The Role of Electronic Engine Control on Real-World NOx Emissions from Ocean-Going Vessels

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Supplemental

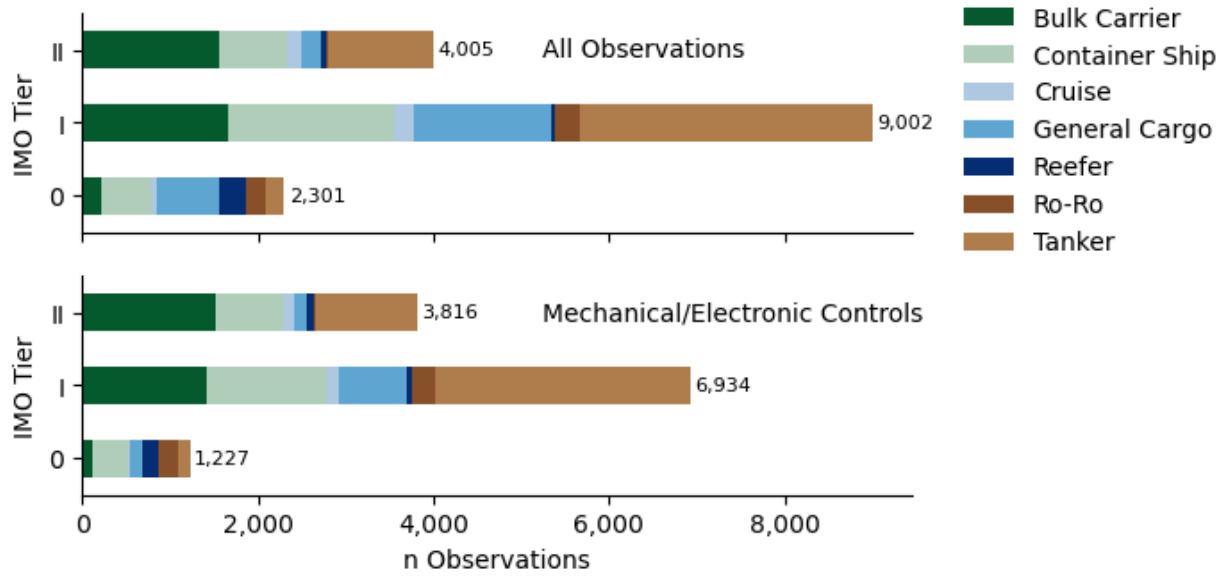

Figure S1 Distribution of ship types in the full dataset (top panel) and in the subset with known engine controls, i.e., mechanical or electronic (lower panel).

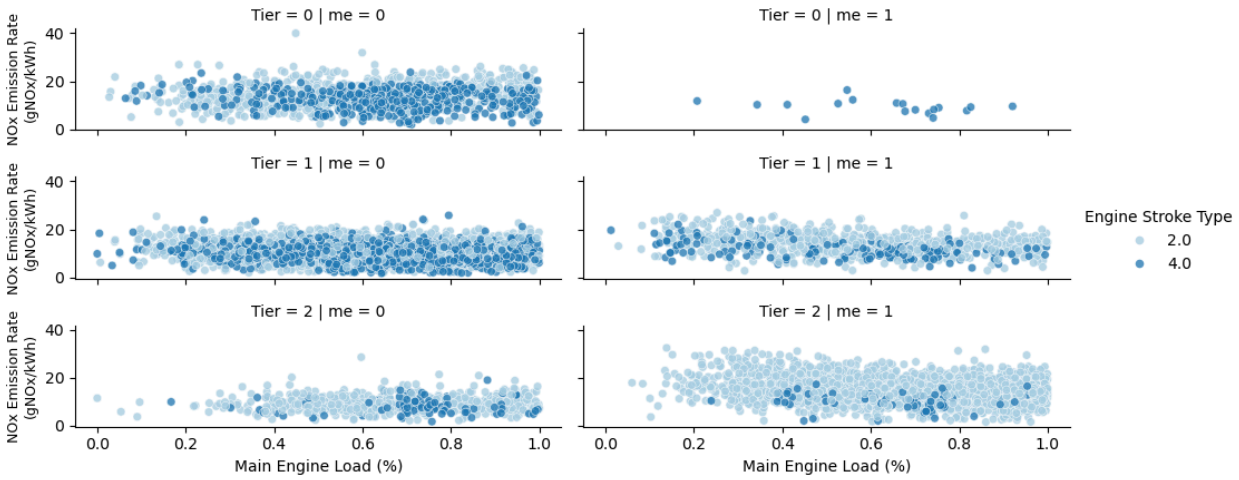

Figure S2 Derived brake-specific NOx emissions (g/kWh) versus main engine load for the full dataset, divided into separate engine Tiers and engine controls (Mechanical: me = 0, Electronic: me = 1).

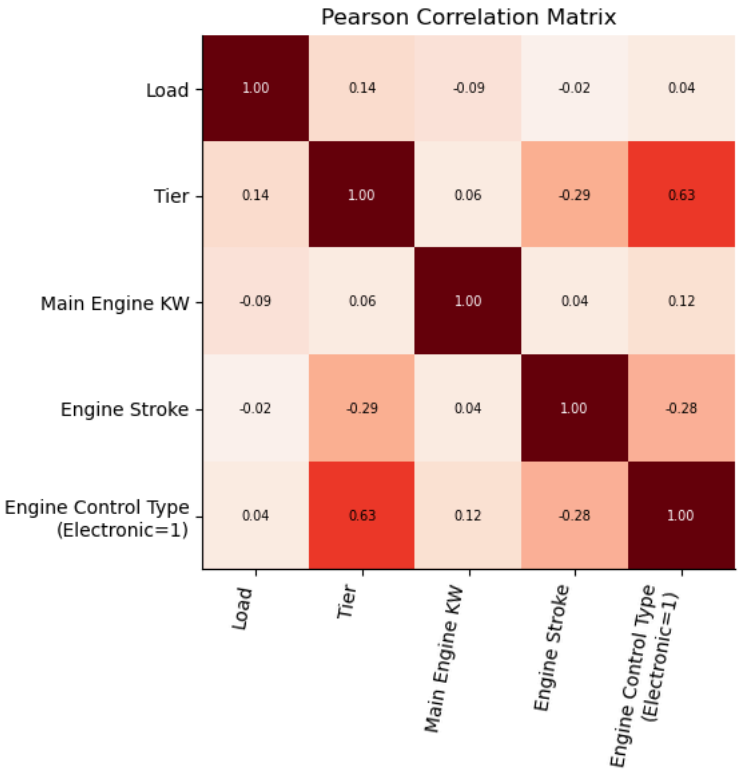

Figure S3. Pearson correlation coefficient matrix for explanatory variables.

Table S1. Mann-Whitney tests comparing observed emission rates from mechanical and electronically controlled engines.

				gNOx/kWh					
Engine Model	Tier	n Mechanical	n Electronic	Median MC (Mechanical)	Median ME (Electronic)	Delta (%)	r_{rb}	p	sig
12K98	I	24	1	20.61	28.75	39.5	-	-	-
5S50	II	33	209	8.43	12.70	50.7	0.789	0.000	***
5S60	I	94	1	10.48	11.03	5.3	-	-	-
5S60	II	42	147	9.01	14.05	55.9	0.742	0.000	***
6L70	I	123	208	13.55	15.34	13.2	0.337	0.000	***
6S35	II	3	7	7.99	4.74	-40.7	-	-	-
6S46	I	261	1	12.80	15.93	24.4	-	-	-
6S46	II	155	51	10.34	13.80	33.4	0.431	0.000	***
6S50	I	1068	5	13.08	18.50	41.5	0.614	0.014	*
6S50	II	114	625	9.79	15.29	56.2	0.688	0.000	***
6S60	I	791	13	10.40	12.32	18.5	0.374	0.021	*
6S60	II	126	312	9.02	16.96	88.1	0.808	0.000	***
6S70	I	134	55	12.98	15.26	17.6	0.272	0.003	**
6S70	II	17	299	8.63	26.85	211.0	0.821	0.000	***
7K80	I	9	15	11.19	20.25	81.1	0.748	0.003	**
7L70	I	39	3	14.73	14.61	-0.8	-	-	-
7S50	I	240	3	13.69	14.37	5.0	-	-	-
7S50	II	55	11	8.75	17.74	102.8	0.864	0.000	***
7S60	I	406	62	10.80	12.45	15.4	0.344	0.000	***
7S60	II	11	40	8.42	17.98	113.6	0.909	0.000	***
7S70	I	22	10	14.86	12.59	-15.3	-0.364	0.108	ns
8K90	I	10	3	14.36	18.35	27.8	-	-	-
8S35	I	11	27	11.31	14.76	30.5	0.556	0.008	**
8S50	I	61	17	14.34	17.21	20.1	0.439	0.006	**

Table S2. Explanations of regression variables used

Variable	Interpretation relative to reference category	Notes
Load and Load^2	Effect of relative main engine load (ranging between 0 and 100 %) on NOx emission rates (g/kWh). Statistically significant coefficients for both the linear and quadratic terms would indicate a nonlinear relationship between NOx emissions and main engine load. The nonlinear relationship is expected to exhibit a nonsymmetrical U-shaped curve based on literature and engine certification results.	Coefficients cannot be interpreted separately without considering both terms.
Tier	IMO NOx engine tier: Tier 0, I, and II, with Tier I being the reference category in the model. Based on the intent of the IMO regulation, a positive coefficient is expected for Tier 0 engines, which would indicate higher NO emission rates for Tier 0 than Tier I engines, whereas a negative coefficient is expected for Tier II engines, which would indicate lower NO emission rates for Tier II than Tier I engines.	The measurements data do not include a sufficient number of Tier III samples; therefore, Tier III are excluded from the analysis.
Stroke	Number of strokes of a main engine: either 2 or 4 strokes, with 2-stroke engine being the reference category in the model. Because 2-stroke ship engines tend to be slow-speed engines (i.e., fewer revolutions per minute, or RPM) and IMO NOx limits are higher for lower-speed engines, 2-stroke engines can be expected to emit NOx at a higher rate than 4-stroke engines; in other words, a negative coefficient is expected for 4-stroke with 2-stroke engines as the reference.	
log Main Engine kW	Change in NOx emission rate per log-unit increase in installed main engine power.	Larger engines may have different design/operation patterns.
Engine Control Type	A binary variable representing the engine control type: either mechanical or electronic, with mechanical control being the reference category in the model (“me” = 0). A significant coefficient would indicate a difference in mean NOx emission rates for electronically controlled compared to mechanically controlled engines.	This variable is only available for ship engines designed by MAN or Wärtsilä. Additionally, it is correlated with Tier — multicollinearity could inflate standard errors; VIF tests indicate acceptable but not negligible correlation.
Vessel Type	Fixed effects to control for differences in NOx emission rates associated with specific vessel types that are typically distinguished by the type of cargo a ship is designed to transport. The measurements data include the	Simple univariate regressions indicate potentially significant differences in NOx emission rates among different vessel types. The

	following ship types: container ships, bulk carriers, cruise ships, general cargo carriers, reefers, roll-on/roll-off vessels (ro-ro), and tankers, with container ships being the reference category in the model. The cargo type can affect a ship's operational pattern (e.g., liner vs. tramper), energy demand from a ship's main and/or auxiliary engines (e.g., energy needed for refrigerated cargos on a reefer or a container ship), etc.	effects observed in univariate regressions may be partially attributable to other control variables that correlate with vessel type (e.g., engine kW and stroke); however, the "vessel type" variable controls for additional, unobserved fixed effects that may contribute to NOx emission rates.
Year of Observation	Fixed effects to control for the year in which the measurements were taken. Controls for unobserved differences in the measurements year-to-year.	

Table S3: Regression model estimates of NOx emission rates, in gNOx/kWh, including fixed effects and interaction variables.

	1	1a	2	3	4	5
Intercept	1.101	-1.852	-0.695	0.996	-1.173	0.724
	(1.209)	(1.661)	(1.461)	(1.489)	(1.460)	(1.484)
Load	-11.465***	-10.887***	-8.643***	-6.164***	-7.781***	-5.988***
	(1.239)	(1.337)	(1.088)	(1.065)	(1.056)	(1.065)
Load^2	7.969***	7.562***	5.992***	4.512***	6.176***	5.053***
	(0.889)	(0.956)	(0.793)	(0.783)	(0.804)	(0.796)
Tier 0 (ref. Tier I)	2.371***	2.052***	2.431***	2.156***	2.485***	2.270***
	(0.280)	(0.426)	(0.427)	(0.371)	(0.426)	(0.359)
Tier II (ref. Tier I)	1.238***	1.625***	-0.581**	-0.091	-0.480**	-0.139
	(0.221)	(0.231)	(0.235)	(0.227)	(0.239)	(0.253)
4S Engine (ref. 2S)	-1.803***	-1.284***	-1.023***	-0.876***	-1.047***	-0.775***
	(0.168)	(0.235)	(0.212)	(0.187)	(0.213)	(0.189)
log Main Engine kW	1.573***	1.823***	1.570***	1.450***	1.553***	1.381***
	(0.116)	(0.161)	(0.142)	(0.141)	(0.141)	(0.148)
Electronic Control			3.427***	2.895***	5.442***	5.864***
			(0.227)	(0.207)	(0.464)	(0.684)
Electronic Control: Load					-3.174***	-2.715***
					(0.548)	(0.493)
Electronic Control: Bulk Carrier						-1.733***
						(0.566)
Electronic Control: Cruise						-4.658***
						(0.902)
Electronic Control: General Cargo						-2.075***
						(0.622)
Electronic Control: Reefer						-0.925
						(0.803)
Electronic Control: Ro-Ro						-3.528***
						(1.021)
Electronic Control: Tanker						-0.837
						(0.574)
Bulk Carrier				-1.756***		-0.980***
				(0.320)		(0.302)
Cruise				-4.916***		-3.602***
				(0.480)		(0.452)
General Cargo				-1.470***		-0.884***
				(0.336)		(0.330)
Reefer				-2.618***		-2.168***
				(0.454)		(0.566)
Ro-Ro				-0.518		0.359
				(0.504)		(0.446)
Tanker				-1.674***		-1.230***
				(0.293)		(0.272)
Year = 2019	0.662***	0.768***	0.737***	0.606***	0.728***	0.607***
	(0.127)	(0.157)	(0.136)	(0.115)	(0.136)	(0.112)
Year = 2020	0.708***	0.753***	0.692***	0.467***	0.671***	0.460***
	(0.144)	(0.161)	(0.146)	(0.134)	(0.144)	(0.129)
Year = 2021	0.924***	1.072***	1.033***	0.819***	1.031***	0.833***
	(0.150)	(0.165)	(0.147)	(0.134)	(0.145)	(0.130)
Year = 2022	-1.897***	-2.078***	-2.213***	-2.259***	-2.221***	-2.306***
	(0.183)	(0.204)	(0.189)	(0.189)	(0.191)	(0.196)

	1	1a	2	3	4	5
Year = 2023	-0.734***	-0.585***	-0.648***	-0.666***	-0.659***	-0.641***
	(0.146)	(0.164)	(0.142)	(0.129)	(0.141)	(0.127)
Year = 2024	-1.002***	-0.958***	-0.980***	-1.072***	-0.991***	-1.056***
	(0.176)	(0.192)	(0.175)	(0.163)	(0.175)	(0.160)
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Vessel Type Fixed Effects	No	No	No	Yes	No	Yes
Sample	Full	EC	EC	EC	EC	EC
Clustered Standard Error	Vessel	Vessel	Vessel	Vessel	Vessel	Vessel
N	14,977	11,977	11,977	11,977	11,977	11,977
R-squared	0.247	0.206	0.280	0.321	0.285	0.337
R-squared Adj.	0.246	0.205	0.279	0.32	0.285	0.335

Standard errors in parentheses. * p<0.1, ** p<0.05, ***p<0.01

EC: Vessels with known engine control type

Table S4: Regression model estimates of NOx emission rates, in gNOx/kg-Fuel, including fixed effects and interaction variables.

	1	1a	2	3	4	5
Intercept	-9.111	-26.087***	-19.316**	-8.781	-21.627***	-9.722
	(6.776)	(9.492)	(8.310)	(8.421)	(8.325)	(8.436)
Load	-17.896***	-14.258**	-1.129	13.121**	3.043	13.303**
	(6.450)	(7.134)	(5.833)	(5.747)	(5.767)	(5.846)
Load^2	15.112***	12.518**	3.33	-5.193	4.222	-2.294
	(4.688)	(5.153)	(4.297)	(4.267)	(4.403)	(4.382)
Tier 0 (ref. Tier I)	9.472***	7.687***	9.908***	8.380***	10.168***	9.083***
	(1.510)	(2.291)	(2.295)	(2.033)	(2.295)	(1.966)
Tier II (ref. Tier I)	7.464***	9.666***	-3.244**	-0.412	-2.757**	-0.768
	(1.289)	(1.345)	(1.355)	(1.315)	(1.376)	(1.471)
4S Engine (ref. 2S)	-13.972***	-11.255***	-9.724***	-8.724***	-9.843***	-8.098***
	(0.952)	(1.298)	(1.166)	(1.050)	(1.172)	(1.063)
log Main Engine kW	9.026***	10.463***	8.985***	8.223***	8.901***	7.806***
	(0.655)	(0.923)	(0.808)	(0.798)	(0.805)	(0.843)
Electronic Control			20.055***	16.998***	29.810***	32.336***
			(1.306)	(1.196)	(2.575)	(3.880)
Electronic Control: Load					-15.366***	-12.355***
					(3.049)	(2.782)
Electronic Control: Bulk Carrier						-10.572***
						(3.270)
Electronic Control: Cruise						-27.430***
						(5.086)
Electronic Control: General Cargo						-12.185***
						(3.559)
Electronic Control: Reefer						-5.145
						(4.466)
Electronic Control: Ro-Ro						-19.867***
						(5.556)
Electronic Control: Tanker						-5.268
						(3.329)
Bulk Carrier				-10.333***		-5.641***
				(1.851)		(1.710)
Cruise				-28.343***		-20.558***
				(2.739)		(2.543)
General Cargo				-8.978***		-5.515***
				(1.903)		(1.834)
Reefer				-15.149***		-12.569***
				(2.493)		(3.081)
Ro-Ro				-3.714		1.296
				(2.718)		(2.389)
Tanker				-9.726***		-7.011***
				(1.700)		(1.546)
Year = 2019	3.836***	4.396***	4.212***	3.472***	4.171***	3.491***
	(0.725)	(0.888)	(0.763)	(0.655)	(0.764)	(0.637)

	1	1a	2	3	4	5
Year = 2020	4.133***	4.364***	4.007***	2.729***	3.905***	2.701***
	(0.819)	(0.919)	(0.830)	(0.766)	(0.821)	(0.737)
Year = 2021	5.301***	6.177***	5.950***	4.733***	5.938***	4.828***
	(0.848)	(0.942)	(0.836)	(0.770)	(0.828)	(0.745)
Year = 2022	-10.800***	-11.734***	-12.525***	-12.760***	-12.564***	-13.030***
	(1.018)	(1.175)	(1.086)	(1.060)	(1.096)	(1.092)
Year = 2023	-4.087***	-3.331***	-3.696***	-3.769***	-3.749***	-3.634***
	(0.827)	(0.944)	(0.816)	(0.745)	(0.814)	(0.732)
Year = 2024	-5.632***	-5.510***	-5.640***	-6.139***	-5.695***	-6.053***
	(0.995)	(1.107)	(1.005)	(0.934)	(1.003)	(0.918)
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Vessel Type Fixed Effects	No	No	No	Yes	No	Yes
Sample	Full	MW	MW	MW	MW	MW
Clustered Standard Error	Vessel	Vessel	Vessel	Vessel	Vessel	Vessel
N	14,977	11,977	11,977	11,977	11,977	11,977
R-squared	0.268	0.211	0.287	0.328	0.291	0.342
R-squared Adj.	0.268	0.21	0.286	0.327	0.29	0.341

SFOC Discussion

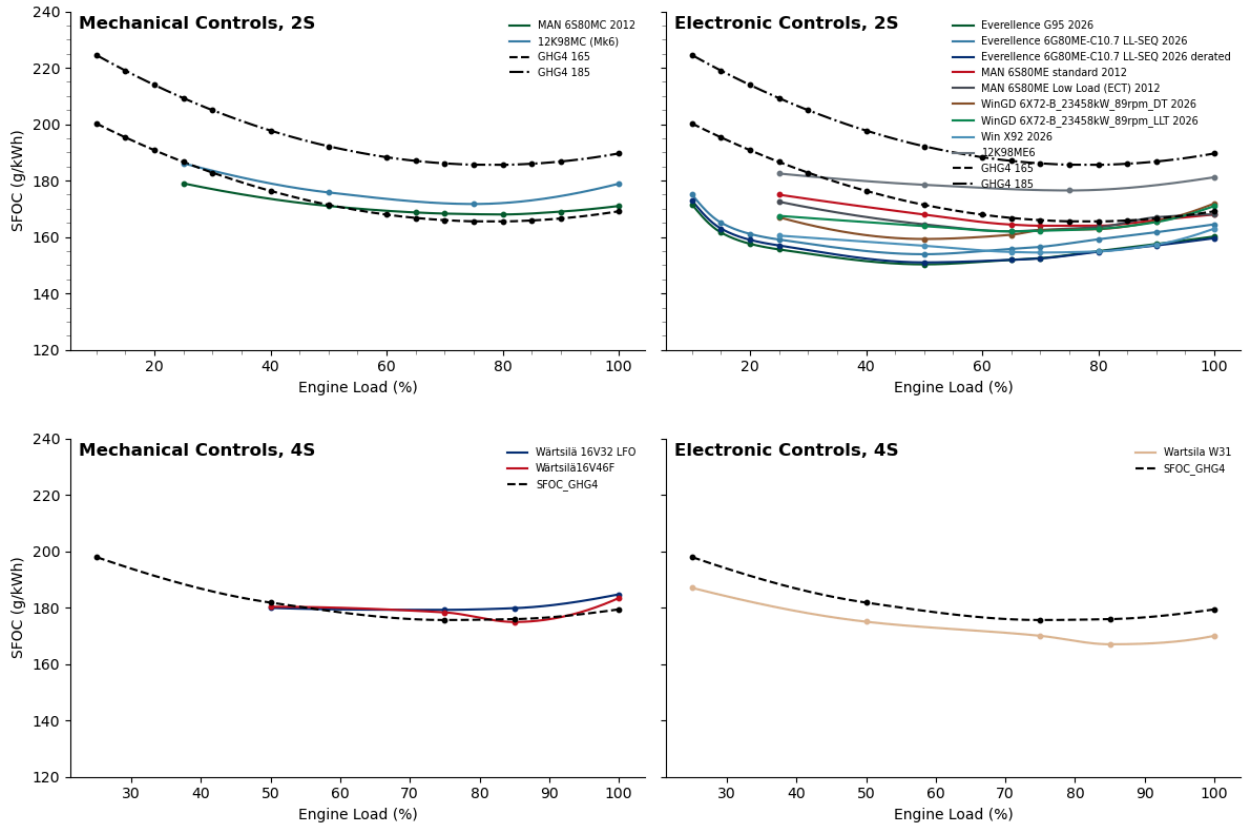

Fig S4. SFOC curves for two-stroke (top panel) and four-stroke (bottom panel) engines are obtained from engine project catalogues. K98 data are derived from published empirical measurements and curves from the IMO GHG4 Study ($SFOC_{Base}$: 165 and 185 g/kWh) show the typically modeled range.

Figure S4 compares SFOC data from engine catalogues and real measurements for K98 engines from two build years (Cheng et al., 2018) against the IMO GHG4 Study reference curves (base SFOC: 165 and 185 g/kWh), illustrating the potential modeled range. Deviations are largest for 2-stroke engines at low loads, reaching approximately 20% at 20% engine load, and diminish at higher loads. Modeled and measured SFOC values should be compared using the same $SFOC_{Base}$. The IMO GHG4 function describes only the shape of the modeled SFOC–load relationship at two $SFOC_{Base}$ values. Direct comparison would apply each engine's manufacturer-specified $SFOC_{Base}$ to generate like-for-like curves. The two reference curves shown here approximate this range.

Figure S5 shows the ratio of NOx emissions (gNOx/kg-fuel) between electronically and mechanically controlled engines by vessel type, derived from Model 5 coefficients. Ratios range from 1.32–1.45 at 10% load (Bulk Carrier to Reefer), 1.23–1.35 at 50% load (Bulk Carrier to Container Ship), and 1.17–1.30 at 75% load (Bulk Carrier to Container Ship). Even accounting

for SFOC uncertainty, these ratios confirm that the emissions gap between electronically and mechanically controlled engines remains substantial across all vessel types and load conditions.

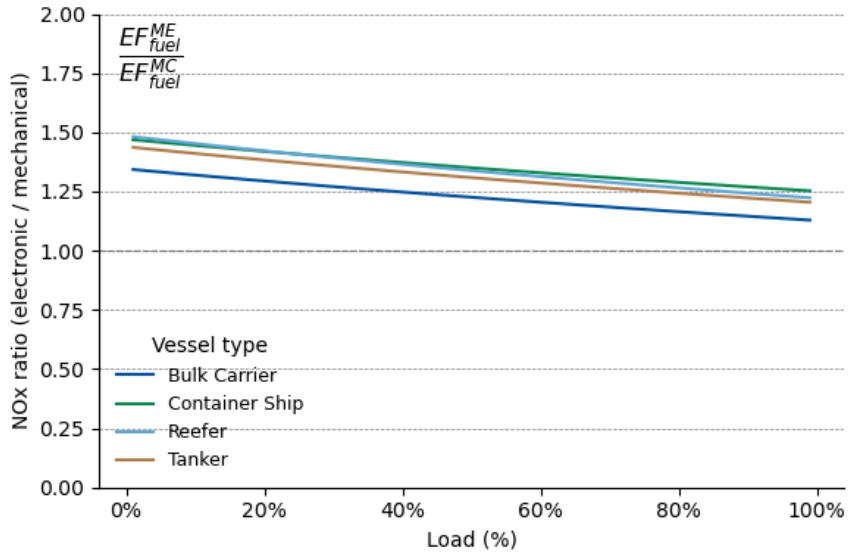

Fig S5. Ratio of estimated NOx emissions (gNOx/kg-Fuel) for selected vessel types using Model 5 regression coefficients. Curves show the NOx ratio is higher at low loads for Electronically Controlled (ME) engines relative to Mechanically Controlled (MC) engines.

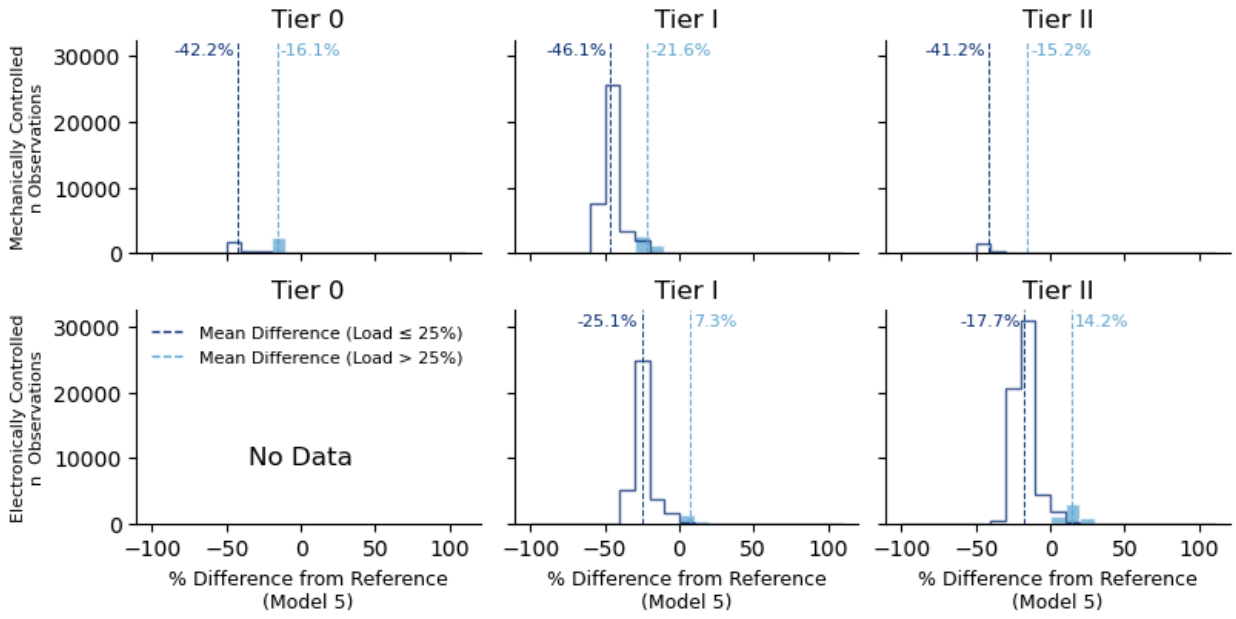

Figure S6: Fleet-level differences in regression-estimated emission rates for container ships calling at the San Pedro Bay Ports in 2014. n represents the number of AIS observations from which emissions were estimated. Histograms show as % deviations from standard emission factors used in emission inventory models, across engine tiers for electronically and mechanically controlled engines.