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MEASUREMENT OF AIR POLLUTANT EMISSIONS FROM IN-SERVICE PASSENGER FERRIES

Emission Data Report

Prepared by:

Engine, Fuel, and Emissions Engineering, Incorporated

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Internal review by ______________on ____/___/____

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The information contained in this working paper represents work in progress. The WTA's final recommendations of ferry service expansion will reflect study in a number of different technical areas. Therefore, information in this report may change depending on the results of the interrelated technical studies.

Prepared for:

WATER TRANSIT AUTHORITY

Measurement of Air Pollutant Emissions from In-Service Passenger Ferries

Emission Data Report

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1. INTRODUCTION

The severe and increasing congestion on the Bay Area's freeways and – especially – its bridges makes it necessary to consider new mass transit measures such as passenger ferries. At the same time, the Bay Area's air quality situation makes it essential that these new transit solutions not contribute to increased emissions that could cause the Bay Area once again to violate federal and state air quality standards for ozone, or that could jeopardize public health.

The San Francisco Bay Water Transit Authority (Authority) has been created and charged by the Legislature with developing a viable plan for a comprehensive regional public water transit system for the Bay Area. To ensure that this plan and the associated environmental impact report (EIR) and environmental impact statement (EIS) adequately account for pollutant emissions from both existing ferries and the new ones to go into service, it is important that these emissions be measured accurately and under representative conditions. This can best be achieved by on-board emission measurements, with the ferries operating under conditions typical of passenger service. To carry out such measurements has required the development and implementation of new emission measurement systems and protocols.

Engine, Fuel, and Emissions Engineering, Inc. (EF&EE) was contracted by the Authority to develop a suitable protocol for measuring ferryboat emissions, and then to carry out a series of emission measurements on ferryboats using this protocol. Experience gained in performing these tests was then used to refine the test protocol. It is intended that the resulting test protocol will be used both to quantify emissions from existing ferries and to specify emission limits for future ferryboats.

Emission measurements were performed on three diesel ferryboats operating in San Francisco Bay: M.V. *Mare Island*, *Peralta*, and *Golden Gate*. *Mare Island* and *Peralta* are relatively new, "fast" catamaran vessels, while *Golden Gate* is and older, monohull design. *Golden Gate* was tested twice, once when operating on regular California diesel fuel, and once using PuriNOx®, a water emulsion fuel. In each case, emission measurements were carried out while the vessels were in normal service, carrying passengers on San Francisco Bay. The Water Transit Authority and EF&EE are grateful to the Golden Gate Bridge District, the City of Vallejo. the City of Oakland, and Blue and Gold Fleet for their cooperation in making these measurements.

2. EMISSION MEASUREMENT PROCEDURE

Emission measurements on all three vessels were performed using the Ride-Along Vehicle Emission Measurement (RAVEM) system developed by Engine, Fuel, and Emissions Engineering, Inc.[1] The RAVEM system uses the constant volume sampling (CVS) method, with isokinetic proportional sampling of the exhaust under closed-loop. CVS using the full exhaust flow is the standard method specified by EPA protocols for measuring emissions from cars, motorcycles, and engines used in heavy trucks and buses; but the size of the dilution system required makes it impractical for very large engines like those used in ferryboats. Isokinetic proportional CVS systems extract and dilute only a small, fixed fraction of the total exhaust gas flow, and can therefore be applied to engines of practically any size.

2.1 ENGINES AND OPERATING CONDITIONS

Emissions were measured from both main propulsion engines on each vessel, and from both generator engines on *Golden Gate*. It was originally planned to measure generator engine emissions on Mare *Island* and *Peralta* as well, but this was not accomplished, due to the difficulty of accessing the exhaust outlets while the vessel was in service. Generator exhaust outlets for both of these vessels are located in the tunnel between the catamaran hulls, and there is no access from within the vessel.

To the extent possible, emissions from each of the main propulsion engines were measured under each of the following six conditions:

1) high-speed cruise (the intended normal operating speed) with the vessel loaded to the equivalent of 90 to 100% of maximum passenger load;
2) high-speed cruise with the vessel loaded at 20 to 30% of rated passenger load;
3) low-speed cruise (operating speed while subject to wake limits);
4) transient maneuvering, repeatedly accelerating and then reversing to stop;
5) idle-ahead (operation with the vessel stationary, the propeller or water-jet in gear and supplying propulsion, and the engines running at idle speed); and
6) idle in neutral.

Since the vessels were in actual passenger service, we were unable to control the passenger loads, but were constrained to test with whatever number of passengers had chosen to travel at that time. In any case, we found little effect on emissions from variations in passenger load.

[1] Weaver, C.S. and M.V. Balam-Almanza, "Development of the 'RAVEM' Ride-Along Vehicle Emission Measurement System for Gaseous and Particulate Emissions", SAE Paper No. 2001-01-3644, September 23, 2001.

2.2 POLLUTANT MEASUREMENTS

The pollutants normally measured by the RAVEM system are: diesel particulate matter, oxides of nitrogen (NOx), carbon monoxide (CO), and carbon dioxide (CO_2). The first three are the pollutants for greatest concern from diesel engines, while CO_2 measurements are useful in relating pollutant emissions to fuel consumption. For the ferry protocol, it was desired to be able to measure a wider range of pollutants in order to characterize emissions of toxic air contaminants, to respond to possible alternative fuels such as natural gas and alcohols, and to characterize emissions such as ammonia and nitrous oxide that could be created by future emission control technologies such as selective catalytic reduction (SCR). Therefore, EF&EE expanded the range of pollutants measured by the RAVEM system. Measurements were performed for the following pollutants and measurement techniques:

- Oxides of nitrogen (NOx) - by chemiluminescence, in real time and integrated samples;
- Nitric oxide (NO) - in integrated samples only, by routing the sample around the NO_2-to-NO converter on the chemilumenescent analyzer;
- Carbon dioxide (CO_2) - by non-dispersive infrared (NDIR), in real time and integrated samples;
- Carbon monoxide (CO) - by NDIR, in real time and integrated samples;
- Particulate matter (PM) – integrated samples by collection and weighing on pre-weighed filters;
- Methane and total non-methane hydrocarbons, by off-board analysis of integrated samples collected in Tedlar® bags using an automated gas chromatographic separator with flame ionization detector (FID). The Tedlar bags were specially "pre-baked" and purged initially to minimize sample contamination by hydrocarbons in the plastic and the glue;
- Speciated non-methane hydrocarbons – by off-board gas chromatograph / mass spectrometer (GC/MS) analysis of selected integrated samples in Tedlar bags;
- Speciated carbonyls by collection of integrated samples in di-nitro phenyl hydrazine (DNPH) cartridges, with off-board analysis of selected samples by high performance liquid chromatography (HPLC);
- Sulfur dioxide (SO_2) - by Fourier Transform Infrared (FTIR) spectroscopy in integrated samples;
- Nitrous oxide (NO_2) - by FTIR analysis of integrated samples;
- Ammonia (NH_3) - by FTIR analysis of integrated samples.

The FTIR measurements of SO_2, N_2O, and NH_3 were expected to yield very low emission results. Typical sulfur levels in California diesel fuel range from a few to a few hundred parts per million, and would be expected to result in SO_2 levels less than 1 ppm in the exhaust. N_2O and NH_3 are not produced in significant amounts by diesel engines, but can be produced by catalytic NOx control technologies such as selective catalytic reduction (SCR). None of the three ferries tested in this project were equipped with NOx control catalysts. Thus, the concentrations of these three pollutants measured by the FTIR system did not differ significantly from background levels.

A similar situation occurred with respect to the measurements of non-methane hydrocarbons. The hydrogen-fueled flame ionization detector was considered to present an unacceptable safety hazard aboard a passenger vessel, so that hydrocarbon measurements on the integrated Tedlar bag samples were done off-board. The NMHC concentrations measured were extremely low, generally less than 2 ppm, and were generally close to background levels. "Hang up" of semi-volatile hydrocarbons in the analytical system and HC emissions from the sample bags appears to have affected the results, despite efforts taken to minimize the latter. In a number of tests, the background NMHC concentrations exceeded the concentration in the dilute exhaust sample, suggesting that the background samples may have been affected by some other hydrocarbon source. The resulting negative NMHC values were excluded from the emissions averages. The fraction of emission tests affected by this problem increased with each round of testing. This suggests that the contamination may have carried over from previous tests, despite the fact that background and sample bags were not mixed between tests. No obvious cases of anomalously high NMHC values were observed in the exhaust sample bags - only in the background bags.

The carbon monoxide (CO) measurements were made using two different NDIR instruments. One was a California Analytical Instruments ZRH CO/CO_2 analyzer. This has a fast response, but the lowest CO range is 0 - 200 ppm, and the uncertainty in the measurements is of the order of 2 ppm. For better accuracy, the CO concentration in the Tedlar bag samples was also measured off-board, using an API model 3000 CO analyzer. This analyzer is precise within a few tens of PPB, but has a response time of about four minutes. The data from the API analyzer were used wherever possible. For a number of the shorter emission tests, too little sample was collected in the Tedlar bags to carry out the API measurements. In this case, the CO results from the ZRH analyzer were used.

In the case of the nitric oxide (NO) measurements, we found that significant conversion of NO to NO_2 was occurring in the sample bag, thus making the result dependent on the residence time of the sample in the bag. Usually, this conversion is attributed to photochemical reactions, but we found that it occurred despite the opaque black covers on the sample bags, and the fact that they were enclosed in an opaque black plastic box. Thus, the NO data that we measured are not reliable.

The following chapters describe the emission testing on each vessel, and summarize the resulting emissions data. Detailed data sheets for each test are given in the Appendices.

3. EMISSION TESTING ABOARD MV *MARE ISLAN*D

Emission testing aboard *Mare Island* took place during March 14 and 15, 2002. The RAVEM system and auxiliary analytical equipment were installed outside on the lower afterdeck, immediately adjacent to the main engine exhausts (Figure 1). This space is normally used for bicycle storage - passengers are not normally allowed on the lower afterdeck when the vessel is underway. The CVS system is on the left side of the picture, next to the rail, while the gas analyzers and FTIR system can be seen on the table in the center of the photo.

Figure 1: RAVEM system and auxiliary equipment installed aboard *Mare Island*.

Figure 2: Sample line to the port main engine exhaust, high speed cruise conditions, *Mare Island*

Mare Island is propelled by two MTU 16V396 TE74L diesel engines rated at 2000 kW each, driving steerable waterjets. Emission measurements were performed on the main engines only, as the vessel's operating schedule made it impractical to access the generator exhausts located between the catamaran hulls. The isokinetic sampling probe was installed in the main engine exhaust, and held in place by a metal "J" bar supported by a band clamp around the exhaust pipe (Figure 2). The isokinetic probe was connected directly to the raw exhaust sample line, which conducted the exhaust sample to the CVS dilution tunnel located against the rail of the afterdeck. This sample line comprised several lengths of 1/2 inch OD stainless steel tubing, connected end-to-end with compression fittings. Except for the part immediately adjacent to the exhaust pipe, this tubing was covered with insulation. A thermocouple wire and lines carrying the differential pressure signal for closed-loop control of the isokinetic sampling were taped to the outside of the sample line.

Table 1: Emission tests performed aboard *Mare Island*

Test No.	Operating Mode	Test Time (secs)	Meas. Fuel (kg)	Calc. Fuel (kg)	Est. BSFC g/HP-hr	Calc. Work BHP-hr	Emissions - Grams					
							Filter PM	ZRH CO2	CAI NOx	API CO	ZRH CO	FID NMHC
1	High-Speed Cruise	2,061		162.7	213	1,024	69.9	515,653	6,608	789	776	182
2	High-Speed Cruise	2,326	203.1	209.8	213	1,321	92.4	664,337	8,322	976	1,315	#N/A
3	Low-speed Cruise	657	10.3	6.0	248	33	1.8	19,071	327	15	30	#N/A
4	Idle In Neutral	898	7.2	0.2	290	1	1.6	714	45	#N/A	-66	-8
7	Low-speed Cruise	754	15.3	7.3	248	39	2.1	23,130	405	29	-14	31
8	High-Speed Cruise	2,593	228.2	242.4	213	1,526	94.9	768,612	9,025	1,025	841	305
9	Low-speed Cruise	471	10.8	6.7	248	36	3.2	21,228	356	#N/A	-3	#N/A
10	High-Speed Cruise	2,475	165.7	233.4	213	1,470	95.7	740,064	8,898	978	998	315
11	Idle in Neutral	1,161	5.2	0.8	290	4	1.6	2,454	73	-37	-15	7
12	Idle in Gear	1,229	6.0	1.4	290	6	2.9	4,320	129	#N/A	0	15
13	High-Speed Cruise	2,561		266.7	213	1,679	245.0	845,583	8,799	1,137	1,131	261
14	Stop and go	551		28.6	237	162	30.4	90,409	999	#N/A	274	24
15	Low Speed Cruise	607		15.0	248	81	14.4	47,579	636	#N/A	121	11
16	High-Speed Cruise	2,548		229.0	213	1,442	112.1	725,985	7,609	961	921	275
17	Idle in Gear	911		1.5	290	7	2.0	4,663	96	-6	81	29
18	Idle in Gear	1,209		0.5	290	2	2.9	1,484	38	8	38	17
19	Low-speed Cruise	598		13.2	248	72	6.6	41,887	531	#N/A	96	14
20	High-Speed Cruise	2,295		245.8	213	1,547	119.6	779,495	7,944	1,081	861	255
21	High-Speed Cruise	2,514		276.9	213	1,743	131.0	877,802	8,606	1,146	1,111	272
22	Low-speed Cruise	461		10.5	248	57	5.5	33,154	458	#N/A	112	21

As shown in Table 1, a total of 20 valid emission tests were performed aboard *Mare Island* during the two-day period. Tests 1 through 12 were performed on the starboard engine, and tests 13 through 22 on the port engine. Tests 5 and 6 were void due to software problems, and are not included in the table. As a quality assurance check, the starboard engine was fitted with a differential fuel flow meter, and the data from this meter are also shown in Table 1. The differential fuel flow meter, comprising two micromotion precision coriolis flow measurement devices and an integrator/comparator, was lent by Detroit Diesel Corporation, and installed by Stewart and Stevenson Services of San Leandro.

Since testing was performed while the vessel was in passenger service, the order of testing in each mode was determined by the vessel's operating condition. High-speed cruise measurements were taken from the time that the vessel began accelerating after leaving the Mare Island channel, until it began decelerating to stop at the San Francisco ferry terminal, and then during the reverse run. Low-speed cruise measurements were made as the vessel passed through the Mare Island channel to and from the Vallejo ferry terminal. These tests were necessarily much shorter. Idle in gear and idle in neutral measurements were made while the ferry was at the dock between runs. Because of the ferry's operating schedule, only a single stop-and-go test was possible.

Detailed emission results for each test are given in the Microsoft Excel® files containing data and calculations for each test. These files are provided on the accompanying CD-ROM. Average emissions data in grams per hour for each operating mode are given in Table 2. The idle/neutral data for this vessel are not considered reliable. Because of the large size of the exhaust pipe, the exhaust velocity in the idle/neutral condition was too low for the isokinetic sampler to be able to match it accurately. The sampling was also affected by a gusty breeze that affected the differential pressure readings on the exhaust probe. Due to the combination of these effects, the measured pollutant concentrations were not stable, but varied significantly over the test period.

Table 2: Average main engine emissions from *Mare Island*, per engine, per hour

Operating Condition	Average Emissions g/hour							
	PM	NOx	CO	CO_2	NMHC	Form-aldehyde	Acet-aldehyde	Total Carbonyls
High-Speed Cruise	177	12,226	1,504	1,095,868	392	60.3	23.5	123.3
Low-Speed Cruise	35	2,833	265	195,063	116	13.9	4.6	22.1
Idle Ahead/In Gear	8	290	0	11,832	69	7.1	1.4	8.5
Idle/Neutral*	6	204	#N/A	5,235	20	#N/A	#N/A	#N/A
Stop and Go	199	6,524	1,790	590,568	160	38.0	18.2	72.7

*Not reliable

Table 3: Average main engine emissions from *Mare Island*, grams per kilogram of fuel

Operating Condition	Average Emissions g/kg Fuel							
	PM	NOx	CO	CO_2	NMHC	Form-aldehyde	Acet-aldehyde	Total Carbonyls
High-Speed Cruise	0.50	35.7	4.4	3,170	1.13	0.175	0.068	0.357
Low-Speed Cruise	0.51	48.3	4.6	3,169	2.03	0.286	0.077	0.416
Idle Ahead/In Gear	3.16	79.0	4.1	3,108	21.86	1.194	0.231	1.424
Idle/Neutral*	5.25	165.7	#N/A	3,207	8.60	#N/A	#N/A	#N/A
Stop and Go	1.06	34.9	9.6	3,162	0.86	0.203	0.097	0.389

*Not reliable

For many purposes, emissions in grams per kilogram of fuel are more useful than data expressed in grams per hour. Table 3 shows the emissions from *Mare Island* in this form for each of the operating modes tested. The fuel consumption used to calculate these values was itself calculated from the measured CO and CO_2 emissions. This means that these values are likely to be somewhat more accurate than those in Table 2, since any errors due to the CVS sampling system would appear in both the numerator and the denominator of the calculation, and thus would cancel out.

For purposes of comparison with established emission standards, it is interesting to express the measured emission results in grams per horsepower-hour as well. Direct measurement of horsepower output is not possible for an engine installed in a vessel, but a good approximation of this output can be calculated if the brake-specific fuel consumption (BSFC) is known. BSFC data for each operating mode were estimated from data provided by the engine manufacturer, and are listed in Table 1. The average brake-specific emission results calculated using these estimates are given in Table 4. For fast ferryboats like *Mare Island*, the overwhelming preponderance of work output and pollutant emissions are produced in the high-speed cruise mode. The brake-specific NOx and PM emission results for this mode compare favorably with present emission standards.

Table 4: Average main engine emissions from *Mare Island*, grams per horsepower hour

Operating Condition	Average Emissions g/BHP-hr (calculated from fuel consumption)							
	PM	NOx	CO	CO_2	NMHC	Form-aldehyde	Acet-aldehyde	Total Carbonyls
High-Speed Cruise	0.08	5.7	0.7	504	0.18	0.028	0.011	0.057
Low-Speed Cruise	0.09	8.9	0.8	586	0.38	0.053	0.014	0.077
Idle Ahead/In Gear	0.68	17.1	0.9	672	4.73	0.258	0.050	0.308
Idle/Neutral*	1.14	35.8	#N/A	748	1.86	#N/A	#N/A	#N/A
Stop and Go	0.19	6.2	1.7	559	0.15	0.036	0.017	0.069

*Not reliable

A comparison of measured fuel flow to fuel consumption calculated from the emissions data by carbon balance provides an important check on the accuracy of the emission sampling process. Such a comparison is shown in Table 5 for the starboard main propulsion engine on *Mare Island*. The table also shows the fuel consumption predicted by the engine manufacturer for the same operating mode. Figure 3 plots the calculated fuel consumption against the measured value.

As these data show, the calculated and measured fuel consumption agree very well for two of the three high-speed runs. For the third high-speed run, Test 10, the measured data are about 25% less than for the other two runs, while the calculated data are about the same. Since the vessel speed and operating conditions did not differ significantly between the three runs, we believe that this discrepancy must be due to an error in the differential fuel flow meter rather than in the emission measurement.

Under low-speed cruise and idle conditions, the carbon balance calculation shows significantly lower fuel consumption than the differential flowmeter. It is not obvious which set of data are closer to being correct. At low power, the volume of fuel flow to the engine is nearly the same as the volume of fuel returned, so measured net fuel consumption (which is equal to the difference of these two flows) is highly uncertain. The results calculated from the exhaust

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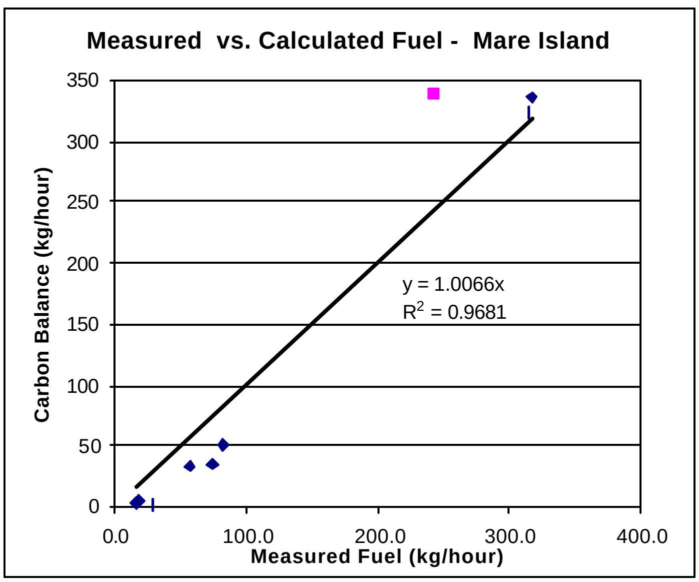
emissions are less affected by this problem. These results are also fairly close to the fuel consumption rates predicted by the manufacturer. However, at very low exhaust velocities, the isokinetic sampling system tends to undersample, and we believe that this would likely have affected the idle/neutral results.

Table 5: Measured fuel consumption rate for *Mare Island* vs. fuel consumption rates calculated from emissions data and predicted by engine manufacturer

Test No	Operating Mode	Fuel Consumption Rate (kg/hr)		
		Measured Micromotion	Calc. Carbon Balance	Predicted by MTU
2	High-Speed Cruise SF-Vallejo	314	325	391
3	Low-Speed Cruise	57	33	46
4	Idle In Neutral	29	1	6
7	Low-speed Cruise	73	35	46
8	High-Speed Cruise SF-Vallejo	317	337	391
9	Low-Speed Cruise	83	51	46
11	Idle in Neutral	16	2	6
12	Idle in Gear	18	4	6
10	High-Speed Cruise SF-Vallejo	241	340	391

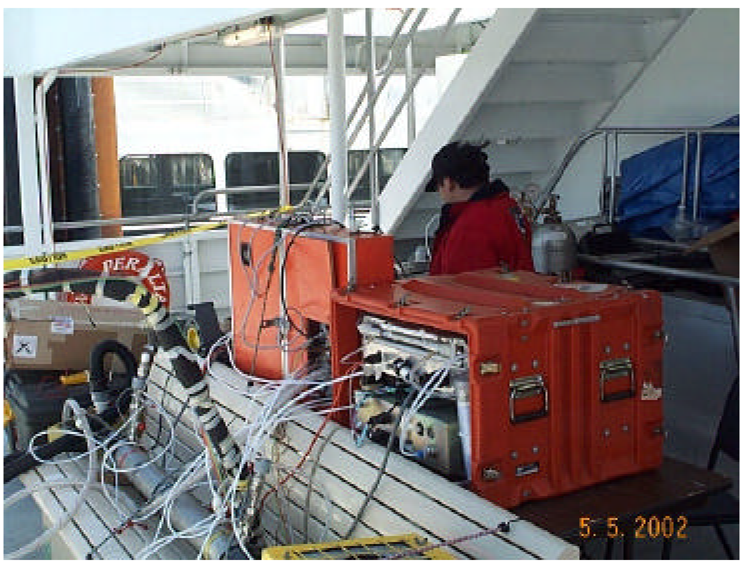
Figure 3: Plot of measured fuel flow vs. fuel use by carbon balance, starboard main engine, *Mare Island*



4. EMISSION TESTING ABOARD MV *PERALTA*

Peralta is propelled by two Cummins KTTA50 diesel engines rated 1193 kW (1600 horsepower) each, driving conventional propellers. The main engine exhausts discharge at the stern of the vessel, just above the waterline. The RAVEM system was therefore installed on the afterdeck, with the dilution tunnel mounted on the rear bench seat, and the gas analyzers located immediately forward of this (Figure 4). The insulated exhaust sample line was run from the dilution tunnel over the after rail to the isokinetic probe mounted in the exhaust pipe. As on *Mare Island*, the isokinetic probe was supported in the exhaust pipe by a metal "J" bar fixed to the end of the exhaust pipe by a metal band clamp custom-made for the purpose. This arrangement is shown in Figure 5. Note that the probe was mounted with its long axis parallel to the axis of the exhaust pipe – the apparent misalignment shown in the photo is due to the camera lens.

Figure 4: Installation of the RAVEM system aboard *Peralta*



Emission testing took place during May 5 through 7, 2002. It was originally planned to take only two days, but the tests performed on May 5 had to be discarded, as a leak was discovered in the CVS system that invalidated the results. The test schedule was therefore restarted on May 6, after the leak was corrected. A total of 18 valid tests were completed on May 6 and 7; these are listed in Table 6.

Figure 5: Isokinetic probe mounted in the starboard exhaust pipe, *Peralta*

Table 6: Emission tests performed aboard *Peralta*

Test No.	Operating Mode	Test Time (secs)	Calc. Fuel (kg)	Est. BSFC g/HP-hr	Calc. Work BHP-hr	Emissions – Grams					
						Filter PM	ZRH CO_2	CAI NOx	API CO	ZRH CO	FID NMHC
70	High Speed Cruise	560.4	36.4	210	232	29.0	115,296	1,262	17	193	29
71	Idle-out of gear	732.7	0.9	290	4	1.6	2,946	60	28	-48	26
72	Low speed cruise	891.0	4.5	250	24	4.7	14,382	168	28	-19	6
73	Idle--out of gear	1012.7	2.0	290	9	3.1	6,161	100	40	25	11
74	High Speed Cruise	677.1	44.4	210	283	32.2	140,593	1,547	203	265	17
75	Slow Cruise	464.2	2.1	250	11	2.4	6,758	86	-3	3	-6
76	High Speed Cruise	1176.9	78.9	210	504	53.4	249,950	2,765	473	504	9
77	Stop and Go	615.4	8.3	220	51	16.5	26,036	331	231	265	6
78	High Speed Cruise	1304.3	85.7	210	547	54.4	271,253	3,055	519	613	26
79	High Speed Cruise loaded	564.1	34.2	210	219	24.0	108,447	1,232	#N/A	209	-27
80	Lo Speed Cruise	755.6	3.3	250	18	3.0	10,590	144	18	11	2
81	High Speed Cruise Loaded	557.8	35.3	210	226	24.6	111,944	1,237	207	222	8
82	Stop and Go	814.7	14.4	220	88	17.9	45,238	623	221	247	-14
83	Lo Speed Cruise	969.3	4.4	250	24	#N/A	14,041	188	25	7	26
84	High Speed Cruise	1116.7	73.0	210	466	#N/A	231,462	2,606	338	329	64
85	Idle--Neutral--Cold Start	960.6	1.7	290	8	3.1	5,357	99	63	35	6
86	Idle--Neutral	929.2	1.4	290	7	2.1	4,533	88	36	14	22
87	Idle--in gear	952.4	7.4	250	40	11.2	23,608	356	44	27	19
88	Idle--in gear	953.7	7.5	250	40	10.2	23,740	368	45	25	-1

Peralta operates between San Francisco, Alameda, and Oakland. High-speed cruise segments occur between the San Francisco ferry terminal and the entrance to the Oakland ship channel. The vessel then normally proceeds at low speed to the Alameda ferry terminal where she discharges and picks up passengers, and then continues at low speed to the Oakland ferry terminal. On return, she cruises at low speed to near the mouth of the Oakland ship channel, and then at high speed to the San Francisco ferry terminal. Typical lengths of the high-speed runs were 8 to 10 minutes, and the low-speed cruise segments ranged from four to eight minutes. This was too little time to collect an adequate sample. To obtain adequate samples for post-analysis, we usually combined two or three short segments together, stopping the sampling during the intervening periods of operation in other modes.

On May 7, *Peralta* was taken out of service to address a generator problem. We were thus unable to take any measurements in cruise mode, but were able to secure several measurements of idle emissions. An attempt was also made to measure emissions from the generator engine, but this proved unsuccessful due to the effects of water injection into the exhaust.

Aside from the leak in the CVS system, testing problems were relatively few. One bag sample, for test No. 79, was too small to permit off-board CO measurements using the API analyzer; and particulate measurements for tests No. 83 and 84 were invalidated when we neglected to change PM filters between the two tests. In addition, four of the off-board NMHC measurements showed high background NMHC concentrations. These measurements are shaded in Table 6, and were excluded from the averages reported below.

Table 7 summarizes the average emissions for each mode, expressed in grams of pollutant per hour; while Table 8 shows the same data expressed in grams per kilogram of fuel. As mentioned earlier, these latter data are considered more reliable, since any errors in the CVS sampling would affect the numerator and denominator in the same way, and would thus be largely canceled out.

Table 7: Average main engine emissions from *Peralta*, per engine, per hour

Operating Condition	Average Emissions g/hour							
	PM	NOx	CO	CO_2	NMHC	Form-aldehyde	Acet-aldehyde	Total Carbonyls
High-Speed Cruise	164	8,209	1,083	737,466	106	13.2	5.7	23.8
Low-Speed Cruise	17	683	67	53,280	45	3.0	1.0	5.4
Idle Ahead/In Gear	40	1,367	169	89,425	72	#N/A	#N/A	#N/A
Idle/Neutral	10	340	163	18,505	69	5.3	2.8	10.2
Stop and Go	88	2,345	1,166	176,093	33	4.7	2.3	10.0

Table 8: Average main engine emissions from *Peralta*, grams per kilogram of fuel

Operating Condition	Average Emissions g/kg Fuel							
	PM	NOx	CO	CO_2	NMHC	Form-aldehyde	Acet-aldehyde	Total Carbonyls
High-Speed Cruise	0.71	35.3	4.6	3,168	0.45	0.056	0.024	0.101
Low-Speed Cruise	1.02	40.8	3.9	3,176	2.67	0.172	0.059	0.307
Idle Ahead/In Gear	1.43	48.5	6.0	3,171	2.55	#N/A	#N/A	#N/A
Idle/Neutral	1.66	59.2	28.2	3,181	13.37	1.084	0.570	2.104
Stop and Go	1.61	41.6	21.6	3,138	0.68	0.088	0.044	0.187

Table 9 expresses the average emissions from *Peralta* in grams per brake horsepower-hour. The estimated work output for each test was calculated from the estimated BSFC in each operating mode, as shown in Table 6. The resulting values are only approximate, but it is interesting to compare them to existing emission standards. Emissions during high-speed and low-speed cruise compare favorably to present emission standards applicable to ferryboat engines.

Table 9: Average main engine emissions from *Peralta*, grams per horsepower-hour

Operating Condition	Average Emissions g/BHP-hr (calculated from fuel consumption)							
	PM	NOx	CO	CO_2	NMHC	Form-aldehyde	Acet-aldehyde	Total Carbonyls
High-Speed Cruise	0.11	5.5	0.7	496	0.07	0.009	0.004	0.016
Low-Speed Cruise	0.19	7.6	0.7	592	0.50	0.032	0.011	0.057
Idle Ahead/In Gear	0.27	9.0	1.1	591	0.48	#N/A	#N/A	#N/A
Idle/Neutral	0.36	12.8	6.1	688	2.89	0.235	0.123	0.455
Stop and Go	0.26	6.8	3.5	515	0.11	0.014	0.007	0.031

Compared to *Mare Island*, the main propulsion engines on *Peralta* showed lower emissions of NMHC and carbonyls, but somewhat higher particulate emissions. The other emissions were similar.

5. EMISSION TESTING ABOARD MV G*OLDEN GATE*

Emission tests on *Golden Gate* were performed using two different fuels: California diesel fuel and a water-diesel emulsion trade-named PuriNOx. Emission testing on California diesel fuel took place during March 20 and 21, 2002; while the testing on the emulsion fuel took place on May 12 and 13. At that time, the *Golden Gate* had been running on the emulsion fuel for approximately ten days.

The main propulsion engines on *Golden Gate* are two Caterpillar 3412C turbocharged and aftercooled diesel engines, rated at 671 horsepower each. Electric generation is provided by two naturally aspirated, 6 cylinder Scania diesels. Exhaust pipes for both sets of engines discharge separately from the tops of two "stacks" on located on either side of the upper deck (Figure 6). This provided easy access for installation of the isokinetic sampling probe.

The main engine exhaust pipes included a sharp bend immediately before the discharge point. This bend is intended to improve exhaust dispersion by creating a vortex in the exhaust plume, but the resulting non-uniform velocity distribution would also have affected the accuracy of the isokinetic sampling. To prevent this, we constructed exhaust pipe extensions 80 inches (10 diameters) in length, with the sample probe mounted in the final eight inches of the extension. The generator exhaust pipe was straight for some distance before discharge, so it was only necessary to insert the isokinetic probe (supported in a section of 4 inch pipe) in the end of exhaust pipe.

Figure 6: RAVEM system and exhaust pipe extension installed aboard *Golden Gate*

The emission tests conducted during March 20 and 21, using California diesel fuel, are listed in Table 10. A total of 25 tests were completed during the two days of testing. Tests 23

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through 35 were performed on the port engine and test 36 on the port generator. The remaining tests were performed on the starboard engine and generator the following day.

Table 10: Emission tests performed aboard *Golden Gate* using California diesel fuel

Test No.	Operating Mode	Test Time (secs)	Calc. Fuel (kg)	Est. BSFC g/BHP-hr	Calc. Work HP-hr	Emissions - Grams Filter PM	ZRH CO2	CAI NOx	API CO	ZRH CO	NMHC
23	High Speed Cruise	1,624	42.6	214	267	43.1	135,024	1,944	158	179	12
24	High Speed Cruise	1,357	33.1	214	207	25.7	104,847	1,519	137	136	7
25	High Speed Cruise	1,539	40.3	214	252	32.2	127,721	1,849	168	176	4
26	Idle in Gear	902	3.1	256	16	6.8	9,659	325	50	53	11
27	Stop and Go	778	7.8	256	41	15.9	24,562	337	109	108	5
28	Stop and Go	1,163	7.9	256	41	16.8	24,855	375	#N/A	151	9
29	Idle in Gear	721	4.4	256	23	7.5	13,736	329	100	101	9
30	Low Speed Cruise	331	1.9	256	10	0.9	5,985	152	#N/A	14	2
31	High Speed Cruise	1,234	32.1	214	201	24.6	101,595	1,342	138	150	8
32	Low Speed Cruise	355	1.5	256	8	1.1	4,633	135	#N/A	10	3
34	Idle Neutral 600 RPM	1,145	0.8	300	3	1.1	2,423	88	29	14	5
35	Idle Neutral 800 RPM	810	0.7	300	3	1.5	2,307	81	25	19	3
36	Generator	1,165	3.0	240	17	11.4	9,574	205	43	43	20
37	High Speed Cruise	1,645	33.9	214	213	45.2	107,452	1,829	208	254	10
38	Stop and Go	988	6.9	256	36	31.1	21,243	263	#N/A	401	6
39	Stop and Go	1,039	6.3	256	33	28.3	19,245	252	#N/A	392	5
40	Idle Ahead	1,706	4.8	256	25	9.5	15,061	509	81	50	21
41	High Speed Cruise	1,317	35.1	214	220	28.1	111,073	756	#N/A	254	-24
42	Low Speed Cruise	343	2.7	256	14	1.1	8,413	128	#N/A	18	-14
43	High Speed Cruise	1,436	43.7	214	274	27.7	138,560	1,562	233	251	-35
44	High Speed Cruise	1,367	35.4	214	222	28.6	112,171	1,410	225	233	-47
45	Idle Ahead	354	1.1	256	6	3.1	3,605	113	9	23	-14
47	Low Speed Cruise	251	1.1	256	6	#N/A	3,601	94	7	12	4
48	Generator	1,802	4.6	240	26	#N/A	14,613	212	64	65	18
49	Generator	1,804	4.6	240	26	12.8	14,440	206	59	63	31

The second round of tests, using emulsion fuel, are summarized in Table 11. Tests 89 through 98 were performed on the port main engine, and tests 99 and 100 on the port generator. The remaining tests were performed on the starboard engine and generator. Carbon balance and BSFC calculations were based on fuel density, carbon content, and energy content values provided by the fuel supplier, Lubrizol.

An attempt was made to measure fuel consumption during both rounds of testing, using a differential fuel flowmeter lent by Lubrizol, and installed on the port engine. Unfortunately, this flowmeter failed to work during the first round of testing due to a power supply problem, so fuel consumption measurements were only obtained using the emulsion fuel. Figure 7 plots the fuel consumption calculated by carbon balance from the emission measurements against the consumption measured by the differential flowmeter. As this figure shows, the correlation is extremely close, but the carbon balance results are about 12% lower than the measured data. No fuel consumption measurements were attempted on the generators.

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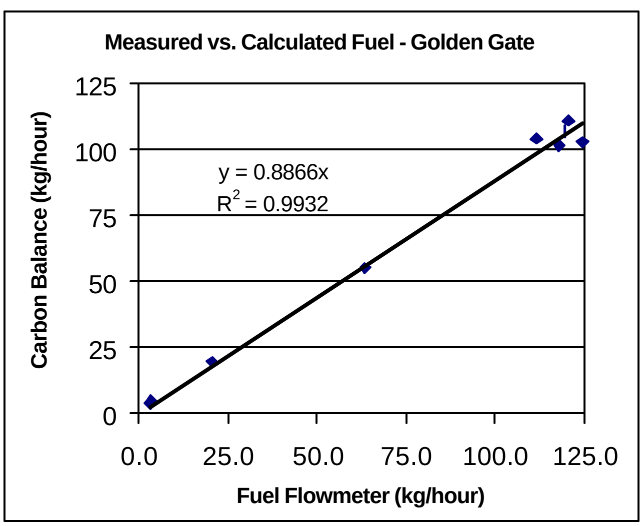
Table 11: Emission tests performed aboard *Golden Gate* using emulsion fuel

Test No.	Operating Mode	Test Time (secs)	Meas. Fuel (kg)	Calc. Fuel (kg)	Est. BSFC g/HP-hr	Calc. Work HP-hr	Emissions - Grams Filter PM	ZRH CO2	CAI NOx	API CO	ZRH CO	FID NMHC
89	High Speed Cruise	1,444	44.7	41.9	270	208	12.6	104,586	1,445	77	78	4
90	Idle Ahead	1,403	7.9	7.7	323	32	37.7	18,935	617	128	137	-1
91	High Speed Cruise	1,338	44.8	41.3	270	205	19.2	103,075	1,411	69	56	18
92	High Speed Cruise	1,311	42.9	37.0	270	184	9.8	92,426	1,266	68	91	30
93	Idle Ahead	1,335	7.1	7.1	323	29	30.9	17,394	564	129	149	62
94	Stop and Go	722	12.7	11.0	323	46	8.0	27,364	383	67	82	-103
95	High Speed Cruise	1,555	51.7	46.3	270	230	16.7	115,596	1,525	58	43	27
96	High Speed Cruise	1,469	50.8	42.1	270	209	11.2	105,113	1,382	72	0	8
97	Idle Neutral	722	0.7	0.9	378	3	2.4	2,145	35	50	54	1
98	Idle Neutral	200	0.2	0.2	378	1	0.5	581	9	#N/A	9	#N/A
99	Generator	1,202		1.6	302	7	6.1	3,991	44	31	30	-5
100	Generator	1,079		1.3	240	7	5.8	3,131	37	25	30	8
101	High Speed Cruise	1,310		38.9	270	193	10.7	97,151	1,232	7	59	-78
102	High Speed Cruise	1,422		40.6	270	202	13.1	101,429	1,288	79	56	-48
103	Idle/Neutral	1,106		1.0	378	3	2.2	2,341	38	#N/A	77	10
104	Stop and Go	612		10.0	323	41	9.1	24,679	295	#N/A	135	4
105	Idle Ahead	1,270		5.2	323	22	21.5	12,971	401	74	82	28
106	Idle Ahead	1,231		4.8	323	20	16.9	11,776	366	67	78	34
107	Idle Neutral	1,145		0.9	378	3	2.5	2,176	38	61	61	10
108	Generator	1,223		1.7	302	7	7.7	4,157	57	34	41	0
109	Generator	1,512		2.0	302	9	10.1	4,799	62	44	50	-1
110	High Speed Cruise	1,476		42.4	270	211	10.8	105,914	1,322	83	84	10
111	High Speed Cruise	1,277		37.6	270	187	9.4	93,743	1,201	82	88	-22

Figure 7: Measured vs. calculated emulsion fuel consumption, port engine, *Golden Gate*



The test protocol developed for this project calls for testing the generators under typical summertime load conditions, and for determining and recording the generator output. Unfortunately, this was not possible, as the ammeter installed on *Golden Gate* was not working during the tests. For the same reason, we were also unable to match the generator output between the two rounds of testing. As the tables show, the generator fuel consumption rate during the first round was significantly higher, most likely due to greater use of electric space heating in the colder March temperatures.

Golden Gate operates between Sausalito and the San Francisco ferry terminal. The operating cycle is dominated by high-speed cruise between these two points. During the March testing, Golden Gate spent approximately 5 minutes at reduced speed during each approach to the Sausalito terminal. This was too little time to collect adequate samples for post-analysis - so that no API CO or aldehyde data were obtained for this condition. During the May testing, a schedule change reduced the time spent at low speed still further, to the point that it was not practical to measure emissions in this condition.

Table 12 summarizes the average emissions in grams per hour from *Golden Gate* for each operating mode when using California diesel fuel, and Table 13 shows these results using the emulsion fuel. Note that data for the low-speed cruise mode were not obtained using the emulsion fuel; and that the grams/hour data for the generators are not comparable, due to the differences in generator load between the two tests.

Table 12: Average main engine and generator emissions from *Golden Gate*, per engine, per hour, using California diesel fuel

Operating Condition	Average Emissions g/hour							
	PM	NOx	CO	CO_2	NMHC	Form-aldehyde	Acet-aldehyde	Total Carbonyls
High-Speed Cruise	79	3,785	449	294,245	20	1.8	-0.2	1.8
Low-Speed Cruise	11	1,429	94	63,028	34	#N/A	#N/A	#N/A
Idle Ahead/In Gear	32	1,364	263	47,917	46	1.3	0.4	2.0
Idle/Neutral	5	319	102	8,937	16	#N/A	#N/A	#N/A
Stop and Go	84	1,138	506	83,672	23	1.9	0.5	2.4
Generator	30	489	126	29,197	53	1.1	0.8	2.3

Table 13: Average main engine and generator emissions from *Golden Gate*, per engine, per hour, using emulsion fuel

Operating Condition	Average Emissions g/hour							
	PM	NOx	CO	CO_2	NMHC	Form-aldehyde	Acet-aldehyde	Total Carbonyls
High-Speed Cruise	32	3,450	170	262,609	41	0.7	0.2	1.9
Idle Ahead/In Gear	73	1,328	270	41,679	115	2.7	1.5	6.9
Idle/Neutral	9	146	221	8,900	32	#N/A	#N/A	#N/A
Stop and Go	47	1,822	333	140,821	23	2.0	0.8	3.5
Generator	21	143	96	11,516	28	2.5	1.0	5.3

Table 14 shows the average emissions in each operating mode expressed in terms of grams per kilogram of California diesel fuel used and

Table 15 shows the same data per kilogram of emulsion fuel. It should be noted that these values cannot be compared directly, as the energy content per kilogram was approximately 21% less for the emulsion fuel than for the California diesel.

Table 14: Average main engine and generator emissions from *Golden Gate*, grams per kilogram of California diesel fuel

Operating Condition	Average Emissions g/kg Fuel							
	PM	NOx	CO	CO_2	NMHC	Form-aldehyde	Acet-aldehyde	Total Carbonyls
High-Speed Cruise	0.87	41.3	4.9	3,168	0.23	0.017	-0.002	0.017
Low-Speed Cruise	0.54	75.8	5.7	3,165	2.02	#N/A	#N/A	#N/A
Idle Ahead/In Gear	2.23	93.4	15.6	3,145	2.92	0.086	0.021	0.129
Idle/Neutral	1.73	112.2	36.0	3,142	5.73	#N/A	#N/A	#N/A
Stop and Go	3.30	42.3	14.0	3,116	0.87	0.077	0.021	0.098
Generator	3.27	52.7	13.6	3,155	5.75	0.121	0.084	0.240

Table 15: Average main engine and generator emissions from *Golden Gate*, grams per kilogram of emulsion fuel

Operating Condition	Average Emissions g/kg Fuel							
	PM	NOx	CO	CO_2	NMHC	Form-aldehyde	Acet-aldehyde	Total Carbonyls
High-Speed Cruise	0.31	32.8	1.6	2,496	0.39	0.007	0.002	0.018
Idle Ahead/In Gear	4.24	78.5	15.8	2,471	7.09	0.157	0.087	0.397
Idle/Neutral	2.42	39.6	61.6	2,403	10.42	#N/A	#N/A	#N/A
Stop and Go	0.82	32.2	6.1	2,482	0.39	0.036	0.014	0.062
Generator	4.51	30.4	20.5	2,463	6.52	0.493	0.208	1.066

Table 16 expresses pollutant emissions from *Golden Gate* using California diesel fuel in grams per horsepower-hour. This calculation uses the estimated BSFC in each operating mode, based on data supplied by Peterson Caterpillar, the local dealership. Estimated BSFC and work output during each test are shown in Table 10.

Table 17 shows the emission results using emulsion fuel, also expressed in grams per BHP-hr. BSFC and work output with the emulsion fuel were calculated by assuming no change in the work output per unit of fuel energy between ordinary diesel fuel and the emulsion fuel. This assumption may understate the actual work output somewhat, as brake-specific energy consumption is often reduced by a few percent when using emulsion fuels. This understatement, if it occurred, would tend to overstate emissions in grams per BHP-hr by a similar percentage.

It was not possible to measure directly the work output from the engine to determine the brake-specific energy consumption. Based on the carbon balance calculations, however, it appears that *Golden Gate* used approximately 12% less fuel energy per hour in high-speed cruise conditions when burning the emulsion fuel instead of California diesel. At idle in neutral, fuel energy consumption per hour was reduced by 20%, but under idle-in-gear conditions the fuel energy consumption increased by 70%. This latter condition was accompanied by emission of a significant amount of grayish-white smoke, as well as a significant increase in PM emissions, both of which are suspected to be due to emissions of unburned fuel.

Table 16: Average main engine and generator emissions from *Golden Gate*, grams per horsepower-hour, California diesel fuel

Operating Condition	Average Emissions g/BHP-hr (calculated from fuel consumption)							
	PM	NOx	CO	CO_2	NMHC	Form-aldehyde	Acet-aldehyde	Total Carbonyls
High-Speed Cruise	0.14	6.6	0.8	506	0.04	0.003	0.000	0.003
Low-Speed Cruise	0.10	14.5	1.1	604	0.39	#N/A	#N/A	#N/A
Idle Ahead/In Gear	0.43	17.8	3.0	601	0.56	0.016	0.004	0.025
Idle/Neutral	0.39	25.1	8.1	703	1.28	#N/A	#N/A	#N/A
Stop and Go	0.63	8.1	2.7	595	0.17	0.015	0.004	0.019
Generator	0.59	9.4	2.4	565	1.03	0.022	0.015	0.043

Table 17: Average main engine and generator emissions from *Golden Gate*, grams per diesel-equivalent horsepower-hour, emulsion fuel

Operating Condition	Average Emissions g/BHP-hr (calculated from fuel consumption)							
	PM	NOx	CO	CO_2	NMHC	Form-aldehyde	Acet-aldehyde	Total Carbonyls
High-Speed Cruise	0.06	6.6	0.3	502	0.08	0.001	0.000	0.004
Idle Ahead/In Gear	1.02	18.9	3.8	595	1.71	0.038	0.021	0.096
Idle/Neutral	0.68	11.2	17.4	677	2.94	#N/A	#N/A	#N/A
Stop and Go	0.20	7.7	1.5	597	0.09	0.009	0.003	0.015
Generator	0.96	6.5	4.4	527	1.17	0.111	0.047	0.240

6. CONCLUSIONS

Emission measurements were performed on-board three ferryboats operating on San Francisco Bay, in accordance with a new measurement protocol developed for this purpose. The test program and protocol were generally successful, but further work is needed to improve the reliability of non-methane hydrocarbon (NMHC) measurements. Alternatively, such measurements could be omitted for diesel ferries, as NMHC emissions from these vessels are low, and may not warrant the costs of measurement. Methods for measuring emissions from generator engines where seawater is mixed with the exhaust before discharge also need to be further developed and tested.

It has been demonstrated that emission measurements can successfully be carried out on passenger ferries while engaged in passenger service. However, the constraints of the ferries' operating schedule make it difficult or impossible to acquire data in some operating conditions that may be of interest. For this reason, we recommend that plans for future testing include some time when the ferry is not committed to scheduled service. This is especially necessary for the maneuvering (stop and go) mode, and for measuring emissions from generator engines.

NOx, PM and toxic air contaminants are the emissions of greatest concern for diesel engines. NOx and PM emissions from the ferryboat engines tested compared favorably with emission standards established for new engines - especially in the high-speed cruise condition, which is the dominant operating mode and accounts for the lion's share of pollutant emissions. The use of water emulsion fuel greatly reduced PM and modestly reduced NOx emissions in high-speed cruise conditions, but increased PM emissions at idle. Emissions of carbonyls (the most significant toxic air contaminants after diesel PM) varied considerably among the different vessels tested; the reasons for this variation are not known.