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SFC-Based Harmonisation of Entec and Trozzi–Vaccaro Ship CO_2 Emission Factors: Vessel-Category-Specific SFC Equivalence Thresholds

Kadir Mersin

Department of Logistics Management, Istanbul Gelisim University, Istanbul 34310, Türkiye; kmersin@gelisim.edu.tr

Abstract

This study examines how published cruising CO_2 factors from Entec UK Ltd. and Trozzi–Vaccaro can be compared on a common engine-energy basis. Multiplication of the Trozzi–Vaccaro factor of 3.2 g CO_2/g fuel by specific fuel consumption (SFC) gives an energy-based factor. Equating this with six Entec category factors yields implied SFC thresholds of 195.94–215.63 g fuel/kWh. A grid of 42 deterministic comparisons illustrates this algebraic relationship; it is not independent validation. The contribution is a diagnostic procedure that links factor differences to conditional inventory consequences and tests whether their ordering survives bounded input changes. A matched-energy container example at an assumed SFC of 190 g/kWh produces 63.5 versus 60.8 t CO_2 per 100,000 kWh. Allowing SFC to vary by ±5% reverses the factor ordering within that example. Independent ±1% changes in the two category factors also make the oil-tanker and Ro-Pax threshold intervals overlap. The thresholds therefore indicate numerical agreement under stated assumptions, rather than physical equivalence, measured vessel efficiency or superior method accuracy. Operational use requires compatible fuel, engine-work and system boundaries, together with verified SFC data.

Keywords: maritime emissions; CO_2 emission factors; specific fuel consumption; method harmonisation; vessel categories

1. Introduction

Maritime transport carries more than 80% of international merchandise trade by volume [1]. Total shipping accounted for approximately 2.89% of global anthropogenic CO_2 emissions in 2018 [2]. Reliable interpretation of ship-emission estimates requires explicit information about fuel consumption, engine work and operating conditions [3].

Ship-emission estimates may be developed from fuel consumption or from vessel activity and technical characteristics. Entec UK Ltd. and Trozzi–Vaccaro are established approaches, but the particular source version, operational mode and factor definition must be specified before comparing their outputs [3–7].

Emission inventories are used to describe the scale and distribution of shipping emissions and to support air-quality and climate policy. Their results depend on how vessel activity, engine performance, fuel consumption and emission factors are represented. Fuel-based and activity-based approaches therefore answer related but not identical questions: one begins with fuel use or fuel sales, while the other reconstructs emissions from vessel characteristics and operating activity. Recent methodological comparisons and inventory

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studies show that the selected approach and its input data can materially affect the resulting estimates [8–13].

These two methods use different calculation bases. The Entec UK Ltd. gives emission factors per unit of energy, and the value varies depending on the ship type. Trozzi–Vaccaro, on the other hand, gives the CO_2 factor per unit of fuel mass, i.e., kg CO_2/ton of fuel.

A direct numerical comparison requires care because a factor expressed per tonne of fuel cannot be compared with a factor expressed per unit of engine work until both are expressed on the same basis. Even after conversion, agreement in units does not make the underlying methods identical: their source factors, vessel classifications and operational assumptions remain method-specific. The present analysis therefore compares the factors on a common energy basis and interprets the resulting differences only within the stated cruising scope.

Indeed, when Ülker et al. [3] applied the Entec and Trozzi–Vaccaro methods to the same Ro-Ro and ferry routes, they calculated the annual CO_2 emissions to be 204,470.99 and 170,459.85 tonnes, respectively. However, the fact that the results differ does not explain under what conditions the difference changed direction. In other words, the main question is not merely how different the results of the Entec and Trozzi–Vaccaro are. The relevant questions are at what SFC value do the two methods yield equivalent factors, and which method yields the higher factor below and above that threshold?

A difference between complete inventories can arise from activity data, engine assumptions and fuel estimates, as well as emission factors. The present comparison isolates the factor component while holding the engine-energy basis constant. It cannot attribute the difference reported by Ülker et al. [3] to SFC alone.

The objective is to formulate a transparent diagnostic for comparing the selected published factors, identify their implied SFC crossovers and determine when a statement about their ordering remains defensible under bounded changes in the inputs.

The conversion and its inverse are elementary algebra. The quantity termed method-equivalent SFC (SFCeq) is the SFC implied by an Entec category factor when the Trozzi–Vaccaro carbon conversion is imposed. The contribution is the combined use of this diagnostic, a matched-energy inventory example and a bounded ordering test. Six vessel categories and seven SFC levels yield 42 illustrations of the same relationship. No claim is made that these scenarios independently substantiate the equation or constitute a new physical emission model.

2. Literature Review

Fuel consumption and emissions from ships have been widely studied in the maritime industry. In recent years, the IMO has focused on reducing greenhouse gas emissions from ships, particularly emissions from ship exhausts. The Energy Efficiency Design Index (EEDI) has also been implemented.

Studies on air emissions from ships predate current climate policies. Kelly et al. [14] calculated NO_x, SO_2, CO, hydrocarbon, and particulate emissions from marine activities in California coastal waters. By examining the activities of commercial ships, they determined emissions for individual activities. This study is one of the early examples of calculating marine emissions by activity.

Corbett and Fischbeck [15] studied ship emissions worldwide. They showed that international shipping is a significant source of NO_x and SO_x.

Trozzi and Vaccaro [4,5] describe fuel-based estimation, whereas the Entec approach combines vessel activity with power-based factors [7]. Applications such as Ülker et al. [3] and Hussain et al. [16] estimate emissions for routes or ports. Reviews of CO_2 reduction measures [17] and vessel EEDI performance [18] address different operational and design

questions. These studies provide context, but do not by themselves establish the practical value of a crossover derived from published category factors.

Inventory methods differ in data requirements, spatial and temporal resolution and the vessel detail represented. Li et al. [8] compare five methods and recommend selecting an approach according to the inventory purpose and available data. The EMEP/EEA guidebook [9] provides a structured basis for compiling navigation inventories. Such comparisons concern the full estimation chain; a common-unit factor comparison isolates only one part of that chain.

Recent work has emphasised that uncertainty can arise at several stages of an activity-based estimate. A systematic review of AIS-based bottom-up studies grouped important sources into AIS data acquisition and processing, ship particulars and engine-load calculation, and the selection of emission factors [10]. High-resolution inventory models consequently combine vessel trajectories with technical specifications, engine-performance assumptions and pollutant factors; updated global inventories demonstrate how such inputs are used in vessel-by-vessel simulations [11]. These studies improve the detail of total-emission estimates, but their outputs do not by themselves provide a common-unit comparison of the Entec and Trozzi–Vaccaro CO_2 factors.

Recent operational methodologies also make the role of SFC explicit. The OECD's 2025 update estimates vessel fuel use from observed activity and engine efficiency before applying fuel-specific CO_2 factors [12]. A 2026 review of ship-emission estimation models identifies continuing challenges in data quality and method selection across top-down, bottom-up and hybrid approaches [13]. Together, this literature supports the need to state clearly which quantities are being compared, how units are harmonised and which assumptions are held constant.

SFC-based conversion between fuel and engine-energy quantities is already part of inventory practice. Entec's earlier technical report explicitly describes the reverse conversion by dividing power-based factors by SFC [19], and the OECD methodology multiplies engine power by SFOC before applying fuel-specific carbon factors [12]. Thus unit conversion itself is not claimed as novel. Relative to comparisons of complete inventory estimates [3,8], this study isolates factor ordering and adds a bounded test of whether that ordering is distinguishable. It does not claim that all earlier literature omitted SFC conversion or that no prior threshold analysis exists.

3. Emission Estimation Methods

The Entec UK Ltd. and Trozzi–Vaccaro methods are two widely used approaches for estimating ship-source exhaust emissions.

3.1. Trozzi and Vaccaro Method

The selected fuel-based formulation follows Trozzi and Vaccaro [4,5]. Later work also accommodates installed-capacity approaches [6]; the present comparison concerns the fixed cruising carbon factor in [5], rather than every version of the wider methodology.

$$E_i = \sum_{j,k,l,m} S_{jklm} t_{jklm} F_{ijlm} \quad (1)$$

$$S_{jklm} = C_{jkl} p_m \quad (2)$$

Here i denotes pollutant, j fuel, k vessel category, l engine type and m operating mode. E_i is total pollutant mass (kg); S_{jklm} is the mode-specific fuel-consumption rate (t fuel/day); t_{jklm} is duration (day); F_{ijlm} is the fuel-based factor (kg pollutant/t fuel); C_{jkl} is the reference full-load fuel-consumption rate (t fuel/day); and p_m is a dimensionless mode coefficient. The indices summed on the right do not remain free on the left. If an inventory contains

multiple vessels in a category, its rates and durations must be summed at vessel level or aggregated without multiplying independent category totals. These inventory equations provide context and are not inputs to the 42 factor comparisons.

The estimated cruising-mode emission factors for different engine types are shown in Table 1 [5].

Table 1. Trozzi–Vaccaro emission factors in cruising mode (kg pollutant/t fuel). Source: Trozzi and Vaccaro [5].

Engine Type	NO_x	CO_2	VOC	PM	SO_x
Steam Turbine—BFO	6.98	3200	0.085	2.50	54
Steam Turbine—MDO	6.25	3200	0.50	2.08	10
High-speed diesel—MDO	60	3200	1.0	0.52	10
Medium-speed diesel—MDO	57	3200	2.4	1.2	10
Slow-speed diesel—BFO	87	3200	2.4	7.6	54

All entries are expressed in kg pollutant/t fuel. The diesel rows correspond to high-speed MDO, medium-speed MDO and slow-speed BFO operation in the source. Only the CO_2 column enters this study.

3.2. The Entec UK Limited Method

For an activity-based inventory, emissions are obtained by multiplying engine work by a compatible energy-based factor and summing across engines. Equation (3) states this general relationship, without imposing a universal main/auxiliary-engine weighting [7,12].

$$M_{CO_2} = 10^{-6} \sum_{e} Q_e \, EF_e \quad (3)$$

MCO_2 is CO_2 mass in tonnes; $Q_e = \int P_e(t)dt$ is engine work in kWh; EF_e is in g CO_2/kWh; and e identifies an engine or a consistently defined aggregate. Time must be expressed in hours when integrating power in kW. Separate engines generally require separate fuel and efficiency assumptions. A single category factor may replace them only for an explicitly matched aggregate energy boundary.

The main analysis compares category factors. Section 5.3 adds a conditional calculation on a common energy basis to illustrate a possible inventory consequence; it does not reconstruct either original inventory or estimate emissions of an observed voyage.

The six category factors are taken from Entec's August 2005 final report ([7], Annex B, Table B.3, p. B-5; PDF p. 130). They describe the year-2000 at-sea baseline, not conditions measured in 2005 or the present fleet. The source codes are A21 Bulk Dry, A33 Container, A12 Chemical, A35 Ro-Ro Cargo, A13 Oil and A36 Passenger/Ro-Ro Cargo. These map to the six study labels in Table 2; Ro-Pax is the study shorthand for the source's passenger/Ro-Ro cargo category. Size, build year and within-category engine variation are not resolved by this mapping.

The factors are category averages, not engine-specific measurements. Entec ([7], Section 2.3.1, p. 13) states that they reflect average main- and auxiliary-engine composition and expected loads. Table B.2 (p. B-4) assumes at-sea main-engine operation at 80% MCR, all main engines operating, 50% of electrical power from shaft generators and auxiliary-engine operation at 30% MCR. These assumptions define the historical aggregate; they do not describe every individual vessel. Table B.16 (p. B-17) gives fuel-based CO_2 factors of 3178 kg/t for marine distillates and 3179 kg/t for residual oil. Therefore, imposing the Trozzi–Vaccaro coefficient of 3200 kg/t changes the carbon-conversion basis. SFCeq denotes numerical agreement on that imposed basis and need not equal Entec's tabulated SFC.

Table 2. Entec year-2000 at-sea CO_2 factors from the 2005 report ([7], Table B.3, p. B-5).

Study Vessel Category	Corresponding Entec Category	Cruising CO_2 Factor (g CO_2/kWh)
Bulk carrier	Bulk Dry	627
Container ship	Container	635
Chemical tanker	Chemical	650
Ro-Ro cargo	Ro-Ro Cargo	655
Oil tanker	Oil	690
Ro-Pax	Passenger/Ro-Ro Cargo	688

4. Materials and Methods

This study compares the Entec UK Ltd. and Trozzi–Vaccaro methods for estimating ship emissions. The methods use different activity bases: Entec expresses its emission factors per unit of engine energy, whereas Trozzi–Vaccaro expresses them per unit of fuel consumed. Their emission factors therefore require unit harmonisation before they can be compared directly [3,5–7,16].

The main calculation converts the selected fuel-based CO_2 factor to g CO_2/kWh and compares it with each Entec category input. Additional analyses hold engine work constant in an illustrative inventory decision and examine bounded changes in the factors and SFC. No observed vessel or fleet dataset is used.

The analysis is limited to CO_2 emissions; NO_x, SO_x, PM, VOCs and other pollutants are not considered. Six vessel categories are examined: bulk carriers, container ships, chemical tankers, Ro-Ro cargo vessels, oil tankers and Ro-Pax vessels.

4.1. SFC-Based Harmonisation

The key difference between the Entec and Trozzi–Vaccaro methods is the activity unit used to express their CO_2 emission factors. Entec reports its factors in g CO_2/kWh, whereas Trozzi–Vaccaro reports them in kg CO_2 per tonne of fuel [5,7]. The Trozzi–Vaccaro factor is therefore converted to an energy-based unit using specific fuel consumption (SFC).

Because SFC is expressed in g fuel/kWh, the fuel-based Trozzi–Vaccaro CO_2 factor can be converted to an energy-specific factor as follows:

$$EF_{CO_2}^{TV,SFC} = SFC\frac{EF_{CO_2}^{TV}}{1000} \quad (4)$$

where $EF_{CO_2}^{TV,SFC}$ denotes the Trozzi–Vaccaro CO_2 factor converted to an energy basis using SFC.

According to Table 1, the Trozzi–Vaccaro cruising CO_2 factor is 3200 kg CO_2 per tonne of fuel [5]. The SFC-converted Trozzi–Vaccaro CO_2 factor can therefore be written as:

$$3200\frac{kgCO_2}{t\ fuel} = 3.2\frac{kgCO_2}{kg\ fuel} = 3.2\frac{gCO_2}{g\ fuel}$$

Thus,

$$EF_{CO_2}^{TV,SFC} = 3.2SFC \quad (5)$$

Equations (4) and (5) are used solely to harmonise the units; they do not modify the Trozzi–Vaccaro method. In the original formulation, the CO_2 emission factor is expressed per unit mass of fuel, while the operational-mode coefficient scales fuel consumption [5,6]. The present conversion uses SFC to express the fuel-based factor per unit of engine energy, leaving the original Trozzi–Vaccaro emission factor unchanged.

The next step is to identify the SFC at which the energy-based CO_2 factors from the two methods are equal. This threshold, termed the method-equivalent SFC (SFCeq), is defined in Equation (6), where k denotes the vessel category. Equations (5) and (6) are used to calculate SFCeq for each category.

$$EF_{CO_2,k}^{ENTEC} = EF_{CO_2}^{TV,SFC} \quad (6)$$

Using Equations (5) and (6), the vessel-category-specific method-equivalent SFC is obtained as follows:

$$SFC_{eq,k} = \frac{EF_{CO_2,k}^{ENTEC}}{3.2} \quad (7)$$

SFCeq is not an SFC value measured on a particular vessel. It is the mathematical threshold at which the Entec factor and the SFC-converted Trozzi–Vaccaro factor are equal, both expressed in g CO_2/kWh. The scenario SFC can therefore be below, equal to or above SFCeq.

$$SFC_s < SFC_{eq,k} \Rightarrow EF_{CO_2,k}^{ENTEC} > EF_{CO_2,s}^{TV,SFC} \quad (8a)$$

SFCeq is an implied SFC conditional on the chosen carbon coefficient and category factor. It is not a measured vessel value, an efficiency target or a boundary between acceptable and unacceptable operation. If the source factor already embodies an SFC assumption, inversion recovers that assumption after adjustment for the imposed carbon conversion. Equality in g CO_2/kWh is a numerical crossover; physical comparability additionally requires the same fuel definition and engine-work boundary.

$$SFC_s = SFC_{eq,k} \Rightarrow EF_{CO_2,k}^{ENTEC} = EF_{CO_2,s}^{TV,SFC} \quad (8b)$$

$$SFC_s > SFC_{eq,k} \Rightarrow EF_{CO_2,k}^{ENTEC} < EF_{CO_2,s}^{TV,SFC} \quad (8c)$$

4.2. SFC Scenario Design

To examine how the difference between the Entec and Trozzi–Vaccaro factors varies with SFC, seven SFC levels were selected: 170, 180, 190, 200, 210, 220 and 230 g fuel/kWh. Each level was applied to all six vessel categories. The analysis covers CO_2 emissions during cruising.

The scenarios do not represent measured fuel-consumption values for specific vessels. Instead, they form a sensitivity analysis in which SFC is varied systematically while the Entec CO_2 factor for each vessel category is held constant.

The scenario grid is designed to bracket all six nominal crossovers, rather than represent the SFC distribution of six vessel populations. Its limits of 170 and 230 g fuel/kWh extend approximately 26 g/kWh below the lowest and 14 g/kWh above the highest nominal threshold. The 10 g/kWh spacing provides a readable common grid; the exact crossings are calculated analytically and are not limited by this spacing. No frequency, probability or fleet representativeness is assigned to the grid.

$$EF_{CO_2,s}^{TV,SFC} = 3.2SFC_s \quad (9)$$

where s denotes the SFC assigned to a scenario. The seven SFC scenarios and their corresponding SFC-converted Trozzi–Vaccaro CO_2 factors are summarised in Table 3.

At a given SFC, the Trozzi–Vaccaro factor is the same for all vessel categories because the original method uses a cruising CO_2 factor of 3200 kg CO_2 per tonne of fuel. By contrast, the Entec cruising factors vary by vessel category. The values used in this study are 627, 635, 650, 655, 690 and 688 g CO_2/kWh, respectively.

Table 3. Definition of SFC scenarios.

Scenario	SFC (g Fuel/kWh)	SFC-Converted T-V CO_2 Factor (g CO_2/kWh)
S1	170	544
S2	180	576
S3	190	608
S4	200	640
S5	210	672
S6	220	704
S7	230	736

For each vessel k and SFC scenario s, the difference between the two factors is calculated as follows:

$$\Delta EF_{k,s} = E_k - EF_s^{TV,SFC} = E_k - 3.2\ SFC_s \quad (10)$$

A positive difference indicates that the Entec factor is higher; a negative difference indicates that the SFC-converted Trozzi–Vaccaro factor is higher. A value of zero indicates that the two factors are equal.

In Equation (10), E_k abbreviates the Entec cruising CO_2 factor for category k. The superscript TV,SFC identifies the converted Trozzi–Vaccaro factor. Both terms use g CO_2/kWh and the same engine-work denominator.

The SFC range is a diagnostic choice. Published operational methods make SFOC depend on engine/fuel characteristics and, for main engines, load [12]. Consequently, a common illustrative grid does not imply a common operating efficiency across vessel categories. Manufacturer data are used only in the explicitly limited benchmark below [20].

SFC denotes actual fuel mass per unit of engine work. For a liquid-fuel engine, SFOC can supply SFC only when its fuel mass, calorific reference, load and output boundary are compatible. A reference-fuel SFOC cannot automatically be interpreted as measured consumption of the fuel used on board. Gas energy consumption in kJ/kWh, pilot-oil consumption and oil-equivalent quantities must be treated separately; the liquid-fuel coefficient 3.2 is not applicable to an LNG energy-equivalent mass.

4.3. Reproducibility and Analytical Procedure

The analysis is a deterministic comparison of published emission factors, not an inventory of observed voyages or a measurement campaign. The Trozzi–Vaccaro cruising CO_2 factor is fixed at 3200 kg CO_2 per tonne of fuel, and the Entec factors are taken from the corresponding vessel categories in Table 2. The six-category mapping is held constant throughout the calculations. Seven SFC values, from 170 to 230 g fuel/kWh in 10 g/kWh increments, are applied to every category. No vessel-specific engine load, voyage duration or fuel-consumption record is used as an input.

For each SFC value, the fuel-based Trozzi–Vaccaro factor is converted to g CO_2/kWh by multiplying 3200 kg CO_2/t fuel by the SFC and applying the unit conversion shown in Equations (4) and (5). With the stated units, this reduces to 3.2 multiplied by SFC. The converted value is then compared separately with each Entec category factor. The difference is calculated as the Entec factor minus the converted Trozzi–Vaccaro factor; its sign identifies which factor is numerically higher. The equivalence threshold is obtained by solving the same equality for SFC, so SFCeq equals the Entec factor divided by 3.2. This produces six thresholds and 42 vessel-category/scenario comparisons.

Below SFCeq the Entec factor is higher; above it the converted Trozzi–Vaccaro factor is higher. None of the seven grid values equals any of the six nominal thresholds, so equality is defined analytically. All calculations use unrounded inputs; two decimal places in threshold tables indicate arithmetic reporting precision, not measurement certainty.

A load-specific reference is the Wärtsilä 8V31 diesel main engine at 750 rpm ([20], Section 3.2, pp. 3-2–3-4). Its HFO SFOC is 170.1 g/kWh at 85% load and 178.5 g/kWh at 50% load. These specifications use a lower calorific value of 42,700 kJ/kg, ISO 15550:2016 reference conditions [21], engine-driven pumps and a 5% tolerance. They describe reference engine performance, not measured ship consumption. Both values lie below the derived thresholds, illustrating why the 170–230 grid is a crossing diagnostic rather than a representative range. Dual-fuel headline values are excluded because fuel modes and energy-based gas consumption require separate treatment.

The Supplementary Materials include a Python 3.12.14 script and CSV tables that reproduce the 42 nominal comparisons, threshold sensitivity envelopes, and worked examples. The analysis uses arithmetic evaluation; no differential-equation solver, fitted stochastic model, or empirical validation is involved.

4.4. Bounded Sensitivity and Ordering Test

Let E_k denote the Entec factor, c the fuel-carbon coefficient (g CO_2/g fuel), and S the SFC (g fuel/kWh). Then $SFCeq_{,k} = E_k/c$ and $\Delta EF = E_k - cS$. The local sensitivities are

$$\frac{\partial SFCeq}{\partial E_k} = \frac{1}{c} \text{ and } \frac{\partial SFCeq}{\partial c} = \frac{-E_k}{c^2}.$$

The relative elasticities are +1 and −1, respectively. These derivatives quantify response to input changes; they do not assign uncertainty distributions.

For positive bounded inputs $E_k \in [E^-_k, E^+_k]$ and $c \in [c^-, c^+]$, the exact threshold envelope is $\left[\frac{E^-_k}{c^+}, \frac{E^+_k}{c^-}\right]$. For $S \in [S^-, S^+]$, the corresponding difference envelope is $\left[E^-_k - c^+S^+, E^+_k - c^-S^-\right]$.

Entec is higher throughout the specified set only if the lower bound is positive. Trozzi–Vaccaro is higher throughout only if the upper bound is negative. Otherwise, the ordering is unresolved within those bounds. Boundary values of zero admit equality.

Two factor tests are reported: $E_k \pm 1\%$ with c fixed, and $E_k \pm 10\%$ jointly with $c \pm 1\%$. The ±1% test examines the resolution of closely spaced category thresholds. The wider ± 10% perturbation is informed by the at-sea CO_2 factor uncertainty scale reported in the earlier Entec study ([19], Table 2.14, p. 23), but is used here as a deterministic stress test, not transferred as a confidence interval for the 2005 inputs. The ±1% carbon perturbation includes both Entec 2005 fuel coefficients, 3.178 and 3.179 ([7], Table B.16), within 3.168–3.232. These chosen bounds are neither a complete fuel-composition range nor probability distributions. For the illustrative inventory, SFC is varied by ±5% as an explicitly assumed input interval, not an inferred measurement error.

The rectangular factor bounds permit different category perturbations and simultaneous endpoint combinations. They are conservative and do not imply statistical independence. Shared fuel-carbon changes rescale all thresholds together and preserve their nominal ordering. Independently varying category factors can change the ordering. Correlated efficiency and carbon assumptions require a joint model before interpreting the bounds probabilistically.

5. Results

5.1. Vessel-Category-Specific Method-Equivalent SFC Thresholds

For each vessel category, SFCeq was calculated by equating the SFC-converted Trozzi–Vaccaro factor with the corresponding Entec CO_2 factor. This threshold marks the SFC at which the higher of the two factors changes. Figure 1 illustrates the nominal Entec and SFC-converted Trozzi–Vaccaro factors and their category-specific SFCeq crossings.

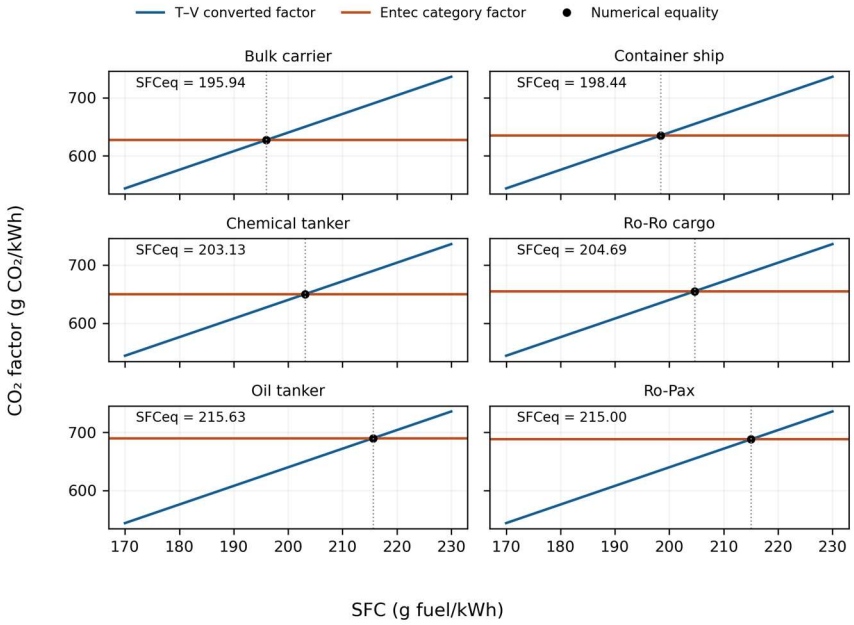


Figure 1. Nominal CO_2 factors (g CO_2/kWh). Dots mark SFCeq where each Entec category factor equals 3.2 × SFC. Entec is higher below each crossing; Trozzi–Vaccaro is higher above it. Equality is numerical and does not establish physical equivalence or accuracy.

The nominal SFCeq values range from 195.94 to 215.63 g fuel/kWh. They equal the Table 2 factors divided by 3.2 and describe numerical agreement conditional on those inputs. Oil tanker and Ro-Pax thresholds differ by only 0.625 g fuel/kWh before rounding; Section 5.3 examines whether such separation survives bounded perturbations.

Table 4 places the implied thresholds beside the SFC values reported in the same Entec table ([7], Table B.3). The reported SFC values are 197, 200, 204, 206, 217 and 217 g fuel/kWh in the study category order. SFCeq is lower by 0.875–2.000 g/kWh. This comparison confirms that the threshold is closely related to an existing source efficiency assumption, rather than a newly discovered physical boundary. Differences also reflect the imposed carbon coefficient, rounding and aggregation; the rounded category ratios should not be treated as exact fuel-carbon measurements. The source SFC values are historical category assumptions, not independent operating observations.

Table 4. Implied equivalence thresholds and reported Entec SFC values ([7], Table B.3). Differences use unrounded thresholds. All SFC values are in g fuel/kWh.

Vessel Type	Entec CO_2 Factor (g/kWh)	SFCeq (g Fuel/kWh)	Source SFC (g/kWh)	SFCeq − Source SFC (g/kWh)
Bulk carrier	627	195.94	197	−1.06
Container ship	635	198.44	200	−1.56
Chemical tanker	650	203.13	204	−0.88
Ro-Ro cargo	655	204.69	206	−1.31
Oil tanker	690	215.63	217	−1.38
Ro-Pax	688	215.00	217	−2.00

5.2. Scenario Matrix

Figure 2 reports $\Delta EF_{k,s} = E_k - 3.2SFC_s$ in g CO_2/kWh. Positive entries mean the Entec input is higher and negative entries mean the converted Trozzi–Vaccaro factor is higher. The 42 entries span −109 to +146 g CO_2/kWh. They are evaluations of Equation (10), rather than independent observations or 42 validation cases. A factor difference becomes a conditional mass difference only after multiplication by compatible engine work, as illustrated in Section 5.3.

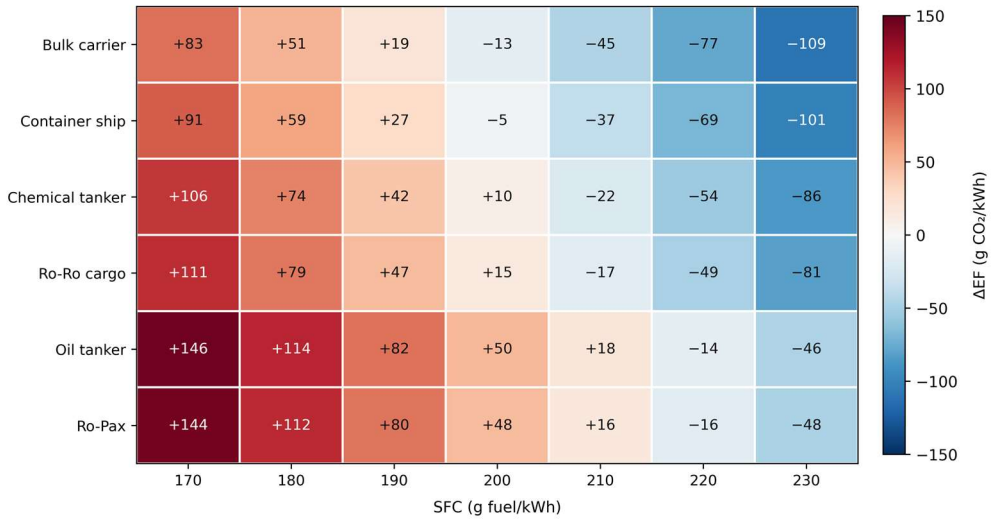


Figure 2. Nominal factor differences $\Delta EF_{k,s} = E_k - 3.2SFC_s$ (g CO_2/kWh) for six vessel categories and seven assumed SFC values (g fuel/kWh). Red positive cells indicate higher Entec factors; blue negative cells indicate higher converted Trozzi–Vaccaro factors. Cell values are factor differences, not voyage emissions or measurement residuals.

5.3. Inventory Illustration and Sensitivity Results

Consider an analyst comparing a container-category factor of 635 g CO_2/kWh with the selected fuel-based coefficient on the same assumed engine-work boundary Q = 100,000 kWh. Assume SFC = 190 g fuel/kWh, a liquid fuel to which c = 3.2 is applied, and identical engine-work coverage in both calculations. Boiler fuel is excluded from both, and Q represents the same included main/auxiliary engine brake work. Fuel mass is $QSFC/10^6$ = 19 t; the fuel-based result is 60.8 t CO_2. Applying the category factor to the same Q gives 63.5 t CO_2. The difference is 2.7 t, or 4.44% relative to the fuel-based value. This is an explicitly constructed, matched-boundary example, not a measured ship case or a reapplication of both complete source methodologies.

The inventory decision is whether the category factor can be described as consistently higher under the available SFC information. At SFC = 190 ± 5%, the input interval is 180.5–199.5 g/kWh. With fixed factors, the converted factor spans 577.6–638.4 g CO_2/kWh and ΔEF spans −3.4 to +57.4 g CO_2/kWh. Its mass consequence spans −0.34 to +5.74 t CO_2 on the same Q. Since the interval crosses zero, a single direction cannot be assigned. The analyst should report the interval or obtain narrower, compatible consumption data rather than select a method because it yields the preferred total.

For comparison, SFC = 180 ± 5% gives 171–189 g/kWh. Even with the container factor and c each varied by ±1%, ΔEF remains positive, between 17.802 and 99.622 g CO_2/kWh. The factor ordering is then stable within the specified bounds, although this does not establish which estimate is more accurate. Table 5 records both illustrative decisions, while Table 6 reports the threshold sensitivity.

Table 5. Constructed container-category decisions on a common engine-work boundary. SFC ranges are assumed, not measured.

SFC (g/kWh)	Factor Bounds	ΔEF Range (g CO_2/kWh)	Ordering
190 ± 5%	E = 635; c = 3.2	−3.4 to +57.4	Unresolved
180 ± 5%	E ± 1%; c ± 1%	+17.802 to +99.622	Entec higher within bounds

Table 6. Nominal thresholds and deterministic sensitivity envelopes (g fuel/kWh). These are arithmetic bounds, not confidence intervals.

Category	Nominal	E ± 1%; c Fixed	E ± 10%; c ± 1%
Bulk carrier	195.94	193.98–197.90	174.60–217.71
Container ship	198.44	196.45–200.42	176.83–220.49
Chemical tanker	203.13	201.09–205.16	181.00–225.69
Ro-Ro cargo	204.69	202.64–206.73	182.39–227.43
Oil tanker	215.63	213.47–217.78	192.14–239.58
Ro-Pax	215.00	212.85–217.15	191.58–238.89

The oil-tanker and Ro-Pax thresholds overlap under independent ±1% factor perturbations even with c fixed: 213.46875–217.78125 and 212.85–217.15 g/kWh, respectively. Equal-sized opposite relative changes can reverse their order once the perturbation exceeds $\frac{(690-688)}{(690+688)} = 0.14514\%$. A shared carbon coefficient cannot reverse that order, but it shifts both crossings. The nominal 0.625 g/kWh separation should therefore not be treated as an operational distinction between vessel populations.

The wider factor test produces broad threshold envelopes for all categories. This result identifies sensitivity to the chosen inputs, not estimated population coverage. It also shows why a fleet-wide method ranking cannot be inferred by counting positive cells in Figure 2. For a heterogeneous fleet, compatible engine work must weight each factor difference:

$$\Delta M = 10^{-6} \sum_k \sum_r Q_{k,r}(E_k - c_{k,r}S_{k,r})$$

with k denoting vessel category, r identifying an operating segment and Q in kWh. Engine/fuel boundaries and within-category variation must be established before this expression has inventory meaning.

For a manufacturer-informed operating illustration, take the 8V31 main-engine rating of 4880 kW and its HFO reference point at 85% load [20]. One assumed hour gives Q = 4148 kWh and fuel mass 0.7055748 t from SFOC = 170.1 g/kWh. Applying c = 3.2 yields 2.25783936 t CO_2. Counterfactually applying the Ro-Pax category factor of 688 g/kWh to the same brake work yields 2.853824 t, a difference of 0.59598464 t. Using a symmetric ± 5% SFOC stress interval, selected from the scale of the manufacturer's stated 5% tolerance, and the illustrative E ± 1%, c ± 1% bounds, ΔEF remains positive at 103.86864–182.94704 g/kWh. The symmetric interval is a sensitivity assumption, not a manufacturer-specified probability distribution. This comparison matches work and liquid-fuel accounting only: a single main-engine reference point does not reproduce Entec's category-average main/auxiliary mix or load assumptions. It demonstrates the audit calculation; it is neither an observed Ro-Pax voyage nor evidence of comparative accuracy.

5.4. Discussion

The threshold is best interpreted as an implied SFC under a prescribed fuel-carbon coefficient. When an energy-based factor already embeds fuel efficiency, dividing by a carbon coefficient is an inversion of that assumption. The 42 scenarios demonstrate its consequences but provide no independent support for its physical realism. Practical value

comes from exposing the hidden assumption, locating a compatible operational SFC relative to it and checking whether the resulting factor ordering survives input bounds. The source SFC comparison in Table 4 makes this relationship explicit. Entec already supplies SFC alongside CO_2 factors, so the present contribution is the conditional ordering diagnostic and its sensitivity analysis, not the first recovery of an otherwise unavailable SFC.

This use complements inventory comparisons [8] and AIS-based uncertainty assessments [10]. Detailed inventories such as SEIM [11] and the OECD method [12] estimate activity and fuel demand; the present diagnostic only audits a selected factor relationship. It cannot resolve errors in AIS tracks, load estimates or time allocation, and it cannot explain an entire inventory discrepancy without holding those inputs and boundaries constant. The historical factors are examined because they remain used in comparative studies, not because they are assumed to represent the current fleet.

An analyst can use the diagnostic when reconciling an inherited power-based inventory with a fuel-based inventory, documenting why a fixed category factor differs from a consumption-based estimate, or prioritising collection of load-matched fuel data. Agreement at SFCeq is not a reason to prefer either source: two estimates can agree because their assumptions coincide while both differ from measurements. Category-level factors also cannot be transferred to an individual vessel without checking its engine configuration, fuel and operating mode.

Physical comparability requires matching the definition of kWh and the fuel mass represented by SFC. Brake work, delivered shaft work and electrical output are different denominators. For multiple engines burning the same fuel, an aggregate SFC must be weighted by their engine work; different fuels require separate carbon coefficients. Applying a main-engine SFOC to combined propulsion, hotel and boiler consumption would violate that boundary. These requirements limit direct operational use of the present category thresholds.

5.5. Limitations and Operational Validation

The analysis uses the verified year-2000 category factors and SFC values in the 2005 Entec report [7] and a fixed Trozzi–Vaccaro cruising CO_2 coefficient. The source documents the aggregate main/auxiliary-engine and load assumptions, but this study does not reconstruct each category's complete engine/fuel weighting, quantify category-assignment error or validate the factors against vessel measurements. The source SFC comparison is a consistency assessment, not an independent validation dataset. The bounded analysis supplies neither confidence intervals nor a comprehensive uncertainty budget. Other operational modes, alternative fuels and lifecycle emissions remain outside scope.

Operational validation would require time-aligned fuel-flow and engine-output measurements, verified fuel carbon content and calorific value, engine load, operating mode and separate main/auxiliary-engine records. For each compatible segment, measured SFC would be computed as fuel mass divided by integrated engine work. Predictions from each factor would then be compared with an independently established CO_2 reference using signed bias, mean absolute error and root mean square error, with measurement uncertainty propagated. A CO_2 reference obtained solely by multiplying the same fuel record by the same assumed carbon coefficient is a mass-balance consistency check, not independent validation of that coefficient. Load- and fuel-stratified testing on additional vessels would be needed to assess transferability.

As a cross-domain methodological example, Ziran et al. [22] evaluate energy-prediction approaches using recorded building consumption and explicit criteria concerning prediction reliability and computational resources. The transferable lesson is to define the observed target and evaluation criteria. Their building dataset, algorithms and performance results

do not validate maritime emission factors. For the present diagnostic, a further evaluation criterion would be whether the sign predicted from SFCeq matches the observed factor residual outside a predeclared uncertainty interval, and whether it improves on direct reporting of implied SFC alone.

6. Conclusions

For the selected cruising inputs, the Trozzi–Vaccaro energy-based CO_2 factor is 3.2 times SFC. Equating it with an Entec category factor gives an implied SFC of 195.94–215.63 g fuel/kWh across six vessel categories. These values are conditional algebraic crossovers, not measured efficiencies, a new emission model or evidence of one method's superior accuracy.

The matched-energy example shows how a factor difference can affect an inventory estimate only after compatible activity and fuel assumptions are supplied. The sensitivity analysis adds a qualification that the nominal scenario grid alone cannot provide: factor ordering can become unresolved over an SFC interval, and the 0.625 g/kWh tanker/Ro-Pax separation does not survive even small independent category-factor changes.

The framework can support auditing and communication of factor assumptions when fuel and engine-work boundaries match. Its practical value remains to be tested using load-matched operational measurements and explicit performance criteria. Individual-vessel and fleet conclusions require additional engine, fuel and activity data. The source verification confirms all six nominal CO_2 inputs; comparison with the tabulated historical SFC strengthens interpretation but does not replace operational validation.

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References

1. United Nations Conference on Trade and Development. *Review of Maritime Transport 2025: Staying the Course in Turbulent Waters*; United Nations: Geneva, Switzerland, 2025. Available online: https://unctad.org/system/files/official-document/rmt2025_en.pdf (accessed on 26 October 2026).
2. International Maritime Organization. *Fourth IMO Greenhouse Gas Study 2020*; IMO: London, UK, 2020. Available online: https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx (accessed on 26 October 2026).
3. Ülker, D.; Bayırhan, İ.; Mersin, K.; Gazioğlu, C. A comparative CO_2 emissions analysis and mitigation strategies of short-sea shipping and road transport in the Marmara Region. *Carbon Manag.* **2021**, *12*, 1–12. [CrossRef]
4. Trozzi, C.; Vaccaro, R. Methodologies for Estimating Air Pollutant Emissions from Ships. In Proceedings of the 22nd CIMAC International Congress on Combustion Engines, Copenhagen, Denmark, 18–21 May 1998; pp. 775–782.

5. Trozzi, C.; Vaccaro, R. Methodologies for Estimating Air Pollutant Emissions from Ships: A 2006 Update. In *Environment & Transport, 2nd International Scientific Symposium, Including the 15th Transport and Air Pollution Conference, Reims, France, 12–14 June 2006*; Joumard, R., Ed.; Actes INRETS No. 108; INRETS: Arcueil, France, 2006; pp. 427–438. Available online: https://www.ifsttar.fr/fileadmin/user_upload/editions/inrets/Actes/Actes_INRETS_A108.pdf (accessed on 26 October 2026).
6. Trozzi, C. Emission Estimate Methodology for Maritime Navigation. In Proceedings of the 19th International Emissions Inventory Conference, San Antonio, TX, USA, 27–30 September 2010. Available online: https://gaftp.epa.gov/air/nei/ei_conference/EI19/session10/trozzi.pdf (accessed on 26 October 2026).
7. Stavrakaki, A.; De Jonge, E.; Hugi, C.; Whall, C.; Minchin, W.; Ritchie, A.; McIntyre, A. *Service Contract on Ship Emissions: Assignment, Abatement and Market-Based Instruments. Task 1—Preliminary Assignment of Ship Emissions to European Countries. Final Report*; Contract 070501/2004/383959/MAR/C1; Archived European Commission Report; Section 2.3.1, Tables B.2, B.3 and B.16, pp. B–4, B-5 and B-17; Entec UK Limited: London, UK, 2005; p. 13. Available online: https://web.archive.org/web/20070709222015id_/http://ec.europa.eu/environment/air/pdf/task1_asign_report.pdf (accessed on 26 October 2026).
8. Li, Y.; Zhang, Y.; Cheng, J.; Zheng, C.; Li, M.; Xu, H.; Wang, R.; Chen, D.; Wang, X.; Fu, X.; et al. Comparative Analysis, Use Recommendations, and Application Cases of Methods for Develop Ship Emission Inventories. *Atmosphere* **2022**, *13*, 1224. [CrossRef]
9. EMEP/EEA. *EMEP/EEA Air Pollutant Emission Inventory Guidebook 2023: 1.A.3.d Navigation (Shipping)*; European Environment Agency: Copenhagen, Denmark, 2023. Available online: https://www.eea.europa.eu/en/analysis/publications/emep-eea-guidebook-2023/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-d-navigation (accessed on 26 October 2026).
10. Chen, X.; Yang, J. Analysis of the Uncertainty of the AIS-Based Bottom-Up Approach for Estimating Ship Emissions. *Mar. Pollut. Bull.* **2024**, *199*, 115968. [CrossRef] [PubMed]
11. Yi, W.; Wang, X.; He, T.; Liu, H.; Luo, Z.; Lv, Z.; He, K. The High-Resolution Global Shipping Emission Inventory by the Shipping Emission Inventory Model (SEIM). *Earth Syst. Sci. Data* **2025**, *17*, 277–292. [CrossRef]
12. OECD. Maritime Transport CO_2 Emissions Methodology Update. May 2025. Available online: https://www.oecd.org/content/dam/oecd/en/data/methods/eea/OECD-maritime-transport-CO2-emissions-methodology.pdf (accessed on 26 October 2026).
13. Abdelghany, G.A.; Guedes Soares, C. Overview and Assessment of Ship Emissions Estimation Models. *J. Mar. Sci. Appl.* **2026**. [CrossRef]
14. Kelly, W.C.; Reckner, L.R.; Maines, G.D. *Inventory of Emissions from Marine Operations Within the California Coastal Waters*; Final Report No. 2581-01-0681; ARB-R-81/40; Prepared for the California Air Resources Board; Scott Environmental Technology, Inc.: San Bernardino, CA, USA, 1981.
15. Corbett, J.J.; Fischbeck, P.S. Emissions from ships. *Science* **1997**, *278*, 823–824. [CrossRef]
16. Hussain, I.; Wang, H.; Safdar, M.; Ho, Q.B.; Wemegah, T.D.; Noor, S. Estimation of shipping emissions in developing country: A case study of Mohammad Bin Qasim Port, Pakistan. *Int. J. Environ. Res. Public Health* **2022**, *19*, 11868. [CrossRef] [PubMed]
17. Mersin, K.; Bayırhan, İ.; Gazioğlu, C. Review of CO_2 emission and reducing methods in maritime transportation. *Therm. Sci.* **2019**, *23*, S2073–S2079. [CrossRef]
18. Tokuşlu, A. Analyzing the Energy Efficiency Design Index (EEDI) performance of a container ship. *Int. J. Environ. Geoinform.* **2020**, *7*, 114–119. [CrossRef]
19. Entec UK Limited. *Quantification of Emissions from Ships Associated with Ship Movements Between Ports in the European Community. Final Report*; Entec UK Limited: London, UK, 2002; Chapter 2; Section 2.5.1, Tables 2.7, 2.11 and 2.14.
20. Wärtsilä Finland Oy. *Wärtsilä 31 Product Guide*; DBAE144585; Wärtsilä Finland Oy: Vaasa, Finland, 2019; Sections 1.2 and 3.2; pp. 1-1–1-2+3-2–3-4. Available online: https://tech-expo.ru/upload/iblock/d98/Instruktsiya-po-ekspluatatsii-W_rtsil_-W31.pdf (accessed on 26 October 2026).
21. *ISO 15550:2016*; Internal Combustion Engines—Determination and Method for the Measurement of Engine Power—General Requirements. International Organization for Standardization: Geneva, Switzerland, 2016.
22. Ziran, Z.; Muzi, F.; Piras, G.; Arman, A.; Mecella, M. Supporting Energy Consumption Prediction: A Sustainable Approach. In *Proceedings of the 21st International Conference on Intelligent Environments (IE)*; IEEE: Piscataway, NJ, USA, 2025; pp. 1–8. [CrossRef]

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