Determination of Emission Factors from Commercial Marine Vessels

Eric Williams, Brian Lerner, and Paul Murphy
NOAA/ESRL/CSD, 325 Broadway, Boulder, CO 80305 and
CIRES/University of Colorado, Boulder, CO 80309
eric.j.williams@noaa.gov

Scott Herndon and Mark Zahniser
Aerodyne Research, Inc., 45 Manning Road, Billerica, MA 01821

EXTENDED ABSTRACT

Commercial marine vessels range in size from small fishing boats (20-30 meters in length) to extremely large tanker ships (>300 meters in length). These ships almost without exception use diesel engines for propulsion and auxiliary power generation. The larger ships, comprising bulk carriers, tankers and container carriers, utilize slow-speed diesel (SSD) engines that produce power in the 10 MW to 100 MW range. These engines typically consume heavy fuel oils (HFO), which are high in sulfur content (1%-4.5% by weight). Smaller vessels use medium-speed diesel (MSD) engines for propulsion, and generally all vessels will use MSD engines for auxiliary power, but may use more refined fuels such as marine diesel oil (MDO) or marine gas oil (MGO). These engines are extremely efficient, converting nearly all of the carbon in the fuel to CO_2, but also emitting NO_x, SO_2, PM, and small quantities of CO and VOCs such as formaldehyde (CH_2O) and ethene (C_2H_4). In general, emissions from these ships are unregulated and uncontrolled.

Emissions from commercial marine vessels have significance on local, regional, and global scales. In ports ship engines are left running not only to provide power for lights, electronics, etc., but also in many cases to power the cranes and pumps that perform loading and unloading operations. This contributes significantly to degradation of local air quality both by direct emission of priority pollutants (e.g., CO and PM) but also due to increased production of secondary pollutants, such as O_3, from emission of precursor species such as NO_x and VOCs (e.g., CH_2O). On a regional scale ship emissions can impact efforts to reach air quality regulatory goals. For example, the county of Santa Barbara, CA, has performed inventory modeling that indicates little or no reduction of overall NO_x emissions between 1999 levels and projected 2015 levels derived from controls on land-based point and area sources. This is due to increased emissions from commercial shipping transiting the sea-lanes just offshore[1].

There has been considerable marine vessel emission inventory modeling conducted over the last decade or so, and a common thread among these inventories is the use of published emission factors that relate mass emission rates of NO_x, SO_2, and other species to ship activity data, such as fuel consumption rates. A widely cited publication of emission factors is the 1995 Lloyd's study[2], which used data from bench-tests and measurements from vessels underway to compile emission factors based on fuel consumption and on power output. A more recent study of emission factors was published by ENTEC[3] which showed some significant differences from the Lloyd's work.

Given the significance of emissions from commercial shipping, which is especially important for regional and local coastal areas, we undertook to determine emission factors from a wide variety of ships under actual operating conditions, both underway and stationary, in the Houston Ship Channel and the Gulf of Mexico.

The measurements reported here were taken aboard a research ship, NOAA R/V Ronald H. Brown, during the Texas Air Quality Study (TexAQS) from early August through mid-September, 2006. The study area spanned the Gulf of Mexico, and included Galveston Bay and the Houston Ship Channel. Instruments to measure NO_y, SO_2, CO, CO_2, VOCs, HCHO, and PM were installed in modified twenty-foot sea-containers that were placed on a forward deck of the ship. Sampling height was ~20 meters above water line. An Automated Identification System (AIS) receiver was used to log continuously data from all ships greater than 100 gross tons (Gt) within about a twelve mile radius of the receiver. The logged data were verified by reference to the 2006 Lloyd's Maritime Directory[4]. In many cases association of a ship with a particular plume was straightforward, but this was not always the case. Thus of the more than 1100 plumes encountered during the study, 212 have been positively associated with a particular vessel.

Emission factors were determined via linear regression analysis of the correlation between exhaust plume mixing ratios of some particular species (e.g., NO_y) and CO_2. The slopes from these fits are used to calculate the mass-based emission factors with the assumptions that all of the carbon in the fuel is converted to CO_2 and that the average mass-fraction of carbon in the fuel is 0.865. Dilution will affect both species equally and the measurements occur very close to the source (stack) so losses are negligible. Uncertainties include: 1) uncertainty of the mixing ratios; 2) errors due to sampling; 3) errors in the least-squares slope determinations; and 4) errors from the assumptions above. We estimate the total RMS uncertainty for any given emission factor to be less than about 24%.

We segregate our data by engine type, using the somewhat arbitrary level of 10 MW to distinguish MSD (<= 10 MW) from SSD (> 10 MW) engines. Plots of emission factors versus the vessel speed (as a surrogate for load) show no obvious relationships for any of the species for either engine type. The principal feature of these plots is the large level of variability, in some cases the relative standard deviation is 100% of the mean value. The mean values of our emission factors are consistent with those previously reported, and in particular our data also show that SSD engines emit more NO_x than MSD engines. The one principal difference in our data from those previously published is in the SO_2 emission factors, where ours are somewhat lower. This is no doubt due to the sulfur levels in the marine fuels being consumed by the vessels that we encountered. We found virtually no emission of VOCs (C10 and less) from these ships, with the exception of formaldehyde. The emission factors for HCHO are quite low but appear to correlated to CO. This is likely related to engine maintenance issues since properly running diesel engines will not emit unburned fuel components to any significant degree. Emission of HCHO, however, is an important point since this very reactive species can contribute to air quality degradation in a number of ways.

Finally, we make a comparison of emissions from marine vessels and point sources in the Houston-Galveston region. Emission of NO_x from ships is considerably greater, up to two orders of magnitude, than for either coal fired or natural gas fired power plants. Emission of SO_2 is quite variable from ships, depending on the fuel, but can be comparable to that from coal burning electric generating units. Emission of CO is quite low from both sources. Using our emission factors and activity data from a 2007 report by the Eastern Research Group[5], we estimate that NO_x emissions from ships in the Houston-Galveston region can be a significant fraction of total NO_x on a tons-per-day basis. Ship emission of SO_2, while non-negligible, is small on a tons-per-day basis compared to other sources, and emission of CO is negligible.

In summary, our data largely confirm published average mass-based emission factors, but also show significant variability especially with NO_x. This variability is a key issue for emissions inventory modeling of marine vessels since the emission factors are only one input to the final result. The variability that we have observed under actual operating conditions is also seen in the extensive Lloyd's study where the engine-to-engine variation of NO_x emissions can be more than a factor of two. One approach to reducing this variability has been to create more categories of emission factors based on vessel type, engine type, fuel used, fuel consumption rates, and operating modes. However, this essentially transfers uncertainty from one part of the inventory to another since acquiring accurate activity data for all the categories must, at least in some cases, be guessed at. On the other hand, with the advent of systems, such as AIS, that can track ship movements easily and continuously within a region it might not be unreasonable to use this approach. Regardless of the approach, more reliable and accurate emission factors will be essential in providing accurate estimates of emissions from this source.

REFERENCES

1. Santa Barbara County Air Pollution Control District, 2001 Clean Air Plan, http://www.sbcapcd.org/itg/shipemissions.htm, 2001.
2. Lloyd's Register, Marine Exhaust Emissions Research Programme, London, 1995.
3. European Commission and ENTEC UK Ltd., Quantification of emissions from ships associated with ship movements between ports in the European Community, Final Report, July, 2002.
4. Lloyd's Marine Intelligence Unit, Lloyd's Maritime Directory, London, 2006.
5. Eastern Research Group, "Houston/Galveston Routine Vessel Identification and Traffic Study"; ERG No. 0196.00.023, prepared for Texas Commission on Environmental Quality by Eastern Research Group, Morrisville, NC, 2007.

KEY WORDS

Pollution from ships
Emission factors