island Nonattainment Area Commercial Marine Vessel Emission Inventory, Vol. 1 - Report," Prepared for the Port Authority of New York & New Jersey, United States and the Army Corps of Engineers, New York District, April.

Starcrest Consulting Group, LLC. 2000. "Houston-Galveston Area Vessel Emissions Inventory," Prepared for the Port of Houston and the Texas Natural Resource Conservation Commission, November 2000. Also Appendix C of HGA Post-1999 ROP/Attainment Demonstration SIP, Texas Natural Resources Conservation Commission, December.

TVA. 2006. "River Efficiency, Fuel Taxes, and Modal Shifts." Bray, L.G., Dager, CA., Henry, R.L., Koroa, C., TR News, Transportation Research Board, July – August 2002. Fuel Consumption Update, personal communication with C.A. Dager, November.

USACE. 2006. Data available online at: for River Barge, http://www.iwr.usace.army.mil/ndc/lockchar/lockchar.htm, Vessel Characteristics, http://www.iwr.usace.army.mil/ndc/veslchar/veslchar.htm, Waterborne Commerce, http://www.iwr.usace.army.mil/ndc/wcsc/wcsc.htm, Dredging, http://www.iwr.usace.army.mil/ndc/dredge/dredge.htm.

U.S. Army Corps of Engineers. 2004. Navigation Data Center, Principal Ports of the United States, 2004, available at http://www.iwr.usace.army.mil/ndc/data/datappor.htm. And U.S. Army Corps of Engineers Navigation Data Center, Vessel Entrances and Clearances, 2004, available at http://www.iwr.usace.army.mil/ndc/data/dataclen.htm.