US Army Corps of Engineers ®
Galveston District

Attachment 1 to Appendix G

Projected Emissions Reductions for Houston Ship Channel Expansion Channel Improvement Project

Harris, Chambers, and Galveston Counties, Texas

Prepared for:

U.S. Army Corps of Engineers, Galveston District

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Abbreviations

AIS	Automatic Identification System
BW	Breakwater
CO	Carbon Monoxide
CO_2	Carbon Dioxide
g/kWh	Grams per Kilowatt Hour
HC	Hydrocarbons
ICFI	ICF International
NED Plan	National Economic Development Plan
LPP	Locally Preferred Plan
NO_X	Nitrogen Oxides
OGV	Ocean Going Vessel
PM_{10}	Particulate Matter less than 10 micrometers in diameter
$PM_{2.5}$	Particulate Matter less than 2.5 micrometers in diameter
PPX3	Post-Panamax Generation III
RO-RO	Roll on Roll off
RSZ	Reduced Speed Zone
SO_x	Sulfur Oxides
SSD	Slow-speed Diesel
tpy	Tons per year
USACE	U.S. Army Corps of Engineers

1.0 Emissions Summary

This analysis was developed to estimate projected air pollutant emissions reductions from Ocean Going Vessels (OGV) as a result of proposed channel improvements within the Port of Houston. Emissions are analyzed for two plans: the National Economic Development Plan (NED Plan), which includes the widening of the Barbours Cut and Bayport Ship Channels and the lower leg of the Houston Ship Channel (HSC) in Galveston Bay, and the Locally Preferred Plan (LPP), which encompasses the NED Plan, plus the additional widening of the remainder of the HSC in Galveston Bay.

Emissions estimates were developed in accordance with methodologies specified in the Current Methodologies in Preparing Mobile Source Port-Related Emission Inventories (ICFI, 2009), and data from the U.S. Army Corps of Engineers (USACE) economic analysis. In general, vessel type, projected calls and activities were sourced from USACE, and emission factors were sourced from best available literature sources.

The following table shows a summary of projected emissions reductions from OGVs in tons per year (tpy) for both the NED Plan and the LPP. For both plans, emissions are estimated based on vessel hourly reductions projected for the years 2029 and 2044, and pollutants of concern for this analysis include criteria pollutants nitrogen dioxide (NO_x), particulate matter 10 micrometers or less in diameter (PM_{10}), PM 2.5 micrometers or less in diameter ($PM_{2.5}$), hydrocarbon (HC), carbon monoxide (CO), sulfur oxides (SO_x) and greenhouse gas pollutant carbon dioxide (CO_2). Note that since these values represent reductions in emissions, higher values indicate greater reductions. For each year analyzed, the percent difference in the two plans is shown, and calculations demonstrate a significant reduction in emissions associated with the LPP for all pollutants, as compared to the NED Plan, with the largest total reduction differences being for NO_x and CO_2.

Table 1: Summary of Emissions Reductions

Emissions Reductions (tpy)								
Year	**Plan**	**NO_x**	**PM_{10}**	**$PM_{2.5}$**	**HC**	**CO**	**SO_x**	**CO_2**
2029	NED Plan	63.33	3.78	3.42	0.05	-0.05	6.64	10,806
	LPP	147.2	15.61	14.24	3.35	7.74	17.98	29,274
	Difference in Plans (%)	132%	313%	316%	6,246%	N/A	171%	171%
2044	NED Plan	167.8	8.16	7.39	0.21	0.13	14.07	22,903
	LPP	334.4	31.61	28.84	6.90	16.03	36.53	59,474
	Difference in Plans (%)	99%	287%	290%	3,200%	11,777%	160%	160%

1.1 Activity Characterization

The purpose of HSC ECIP study is to evaluate Federal interest in alternative plans (including the No-Action Plan) for reducing transportation costs while providing for safe, reliable navigation on the HSC system. As such, the LPP and NED Plan address multiple navigation problems and opportunities related to transportation delays, inefficiencies, and the related costs. Addressing these problems and opportunities directly decreases the time and fuel spent transporting the commodities shipped through the HSC system, and therefore, the associated emissions from OGVs. The reduction of transportation costs by both plans is achieved in two primary ways. One way is by reducing transportation delays in the form of slower or delayed navigation, and waiting at docks and anchorages due to navigation restrictions.

Another way is to reduce inefficient delivery of cargo imposed by draft restrictions by deepening the channel to alleviate light loading of vessels. Doing this reduces the amount of vessels it takes to deliver a given annual tonnage of cargo. Economic analysis to characterize the vessel movement through the HSC system and its associated costs is central to the HSC ECIP study, because justification of a Civil Works project requires estimating the benefits of a project against its costs. Those benefits for a navigation-purpose study are primarily reductions in transportation costs, which in turn, require estimating the reduction in activity incurring those costs. This activity is vessel transit and waiting which incur operational costs. The following subsection summarizes the economic model to estimate these costs.

1.1.1 Use of Harborsym

Navigation economists conducted the economic analysis required for this feasibility study which included detailed estimates of projected future commodities, vessel fleets, vessel movement, and associated transportation costs. Harborsym, the USACE's certified economic analysis computer simulation model developed by the Institute for Water Resources (IWR), was used to aid the analysis. The use of Harborsym to characterize the vessel movement of OGVs through a channel and harbor system is analogous to the travel demand highway and road models used by Metropolitan Planning Organizations (e.g. Houston-Galveston Area Council) and departments of transportation (e.g. TxDOT) to characterize how cars, trucks etc. move through a road network and how much time and delay they experience. In the same way that highway travel demand modeling uses statistics and urban area attributes (i.e. population, trip generation centers) to estimate needed vehicle trips, and incorporates road capacity and rules (i.e. direction, speed, number of lanes), Harborsym also uses port attributes (e.g. docks, load centers) and channel characteristics (e.g. size, direction, vessel pilot rules) to likewise estimate and simulate vessel trips and movement. In the same fashion that the output of highway travel demand models are used to estimate emissions from mobile source models such as Motor Vehicle Emissions Simulation System (MOVES), the output of Harborsym can be used to estimate OGV emissions.

Harborsym is based on the creation of discrete event Monte Carlo simulations that mimic movement of vessels through a harbor (USACE IWR 2012). The model uses these event simulations along with user-defined statistical inputs to generate trips and calculate vessel transit time, loading and unloading time at docks, and docking and undocking time. A model of the harbor network that physically and statistically represents the navigation conditions of the harbor and its channels is developed as part of the analysis, and incorporates the vessel pilot rules that govern how different classes of vessels can move (one-way, two-way, loaded etc.) given the size, channel dimensions, and other navigation conditions. The model provides a detailed estimate of vessel calls (i.e. trips) and transit times by major vessel categories (i.e. tankers, containers, bulkers by different size classes) and can be used to quantify the extra or reduced time involved in transporting cargo by comparing with-project scenarios to without project conditions. An economic model for the HSC system, using Port of Houston-specific vessel fleets, current and future commodities throughput, and vessel pilot rules from the Houston Pilots Association, was developed for this study's economic analysis.

1.1.2 Vessel Delay and Transit Reduction from Harborsym Output

Harborsym output for vessel transit and waiting time provided by the USACE economists was used to support the operational air analysis. The vessel transit and waiting time for the Without-Project Condition (i.e. No Action Plan), the NED Plan, and LPP were used to calculate the reduction in transit and waiting that the NED Plan, and LPP provide compared to No Action. Due to the way specific channel improvements work to reduce transportation time, the reduced hours associated with certain groups of measures making up the project (e.g. channel widening, deepening) and study segments, can be generally categorized as waiting (hours spent waiting at berth or anchorage) or steaming (under way using propulsion). These assumptions were used to employ the appropriate emissions factors and activity. The annual in-port reduction in these hours by vessel category and by study segment were used to estimate emissions reduced by the action alternatives. Besides in-port reductions, which would occur landward of the entrance buoy to the HSC, the proposed action alternatives would also reduce vessel transit hours and emissions seaward of the buoy in the shipping lanes of the Gulf of Mexico through the elimination of vessel trips. These reductions would take place mostly outside of the HGB NAA, but would still represent substantial emissions reductions in the North American Emissions Control Area (ECA), which encompasses the US Gulf of Mexico. In-port reductions would take place within the HGB NAA. The annual in-port reduction in hours for the Years 2029 and 2044 were used to provide a range of reduction reflecting the increasing reduction occurring as traffic increases in the future due to increased commodity demand.

Projected hourly reductions from channel widening are broken down by plan, year of analysis, and vessel type, as provided by USACE (Table 2 and Table 3). Hourly reductions incorporate both waiting hours (Table 2), in which the vessel is assumed to be at berth or at anchor, and steaming hours (Table 3), in which the vessel is assumed to be in transit. Vessel types included in this analysis are container ships, tankers, bulk carriers, general cargo ships, and roll-on roll-off (RoRo) vessels.

Hourly reductions were projected for years 2029, 2034, 2039, and 2044 for all vessel types. For calculation of emissions and plan comparison, only years 2029 and 2044 were considered, as they provide both the minimum and maximum total emissions reductions, respectively.

Table 2: Projected Hourly Reductions (Waiting Hours)

Type of Reduction	Vessel Class	Hourly Reductions per vessel Class – NED Plan				Hourly Reductions per vessel Class - LPP			
		Total Time Reduced (hrs)				Total Time Reduced (hrs)			
		2029	2034	2039	2044	2029	2034	2039	2044
Waiting Hours	Sub-Panamax	133	242	370	476	195	372	574	748
	Panamax	249	404	594	618	365	684	1000	978
	Post-Panamax Generation I	655	919	1552	2003	2901	3576	5438	5969
	Post-Panamax Generation II	4664	7691	11309	13825	5355	8852	12894	15586
	Post Panamax Generation III	-4995	-8699	-12072	-15205	-4182	-7280	-10092	-12812
	10k-30k Tanker	169	156	344	401	221	232	468	530
	30k-55k Tanker	170	461	482	611	325	653	667	897
	55k-75k Tanker	129	199	247	254	158	269	313	339
	75k-100k Tanker	334	303	431	584	520	547	843	1018
	100k-130k Tanker	1503	1835	2306	2438	2700	3446	4121	4390
	130k-157.5k Tanker	2	249	379	-30	585	1151	1706	1384
	157.5k-215k Tanker	195	93	24	89	567	683	1048	1087
	7.5k-30k Bulker	20	65	70	92	30	80	104	128
	30k-45k Bulker	93	121	225	281	147	183	341	407
	45k-70k Bulker	173	344	444	558	265	486	651	781
	70k-110k Bulker	43	42	68	89	52	58	99	113
	110k-135k Bulker	0	0	0	0	0	0	0	0
	2.5k-13.5k LPG	178	498	537	656	554	1238	1290	1563
	13.5k-33.5k LPG	220	251	325	503	717	810	966	1191
	33.5k-49.2k LPG	69	22	93	120	181	109	203	240
	49.2k-64.2k LPG	481	735	1204	1364	1268	1831	2314	2558
	5.5k-12.5k General Cargo	188	301	419	509	279	424	609	716
	12.5k-15k General Cargo	58	114	167	196	79	168	222	287
	15k-18k General Cargo	44	71	82	126	60	105	114	166
	18k-22k General Cargo	13	61	97	129	28	90	134	174
	22k-27k General Cargo	26	54	76	90	45	76	117	136
	27k-30k General Cargo	64	89	182	227	86	131	279	328
	3.65k-9.15k RoRo	1	3	5	1	1	4	5	1
	9.15k-15.9k RoRo	13	25	44	41	27	43	65	58
	15.9k-20.9k RoRo	56	95	115	170	84	122	155	242
	4.5k-13.5k Chem Tanker	116	189	261	347	167	284	370	516
	13.5k-21.5k Chem Tanker	57	104	175	180	97	151	260	302
	21.5k-29k Chem Tanker	15	9	16	46	27	24	33	68
	29k-33k Chem Tanker	30	49	99	101	56	86	150	153

Table 3: Projected Hourly Reductions (Steaming Hours)

Type of Reduction	Vessel Class	Hourly Reductions per vessel Class – NED Plan Total Time Reduced (hrs)				Hourly Reductions per vessel Class - LPP Total Time Reduced (hrs)			
		2029	2034	2039	2044	2029	2034	2039	2044
Steaming Hours	Sub-Panamax	0	0	0	0	0	0	0	0
	Panamax	0	0	0	0	0	0	0	0
	Post-Panamax Generation I	0	0	0	0	0	0	0	0
	Post-Panamax Generation II	0	0	0	0	0	0	0	0
	Post Panamax Generation III	0	0	0	0	0	0	0	0
	10k-30k Tanker	319	97	54	54	319	97	54	54
	30k-55k Tanker	1919	3141	4644	4644	1919	3141	4644	4644
	55k-75k Tanker	922	1011	954	954	922	1011	954	954
	75k-100k Tanker	-394	-499	-731	-731	-394	-499	-731	-731
	100k-130k Tanker	-2527	-3525	-4639	-4639	-2527	-3525	-4639	-4639
	130k-157.5k Tanker	0	0	0	0	0	0	0	0
	157.5k-215k Tanker	0	0	0	0	0	0	0	0
	7.5k-30k Bulker	162	150	365	365	162	150	365	365
	30k-45k Bulker	216	217	82	82	216	217	82	82
	45k-70k Bulker	-174	-172	-187	-187	-174	-172	-187	-187
	70k-110k Bulker	-9	-19	-14	-14	-9	-19	-14	-14
	110k-135k Bulker	0	0	0	0	0	0	0	0
	2.5k-13.5k LPG	-9	6	-1	-1	-9	6	-1	-1
	13.5k-33.5k LPG	8	1	15	15	8	1	15	15
	33.5k-49.2k LPG	2	3	5	5	2	3	5	5
	49.2k-64.2k LPG	51	66	55	55	51	66	55	55
	5.5k-12.5k General Cargo	422	513	465	465	422	513	465	465
	12.5k-15k General Cargo	29	11	6	6	29	11	6	6
	15k-18k General Cargo	34	56	0	0	34	56	0	0
	18k-22k General Cargo	29	-11	-1	-1	29	-11	-1	-1
	22k-27k General Cargo	0	0	96	96	0	0	96	96
	27k-30k General Cargo	-294	-305	-323	-323	-294	-305	-323	-323
	3.65k-9.15k RoRo	0	0	0	0	0	0	0	0
	9.15k-15.9k RoRo	0	-1	1	1	0	-1	1	1
	15.9k-20.9k RoRo	0	0	1	1	0	0	1	1
	4.5k-13.5k Chem Tanker	2	2	4	4	2	2	4	4
	13.5k-21.5k Chem Tanker	1	1	1	1	1	1	1	1
	21.5k-29k Chem Tanker	0	0	0	0	0	0	0	0
	29k-33k Chem Tanker	-3	-3	-4	-4	-3	-3	-4	-4

1.1.3 Engine and Vessel Speed Data

The OGV main engine, auxiliary engine, and boilers are the primary sources of emissions from OGVs and are included in this assessment. Main engines, also known as propulsion engines, operate primarily when the vessel is in transit. Auxiliary engines and boilers are primarily used for electricity generation, heating and steam production, and operate primarily while vessels are moving at slow speeds, berth or anchor. Main engines, auxiliary engines and boilers all operate at different loads as dictated by the vessel's mode of operation which contributes to varying emission rates.

OGVs operate within one of four different modes: cruising, reduced speed zone (RSZ), maneuvering, and hotel (berth) mode. Vessel speeds vary for each of these modes of operation, and Table 4 displays the average vessel speeds used in this assessment, which were estimated from the *Houston Ship Channel Expansion Channel Improvement Project, Harris, Chambers, and Galveston Counties, Texas*, Appendix B, Table 4-2. For purposes of modeling the Port of Houston, it was assumed that steaming hour reductions are split evenly between speeds which would represent traveling outside or inside the breakwater (Outside BW and Inside BW) at a typical port. It is also assumed that maneuvering time for a vessel will not change drastically because of the proposed channel widening. Therefore, reductions in steaming hours represent only activity in the RSZ. Each mode of operation can be described as follows:

- Cruising mode: Considered to be 94 percent of maximum speed, generally outside of the port boundary.
- Reduced speed zone: Occurs where vessels are operating at less than cruising speed and greater than maneuvering (9-12 knots), generally within the bay or harbor.
- Maneuvering: This occurs when the vessel is close to the dock maneuvering into or out of berth (approximately 4 knots), typically with assist tugs.
- Hotel mode: This is when the vessel is at berth typically working cargo to and from the port. The main engines are turned off and the vessel is operating on auxiliary engines.

Table 4: Average Vessel Speed per Operating Mode (knots)

Vessel Type	Cruise	RSZ (Outside BW)[2]	RSZ (Inside BW)[2]	Maneuver	Hotel
Container	21.6	12	10	4	-
Bulk Carrier	14.5	12	7	4	-
General Cargo	15.2	12	7	4	-
RoRo	16.8	12	7	4	-
Tanker	14.8	12	10	4	-

Notes:

[1] *Average vessel speeds estimated from Houston Ship Channel Expansion Channel Improvement Project, Harris, Chambers, and Galveston Counties, Texas, Appendix B, Table 4-2.*

[2] *RSZ = Reduced Speed Zone, BW = Break Water.*

OGV main engine size and auxiliary engine size was obtained from Automatic Identification System (AIS) data consisting of every vessel that calls at the port. Engine data was averaged for each vessel category included in this analysis and are displayed in Table 5 below. Average cruise speeds are also displayed in Table 5 and are assumed per vessel type per guidance found in ICFI, 2009. It was assumed that all propulsion engines operate on residual oil, while all auxiliary engines operate on distillate fuel oil. Boiler size data is not widely available, therefore boiler size assumptions per ship type were assumed per methodology in ICFI, 2009, and are shown in Table 6 below.

Table 5: Vessel Engine Data per Vessel Class

Vessel Class	Fuel type (Propulsion Engines)[1]	Maximum Speed (knots)[2]	Propulsion Engine Power (kW)	Fuel type (Auxiliary Engines)[1]	Total Aux Engine Power (kW)
Sub-Panamax	Residual	22.98	40,328	Distillate	2,156
Panamax	Residual	22.98	40,328	Distillate	2,156
Post-Panamax Generation I	Residual	22.98	56,429	Distillate	3,167
Post-Panamax Generation II	Residual	22.98	56,429	Distillate	3,167
Post-Panamax Generation III	Residual	22.98	56,429	Distillate	3,167
10k-30k Tanker	Residual	15.74	4,764	Distillate	663
30k-55k Tanker	Residual	15.74	9,121	Distillate	821
55k-75k Tanker	Residual	15.74	11,848	Distillate	920
75k-100k Tanker	Residual	15.74	12,971	Distillate	923
100k-130k Tanker	Residual	15.74	13,366	Distillate	994
130k-157.5k Tanker	Residual	15.74	16,877	Distillate	1,432
157.5k-215k Tanker	Residual	15.74	17,901	Distillate	1,023
7.5k-30k Bulker	Residual	15.43	5,322	Distillate	525
30k-45k Bulker	Residual	15.43	6,802	Distillate	635
45k-70k Bulker	Residual	15.43	8,559	Distillate	650
70k-110k Bulker	Residual	15.43	10,324	Distillate	643
110k-135k Bulker	Residual	15.43	13,745	Distillate	841
2.5k-13.5k LPG	Residual	15.74	3,501	Distillate	589
13.5k-33.5k LPG	Residual	15.74	8,331	Distillate	1,080
33.5k-49.2k LPG	Residual	15.74	11,031	Distillate	1,402
49.2k-64.2k LPG	Residual	15.74	13,023	Distillate	1,300
5.5k-12.5k General Cargo	Residual	16.17	3,454	Distillate	378
12.5k-15k General Cargo	Residual	16.17	4,946	Distillate	578
15k-18k General Cargo	Residual	16.17	6,380	Distillate	581
18k-22k General Cargo	Residual	16.17	7,905	Distillate	653
22k-27k General Cargo	Residual	16.17	7,965	Distillate	703
27k-30k General Cargo	Residual	16.17	7,876	Distillate	786
3.65k-9.15k RoRo	Residual	17.87	11,393	Distillate	1,127
9.15k-15.9k RoRo	Residual	17.87	11,393	Distillate	1,127
15.9k-20.9k RoRo	Residual	17.87	11,393	Distillate	1,127
4.5k-13.5k Chem Tanker	Residual	15.74	3,483	Distillate	511
13.5k-21.5k Chem Tanker	Residual	15.74	5,642	Distillate	718
21.5k-29k Chem Tanker	Residual	15.74	7,047	Distillate	811
29k-33k Chem Tanker	Residual	15.74	7,592	Distillate	938

Notes:

[1] *Projections assume all propulsion engines operate on residual oil, and all auxiliary engines operate on distillate oil.*

[2] *Average maximum speeds per ship type from ICFI, 2009, Table 2-6. It was assumed that cruise speed represented 94% of maximum service speed.*

[3] *Average main and auxiliary engine size for each vessel class from Automatic Identification System (AIS) data consisting of all vessels which make calls at Port of Houston.*

Table 6: Auxiliary Boiler Energy Defaults by Operating Mode, kW

Ship Type	Cruise	RSZ	Maneuver	Hotel
Bulk Carrier	0	0	109	109
Container	0	0	506	506
General Cargo	0	0	106	106
RoRo	0	0	109	109
Tanker	0	0	371	3,000

Notes:

[1] Boiler sizing data from ICFI, 2009, Table 2-17.

2.0 Emission Factors and Calculations

Emissions factors were sourced from ICFI, 2009. Table 7 through Table 9 contain emission factors for main (propulsion) engines, auxiliary engines and boilers, respectively. The 2016 IMO tier 3 standard for NO_x was used for Post-Panamax Generation III (PPX3) auxiliary engines as the average age of this fleet is relatively new. Propulsion engine emissions factors for PPX3 vessels were not analyzed as all hourly projections are assumed as waiting hours, and therefore only associated with auxiliary engines. Although some in-port vessel transit would be eliminated due to reducing vessel calls (thereby eliminating steaming), the reduced operating hours were conservatively estimated to be waiting hours for container vessels. Auxiliary engines are smaller, and less emitting than main propulsion engines, and therefore the analysis conservatively estimates operational reductions. For purposes of emissions projections, propulsion engines were all assumed to be slow speed diesel engines. Emission factors for NO_x and SO_x were adjusted to reflect emission rate and fuel standards for the target years being analyzed. For boilers, emission factors for steam turbines were used, per ICFI, 2009.

Table 7: Emission factors for OGV Main Engines

Engine Type	Fuel Type	Sulfur (%)	Emission Factors (g/kWh)						
			NO_x[2]	PM_{10}	$PM_{2.5}$	HC	CO	SO_x[3]	CO_2
SSD	Residual	0.10	5.76	1.42	1.31	0.60	1.40	0.38	620.62

Notes:

[1] Emission factors from ICFI, 2009, Table 2-9. For purposes of emissions projections, assumed all propulsion engines to be slow speed diesel operating on residual oil.

[2] NOx emission factors adjusted for IMO standard reduction, ICFI, 2009 Table 2-12. Analysis year 2030 in emission control areas applied for all projected emissoins.[3] HC emissions are based on Hydrocarbon emission rates specified in Table 2-9 (ICFI, 2009).

[3] SO_x emission factors adjusted for sulfur content of 0.1%, per International Maritime Organization fuel standard for Emission Control Areas.

Table 8: Emission Factors for OGV Auxiliary Engines

Fuel Type	Sulfur (%)	Emission Factors (g/kWh)						
		NOx	PM_{10}	$PM_{2.5}$	HC	CO	SO_x[2]	CO_2
Distillate	0.10	13.9	0.49	0.45	0.40	1.10	0.42	690.71

Notes:

[1] Emission factors from ICFI, 2009, Table 2-16. For purposes of emissions estimation, all auxiliary engines are assumed to use distillate fuel oil.

[2] SO_x emission factors adjusted for sulfur content of 0.1%, per International Maritime Organization fuel standard for Emission Control Areas.

Table 9: Emission Factors for PPX III Auxiliary Engines

Fuel Type	Sulfur (%)	Emission Factors (g/kWh)						
		NO_x[3]	PM_{10}	$PM_{2.5}$	HC	CO	SO_x[2]	CO_2
Distillate	0.10	3.40	0.49	0.45	0.40	1.10	0.42	690.71

Notes:

[1] For purposes of emissions estimation, all auxiliary engines are assumed to use distillate fuel oil. NO_x factors for Post-Panamax III auxiliary engines comply with IMO Tier 3 standards for vessels constructed beginning January 2016. Assumed all engines are medium speed Category 2 engines, per ICFI, 2009 Tables 2-2 and 2-3. All other emission factors from ICFI, 2009, Table 2-16.

[2] SO_x emission factors adjusted for sulfur content of 0.1%, per International Maritime Organization fuel standard for Emission Control Areas.

[3] Conservatively assumed an engine speed of 130 rpm for calculation of NO_x emission factor.

Table 9: Emission Factors for OGV Auxiliary Boilers

Engine Type	Fuel Type	Sulfur (%)	Emission Factors (g/kWh)						
			NO_x	PM_{10}	$PM_{2.5}$	HC	CO	SO_x[3]	CO_2
Steam Turbine	Distillate	0.10	2.00	0.58	0.53	0.10	0.20	0.57	922.97

Notes:

[1] Emission factors for steam turbines used for boiler emissions calculations, per ICFI, 2009, Chapter 2. Emission factors from ICFI, 2009, Table 2-9.

[2] Assume all auxiliary boilers burned distillate fuel only.

[3] SO_x emission factors adjusted for sulfur content of 0.1%, per International Maritime Organization fuel standard for Emission Control Areas.

Because vessel engines operate under a variety of loads depending on the mode of activity at any given time, load factors are applied to emissions calculations to better reflect emission rates during different operating modes. Load factors for propulsion engines were calculated using the Propeller Law as shown below, according to ICFI, 2009, Section 2.5.

$$Load\ Factor = \left(\frac{Actual\ Speed}{Maximum\ Speed}\right)^3$$

For propulsion engines operating at loads of less than 20%, an additional low-load adjustment factor is applied to reflect greater inefficiencies of engines operating at very low loads. These factors, from ICFI, 2009, Table 2-15, can be seen in Table 10 below.

Table 10: Low Load Multiplicative Adjustment Factors

Load	NO_x	PM_{10}	$PM_{2.5}$	HC	CO	SO_x	CO_2
1%	11.47	19.17	19.17	59.28	19.32	5.99	5.82
2%	4.63	7.29	7.29	21.18	9.68	3.36	3.28
3%	2.92	4.33	4.33	11.68	6.46	2.49	2.44
4%	2.21	3.09	3.09	7.71	4.86	2.05	2.01
5%	1.83	2.44	2.44	5.61	3.89	1.79	1.76
6%	1.60	2.04	2.04	4.35	3.25	1.61	1.59
7%	1.45	1.79	1.79	3.52	2.79	1.49	1.47
8%	1.35	1.61	1.61	2.95	2.45	1.39	1.38
9%	1.27	1.48	1.48	2.52	2.18	1.32	1.31
10%	1.22	1.38	1.38	2.20	1.96	1.26	1.25
11%	1.17	1.30	1.30	1.96	1.79	1.21	1.21
12%	1.14	1.24	1.24	1.76	1.64	1.18	1.17
13%	1.11	1.19	1.19	1.60	1.52	1.14	1.14
14%	1.08	1.15	1.15	1.47	1.41	1.11	1.11
15%	1.06	1.11	1.11	1.36	1.32	1.09	1.08
16%	1.05	1.08	1.08	1.26	1.24	1.07	1.06
17%	1.03	1.06	1.06	1.18	1.17	1.05	1.04
18%	1.02	1.04	1.04	1.11	1.11	1.03	1.03
19%	1.01	1.02	1.02	1.05	1.05	1.01	1.01
20%	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Notes:

[1] *Low load factors from ICFI, 2009, Table 2-15.*

For auxiliary engines, load factors are assumed according to ICFI, 2009, Table 2-7. These load factors vary according to vessel type and operating mode and are displayed in Table 11 below.

Table 11: Auxiliary Engine Load Factors

Vessel Type	Cruise	RSZ	Maneuver	Hotel
Container	0.13	0.25	0.48	0.19
Bulk Carrier	0.17	0.27	0.45	0.10
General Cargo	0.17	0.27	0.45	0.22
RoRo	0.15	0.30	0.45	0.26
Tanker	0.24	0.28	0.33	0.26

Notes:

[1] *Load factors are from ICFI, 2009, Table 2-7.*

The following equation was used to calculate emissions from OGVs for all vessel types using the outputs and information from above. Equation inputs were described in detail in the preceding sections of this attachment.

$$Emissions = \frac{Total\ Hours\ in\ Mode}{Vessel\ Type} \times Engine\ Size\ \times Load\ Factor \times Low\ Load\ Adjustment\ Factor\ \times Emission\ Factor \times \frac{1\ lb}{453.5\ g} \times \frac{1\ ton}{2{,}000\ lb}$$

3.0 References

ICF International. (2009, April). Current Methodologies in Preparing Mobile Source Port-Related Emission Inventories, Final Report. Retrieved June 3, 2017, from https://archive.epa.gov/sectors/web/pdf/ports-emission-inv-april09.pdf

AECOM. (2017, August). Houston Ship Channel Expansion Channel Improvement Project, Harris, Chambers, and Galveston Counties, Texas, Appendix B, Table 4-2

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