MEMORANDUM

To: Trish Koman, Clean Ports USA Program Manager, EPA Office of Transportation and Air Quality

Kathleen Bailey, National Port Sector Lead, EPA Office of Policy, Economics and Innovation

From: Lou Browning

Date: April 29, 2009

Re: Integration of OGVs into DEQ

The Diesel Emission Quantifier (DEQ) is an interactive tool to help state and local governments, fleet owners/operators, contractors, port authorities, and others to estimate emission reductions and cost effectiveness for clean diesel projects. Estimates are made using specific information about a fleet. EPA based the Quantifier on existing EPA tools and guidance. The DEQ may be useful as reference when studying project-specific activity such as evaluating control options or applying for grants. The Quantifier uses emission factors and other information from EPA's National Mobile Inventory Model (NMIM), which includes the MOBILE 6.2 and NONROAD2005 models.

Currently, ocean going vessels (OGVs) with Category 3 diesel engines are not part of the DEQ. OGVs have a unique duty cycle which is significantly different from other categories of engines, vehicles, and equipment currently in the DEQ. Because of this, specific inventory calculations will have to be added to the DEQ to handle OGVs.

The current practice to calculate emissions from OGVs is to use energy-based emission factors together with activity profiles for each vessel. The bulk of the work involves determining representative engine power ratings for each vessel and the development of activity profiles for each ship call. Using this information, emissions per ship call and mode can be determined using the equation below.

$$\mathbf{E = P \times LF \times A \times EF} \qquad \mathbf{(1)}$$

Where **E** = Emissions (grams [g])
P = Maximum Continuous Rating Power (kilowatts [kW])
LF = Load Factor (percent of vessel's total power)
A = Activity (hours [h])
EF = Emission Factor (grams per kilowatt-hour [g/kWh])

The emission factor is in terms of emissions per unit of energy from the engine. It is multiplied by the power needed to move the ship in a particular activity. The following subsections discuss ship characteristics, engine power, load factor, activity measures and emission factors. Further guidance can be found in the *Current Methodologies in Preparing Mobile Source Port Related Emission Inventories*.[1]

[1] ICF International, *Current Methodologies in Preparing Mobile Source Port Related Emission Inventories,* Final Report, April 2009.

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Ship Characteristics

OGVs vary greatly in speed and engine sizes 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 1 lists various OGV types that should be described in any detailed inventory.

Table 1: Oceangoing Vessel Ship Types

Ship Type	Description
Auto Carrier	Self-propelled dry-cargo vessels that carry containerized automobiles.
Barge Carrier	Self-propelled vessel that tows lashed barges.
Bulk Carrier	Self-propelled dry-cargo ship that carries loose cargo.
Container Ship	Self-propelled dry-cargo vessel that carries containerized cargo.
Cruise Ship	Self-propelled cruise ships.
General Cargo	Self-propelled cargo vessel that carries a variety of dry cargo.
Miscellaneous	Category for those vessels that do not fit into one of the other categories or are unidentified.
Oceangoing Tugs/Tows	Self-propelled tugboats and towboats that tow/push cargo or barges in the open ocean.
Reefer	Self-propelled dry-cargo vessels that often carry perishable items.
Roll-on/Roll-off (RoRo)	Self-propelled vessel that handles cargo that is rolled on and off the ship, including ferries.
Tanker	Self-propelled liquid-cargo vessels including chemical tankers, petroleum product tankers, liquid food product tankers, etc.

Engine Power

Various ship characteristics can be determined from Lloyd's Data[2]. These include the propulsion engine power and engine speed, maximum vessel speed, and engine speed. EPA defines marine vessel engines (propulsion and auxiliary) in terms of categories as shown in Table 2. These categories relate to land-based engine equivalents. Most OGVs have Category 3 propulsion engines and Category 2 auxiliary engines. Engine speed designations are shown in Table 3. Propulsion engines can be either medium speed diesel (MSD) or slow speed diesel (SSD) engines, while auxiliary engines are always MSD engines[3]. In addition, some ships have steam turbine (ST) or gas turbine (GT) propulsion engines. Based upon national averages[4], the breakdown of diesel engine types used for propulsion is given in Table 4 by ship type.

[2] Lloyd's Register-Fairplay provides the largest database of commercially available maritime data in the world. It is an internet based database which requires a yearly subscription and can be found at http://www.lrfairplay.com/Maritime_data/ships.html.

[3] Propulsion engines can also be gas turbines or steam turbines, but since the DEQ deals exclusively with diesel engine emissions, these are not discussed in this memo.

[4] ICF International, *Commercial Marine Port Inventory Development—2002 and 2005 Inventories*, September 2007.

Table 2: EPA Marine Compression Ignition Engine Categories

Category	Specification	Use	Approximate Power Ratings
1	Gross Engine Power ≥ 37 kW[a] 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

[a] 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.

Table 3: Marine Engine Speed Designations

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

[a] RPM = revolutions per minute

Table 4: Propulsion Engine Breakdown by Ship Type

Ship Type	MSD	SSD	ST	GT
Auto Carrier	7%	93%	0%	0%
Bulk Carrier	2%	97%	1%	0%
Container Ship	5%	94%	1%	0%
Cruise Ship	90%	4%	1%	5%
General Cargo	31%	68%	1%	0%
Miscellaneous	48%	46%	6%	0%
Reefer	9%	91%	0%	0%
RoRo	42%	58%	0%	0%
Tanker	5%	92%	3%	0%

Average propulsion and auxiliary engine sizes were taken from a survey of 327 ships done at by ARB.[5] These are shown in Table 5. These can be used for default values or port specific values can be used. Generally ship size and therefore propulsion and auxiliary power will vary by port. If a specific ship is chosen, propulsion power should be inputted and auxiliary power calculated based upon the ratios in Table 5.

[5] California Air Resources Board, *2005 Oceangoing Ship Survey, Summary of Results,* September 2005.

Table 5: Auxiliary Engine Power Ratios (ARB Survey)

Ship Type	Average Propulsion Engine (kW)	Average Auxiliary Engines				Auxiliary to Propulsion Ratio
		Number	Power Each (kW)	Total Power (kW)	Engine Speed	
Auto Carrier	10,700	2.9	983	2,850	Medium	0.266
Bulk Carrier	8,000	2.9	612	1,776	Medium	0.222
Container Ship	30,900	3.6	1,889	6,800	Medium	0.220
Cruise Ship[a]	39,600	4.7	2,340	11,000	Medium	0.278
General Cargo	9,300	2.9	612	1,776	Medium	0.191
RORO	11,000	2.9	983	2,850	Medium	0.259
Reefer	9,600	4.0	975	3,900	Medium	0.406
Tanker	9,400	2.7	735	1,985	Medium	0.211

[a] Cruise ships typically use a different engine configuration known as diesel-electric. These vessels use large generator sets for both propulsion and ship-board electricity. The figures for cruise ships above are estimates taken from the Starcrest Vessel Boarding Program.

Activity Determinations

The description of a vessel's movements during a typical call is best accomplished by breaking down the call into sections that have similar speed and load characteristics. Vessel movements for each call are described by using four distinct time-in-mode calculations. A call combines all four modes, while a shift normally occurs as maneuvering. 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 should be calculated for each vessel call occurring in the analysis year over the waterway area covered by the corresponding Marine Exchange/Port Authority (MEPA). The time-in-modes are described in Table 6.

Table 6: Vessel Movements and Time-In-Mode Descriptions within the MEPA Areas

Summary Table Field	Description
Call	A call is one entrance and one clearance from the MEPA area.
Shift	A shift is a vessel movement within the MEPA area. Shifts are contained in calls. While many vessels shift at least once, greater than 95 percent of vessels shift three times or less within most MEPA areas. Not all MEPAs record shifts.
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 maximum continuous rating (MCR). Calculated for each MEPA area from the port boundary to the breakwater or reduced speed zone. The breakwater is the geographic marker for the change from open ocean to inland waterway (usually a bay or river).
Reduced Speed Zone[a] (RSZ) (hr/call)	Time in the MEPA area at a speed less than cruise and greater than maneuvering. This is the maximum safe speed the vessel uses to traverse distances within a waterway leading to a port. Reduced speeds can be as high as 15 knots in the open water of the Chesapeake Bay, but tend to be more in the order of 9 to 12 knots in most other areas. Some ports are instituting RSZs to reduce emissions from OGVs as they enter their port.
Maneuver (hr/call)	Time in the MEPA area between the breakwater and the pier/wharf/dock (PWD). Maneuvering within a port generally occurs at 5 to 8 knots on average, with slower speeds maintained as the ship reaches its PWD or anchorage. Even with tug assist, the propulsion engines are still in operation.
Hotelling (hr/call)	Hotelling is the time at PWD or anchorage when the vessel is operating auxiliary engines only or is cold ironing. 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. Cold ironing uses shore power to provide electricity to the ship instead of using the auxiliary engines. Hotelling needs to be divided into cold ironing and active to accurately account for reduced emissions from cold ironing.

[a] Referred to as the Transit zone in many inventory documents.

Cruise speed (also called service speed) is generally assumed to be 94 percent of the maximum ship speed. Distances from the maximum port boundary to either the RSZ or the breakwater[6] are used with the cruise speed to determine cruise times into and out of the port. Some MEPAs record which route was used to enter and leave the port and this information can be used to determine the actual distances the ships travel. Average cruise speeds by ship type from the Category 3 inventory[4] are given in Table 7. While actual cruise speeds should be used for a specific ship, the values in Table 7 can be used as default values.

RSZ time-in-mode also is an estimation based on average ship speed and distance. Many ports refer to this time-in-mode as “Transit”. Pilots generally can report average ship speeds for a precautionary or reduced speed zone. Table 8 provides one-way RSZ distances and speeds for most ports. In addition, each port is matched to a similar port for which maneuvering and hotelling times can be used as a surrogate for actual maneuvering and hotelling information. Table 9 provides regional descriptions.

[6] Not all ports have a physical breakwater. Thus for these ports, an imaginary breakwater needs to be defined.

Table 7: Average Cruise Speeds by Ship Type

Ship Type	Cruise Speed (knots)
Auto Carrier	18.7
Bulk Carrier	14.5
Container Ship	21.6
Cruise Ship	20.9
General Cargo	15.2
Miscellaneous	13.0
OG Tug	14.5
RORO	16.8
Reefer	19.5
Tanker	14.8

One Knot,
or one nautical mile per hour,
is equivalent to
1.15 miles per hour.

Table 8. Matched ports and Reduced Speed Zone Information

Port Name	Similar Port	RSZ Distance (nt mi)	RSZ Speed (knts)	Region
Anacortes, WA	Puget Sound	108.3	13.2	NP
Barbers Point, HI	Puget Sound	5.1	10.0	SP
Everett, WA	Puget Sound	123.3	14.8	NP
Grays Harbor, WA	Puget Sound	4.9	13.4	NP
Honolulu, HI	Puget Sound	10.0	10.0	SP
Kalama, WA	Puget Sound	68.2	8.4	NP
Longview, WA	Puget Sound	67.3	8.4	NP
Olympia, WA	Puget Sound	185.9	13.9	NP
Port Angeles, WA	Puget Sound	65.0	14.4	NP
Portland, OR	Puget Sound	105.1	8.4	NP
Seattle, WA	Puget Sound	133.3	19.3	NP
Tacoma, WA	Puget Sound	150.5	18.3	NP
Vancouver, WA	Puget Sound	95.7	9.3	NP
Valdez, AK	Puget Sound	27.2	10.0	NP
Other Puget Sound	Puget Sound	106.0	12.0	NP
Anchorage, AK	Coos Bay	143.6	14.5	NP
Coos Bay, OR	Coos Bay	13.0	6.5	NP
Hilo, HI	Coos Bay	7.1	10.0	SP
Kahului, HI	Coos Bay	7.5	10.0	SP
Nawiliwili, HI	Coos Bay	7.3	10.0	SP
Nikishka, AK	Coos Bay	90.7	14.5	NP
Beaumont, TX	Houston	53.5	7.0	GC
Freeport, TX	Houston	2.6	10.8	GC
Galveston, TX	Houston	9.3	10.9	GC
Houston, TX	Houston	49.6	10.8	GC
Port Arthur, TX	Houston	21.0	7.0	GC

Table 8. Matched ports and Reduced Speed Zone Information (continued)

Port Name	Similar Port	RSZ Distance (nt mi)	RSZ Speed (knts)	Region
Texas City, TX	Houston	15.1	10.7	GC
Corpus Christi, TX	Corpus Christi	30.1	11.1	GC
Lake Charles, LA	Corpus Christi	38.0	6.0	GC
Mobile, AL	Corpus Christi	36.1	11.0	GC
Brownsville, TX	Tampa	18.7	8.8	GC
Gulfport, MS	Tampa	17.4	10.0	GC
Manatee, FL	Tampa	27.4	9.0	GC
Matagorda Ship	Tampa	24.0	7.3	GC
Panama City, FL	Tampa	10.0	10.0	GC
Pascagoula, MS	Tampa	17.5	10.0	GC
Pensacola, FL	Tampa	12.7	12.0	GC
Tampa, FL	Tampa	30.0	9.0	GC
Everglades, FL	Tampa	2.1	7.5	GC
New Orleans, LA	Lower Mississippi	104.2	10.0	GC
Baton Rouge, LA	Lower Mississippi	219.8	10.0	GC
South Louisiana, LA	Lower Mississippi	142.8	10.0	GC
Plaquemines, LA	Lower Mississippi	52.4	10.0	GC
Albany, NY	New York/New Jersey	142.5	7.8	EC
New York/New Jersey	New York/New Jersey	15.7	8.5	EC
Portland, ME	New York/New Jersey	11.4	10.0	EC
Georgetown, SC	Delaware River	17.6	12.0	EC
Hopewell, VA	Delaware River	91.8	10.0	EC
Marcus Hook, PA	Delaware River	94.7	c	EC
Morehead City, NC	Delaware River	2.2	10.0	EC
Paulsboro, NJ	Delaware River	83.5	9.0	EC
Chester, PA	Delaware River	78.2	10.4	EC
Fall River, MA	Delaware River	22.7	9.0	EC
New Castle, DE	Delaware River	60.5	9.0	EC
Penn Manor, PA	Delaware River	114.5	9.0	EC
Providence, RI	Delaware River	24.9	9.0	EC
Brunswick, GA	Delaware River	38.8	13.0	EC
Canaveral, FL	Delaware River	4.4	10.0	EC
Charleston, SC	Delaware River	17.3	12.0	EC
New Haven, CT	Delaware River	2.1	10.0	EC
Palm Beach, FL	Delaware River	3.1	3.0	EC
Bridgeport, CT	Delaware River	2.0	10.0	EC
Camden, NJ	Delaware River	94.0	9.0	EC
Philadelphia, PA	Delaware River	88.1	9.4	EC
Wilmington, DE	Delaware River	65.3	10.0	EC
Wilmington, NC	Delaware River	27.6	10.0	EC
Richmond, VA	Delaware River	106.4	10.0	EC
Jacksonville, FL	Delaware River	18.6	10.0	EC
Miami, FL	Delaware River	3.8	12.0	EC
Searsport, ME	Delaware River	22.2	9.0	EC

Table 8. Matched ports and Reduced Speed Zone Information (continued)

Port Name	Similar Port	RSZ Distance (nt mi)	RSZ Speed (knts)	Region
Boston, MA	Delaware River	14.3	10.0	EC
New Bedford/Fairhaven, MA	Delaware River	22.4	9.0	EC
Baltimore, MD	Patapsco River	157.1	14.0	EC
Newport News, VA	Patapsco River	24.3	14.0	EC
Savannah, GA	Patapsco River	45.5	13.0	EC
Catalina, CA	California	11.9	12.0	SP
Carquinez, CA	California	39.0	12.0	SP
El Segundo, CA	California	23.3	12.0	SP
Eureka, CA	California	9.0	12.0	SP
Hueneme, CA	California	2.8	12.0	SP
Long Beach, CA	California	18.1	12.0	SP
Los Angeles, CA	California	20.6	12.0	SP
Oakland, CA	California	18.4	12.0	SP
Redwood City, CA	California	36.0	12.0	SP
Richmond, CA	California	22.6	12.0	SP
Sacramento, CA	California	90.5	12.0	SP
San Diego, CA	California	11.7	12.0	SP
San Francisco, CA	California	14.4	12.0	SP
Stockton, CA	California	86.9	12.0	SP

Table 9. Regional definitions

Region	Definition
SP	South Pacific
HI	Hawaii
NP	North Pacific
EC	East Coast
GC	Gulf Coast

Maneuvering time-in-mode is estimated based on the distance a ship travels from the breakwater to the pier/wharf/dock (PWD). Average maneuvering speeds vary from 3 to 8 knots depending on direction and ship type but can be estimated at 5.8 knots which is the general ship stall speed.

Hotelling time-in-mode is the time a ship is at the PWD. If possible, anchorage time (time at anchorage within the port but not at a PWD) should be broken out from time at a PWD. During hotelling, the main propulsion engines are off, and only the auxiliary engines are operating, unless the ship is cold ironing. Hotelling times can also be determined from pilot records of vessel arrival and departure times when other data is not available. Default maneuvering and hotelling times are given in Table 10 for each of the similar ports listed in Table 8 by ship type.

Table 10. Average Maneuvering and Hotelling Times

Port	Ship Type	Maneuvering Time (hrs)	Hotelling Time (hrs)
Puget Sound	Auto Carrier	11.6	19.1
	Bulk Carrier	9.9	103.9
	Container	9.4	30.8
	Cruise Ship	9.1	63.6
	General Cargo	9.5	49.4
	Miscellaneous	13.6	135.0
	Reefer	9.6	140.8
	RoRo	10.6	24.2
	Tanker	12.3	56.9
Coos Bay	Bulk Carrier	0.6	69.6
	General Cargo	0.6	66.3
	Miscellaneous	0.3	128.7
Houston	Auto Carrier	1.2	66.4
	Bulk Carrier	1.2	61.4
	Container	1.2	24.1
	Cruise Ship	1.9	67.1
	General Cargo	1.8	54.9
	Miscellaneous	1.2	68.5
	Reefer	2.2	66.4
	RoRo	2.2	66.3
	Tanker	2.2	28.7
Corpus Christi	Auto Carrier	2.4	33.3
	Bulk Carrier	2.8	49.8
	Container	3.0	48.6
	Cruise Ship	2.4	58.6
	General Cargo	2.4	41.4
	Miscellaneous	2.4	43.1
	Reefer	2.4	63.3
	RoRo	2.4	56.4
	Tanker	3.1	30.1
Tampa	Auto Carrier	1.3	20.1
	Bulk Carrier	2.3	71.3
	Container	2.6	84.1
	Cruise Ship	1.0	10.7
	General Cargo	1.3	57.0
	Miscellaneous	1.0	109.8
	Reefer	1.2	36.1
	RoRo	2.5	223.6
	Tanker	1.5	30.7
Lower Mississippi	Auto Carrier	2.7	169.3
	Bulk Carrier	2.6	94.2
	Container	1.7	32.8
	Cruise Ship	1.5	19.5
	General Cargo	2.1	103.1
	Miscellaneous	2.6	230.5
	Reefer	1.8	261.4
	RoRo	1.8	39.3
	Tanker	2.4	75.3

Table 10. Average Maneuvering and Hotelling Times (continued)

Port	Ship Type	Maneuvering Time (hrs)	Hotelling Time (hrs)
New York/New Jersey	Auto Carrier	2.0	20.1
	Bulk Carrier	2.5	121.2
	Container	1.1	22.5
	Cruise Ship	1.3	9.9
	General Cargo	1.7	53.7
	Miscellaneous	3.3	179.5
	Reefer	1.1	35.5
	RoRo	2.0	30.4
	Tanker	3.6	55.8
Delaware River	Auto Carrier	1.2	28.8
	Bulk Carrier	1.8	99.1
	Container	1.2	33.6
	Cruise Ship	1.1	21.5
	General Cargo	1.6	99.7
	Miscellaneous	2.5	131.1
	Reefer	1.4	64.1
	RoRo	1.2	58.4
	Tanker	2.5	87.2
Patapsco River	Auto Carrier	1.8	25.7
	Bulk Carrier	1.5	95.4
	Container	1.3	21.9
	Cruise Ship	1.3	99.0
	General Cargo	1.6	79.7
	Miscellaneous	2.2	25.5
	Reefer	1.6	531.4
	RoRo	1.5	35.4
	Tanker	1.6	35.3
California	Auto Carrier	3.0	45.0
	Bulk Carrier	2.0	88.0
	Container	2.0	48.0
	Cruise Ship	1.0	11.0
	General Cargo	2.0	88.0
	Miscellaneous	2.0	88.0
	Reefer	3.0	60.0
	RoRo	3.0	45.0
	Tanker	2.0	38.0

Load Factors

Propulsion engine load factors are expressed as a percent of the vessel's total propulsion or auxiliary power. At service or cruise speed, the propulsion load factor is 83 percent. At lower speeds, the Propeller Law should be used to estimate ship propulsion loads, based on the theory that propulsion power varies by the cube of speed as shown in the equation below.

$$\mathbf{LF = (AS/MS)^3} \qquad \textbf{(2)}$$

Where **LF** = Load Factor (percent)
AS = Actual Speed (knots)
MS = Maximum Speed (knots)

Cruise or service speed listed in Table 7 is 94 percent of maximum speed. Because of vessel stall speeds, LF should never be less than 2 percent.

Load factors for auxiliary engines vary by ship type and time-in-mode. The auxiliary engine load factors are shown in Table 11. Auxiliary load factors should be used in conjunction with total auxiliary power. While best practice is to actually determine auxiliary load factors from pilots and ship boarding programs, the Table 11 can be used together with the total auxiliary engine power from Table 5.

Table 11: Auxiliary Engine Load Factor Assumptions

Ship-Type	Cruise	RSZ	Maneuver	Hotel
Auto Carrier	0.15	0.30	0.45	0.26
Bulk Carrier	0.17	0.27	0.45	0.10
Container Ship	0.13	0.25	0.48	0.19
Cruise 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
OG Tug	0.17	0.27	0.45	0.22
RORO	0.15	0.30	0.45	0.26
Reefer	0.20	0.34	0.67	0.32
Tanker	0.24	0.28	0.33	0.26

Emission Factors

Emission factors for propulsion engines depend on engine type and fuel type. Emission factors for propulsion engines are shown in Table 12 for slow speed diesel (SSD), medium speed diesel (MSD), gas turbine (GT), and steam turbine (ST) propulsion engines on various grades of fuel. Most ships use residual oil (RO) in their propulsion engines, although there are future regulations that will require either marine diesel oil (MDO) or marine gas oil (MGO) to be used when entering ports. Typical sulfur levels for the various grades of fuel are also given in Table 12.

Table 12: Emission Factors for OGV Main Engines, g/kWh

Engine Type	Fuel Type	Sulfur	Emission Factors (g/kWh)							
			NOx	PM_{10}	$PM_{2.5}$	HC	CO	SOx	CO_2	BSFC
SSD	RO	2.70%	18.10	1.42	1.31	0.60	1.40	10.29	620.62	195
	MDO	1.00%	17.00	0.45	0.42	0.60	1.40	3.62	588.79	185
	MGO	0.50%	17.00	0.31	0.28	0.60	1.40	1.81	588.79	185
	MGO	0.10%	17.00	0.19	0.17	0.60	1.40	0.36	588.79	185
MSD	RO	2.70%	14.00	1.43	1.32	0.50	1.10	11.24	677.91	213
	MDO	1.00%	13.20	0.47	0.43	0.50	1.10	3.97	646.08	203
	MGO	0.50%	13.20	0.31	0.29	0.50	1.10	1.98	646.08	203
	MGO	0.10%	13.20	0.19	0.17	0.50	1.10	0.40	646.08	203
GT	RO	2.70%	6.10	1.47	1.35	0.10	0.20	16.10	970.71	305
	MDO	1.00%	5.70	0.58	0.53	0.10	0.20	5.67	922.97	290
	MGO	0.50%	5.70	0.35	0.32	0.10	0.20	2.83	922.97	290
	MGO	0.10%	5.70	0.17	0.15	0.10	0.20	0.57	922.97	290
ST	RO	2.70%	2.10	1.47	1.35	0.10	0.20	16.10	970.71	305
	MDO	1.00%	2.00	0.58	0.53	0.10	0.20	5.67	922.97	290
	MGO	0.50%	2.00	0.35	0.32	0.10	0.20	2.83	922.97	290
	MGO	0.10%	2.00	0.17	0.15	0.10	0.20	0.57	922.97	290

PM and SOx emissions are affected by fuel sulfur levels. To calculate PM_{10} emissions for fuels with different sulfur levels, the following equations should be used:

For RO PM_{10} **EF = 1.35 + BSFC x 7 x 0.02247 x (Fuel Sulfur Fraction – 0.0246)** **(3)**

For MDO & MGO PM_{10} **EF = 0.23 + BSFC x 7 x 0.02247 x (Fuel Sulfur Fraction – 0.0024)** **(4)**

$PM_{2.5}$ emission EFs should be calculated as 92 percent of PM_{10} emissions. For SOx emissions, the following formula should be used:

$$SO_2 \text{ EF} = \text{BSFC} \times 2 \times 0.97753 \times \text{Fuel Sulfur Fraction} \quad (5)$$

The International Maritime Organization (IMO) adopted NOx limits in Annex VI to the International Convention for Prevention of Pollution from Ships in 1997. These NOx limits apply for all marine engines over 130 kilowatts (kW) for engines built on or after January 1, 2000, including those that underwent a major rebuild after January 1, 2000. The required number of countries ratified Annex VI in May 2004 and it went into force for those countries in May 2005. The Annex has been ratified by the United States on October 8, 2008. Most ship engine manufacturers have been building engines compliant with Annex VI since 2000. Annex VI emission standards are given in Table 13.

Table 13: Annex VI NOx Emission Standards (g/kWh)

Engine Speed (n)		
n ≥ 2000 rpm	**2000 > n ≥ 130 rpm**	***n < 130 rpm***
9.8	*45.0 x* $n^{-0.2}$	*17.0*

Most manufacturers build engines to emit well below the standard. EPA determined the effect of the IMO standard to be a reduction in NOx emissions of 11 percent below engines built before 2000.[7] Therefore for engines built in 2000 and later, a NOx factor of 0.89 should be applied to the calculation of NOx emissions for both propulsion and auxiliary diesel engines. Since this standard only applies to diesel engines, the factor is not applied to either steam turbines or gas turbines.

New Emission Control Area (ECA) standards were adopted by IMO in October 2008. These new proposed standards are listed in Table 14. The U.S. has applied to become an ECA area but most likely won't be in force until August 2012.[8]

In addition, as part of the new IMO standards, marine diesel engines built between 1990 and 1999 that are 90 liters per cylinder or more need to be retrofit to meet Tier 1 emission standards. Generally all SSDs are 90 liters per cylinder or more, but only 35% of MSD propulsion engines are greater than 90 liters per cylinder.

[7] Conversation with Michael Samulski of EPA, May 2007.

[8] EPA, *Frequently Asked Questions about the Emission Control Area Application Process*, http://epa.gov/OMS/oceanvessels.htm#controlprocess

Table 14: International Ship Engine and Fuel Standards (MARPOL Annex VI)

Area	Year	Fuel Sulfur	NOx
Emission Control Area	Today to Jul 2010	15,000 ppm	
	2010	10,000 ppm	
	2015	1,000 ppm	
	2016		Tier 3 Aftertreatment*
Global	Today to Jan 2012	45,000 ppm	
	2012	35,000 ppm	
	2020	5,000 ppm	
	2011		Tier 2 Engine Controls*

* Today's Tier 1 NOx standards range from approximately 10 to 17 g/kW-h, depending on engine speed. The Tier 2 standards represent a 20% NOx reduction below Tier 1, and the Tier 3 standards represent an 80% NOx reduction below Tier 1.

Based upon the national inventory of ships stopping at US ports in 2005, the adjustment factors listed in Table 15 can be applied to the NOx emission factors listed in Table 12 by analysis year to account for Tier 1, Tier 2, and Tier 3 IMO standards. Best practice is to determine adjustment factors based upon the age profiles of ships calling on a specific port.

Table 15: ECA and Global Control NOx Adjustment Factors

Analysis Year	Global		ECA	
	Main	Auxiliary	Main	Auxiliary
2005	0.9024	0.9060	0.9024	0.9060
2010	0.8750	0.8767	0.8750	0.8767
2015	0.8020	0.8059	0.8020	0.8059
2020	0.7565	0.7478	0.5958	0.5842
2025	0.7319	0.7173	0.4278	0.4108
2030	0.7149	0.6955	0.3184	0.2989

While the majority of greenhouse gas emissions from ships are CO_2, additional GHG emissions include methane (CH_4) and nitrous oxide (N_2O). Emission factors for various engine types are listed in Table 16. To estimate CO_2 equivalents, CH_4 emissions should be multiplied by 21 and N_2O emissions should be multiplied by 310.

Table 16: Greenhouse Gas Emission Factors, g/kWh

Engine Type	RO		MDO or MGO	
	CH_4	N_2O	CH_4	N_2O
SSD Propulsion	0.006	0.031	0.006	0.031
MSD Propulsion	0.004	0.031	0.004	0.031
ST Propulsion	0.002	0.080	0.002	0.080
GT Propulsion	0.002	0.080	0.002	0.080
Auxiliary	0.004	0.031	0.004	0.031

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 BSFC tends to increase. The low-load emission factor adjustment factors given in Table 17 were developed based upon the concept that the BSFC increases as load decreases below about 20 percent load.

Table 17: Calculated Low Load Multiplicative Adjustment Factors

Load	NOx	HC	CO	PM	SO_2	CO_2
1%	11.47	59.28	19.32	19.17	5.99	5.82
2%	4.63	21.18	9.68	7.29	3.36	3.28
3%	2.92	11.68	6.46	4.33	2.49	2.44
4%	2.21	7.71	4.86	3.09	2.05	2.01
5%	1.83	5.61	3.89	2.44	1.79	1.76
6%	1.60	4.35	3.25	2.04	1.61	1.59
7%	1.45	3.52	2.79	1.79	1.49	1.47
8%	1.35	2.95	2.45	1.61	1.39	1.38
9%	1.27	2.52	2.18	1.48	1.32	1.31
10%	1.22	2.20	1.96	1.38	1.26	1.25
11%	1.17	1.96	1.79	1.30	1.21	1.21
12%	1.14	1.76	1.64	1.24	1.18	1.17
13%	1.11	1.60	1.52	1.19	1.14	1.14
14%	1.08	1.47	1.41	1.15	1.11	1.11
15%	1.06	1.36	1.32	1.11	1.09	1.08
16%	1.05	1.26	1.24	1.08	1.07	1.06
17%	1.03	1.18	1.17	1.06	1.05	1.04
18%	1.02	1.11	1.11	1.04	1.03	1.03
19%	1.01	1.05	1.05	1.02	1.01	1.01
20%	1.00	1.00	1.00	1.00	1.00	1.00

CH_4 propulsion emission factors are multiplied by HC low load adjustment factors for load factors below 20 percent based upon the premise that CH_4 emissions are tied to HC emissions. N_2O propulsion emission factors are multiplied by NOx low load adjustment factors on the premise that N_2O is linked to NOx.

Table 18 provides auxiliary engine emission factors. There is no need for a low load adjustment factor for auxiliary engines, because they are generally operated in banks. When low loads are needed, one or more auxiliary engines are shut off, allowing the remaining engines to operate at a more efficient level.

Table 18: Auxiliary Engine Emission Factors, g/kWh

Fuel Type	Sulfur	Emission Factors (g/kWh)							
		NOx	PM_{10}	$PM_{2.5}$	HC	CO	SOx	CO_2	BSFC
RO	2.70%	14.7	1.44	1.32	0.40	1.10	11.98	722.54	227
MDO	1.00%	13.9	0.49	0.45	0.40	1.10	4.24	690.71	217
MGO	0.50%	13.9	0.32	0.29	0.40	1.10	2.12	690.71	217
MGO	0.10%	13.9	0.18	0.17	0.40	1.10	0.42	690.71	217

In addition to the auxiliary engines that are used to generate electricity onboard ships, most OGVs also have boilers used to heat RO to make it fluid enough to use in diesel engines and to produce hot water. These boilers are not typically used during cruise or reduced speed zone modes because most vessels are equipped with exhaust heat recovery systems ("economizers") that use heat from the main engine's exhaust for their hot water needs. The fuel-fired boilers are used when the main engine exhaust flow and/or temperature fall below what is needed for the economizer to provide adequate heat, such as during maneuvering and when the main engines are shut down at berth. In Starcrest's newest inventory for Port of Los Angeles[9], boiler loads were calculated from boiler fuel use determined during Starcrest's vessel boarding program. These loads are presented in Table 19.

Table 19: Auxiliary Boiler Energy Defaults, kW

Ship-Type	Cruise	RSZ	Maneuver	Hotel
Auto Carrier	0	0	371	371
Bulk Carrier	0	0	109	109
Container Ship	0	0	506	506
Cruise Ship	0	0	1,000	1,000
General Cargo	0	0	106	106
Miscellaneous	0	0	371	371
OG Tug	0	0	0	0
RORO	0	0	109	109
Reefer	0	0	464	464
Tanker	0	0	371	3,000
Tanker – ED	0	0	346	346

Steam turbine propulsion emission factors should be used for calculating boiler emissions in the various modes. Emissions from boilers should be calculated as follows.

Boiler emissions (g/mode) = Boiler Energy (kW) x ST EFs (g/kWh) x time in mode (hrs)

Cruise ships and tankers (except for electric drive tankers) have much higher auxiliary boiler usage rates than the other vessel types. Cruise ships have higher boiler usage due to the number of passengers and need for hot water. Tankers provide steam for steam-powered liquid pumps, inert gas in fuel tanks, and to heat fuel for pumping.

Input Variables

This section discusses the input variables required and optional for calculating baseline emissions.

Required Input Variables

To calculate baseline emissions, several required pieces of information are necessary to apply default values. Optional inputs are discussed in the next section.

To perform the calculations, only two inputs need to be specified, namely ship type and port. With this information, defaults can be used to specify other variables.

[9] Starcrest Consulting Group, *Port of Los Angeles Air Emissions Inventory for Calendar Year 2005*, September 2007

Optional Input Variables

Various inputs could be entered to make the calculations more accurate for a given ship and port. These would include the following:

- Ship propulsion and/or auxiliary power (kW)
- Propulsion engine type (MSD, SSD)
- Ship build date (year)
- Ship cruise speed (knots)
- One way cruise distance (nautical miles)
- One way transit or RSZ distance (nautical miles)
- RSZ speed (knots)
- Maneuvering time per call (hrs)
- Average maneuvering speed (knots)
- Hotelling time per call (hrs)

The following can be specified for propulsion and auxiliary engines separately.

- Fuel type (RO, MDO, MGO)
- Fuel sulfur level (ppm sulfur in fuel)

Baseline Emissions Calculations

In this section, calculations of emissions for ships are laid out in detail in a stepwise manner. Each time in mode is calculated separately and then summed.

Cruise

Average time in mode should be determined using the average service speed assuming a 25 nautical mile distance into and out of the port for deep sea ports. This value can be varied if inputted. Emissions for propulsion (main) engines should be calculated using propulsion power, load factor, emission factor and time in mode. Auxiliary engine emissions should be calculated using auxiliary power, auxiliary load factor, auxiliary emissions factor and time in mode.

First cruise time should be calculated as follows:

Time [hrs/call] = Cruise Distance [miles]/Cruise Speed [knots] x 2 trips/call **(6)**

Cruise speed should come from Table 7 based upon ship type, unless inputted as an optional input. Next propulsion and auxiliary engine power should be determined from Table 5. If propulsion engine power is input but not auxiliary power, the auxiliary power should be calculated from the propulsion power using the ratios in Table 5 for the specific ship type.

As it is assumed that ships will be going full cruise speed during the cruise mode and that the cruise speed is 94 percent of maximum speed, the propulsion load factor is 0.83. Auxiliary load factors should be taken from Table 11 for the specific ship type.

Emission factors for propulsion engines depend upon engine type, fuel type and sulfur level, and build year. If both are specified, then the emission factor can be taken from Table 12 and NOx reductions can be applied for Tier 1, 2 or 3 controls. For ships built before 2000, use the values directly from Table 12 based upon the fuel sulfur level. Propulsion fuel should be assumed to be RO with a fuel sulfur level of 2.7 percent which are considered global average fuel sulfur levels. If sulfur levels are input and different from those in Table 12, PM and SOx emission factors should be recalculated using equations (3) through (5) depending on fuel type.

For ships built between 2000 and 2011, NOx emission factors in Table 12 should be multiplied by 0.89 to estimate Tier 1 emission levels. For ships built in 2011 and later, the NOx emission factors in Table 12 should be multiplied by 0.89 x 0.8. For ships built in 2016 and later and in an ECA area, the NOx emission factors in Table 12 should be multiplied by 0.89 x 0.2.

If propulsion engine type is not specified, both MSD and SSD emission factors should be calculated and the percentages by ship type in Table 4 applied. If ship build date is not specified, the NOx adjustment factors in Table 15 should be applied to the calculation of NOx emissions to account for average ship emission Tier levels based upon the year of analysis.

For auxiliary engines, emission factors should be calculated assuming the auxiliary engines are operating on RO unless specified. Some ships use MGO in their auxiliary engines, however. In the ARB survey[5], it was found that 29 percent of all ships used MGO with a sulfur content of 0.5 percent in their auxiliary engines while 71 percent used RO with a sulfur content of 2.7 percent. The one exception to this rule was cruise ships which were found to use MGO in only 8 percent of the ships surveyed. These percentages can be used in determining emission factors for auxiliary engines if fuel type and sulfur levels aren't specified.

Once the power, load factor, emission factors, and time in mode are calculated as discussed above, emissions during the cruise mode should be calculated using the formulas below:

$$\text{Emissions}_{\text{propulsion, cruise}} \text{ (tonnes per call)} = \text{Power}_{\text{propulsion}} \text{ (kW)} \times LF_{\text{propulsion, cruise}} \times EF_{\text{propulsion}} \text{ (g/kWh)} \times \text{Time (hrs)} / 1000000 \text{ g/tonne} \quad (7)$$

$$\text{Emissions}_{\text{auxiliary, cruise}} \text{ (tonnes per call)} = \text{Power}_{\text{auxiliary}} \text{ (kW)} \times LF_{\text{auxiliary, cruise}} \times EF_{\text{auxiliary}} \text{ (g/kWh)} \times \text{Time (hrs)} / 1000000 \text{ g/tonne} \quad (8)$$

Reduced Speed Zone

Average time in mode should be determined using the average RSZ speed and distance from Table 8 unless the user specifies these values. Emissions for propulsion (main) engines should be calculated using propulsion power, load factor, emission factor, and time in mode. Auxiliary engine emissions should be calculated using auxiliary power, auxiliary load factor, auxiliary emissions factor, and time in mode.

First RSZ time should be calculated as follows:

$$\text{Time [hrs/call]} = \text{RSZ Distance [miles]/RSZ Speed[knots]} \times 2 \text{ trips/call} \quad (9)$$

The same propulsion and auxiliary engine power used in the cruise zone calculations should be used here. Propulsion load factors should be calculated as follows:

$$LF_{\text{propulsion, RSZ}} = (\text{RSZ Speed (knots)/Cruise Speed (knots)} \times 0.94)^3 \quad (10)$$

Auxiliary engine load factor should be taken from Table 11. Emission factors should be calculated similarly to those used for the cruise mode with one exception. If the load factor is less than 0.20 for propulsion engines, then a low load multiplicative adjustment factor needs to be applied to the emission factors determined in the cruise mode for propulsion engines only. If the propulsion is electric drive, then no low load adjustment factor should be applied.

Once the power, load factor, emission factors and time in mode are calculated above, emissions during the RSZ mode should be calculated using the formulas below:

$$\text{Emissions}_{\text{propulsion, RSZ}} \text{ (tonnes per call)} = \text{Power}_{\text{propulsion}} \text{ (kW)} \times \text{LF}_{\text{propulsion, RSZ}} \times \text{EF}_{\text{propulsion}} \text{ (g/kWh)} \times \text{Low Load Adjustment Factor} \times \text{Time (hrs)} / 1000000 \text{ g/tonne} \quad (11)$$

$$\text{Emissions}_{\text{auxiliary, RSZ}} \text{ (tonnes per call)} = \text{Power}_{\text{auxiliary}} \text{ (kW)} \times \text{LF}_{\text{auxiliary, RSZ}} \times \text{EF}_{\text{auxiliary}} \text{ (g/kWh)} \times \text{Time (hrs)} / 1000000 \text{ g/tonne} \quad (12)$$

Maneuvering

Average time in mode for maneuvering should be taken from Table 10 for the similar port to the port being modeled as shown in Table 8. Maneuvering speed should be 5.8 knots unless otherwise specified.

The same propulsion and auxiliary engine power used in the cruise zone calculations should be used here. Propulsion load factors should be calculated as follows:

$$\text{LF}_{\text{propulsion, maneuver}} = (\text{Maneuvering Speed (knots)}/\text{Cruise Speed (knots)} \times 0.94)^3 \quad (13)$$

If the above LF calculation results in a load factor below 0.02, it should be set to 0.02. Auxiliary engine load factor should be taken from Table 11. Emission factors should be calculated similarly to those used for the cruise mode except a low load multiplicative adjustment factor should be applied to the emission factors determined in the cruise mode for propulsion engines only. If the propulsion is electric drive, then no low load adjustment factor should be applied.

Once the power, load factor, emission factors and time in mode are calculated above, emissions during maneuvering mode should be calculated using the formulas below:

$$\text{Emissions}_{\text{propulsion, maneuver}} \text{ (tonnes per call)} = \text{Power}_{\text{propulsion}} \text{ (kW)} \times \text{LF}_{\text{propulsion, maneuver}} \times \text{EF}_{\text{propulsion}} \text{ (g/kWh)} \times \text{Low Load Adjustment Factor} \times \text{Time (hrs)} / 1000000 \text{ g/tonne} \quad (14)$$

$$\text{Emissions}_{\text{auxiliary, maneuver}} \text{ (tonnes per call)} = \text{Power}_{\text{auxiliary}} \text{ (kW)} \times \text{LF}_{\text{auxiliary, maneuver}} \times \text{EF}_{\text{auxiliary}} \text{ (g/kWh)} \times \text{Time (hrs)} / 1000000 \text{ g/tonne} \quad (15)$$

Hotelling

Average time in mode for hotelling should be taken from Table 10 for the similar port to the port being modeled as shown in Table 8. Propulsion engines are shut off during hotelling. The same auxiliary engine power used in the cruise zone calculations should be used here. Auxiliary engine load factor should be taken from Table 11.

$$\text{Emissions}_{\text{auxiliary, hotel}} \text{ (tonnes per call)} = \text{Power}_{\text{auxiliary}} \text{ (kW)} \times \text{LF}_{\text{auxiliary, hotel}} \times \text{EF}_{\text{auxiliary}} \text{ (g/kWh)} \times \text{Time (hrs)} / 1000000 \text{ g/tonne} \quad (16)$$

Summing Emissions

Once the emissions by mode have been calculated, they should be summed by both propulsion and auxiliary engine emissions. Propulsion and auxiliary engine emissions should then be added together to obtain total emissions from a specific vessel per call at a given port.

$$\text{Emissions}_{\text{propulsion}} = \text{Emissions}_{\text{propulsion, cruise}} + \text{Emissions}_{\text{propulsion, RSZ}} + \text{Emissions}_{\text{propulsion, maneuver}} \quad (17)$$

$$\text{Emissions}_{\text{auxiliary}} = \text{Emissions}_{\text{auxiliary, cruise}} + \text{Emissions}_{\text{auxiliary, RSZ}} + \text{Emissions}_{\text{auxiliary, maneuver}} + \text{Emissions}_{\text{auxiliary, hotel}} \quad (18)$$

$$\text{Emissions}_{\text{Total}} = \text{Emissions}_{\text{propulsion}} + \text{Emissions}_{\text{auxiliary}} \quad (19)$$

It should be noted that additional emissions are generated by auxiliary boilers to heat residual oil to make it fluid enough to use in diesel engines and to produce hot water. They are generally used only during maneuvering and hotelling as most vessels are equipped with exhaust heat recovery systems ("economizers") that use heat from the main engine's exhaust for their hot water needs. Since these emissions are not "diesel engine emissions", they are not quantified here.

Emission Reduction Strategies

Various emission reduction strategies are discussed in this section including fuel switching, speed reduction, emulsified fuels, direct water injection, humid air motor, exhaust gas recirculation, retrofitting Tier 0 engines with slide fuel valves, seawater scrubbers, selective catalytic reduction (SCR), and cold ironing. In addition, supplemental wind power and hull coatings are examined.

Fuel Switching

Fuel switching involves switching from higher sulfur RO to lower sulfur MDO or MGO. This can be done for just the auxiliary engines or both auxiliary and propulsion engines. Fuel switching can occur while at cruise before entering a reduced speed zone or in the reduced speed zone or only at a port when operating the auxiliary engines during hotelling. The main cost of fuel switching is the cost differential between MDO or MGO and RO. Currently RO is $243.50 per metric tonne, while MDO is $414.00 per metric tonne.[10] MGO is approximately $10.00 higher than MDO. These prices change daily and should be updated when making cost calculations.

In addition to emission calculations, the amount of fuel used also needs to be calculated to determine the cost of fuel switching. First the amount of RO that would have been used needs to be calculated for the time in modes and engines affected by the fuel switching as well as NOx, PM, SOx and CO_2 emissions. For fuel calculations, the brake specific fuel consumption (BSFC) in Table 12 and Table 18 should replace the EF in equations (7), (8), (11), (12), (14), (15), and (16) to calculate the tonnes of RO used in the baseline. For any times in mode which have propulsion load factors below 20 percent, the CO_2 low load adjustment factor should be applied to BSFC propulsion engine calculations. Similar calculations should be done for using MDO or MGO depending upon the sulfur level. The use of MDO or MGO should only be applied to the engine(s) and time in modes affected by the switching. Cost differential should be calculated based upon the difference of RO used versus MDO or MGO used.

Speed Reduction

Reducing speed during either the cruise mode or the RSZ can reduce both emissions and fuel consumption. There is generally a cost savings along with emissions reductions if some delay in shipments is tolerable. However, there may be additional costs associated with delays. There is also anecdotal information that ship operators increase speed prior to the reduced speed area to keep on schedule, thereby negating any fuel consumption savings. Costs vary depending upon the source and they have not been quantified in any meaningful way. Costs might include setting up monitoring systems to gauge compliance, record keeping and on-ship crew costs for additional time on board the ship. ARB is currently surveying ship operators to determine more quantitative costs and the results should be available in Spring 2009.

Emission reductions can be calculated first for the baseline condition and then for the reduced speed condition. The RSZ distance should be expanded and the cruise distance reduced to

[10] http://www.bunkerworld.com/ for Houston as of March 19, 2009.

accommodate a reduced speed zone. Both emissions and fuel consumption should be calculated for each condition. When slowing, the load factor and thus the emissions and fuel consumption decrease by the cube of the speed reduction, however, it takes longer to get to the destination, therefore the reduction is less. In addition, auxiliary engines operate for longer periods. The net reduction is near the percent of speed reduction.

Emulsified Fuels

Emulsified diesel fuel is a mixture of diesel fuel with water and emulsifying and stabilizing additives. The water in the fuel increases fuel dispersion and hence combustion is more efficient. The limiting factor for water emulsions is the delivery capacity of the injection system. Depending on the application, the water content may vary from 8-35%.

Water emulsion systems require modification to the fuel pump, camshaft and control system to handle additional water for full load operation. A pressurized system is also needed to avoid cavitation and boiling off in the low pressure part of the fuel system. In addition, a water dosage system and homogenizer is needed. Water's higher viscosity requires the mixture be heated further by about 20°C to properly flow through the injection system. The fuel pressure also needs to be raised to keep the water from boiling.

Emulsified fuel with 20percent water will typically result in 15 percent NOx reduction, though many papers indicate a slight PM increase due to less stable combustion. Since water does not have combustion energy associated with it, it tends to reduce the energy density of the fuel. Adding 20% water to the fuel results in 20% less power at full load because the fuel injectors will only allow so much fuel (or in this case fuel and water) to pass through them. Therefore, it is unlikely that ships will use it during the full voyage. It would most likely be used in the transit and maneuvering modes for the main engine, although it could also be used in auxiliary engines during those modes and during hotelling as well.

The most realistic estimate would be to assume 20 percent water resulting in a 15% NOx reduction, a 2% increase in PM and a 3.5% increase in CO_2. Assuming this will be used in the main engine only, the above percentages should be applied to propulsion engine emissions only during the 25 nm cruise, RSZ and maneuvering modes.

Costs will vary by engine type and engine power. [11] For medium speed engines, the capital cost can be calculated as follows:

$$\textbf{Cost (\$) per engine} = 2816.7 \times \text{engine power (kW)}^{-0.5925} \times \text{engine power (kW)} \qquad \textbf{(20)}$$

For slow speed engines, the capital cost can be calculated as follows:

$$\textbf{Cost (\$) per engine} = 6536 \times \text{engine power (kW)}^{-0.677} \times \text{engine power (kW)} \qquad \textbf{(21)}$$

It is assumed that enough water will be generated using a fresh water generator. Fresh water generators can be heated using engine cooling water or using steam from an exhaust gas economizer.

Direct Water Injection

Direct Water Injection (DWI) is another method to reduce in-cylinder temperatures and therefore lower NOx emissions. This method has been under development for Sulzer low-speed engines

[11] ICF International, *Costs of Emission Reduction Technologies for Category 3 Marine Engines,* March 2009.

since 1993. Unlike other water techniques, DWI enables water to be injected at the right time and place to obtain the greatest reductions in NOx emissions. The water is injected into the cylinder using a fully independent, second common rail injection system under electronic control. Also in comparison to emulsification, it allows water to be injected into the engine without derating the engine and allows the fuel and water to be injected at different times. Injection can occur either during the compression stroke or with fuel injection so that injection timing can be optimized to both reduce NOx and other emissions without affecting engine reliability. Water injection can be turned off or on without affecting fuel injection behavior. NOx emissions can be reduced 50 percent using a 0.7 water/fuel ratio. [12] Water is fed to the cylinder head at high pressure (210-400 bar depending on the engine type). High water pressure is generated in a high-pressure water pump module. A low-pressure pump is also necessary to ensure a sufficiently stable water flow to the high-pressure pump. Water entering the low pressure pump needs to be filtered to remove all solid particles.

With 50 percent of fuel water injection, NOx emissions can be 40 percent lower. Many papers indicate a slight PM increase due to less stable combustion. Wärtsilä estimates a 4.5% fuel penalty for water injection.[12] For purposes of the DEQ, a 40 percent NOx reduction, a 2 percent increase in PM and a 4.5 percent increase in CO_2 for a 50 percent water injection rate. This should only be applied to the propulsion engines during the 25 mile cruise, RSZ, and maneuvering modes.

Costs will vary by engine type and engine power.[11] For medium speed engines, the capital cost can be calculated as follows:

$$\textbf{Cost (\$) per engine} = 822.57 \times \textbf{engine power (kW)}^{-0.3566} \times \textbf{engine power (kW)} \qquad \textbf{(22)}$$

For slow speed engines, the capital cost can be calculated as follows:

$$\textbf{Cost (\$) per engine} = 286.63 \times \textbf{engine power (kW)}^{-0.2305} \times \textbf{engine power (kW)} \qquad \textbf{(23)}$$

It is assumed that enough water will be generated using a fresh water generator. Fresh water generators can be heated using engine cooling water or using steam from an exhaust gas economizer.

Humid Air Motor

The Humid Air Motor (HAM) process was developed by Munters Europe AB, and has undergone trials for 4000 hours on the MS Mariella in the Viking Line. The HAM system uses heated charge air enriched with evaporated seawater to reduce NOx emissions during the combustion process. The HAM system is used to replace the conventional engine air intercooler. Since it uses engine heat to heat the seawater, additional boiler capacity may be needed for other ship needs.

The central part of the HAM system is a special humidification unit, which is effectively a heat exchanger. This must be mounted very near the engine. Other equipment includes a circulation pump and filter, a heat exchanger (to heat the incoming water), a “bleed-off” system (to control the contents of salt and minerals in the water) and a water tank.

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[12] H. Schmid and G. Weisser, “Marine Technologies for Reduced Emissions,” Wärtsilä Corporation, April 2005. Available at http://www.wartsila.com/Wartsila/global/docs/en/ship_power/media_publications/technical_papers/sulzer/marine_technologies_for_reduced_emissions.pdf

Water, which has already been heated by the engine cooling system, is additionally heated and vaporized using hot air from the turbocharger. This humidified charge air is directed into the combustion chamber after filtration for debris. The system has been reported to reduce NOx by 70-80% with water to fuel ratios of 2.8 at normal operating speeds and loads. [13] While MAN B&W has tested HAM units on smaller engines (typically on ferries), no tests to date have been done on engines the size used on container or bulk carrier vessels.

The DEQ should assume a water to fuel ratio of 2.8 resulting in a 75% NOx reduction. This should be applied to propulsion engine emissions only during the 25 mile cruise, RSZ, and maneuvering modes.

Costs will vary by engine type and engine power.[11] For medium speed engines, the capital cost can be calculated as follows:

$$\textbf{Cost (\$) per engine} = 579.47 \times \text{engine power (kW)}^{-0.327} \times \text{engine power (kW)} \qquad (24)$$

For slow speed engines, the capital cost can be calculated as follows:

$$\textbf{Cost (\$) per engine} = 1124.60 \times \text{engine power (kW)}^{-0.362} \times \text{engine power (kW)} \qquad (25)$$

It is assumed that enough water will be generated using a fresh water generator. Fresh water generators can be heated using engine cooling water or using steam from an exhaust gas economizer.

Exhaust Gas Recirculation

MAN diesel tested EGR with a scrubber and water treatment, obtaining a 70 percent reduction in NOx emissions with a relatively small increase in brake specific fuel consumption (BSFC).[14] MAN diesel used an EcoSilencer® to clean the exhaust gas before reintroducing it into the air cooler and scavenge air. The scrubber removed 90 percent of the PM emissions and 70 percent of the SOx with no water carry over of the exhaust recycled back into the engine.

For purposes of the DEQ, a 20 percent EGR rate would provide a 50 percent reduction in NOx, a 20 percent reduction in PM, a 10 percent reduction in HC emissions and a 1.5 percent increase in CO_2 emissions. This should be applied to propulsion engine emissions only for the 25 nm cruise, RSZ and maneuvering modes.

Costs will vary by engine type and engine power.[11] For medium speed engines, the capital cost can be calculated as follows:

$$\textbf{Cost (\$) per engine} = 2395 \times \text{engine power (kW)}^{-0.576} \times \text{engine power (kW)} \qquad (26)$$

For slow speed engines, the capital cost can be calculated as follows:

$$\textbf{Cost (\$) per engine} = 1780.3 \times \text{engine power (kW)}^{-0.5392} \times \text{engine power (kW)} \qquad (27)$$

Slide Valves

Slide valves reduce the sac volume in the fuel injector nozzle and thereby reduce both PM and HC emissions. When fuel is injected into the cylinder, fuel tends to remain in the sac volume

[13] Peter Mullins, "The H.A.M. System Approach to Reducing NOx," Diesel & Gas Turbine Worldwide, November 2000.

[14] MAN Diesel, "Exhaust Gas Emission Control Today and Tomorrow," August 19, 2008," available at http://www.manbw.com/article_009187.html

and dribble out later in the cycle causing high hydrocarbon (HC) and PM emissions. Slide valves can optimize spray distribution in the combustion chamber of two-stroke engines and thus reduce in-cylinder temperature and NOx formation.[15] Slide valves can also reduce HC emissions and PM by decreasing fuel seepage. In addition, slide valves allow better combustion timing and therefore can reduce NOx emissions. MAN B&W estimates that slide valves can reduce NOx emissions by 30%, PM emissions by 25% and HC emissions by 30%. Generally slide valves are only built for SSDs although some form of slide valves will be available for MSDs that are 90 liters per cylinder or larger. Only about 35 percent of MSDs are 90 liters per cylinder or larger which are mostly on large cruise ships or auto carriers.

For purposes of the DEQ, slide valve reductions of 30 percent NOx, 25 percent PM and 30 percent HC should be applied to propulsion engine emissions only during the cruise, RSZ and maneuvering modes. These should not be applied to medium speed propulsion engines less than 90 liters per cylinder. Generally only large cruise ships and auto carriers have medium speed propulsion engines that large.

Slide valve costs for slow speed engines vary by engine power.[11] Typically for slow speed engines, costs can be calculated using the below equation. These would not be applied to auxiliary engines as most auxiliary engines are medium speed engines less than 90 liters per cylinder.

Cost ($) per engine = (26.436 - 0.0003 x engine power (kW)) x engine power (kW) (28)

For large MSD engines, the following equation should be used to calculate costs

Cost ($) per engine = 11.756 x engine power (kW) (29)

Sea Water Scrubbers

Another approach to reduce PM and SOx emissions from main propulsion engines is the use of seawater scrubbers. Scrubber use the principles of wet Flue Gas Desulfurization, which is the mixing of hot exhaust flu gases in a turbulent cascade with seawater. Seawater is alkaline by nature, with typical pH values of 8.0 - 8.3 and it is therefore very suitable for absorption of acidic gases like SO_2. SO_2 reacts with calcium carbonate to form calcium sulfates which are soluble in water. The PM particles are removed through impaction; however, much of the PM is hidden in bubbles and may escape through the scrubber.

The scrubbing water is then filtered to remove the potentially harmful components and kept in a settling or sludge tank for later safe disposal ashore. Under optimal conditions, seawater scrubbers tend to reduce SOx by 95%+ and PM 80%+.[16][17] However, sea water scrubbers work by neutralizing SO_2 and SO_4 by carbonates and other compounds in the wash water. The neutralization process increases CO_2 emissions by about 2.5%.

[15] Entec UK Limited, *2005 Task 2b - Assignment, Abatement and Market-based Instruments, Task 2b – NOx abatement*, prepared for the European Commission, Directorate-General Environment, United Kingdom.

[16] See: Krystallon Sea Water Scrubbing Technical Case at http://www.krystallon.com/technical-case.html, last visited July 1, 2008.

[17] The U.S. EPA and the Puget Sound Clean Air Agency have partnered with Holland America Lines, British Petroleum, Caterpillar, Environment Canada, and the British Columbia Clean Air Research Fund to demonstrate the feasibility and effectiveness of a seawater scrubbing technology to reducing emissions on a Holland America Line cruise ship. The project is to design, install and test the scrubbing technology on a 1,500 passenger cruise ship, named Vessel ms Zaandam, which operates in Hawaii, Alaska, and along the West Coast. The pilot test is currently underway, with final results scheduled for late Winter (Jan/Feb) 2009.

For purposes of the DEQ, scrubbing should include both the propulsion and auxiliary engine exhausts during the 25 nm cruise, RSZ, maneuvering and hotelling modes. SOx reductions should be calculated at 95 percent, PM emission reductions at 80 percent and CO_2 emission increase at 2.5 percent.

Costs will vary by engine type and engine power.[11] For medium speed engines, the capital cost can be calculated as follows:

Cost ($) per engine = 4306.3 x engine power (kW)$^{-0.4556}$ x engine power (kW) **(30)**

For slow speed engines, the capital cost can be calculated as follows:

Cost ($) per engine = 2836.7 x engine power (kW)$^{-0.4056}$ x engine power (kW) **(31)**

Selective Catalytic Reduction

There are reports that a properly designed Urea Selective Catalytic Reduction (SCR) system can reduce NOx emission by more than 98% but this is most likely with very low sulfur fuel. Clean Diesel Technologies is one company that markets diesel exhaust aftertreatment technologies for various applications including marine and claims that typical NOx conversion efficiency is between 70 to 90 percent in reactors that maintain temperatures above 320°C.[18] Argillon consistently reports that their best designs can maintain 95 percent efficiency under most conditions.[19] Most companies suggest that for analysis purposes 90 to 95 percent NOx reduction efficiency can be assumed for properly designed systems. However, as exhaust temperature decreases due to low load operation, SCR becomes less efficient. SCR will most likely need low sulfur distillate fuel to operate properly as high sulfur fuels can create large amounts of SOx which keep urea SCR reactors from operating effectively. Sulfur oxides can react with oxygen in the exhaust and form sulfuric acid, which can cause corrosion and reduce SCR system life. Also high levels of SOx can interfere with the NOx reduction reaction decreasing the SCR system effectiveness. In addition if the exhaust temperature is too low, ammonia salts will form on the SCR unit which can essentially plug the reactor. This is more a problem with low speed engines than medium speed engines. In those cases, the SCR unit will be shut off to prevent ammonia salt formation.

For purposes of the DEQ, SCR can be applied to the propulsion and/or the auxiliary engines. For low and medium speed propulsion engines, a 90 percent reduction in NOx should be applied to the 25 nm cruise and RSZ modes. For medium speed propulsion engines, a 75 percent reduction should be applied to the maneuvering mode. For auxiliary engines, a 90 percent reduction in NOx should be applied to all modes.

Costs will vary by engine type and engine power.[11] If auxiliary engines are added to propulsion engines, the auxiliary engine power should be added to the propulsion power when calculating costs. For medium speed engines, the capital cost can be calculated as shown in equation 32.

Cost ($) per engine = 11119 x engine power (kW)$^{-0.5769}$ x engine power (kW) **(32)**

For slow speed propulsion engines, the capital cost can be calculated as shown in equation 33.

Cost ($) per engine = 1224.4 x engine power (kW)$^{-0.3096}$ x engine power (kW) **(33)**

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[18] Clean Diesel Technologies corporate website http://www.cdti.com/content/technology/overview.htm

[19] Argillon Website, http://www.argillon.com/business-segments/systems/industrial-applications/overview.html

In addition the cost of urea is an operating cost necessary for the SCR system. Operating costs for urea calculated at $1.52 per gallon with a 7.5 percent dosing rate are given below in equation 34 for medium speed engines and equation 35 for slow speed engines.

Urea Cost ($) per hour = 0.0025 x engine power (kW) (34)

Urea Cost ($) per hour = 0.0023 x engine power (kW) (35)

Cold Ironing

Cold ironing, also known as shore power, is a means of reducing ship emissions while at port. When a ship is at berth, it can be plugged into a land-based electric grid and the auxiliary engines can be shut off. This displaces emissions from the ship to the power generating facility, which can be more easily controlled. Shore power requires building the landside power delivery infrastructure and retrofitting the ships for the connection. The size and proximity of the power supply to the port is crucial in determining the required shore power delivery infrastructure.[20] The infrastructure configuration also depends on vessel type. Ships that do not always dock in the same position or require various loading and unloading mechanisms (such as container or cargo ships) require a more flexible shore power infrastructure than tankers.

Emissions during hotelling are calculated as zero during cold ironing provided the ship is at berth. If the power plant is in the same air basin as the ship, emissions from the power plant may need to be considered. Typically these are much lower per kWh than those for generating electricity on board.

The cost to install shore power infrastructure is approximately $1M – $17M, coupled with approximately $500,000 - $2.5M to retrofit a ship to allow use of shore power.[21]

For purposes of the DEQ, hotelling emissions should be set to zero. This of course assumes that the power plant is outside the air basin in which the port is located. Capital costs of shore power are highly variable depending on ship type and size as well as by how many ships with shore power stop at a given terminal. In addition, the cost of electricity versus residual fuel needed for cold ironing needs to be calculated to estimate the additional operating costs.

The power required for hotelling should be calculated as shown in equation 36 for purposes of calculating electricity costs:

Hotelling Load (kWh) = Auxiliary Engine Power (kW)
x Auxiliary Hotelling Load Factor x Hotelling time (hrs) (36)

Supplemental Wind Power

Wind power is utilized on cargo ships by use of special kites. These kites use wind power to help pull the ship along and reduce power required from the propulsion engine. The SkySails system[22] consists of three main components: a towing kite with rope, a launch and recovery system, and a control system for automatic operation. Currently SkySails are only available for smaller tankers and bulk carriers, but the company plans to offer bigger kites for larger vessels.

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[20] California Air Resources Board (CARB). "Proposed Regulation for Auxiliary Diesel Engines and Diesel-electric Engines Operated on Ocean-going Vessels with California Waters and 24 Nautical Miles of the California Baseline." 2005.

[21] Personal email correspondence. Allyson Teramoto, Port of Long Beach, 12 June 2008. See: *Cold Ironing Effectiveness Study: Volume 1-Report* at: http://www.polb.com/civica/filebank/blobdload.asp?BlobID=2157.

[22] http://www.skysails.info/english/

For a tanker with a 6800 kW propulsion engine, a SkySail system would cost approximately $1.5M installed plus annual maintenance cost of $230,000. SkySail claims a 18 percent reduction in fuel consumption during cruise which would translate to an 18 percent reduction in all emissions during the cruise portion of the trip. Since the main advantage of this system would be to reduce fuel consumption and CO_2 emissions over the entire voyage of the vessel, a near port analysis would only provide limited benefits. Emission reductions for near port calculations should be limited to the 25 nm cruise for propulsion engines only. The 18 percent reduction to all emissions could be applied.

Hull Coatings

Hull coatings reduce hull surface roughness which thereby improves fuel efficiency. A fluoropolymer foul release coating such as Intersleek®900[23] provides exceptionally smooth hull surface combined with excellent foul release capabilities and good resistance to mechanical damage. It is recommended for ships with speeds over 10 knots. The coating, which is painted on the hull, is estimated to reduce fuel consumption by 6 percent which would translate to emission reductions of a similar amount during the cruise portion of the near port inventory for the propulsion engines only. The main advantage of such a coating would be fuel savings and CO_2 emission reductions during the entire voyage of the vessel at cruise speed. Rough costs for coating a 3400 TEU container ship would be approximately $425,000.

[23] http://www.international-marine.com/Literature/Intersleek%20900.pdf