A Critical Review of Ocean-Going Vessel Particulate Matter Emission Factors

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Abstract

California Air Resources Board staff has conducted an exhaustive evaluation of available data to assess ocean-going vessel particulate matter (PM) emission factors. The goals of this assessment were to compile available testing data, analyze potential confounding relationships in the data, and assess emission factors. Our analysis identified no significant difference between emission factors for auxiliary and main engines and between emission factors and load factor, installed power, or model year. We found PM emission factors for vessels operating on heavy fuel oil at 2.5% sulfur content were statistically significantly higher (1.5 g/KW-hr) than vessels operating on distillate fuel (0.3 g/KW-hr). While we expected to identify a clear relationship between fuel sulfur content and PM emission factors, our analysis identified only a weak relationship. A future sulfur emission control area may be defined across North America with a 1.5% fuel oil sulfur content limit. Based on the weak relationship between PM emission factors and fuel sulfur content identified in this paper, we estimate the PM emission factor at 1.5% fuel sulfur would be reduced by about 30% to 1 g/KW-hr. Future research and additional testing is necessary to improve PM emission factor measurements from large vessel engines, and to better assess the relationship between PM emission factors and fuel sulfur content.

Introduction

Ocean-going vessels generate emissions of nitrogen oxide (NOx), sulfur oxides (SOx), and particulate matter (PM) through the burning of fuels in main engines, auxiliary engines, and boilers. These emissions significantly impact air quality in coastal regions of California. The characteristics of emissions change based on the type of fuel burned. Heavy fuel oil is a residual fuel generally left over from refining processes which tends to have a high sulfur and metals content, while distillate fuels are a cleaner fuel which are a product of refining processes. Assessing air quality impacts requires development of an inventory of emissions from these ships; and development of such an inventory requires the assignment of an emission factor, in terms of grams of pollutant per kilowatt-hour operated (g/KW-hr). While NOx and SOx emission factors from ocean-going vessels are relatively well-understood, PM emission factors are much more uncertain due to limited data and variability in measurement techniques.

The California Air Resources Board (CARB) has previously estimated a PM emission factor of 1.5 g/KW-hr based on an analysis of PM emission tests (CARB, 2005b). This PM emission factor applies to both auxiliary engines (ship engines used to produce electrical power) and propulsion engines (larger, slower speed engines used for propulsion) operating on heavy fuel oil (HFO) with 2.5% sulfur content (CARB, 2005b). The choice of PM emission factor to use is important, because it affects the estimated impact of primary PM emissions on overland PM concentrations. As regulations are implemented to reduce fuel sulfur content (either through a Sulfur Emission Control Area developed by international agreements, or other regulations at the National or State level), PM emission factors are expected to decrease.

This paper provides an exhaustive evaluation of available data to assess the appropriate ocean-going vessel PM emission factor for emissions inventory development, and what relationship if any is present between fuel sulfur content and PM emissions from ships. In performing this analysis, we defined several objectives:

- compile available research on PM emission rates and results of PM emission tests;
- determine potential confounding factors in the data and how those factors may affect our interpretation of data analysis;
- analyze the average PM emission factor for engines burning HFO at 2.5% sulfur, whether or not this average factor is different for auxiliary and propulsion engines, and how this emission factor will change if HFO sulfur content is reduced.

This paper describes the results of this analysis.

Compiling Available Research

Appendix A provides a complete listing of all available PM emission factor test results by data source, as well as an accounting of our knowledge about key factors or characteristics of each test performed. We collected relevant information from more than 10 different sources of emission tests and related data. Although there are a number of emission studies on marine engines, relatively few provide PM emission factor estimates, and fewer provide PM emission factors based on tests of ship engines burning HFO. Each of these studies was conducted under different conditions, on different types of engines and fuels, using different methodologies. As a result, emission factor test results are variable, and dependent on many different factors.

The most widely-cited emission tests, which formed the basis for the CARB emission factor estimate came from data published by Wright (1997). The Wright (1997) study focused on tests from 6 engines which was summarized as the basis for Lloyds (1995). Four of these tests were conducted on engines burning HFO and two on distillate fuels; the tests on engines burning HFO were conducted on relatively small engines that were less than one quarter of the average size of engines installed in ocean-going vessels that visited California's ports in 2004 (CARB, 2005a).

Other tests, which were not directly used to generate the original PM emission factor estimate, but are considered for this analysis were conducted by Environment Canada (Rideout, 1997), Cooper (2001, 2003, 2004), and others. The Environment Canada data are notable because the duration of tests was relatively short – about 12 minutes per test. The Cooper data are notable because results are significantly lower than other studies. More recently, the Port of Los Angeles has funded emissions testing on ocean-going vessels (Miller et al., 2007). Limited test information provided by Maeda (2004) and Fleisher (1998) are also included in this analysis.

While evaluating each data point, we identified two corrections to the data. First, we identified an error in (Rideout, 1997) where PM emissions for a Sulzer V12 12ZAV40 auxiliary engine was reported as 0.65 kg/tonne; while this reading should have been reported as 5.04 kg/tonne (Lee, 2005). Second, we identified that several measurements citied in Cooper (2003) were made without a dilution tunnel and were potentially low as a result (Milkey, 2004).

Potential Confounding Factors in Data

PM emission factors are affected by the way samples are collected, the operating conditions of the vessel at the time of the test, the type of fuel burned, and many other influences. Variations in test conditions can cause significant variability in test results. Controlling for these variations across multiple studies is challenging; relationships that may be visible in a single set of well-controlled data may not be present when evaluating the larger mixed data set. We believe it is fundamentally appropriate to evaluate as much available data as possible, because given the inherent uncertainty in test measurements and conditions it is not likely one test or set of tests adequately captures emission factors during the normal variability in vessel operations and uncertainty in measuring emissions from these large engines. Our approach was to evaluate potential confounding relationships to determine how best to analyze the data.

We conducted our analysis using two different approaches. In one approach, we counted each test result from each vessel as an individual test. We used this approach to account for the fact that each test was conducted under different conditions, and is therefore unique. In another approach, we averaged all available tests on each engine, so that we accounted for one average result for each engine test. Doing so avoided potential weighting of emissions based on number of tests on each engine. For both analyses we first eliminated several tests conducted at low loads (less than 18% of rated power) to eliminate potential bias in the data due to low load emissions tests.

Upon initial evaluation of the data, several relationships or lack of relationships become apparent. First, emission factors representing engines burning distillate fuel are approximately five times lower at 0.3 g/KW-hr than engines burning HFO at 1.3 g/KW-hr. This relationship is statistically significant at 95% confidence. The relationship makes sense because HFO has a higher sulfur content (~2.5%) which is converted when combusted to sulfate in PM, and has a higher ash and metal content that also becomes particulate when the fuel is burned. In contrast, marine distillate fuels have a sulfur content of approximately 0.25%. We also compared HFO PM emission factors at less than 1% fuel sulfur (four data points) against distillate fuel PM emission factors; there was no significant difference between the data groups. While we believe there may be a significant difference between PM emission factors on distillate (a refined fuel) and HFO (an unrefined fuel) even with low sulfur content, we did not observe this difference in the data. This may be due to small sample size of the HFO low sulfur PM emission factors, and potentially other confounding factors like fuel misclassification.

Second, evaluating PM emission factors by fuel type, engine type, engine age, or by load factor does not reveal a significant relationship in the data as a whole. In general, since emission factors are normalized by power one might not expect a relationship except at low loads. Sierra Research (2000) identified an increase in PM emission factors at less than 20% load relative to greater than 20% load for distillate fueled marine engines. This relationship was not observed in our analysis, possibly due to the limited number of tests conducted on HFO at low loads. We also evaluated PM emission factors against rated engine power and model year, but did not identify a significant relationship between those variables and PM emission factors.

Finally, we evaluated differences in emission factors for auxiliary and main slow speed engines burning HFO with greater than 1% sulfur content. Results were not significantly different at 95% confidence. We conducted both parametric and nonparametric tests on the data; nonparametric tests indicated the distributions might be different at 90% confidence while parametric tests indicated the distributions were indistinguishable at 90% confidence. Given data from Cooper (2001, 2003, 2004) represented about half of the auxiliary engine emission factors but none of the main slow speed HFO engine emission factors, we decided to test whether data from Cooper are statistically lower than other studies. We found that Cooper's auxiliary engine emission factors for burning HFO at >1% sulfur were significantly lower at 95% confidence than other studies. Cooper indicated to ARB several tests were 5% to 25% low due to conducting several tests without a dilution tunnel (Cooper, 2004). This meant that any statistical difference between auxiliary and main engines may be due to a real difference or to methodological differences that result in lower emission tests reported by Cooper (2001, 2003, 2004). Based on these results we decided not to separate auxiliary engine tests from propulsion engine tests.

The most important confounding factor in the data appears to be differences in measurement methodologies between the studies. Measuring PM emissions on marine vessels is difficult because of the size of marine engines and lack of

available space for conducting testing. PM emissions collected within a stack must be sampled in isokinetic conditions and diluted prior to collection. International Standards Organization (ISO) Standard 8178 is the currently accepted method for conducting PM emissions testing on marine vessels. This method was generally used by most of the studies included in Appendix A. However, Bastenhof (1995) found that method 8178 is only valid for testing on fuels containing less than 0.8% sulfur, testing at more typical HFO sulfur content revealed variability in emission rates from 20-50%. Most HFO tested in each of the studies identified in Appendix A exceeded this fuel sulfur level.
A second important factor may be heterogeneity in heavy fuel oil composition. Heavy fuel oils are essentially waste products generated by petroleum refineries; their composition is dependent upon the type and composition of crude oil processed through each refinery and specific refining processes of each facility. HFO fuels from different refineries may vary in ash, aromatic, and metal content as well as other parameters, many of which affect emissions and testing.

Preliminary PM emission testing results from Miller (2007) on one marine vessel indicate the sampling tube used to route emissions from the stack to dilution tunnel can have a major impact on measured PM emissions. Miller (2007) collected PM emissions on a ship with and without a five meter sampling tube; PM losses exceeded 40% with the sampling tube. None of the published studies included in Appendix A described the length of their sampling tube.

Variability in PM emission factors due to limitations in method 8178 (Bastenhof, 1995) and sampling tube length (Miller, 2007) appears to be significant. Given this variability we might expect results in Appendix A to vary by as much as 20 to 90% from each other based only upon differences in sampling methods. This variability is both significant and irreducible; and indicates trends which we might expect to be present in the data may be obscured.

Results

Accounting for all available emission factor data in each individual test, regardless of fuel sulfur content, we calculate an average HFO PM emission factor of 1.5 g/KW-hr with a 95% confidence interval range from 1.3-1.6 g/KW-hr, and an average sulfur content of 2.4%. Accounting for the same test data averaged for each vessel, we calculate an average HFO PM emission factor of 1.3 g/KW-hr with a 95% confidence interval range from 1.1-1.6 g/KW-hr, with the same average fuel sulfur content. Our previously chosen 1.5 g/KW-hr emission factor at 2.5% sulfur is within this range. We also calculated a PM emission factor of 0.3 (0.2-0.4) g/KW-hr for distillate fuel. These results are generally consistent with other studies including Lloyds (1995) for HFO (1.5 g/KW-hr) and Sierra Research (2000) for distillate (0.3 g/KW-hr).

Given the sources of variability and uncertainty in PM emission factor data, deriving a continuous relationship between fuel sulfur content and PM emission factors is problematic. Well-controlled studies on stationary sources show a clear linear relationship. Figure 1 displays a relationship identified by Lee et al., (2002) in a study of furnaces, which is clearly linear. AP-42 also predicts a linear relationship between fuel sulfur and PM emission factors for HFO external combustion processes (USEPA, 1998). It is important to note that external combustion processes involving an open flame represent a different process from internal combustion used in auxiliary and main ocean-going vessel engines, so the transferability of these results is not clear.

Figure 1. Furnace External Combustion PM Emission Factor vs Fuel sulfur Content (Adopted from Lee et al., 2002)

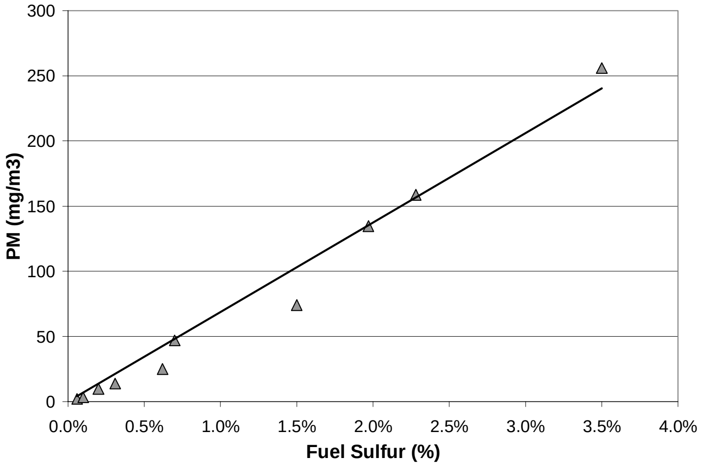


Figure 2 provides a chart of all HFO emission factor test results by fuel sulfur content and data source. Results indicate a relatively poor relationship between HFO emission factors and PM sulfur content, whether modeled as linear (r^2 = 0.2) or exponential (r^2 = 0.3). Even this poor relationship is completely dependent on several low sulfur HFO emission factor tests provided by Cooper (2001, 2003, 2004), which may be biased low as described earlier. If these tests are removed from the analysis, there is no observable relationship between fuel sulfur content and PM emission factors in available HFO test data.

Since our analysis suggested no statistically significant difference between distillate and low sulfur HFO PM emission factors, all distillate and HFO data can be combined and analyzed. Figure 3 provides all distillate and HFO PM emission factor data by source and fuel sulfur content. By adding PM emission factors from distillate fueled tests, both linear and exponential regression models improve to r^2 = 0.5. This improvement is due to the fact that almost all distillate data represent low emission factors at less than 0.5% fuel sulfur content. Even so, regression models between PM emission factors and fuel sulfur content can explain only 50% of variability in measured data.

As Figure 3 shows, PM emission factor data fall into two groups. Emission factors derived from tests on less than 0.5% fuel sulfur are clustered about 0.2-0.4 g/KW-hr, with one outlier at 1.3 g/KW-hr. As discussed earlier and shown in Figure 2, emission factors derived from tests on fuels exceeding 1% sulfur content have an average value of 1.4 g/KW-hr with a wide standard deviation and no relationship with fuel sulfur content. While a regression model can be fit to the data with some success, the shape of this relationship is determined by the relative weight placed on low sulfur emission factor tests.

Figure 2. PM Emission Factor by HFO Fuel Sulfur Content: All Engines and Sources

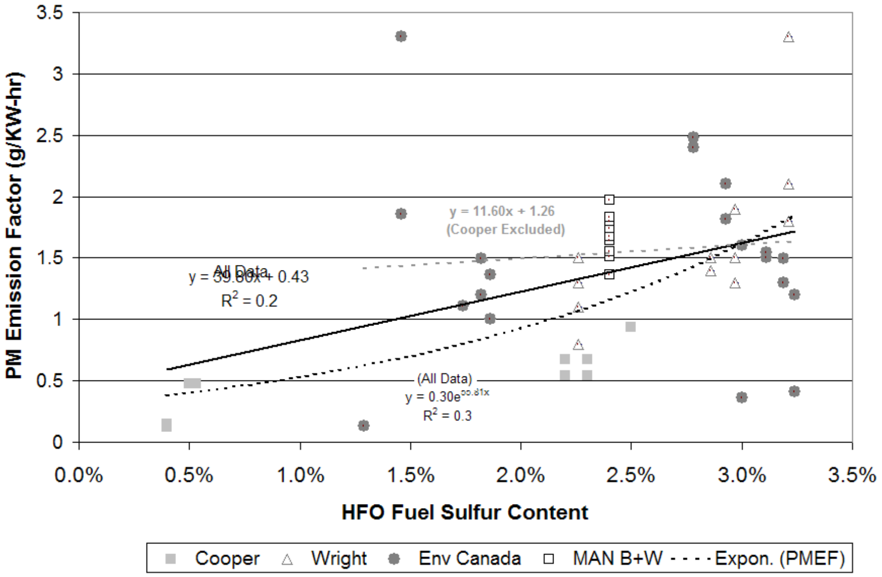
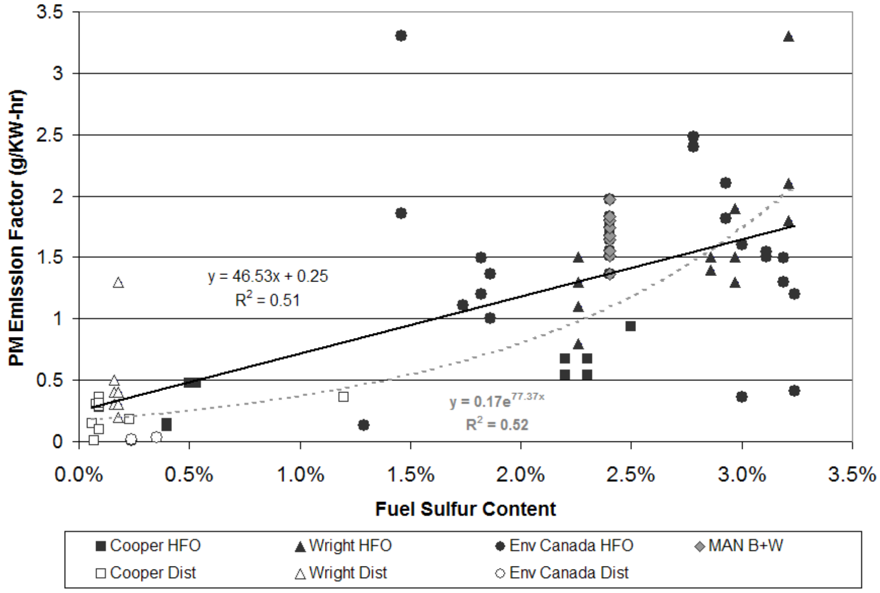


Figure 3. PM Emission Factor by Fuel Sulfur Content: All Engines, Sources, Fuels



Figures 2 and 3 show wide scatter in the data, and the lack of a strong apparent relationship between fuel sulfur content and PM emission factor. Given this poor relationship it is useful to conduct a theoretical assessment of the decreasing contribution of PM sulfate in total PM as fuel sulfur content decreases. This calculation is conducted as follows (ENVIRON, 2002):

$$Tc = (((Sf-St) * (F*Mr*Psc))/100) + Tr \qquad (1)$$

Where
Tc = converted test result
Sf = fuel sulfur content of test
St = fuel sulfur content of original test result
F = fuel consumption (assumed 200 g/KW-hr)
Mr = molecular ratio of direct sulfate PM to S (assumed 7)
Psc = percent of sulfur in fuel converted to direct sulfate PM (assumed 2.25%)
Tr = test result that is to be converted

We applied this method by adjusting the average PM emission factor estimate of 1.4 g/KW-hr using this equation. We estimated a range of values by adjusting the upper and lower confidence interval estimates of the mean PM emission factor. These results can be compared to a linear interpolation between average and confidence interval ranges for high and low sulfur fuel PM emission factors. Results are summarized in Figure 4. Figure 4 displays the same HFO test data shown in Figures 2 and 3, which provide only a weak correlation with fuel sulfur content.

As shown in Figure 4, a linear interpolation between high and low sulfur fuels generates a different estimate for the relationship between fuel sulfur content and PM emission factor than does the ENVIRON (2002) calculation-based approach. At 1.5% fuel sulfur content, the proposed value for a Sulfur Emission Control Area off the coast of North America (ARB, 2006) PM emissions estimates range from 0.7-1.3 g/KW-hr. We propose that the mid-point value of 1 g/kw-hr be used for analyses such as development of a Sulfur Emission Control Area.

Given no statistical difference between auxiliary and main engines, ARB applies PM emission factors derived in this paper to both engine types. However, a survey conducted by ARB in 2005 identified that some vessels use marine diesel (distillate fuels) while other vessels use heavy fuel oils in their auxiliary engines (CARB, 2005a). On average, the 2005 survey identified that 92% of auxiliary fuels burned on passenger vessels are HFO, with the remaining 8% distillate; and 71% of auxiliary fuels burned on all other vessel types are HFO, with the remaining 29% consisting of distillate. For emissions inventory purposes, a composite emission factor is used that represents the combined usage of both fuels. Table 1 provides CARB's PM emission factors used for California's ocean-going vessel emissions inventory (CARB, 2005b).

Figure 4. Fuel Sulfur PM Emission Factor Relationships

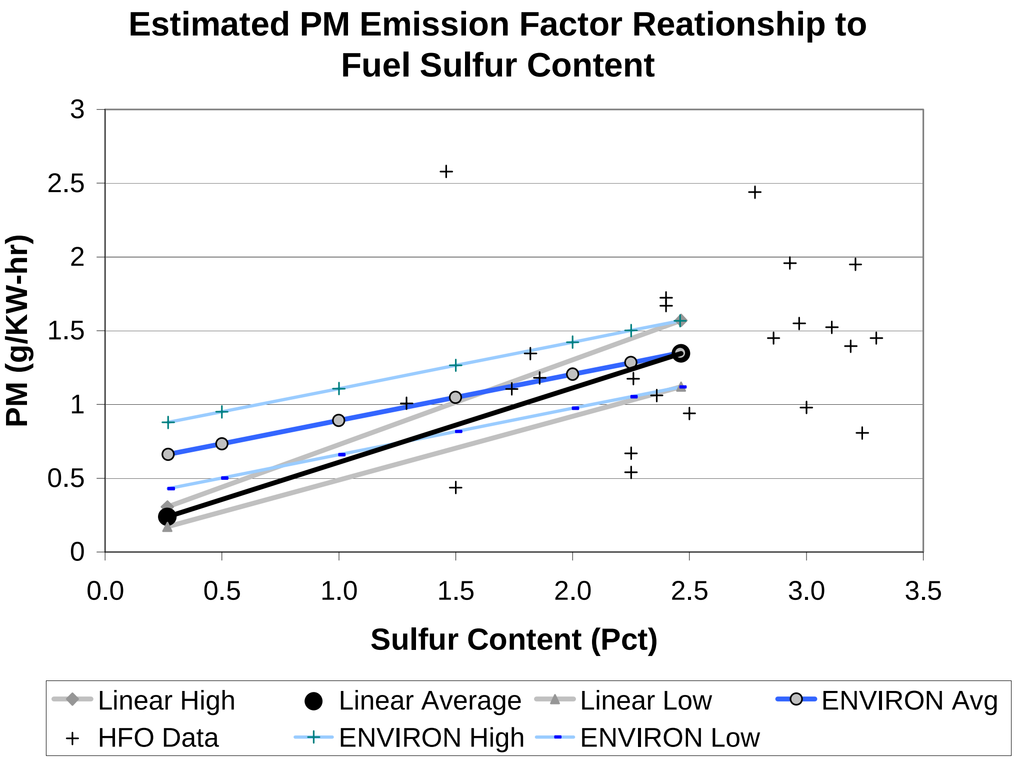


Table 1. Air Resources Board Ocean Going Vessel PM Emission Factors for Auxiliary and Main Engines

Engine/Ship Type	Fuel	PM Emission Factor g/KW_hr
Main Engine - Slow Speed	HFO	1.5
Main Engine - Medium Speed	HFO	1.5
Auxiliary Engine	HFO	1.5
Auxiliary Engine	Distillate	0.3
Aux-Passenger	HFO/Distillate	1.4
Aux-Others	HFO/Distillate	1.2

Conclusions

Based on our analysis of available emission factor test data of marine vessel auxiliary and main engines operating on distillate and HFO fuels of varying sulfur contents, we derive a PM emission factor of 1.5 g/KW-hr (1.2-1.6 g/KW-hr) for all HFO fueled auxiliary and main engines, based on a sulfur content average of 2.5% in test data. We also derive a PM emission factor of 0.3 g/KW-hr (0.2-0.4 g/KW-hr) for emissions from distillate fueled engines, based on a sulfur content of 0.25% in test data. These results are statistically identical to those originally developed by CARB staff based primarily on Wright (1997).

There are many factors that confound the data and obscure data relationships we might have expected to observe in the data. The two most important confounding factors appear to be differences in testing methodologies between the studies, especially in terms of sampling tube path length, and limitations in the standard method (ISO 8178) for testing PM emissions from marine vessels at fuel sulfur contents typically tested in these studies. Because of these factors we find only weak support in the data for a relationship between fuel sulfur content and PM emission factors representing HFO fueled engines. However, we believe a relationship between fuel sulfur content and PM emission factor should be present due to the fact that a significant portion of PM is composed of sulfate. Therefore, we recommend a PM emission factor of 1 g/KW-hr at 1.5% sulfur for analyses related to development of a Sulfur Emission Control Area off the coast of North America.

More research is needed to develop a standardized methodology to measure PM emissions from ocean-going vessels, and conduct well-controlled studies to assess both average PM emission factors and relationships between PM emission factors, fuel sulfur content, and other engine test parameters.

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Appendix A. PM Emission Factor Test Results by Data Source

Data Source	Vessel	Year Built or Launched	Engine Type	Rated Power of Tested Engine (KW)	Fuel Grade	Percent Sulfur	Load Factor	PM (g/KW-hr)	PM (kg/tonne fuel)	PM Average	S Average
Cooper (2003)	F3_Tanker_3 - Carerpillar 3508	n/a	Auxiliary	720	Dist	0.06	63	0.14		0.15	0.06
Cooper (2003)	F3_Tanker_3 - Carerpillar 3508	n/a	Auxiliary	720	Dist	0.06	63	0.16			
Cooper (2003)	A1_Ferry_5 - Sulzer 6ASL	n/a	Auxiliary	960	Dist	0.08	45-63	0.21		0.33	0.08
Cooper (2003)	A1_Ferry_5 - Sulzer 6ASL	n/a	Auxiliary	960	Dist	0.08	45-63	0.45			
Cooper (2001)	A_High Speed Passenger Ferry	unk	Main_SS	6875	Dist	0.09	90	0.1		0.1	0.09
Cooper (2001)	A_High Speed Passenger Ferry	unk	Auxiliary	6875	Dist	0.09	46	0.28		0.31	0.09
Cooper (2001)	A_High Speed Passenger Ferry	unk	Auxiliary	6875	Dist	0.09	53	0.29			
Cooper (2001)	A_High Speed Passenger Ferry	unk	Auxiliary	6875	Dist	0.09	26	0.36			
Cooper (2001)	B_High Speed Passenger Ferry	unk	Gas Turbine	550	Dist	0.07	87	0.007		Gas Turbine	Gas Turbine
Cooper (2003)	B2_Ferry_1 - Sulzer 8ASL	n/a	Auxiliary	1270	Dist	0.09	59	0.31		0.31	0.09
Wright (1997)	E4_Naval Unit	n/a	Auxiliary	3933	Dist	0.18	80	0.2	1	0.275	0.18
Wright (1997)	E4_Naval Unit	n/a	Auxiliary	3933	Dist	0.18	60	0.2	1		
Wright (1997)	E4_Naval Unit	n/a	Auxiliary	3933	Dist	0.18	40	0.3	1.2		
Wright (1997)	E4_Naval Unit	n/a	Auxiliary	3933	Dist	0.18	25	0.4	1.6		
Wright (1997)	E4_Naval Unit	n/a	Auxiliary	3933	Dist	0.18	11	1.3	3.9	Load <18%	Load <18%
Cooper (2003)	D1_Ro-ro Ferry_2 - Watersila4R32	n/a	Auxiliary	1480	Dist	0.23	43-48	0.17		0.18	0.23
Cooper (2003)	D1_Ro-ro Ferry_2 - Watersila4R32	n/a	Auxiliary	1480	Dist	0.23	43-48	0.19			
Cooper (2003)	C1_Ferry_6 - Wartsila 824	n/a	Auxiliary	940	Dist	1.2	36-50	0.3		0.37	1.2
Cooper (2003)	C1_Ferry_6 - Wartsila 824	n/a	Auxiliary	940	Dist	1.2	36-50	0.44			
Cooper (2002-Entec)	High Speed Passenger Ferry__Volvo TAMD 120A	1994	Auxiliary	unclear	HFO	0.4	NA	0.12		0.12	0.4
Cooper (2002-Entec)	High Speed Passenger Ferry__Wärtsilä 8R32E	1995	Auxiliary	unclear	HFO	0.4	NA	0.15		0.15	0.4
Cooper (2002-Entec)	High Speed Passenger Ferry__Sulzer ASL 25	2002	Auxiliary	unclear	HFO	0.5	NA	0.48		0.48	0.5
Cooper (2002-Entec)	High Speed Passenger Ferry__Wärtsilä 6R32E	2002	Auxiliary	unclear	HFO	2.3	NA	0.54		0.54	2.3
Cooper (2002-Entec)	High Speed Passenger Ferry__Wärtsilä 8R32E	2002	Auxiliary	unclear	HFO	2.3	NA	0.67		0.67	2.3

Data Source	Vessel	Year Built or Launched	Engine Type	Rated Power of Tested Engine (KW)	Fuel Grade	Percent Sulfur	Load Factor	PM (g/KW-hr)	PM (kg/tonne fuel)	PM Average	S Average
Cooper (2002-Entec)	High Speed Passenger Ferry__Man B&W 5L28/32	1990	Auxiliary	unclear	HFO	2.5	NA	0.94		0.94	2.5
Rideout and Radloff (1997)	UNK__Sulzer V12 12ZAAV40	n/a	Auxiliary	11737	HFO	1.29	66	1.0	5.04	1.008	1.29
Rideout and Radloff (1997)	UNK__Sulzer V12 12ZAAV40	n/a	Auxiliary	11737	HFO	1.74	66	1.1	5.53	1.106	1.74
Man B&W Diesel Inc (2004)	Container_7L32/40	1998	Auxiliary	3125	HFO	2.4	33	1.64		1.7225	2.4
Man B&W Diesel Inc (2004)	Container_7L32/40	1998	Auxiliary	3125	HFO	2.4	53	1.68			
Man B&W Diesel Inc (2004)	Container_7L32/40	1998	Auxiliary	3125	HFO	2.4	22	1.74			
Man B&W Diesel Inc (2004)	Container_7L32/40	1998	Auxiliary	3125	HFO	2.4	73	1.83			
Rideout and Radloff (1997)	UNK__3*MAN B&W 7L23/30 H	n/a	Auxiliary	1236	NA		66	2.0	9.97	1.994	NA
Rideout and Radloff (1997)	UNK__3* Bergen KRG-6	n/a	Auxiliary	1440	NA		66	1.8	8.89	1.778	NA
Rideout and Radloff (1997)	Tugboat_2 Detroit Diesel Series 149T	1986	Main_HS	895.2	Dist	0.2364	"Low Cruise"	0.01	1.78	0.014275	0.2364
Rideout and Radloff (1997)	Tugboat_2 Detroit Diesel Series 149T	1986	Main_HS	895.2	Dist	0.2364	"Normal Cruise"	0.02	3.93		
Rideout and Radloff (1997)	Ferry_12 MAK 12M551AK	1976	Main_MS	4364.1	Dist	0.3541	"Normal Cruise"	0.03	6.64	0.0332	0.3541
Wright (1997)	E5_Tanker	1990	Main_MS	1492	Dist	0.16	75	0.3	1.4	0.4	0.16
Wright (1997)	E5_Tanker	1990	Main_MS	1492	Dist	0.16	62	0.4	1.8		
Wright (1997)	E5_Tanker	1990	Main_MS	1492	Dist	0.16	21	0.4	1.6		
Wright (1997)	E5_Tanker	1990	Main_MS	1492	Dist	0.16	42	0.5	2.1		
Wright (1997)	E2_Ro-ro Ferry	1982	Main_MS	3160	HFO	2.86	85	1.4	6.8	1.45	2.86
Wright (1997)	E2_Ro-ro Ferry	1982	Main_MS	3160	HFO	2.86	59	1.4	6.4		
Wright (1997)	E2_Ro-ro Ferry	1982	Main_MS	3160	HFO	2.86	41	1.5	6.6		
Wright (1997)	E2_Ro-ro Ferry	1982	Main_MS	3160	HFO	2.86	31	1.5	6.5		
Wright (1997)	E1_Ro-ro Ferry	1986	Main_MS	4840	HFO	3.21	35	1.8	7.7	1.95	3.21
Wright (1997)	E1_Ro-ro Ferry	1986	Main_MS	4840	HFO	3.21	70	2.1	10.5		
Wright (1997)	E1_Ro-ro Ferry	1986	Main_MS	4840	HFO	3.21	14	3.3	9.4	Load <18%	Load <18%
Wright (1997)	E1_Ro-ro Ferry	1986	Main_MS	4840	HFO	3.21	0		2.3	Load <18%	Load <18%

Data Source	Vessel	Year Built or Launched	Engine Type	Rated Power of Tested Engine (KW)	Fuel Grade	Percent Sulfur	Load Factor	PM (g/KW-hr)	PM (kg/tonne fuel)	PM Average	S Average
Rideout and Radloff (1997)	Cargo_Mitsui Man B&W 5S60MC	1992	Main_SS	9511.5	HFO	3.11	"Normal Cruise"	1.5	7.43	1.523	3.11
Rideout and Radloff (1997)	Cargo_Mitsui Man B&W 5S60MC	1992	Main_SS	9511.5	HFO	3.11	"Low Cruise"	1.5	7.73		
Rideout and Radloff (1997)	Cargo_B&W Mitsui 7K67GF	1978	Main_SS	9772.6	HFO	1.86	"Normal Cruise"	1	4.9	1.18	1.86
Rideout and Radloff (1997)	Cargo_B&W Mitsui 7K67GF	1978	Main_SS	9772.6	HFO	1.86	"Low Cruise"	1.4	6.8		
Rideout and Radloff (1997)	Cargo_Kawasaki MAN K7SZ70/125	1978	Main_SS	9921.8	HFO	3.19	"Normal Cruise"	1.3	6.4	1.396	3.19
Rideout and Radloff (1997)	Cargo_Kawasaki MAN K7SZ70/125	1978	Main_SS	9921.8	HFO	3.19	"Low Cruise"	1.5	7.46		
Rideout and Radloff (1997)	Cargo_Sulzer 7RTA52U	1996	Main_SS	11070.6	HFO	3.24	"Low Cruise"	0.4	2.07	0.807	3.24
Rideout and Radloff (1997)	Cargo_Sulzer 7RTA52U	1996	Main_SS	11070.6	HFO	3.24	"Normal Cruise"	1.2	6.24		
Rideout and Radloff (1997)	Cargo_Sulzer RND90	1980	Main_SS	22380	HFO	2.93	"Low Cruise"	1.8	9.09	1.959	2.93
Rideout and Radloff (1997)	Cargo_Sulzer RND90	1980	Main_SS	22380	HFO	2.93	"Normal Cruise"	2.1	10.49		
Rideout and Radloff (1997)	Cargo_Sulzer RND90	1980	Main_SS	22380	HFO	1.82	"Normal Cruise"	1.2	6.21	1.346	1.82
Rideout and Radloff (1997)	Cargo_Sulzer RND90	1980	Main_SS	22380	HFO	1.82	"Low Cruise"	1.5	7.46		
Rideout and Radloff (1997)	Container_Sulzer 9RTA 84C	1991	Main_SS	33570	HFO	3	"Low Cruise"	0.4	1.79	0.979	3
Rideout and Radloff (1997)	Container_Sulzer 9RTA 84C	1991	Main_SS	33570	HFO	3	"Normal Cruise"	1.6	8.03		
Rideout and Radloff (1997)	Container_Kawasaki MAN B&W 10L90MC MKD	1997	Main_SS	43716	HFO	2.78	"Normal Cruise"	2.4	11.84	2.44	2.78
Rideout and Radloff (1997)	Container_Kawasaki MAN B&W 10L90MC MKD	1997	Main_SS	43716	HFO	2.78	"Low Cruise"	2.5	12.4		
Rideout and Radloff (1997)	Container_Kawasaki MAN B&W 10L90MC MKD	1997	Main_SS	43716	HFO	1.46	"Low Cruise"	1.9	9.3	2.58	1.46
Rideout and Radloff (1997)	Container_Kawasaki MAN B&W 10L90MC MKD	1997	Main_SS	43716	HFO	1.46	"Normal Cruise"	3.3	16.32		
Man B&W Diesel Inc (2004)	Container_Hitachi 12K90MC mk6	1998	Main_SS	54,860	HFO	2.4	25	1.36		1.67 Load <18%	2.4 Load <18%
Man B&W Diesel Inc (2004)	Container_Hitachi 12K90MC mk6	1998	Main_SS	54,860	HFO	2.4	12	1.51			
Man B&W Diesel Inc (2004)	Container_Hitachi 12K90MC mk6	1998	Main_SS	54,860	HFO	2.4	53	1.55			
Man B&W Diesel Inc (2004)	Container_Hitachi 12K90MC mk6	1998	Main_SS	54,860	HFO	2.4	78	1.8			

Data Source	Vessel	Year Built or Launched	Engine Type	Rated Power of Tested Engine (KW)	Fuel Grade	Percent Sulfur	Load Factor	PM (g/KW-hr)	PM (kg/tonne fuel)	PM Average	S Average
Man B&W Diesel Inc (2004)	Container_Hitachi 12K90MC mk6	1998	Main_SS	54,860	HFO	2.4	86	1.97			
Wright (1997)	E3_Tanker	1990	Main_SS	8130	HFO	2.26	81	0.8	4.1	1.175	2.26
Wright (1997)	E3_Tanker	1990	Main_SS	8130	HFO	2.26	63	1.1	5.3		
Wright (1997)	E3_Tanker	1990	Main_SS	8130	HFO	2.26	19	1.3	5.9		
Wright (1997)	E3_Tanker	1990	Main_SS	8130	HFO	2.26	40	1.5	7.4		
Wright (1997)	E6_Tanker	1982	Main_SS	12505	HFO	2.97	61	1.3	6.5	1.55	2.97
Wright (1997)	E6_Tanker	1982	Main_SS	12505	HFO	2.97	78	1.5	7.6		
Wright (1997)	E6_Tanker	1982	Main_SS	12505	HFO	2.97	40	1.5	7.3		
Wright (1997)	E6_Tanker	1982	Main_SS	12505	HFO	2.97	18	1.9	8.7		
Miller et al. (2007)	unclear	unclear	unclear	unclear	dist	0.159	unclear	0.27	1.29	0.27	0.159
Fleischer (1998)	MAN B&W 7L40/45	unclear	Main_MS	unclear	HFO	1.5	unclear	0.436	2.08	0.436	1.5
Maeda (2004)	unclear	unclear	unclear	unclear	HFO	2.36	unclear	1.06	5.05	1.06	2.36
Miller et al. (2007)	unclear	unclear	unclear	unclear	HFO	3.3	unclear	1.45	6.90	1.45	3.3
Maeda (2004)	unclear	unclear	unclear	unclear	Dist	0.76	unclear	0.4		0.4	0.76
Maeda (2004)	unclear	unclear	unclear	unclear	Dist	0.04	unclear	0.2		0.2	0.04

Grey box indicates emission factor converted from kg/tonne fuel to g/KW-hr assuming a brake specific fuel consumption of 200 g fuel / KW-hr