Evaluation of Vessel CO_2 Emissions Methods using AIS Trajectories

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Motivation

Background

1. growing interest of society in environmental friendliness and sustainability
2. about 90% of global trade is fulfilled by shipping
3. accurate estimation of shipping CO_2 emissions is important for developing regulations

Research gap

- None of the review studies [1, 2, 3] does a quantitative comparison of models
- The comparative studies [4, 5] are limited to a small area near the Strait of Gibraltar

Contribution

- a general data-driven framework to compare/validate ship emission models
- extensive experiments are conducted using data from 1,571 cargo ships and insights are presented

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Framework Design

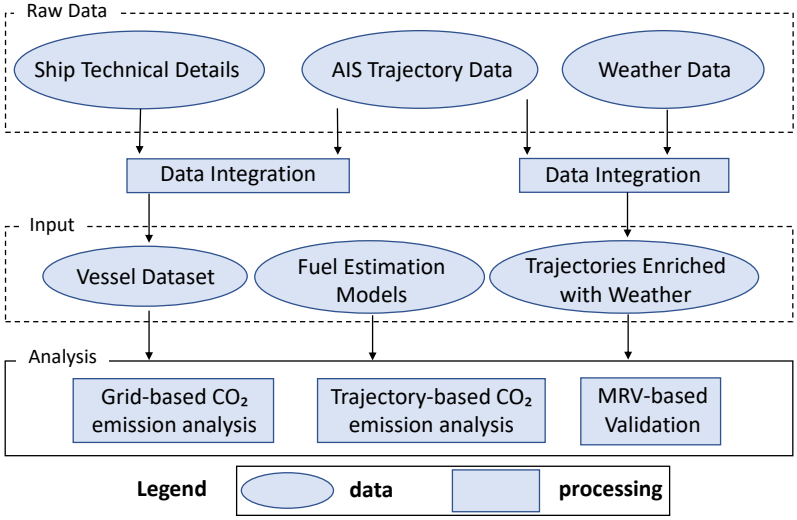

Figure: Overview of the Evaluation Framework

Currently, five models are considered in our framework.

- **Baseline**: assumes a certain amount of CO_2 are emitted per metric ton of cargo per kilometer of transport, 3 grams CO_2 / (ton · km) [6].
- **GrossTonnage [7]**: The daily fuel consumption C is linearly related to the gross tonnage of a ship, and the CO_2 emissions per ton of fuel depends on operation mode.
- **SpeedCubic [8]**: speed is considered, and the emission factor (gCO_2/kWh) depends on engine type and fuel type.
- **IMO [9]**: speed and draught are considered. The emission factor (gCO_2/kWh) depends on engine type/load/generation and fuel type.
- **STEAM [10]**: speed is considered. A speed penalty is added based on wave conditions.

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summary of required input by the five models

Models	TPC	DWT	D	P	S	GT	RPM	Year	Length	Beam	Wave
Baseline	✓	✓	✓								
GrossTonnage					✓	✓					
SpeedCubic				✓	✓		✓				
IMO			✓	✓	✓		✓	✓			
STEAM				✓	✓				✓	✓	✓

TPC: tons per centimeter
D: maximum draught
S: maximum speed
RPM: revolutions per minute

DWT: deadweight
P: maximum power
GT: gross tonnage

AIS data

One-month data from May 2022 was downloaded from the Danish Maritime Authority[1].
41,024,724 records from 1,571 cargo ships were used.

Table: The number of AIS messages after each step

step	# of AIS messages
raw AIS messages from cargo ships	63,352,466
spatial filtering	61,097,446
outlier removal	60,832,556
AIS messages from the final 1571 ships	42,039,748
removal of short or non-moving trajectories	41,024,724

[1] https://web.ais.dk/aisdata/

Ship Technical Details

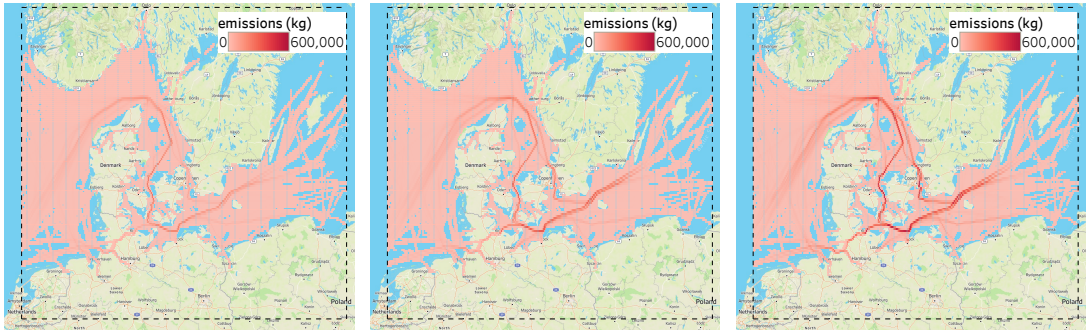
Public information in six websites were collected.
① BalticShipping ② Bureau Veritas ③ FleetMon
④ MarineTraffic ⑤ ShipAtlas ⑥ VesselTracker

Wave Data (wave height and direction)

Two products were used from the Copernicus Marine Service.
- Baltic Sea[2]: spatial res. 1nm $\times$ 1nm ; temporal res. 1 hour
- North Sea[3]: spatial res. 3km $\times$ 1.5km ; temporal res. 1 hour

[2] https://goo.by/FKzLj
[3] https://goo.by/vPwnP

The area of interest in divided into 0.05° by 0.05° grids



(a) Baseline (b) IMO (c) GrossTonnage

Figure: Spatial distribution of CO_2 emissions by each model

Comparison of absolute emissions by each model

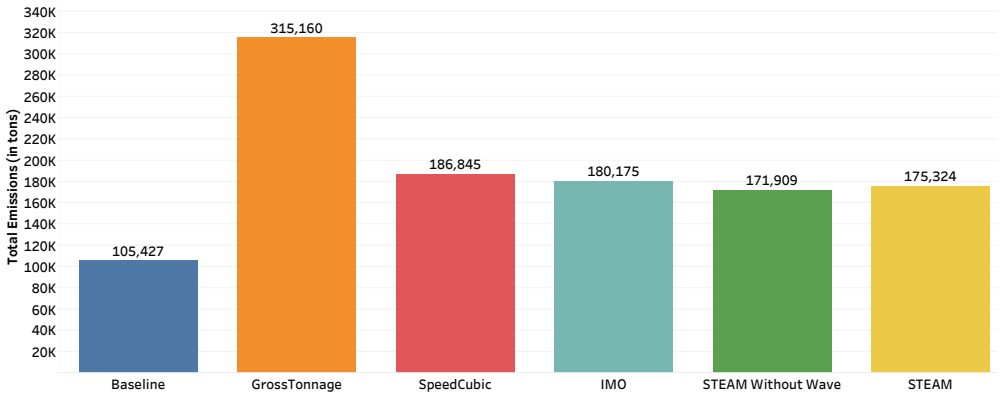


Figure: Total CO_2 emissions of the 1,571 ships by each model

Wave effects on CO_2 emissions (assuming wave conditions are the same everywhere)

40 combinations (4 angle ranges * 10 wave heights)

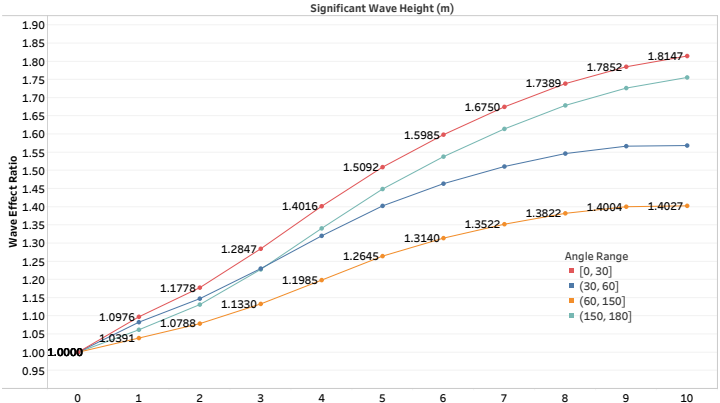
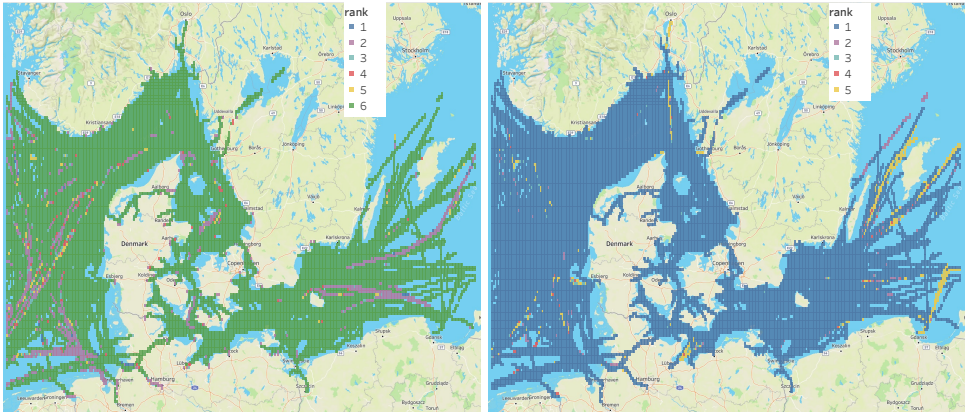


Figure: The effect of wave angle and wave height on the total CO_2 emissions

Grid-level ranking of each model: "1" highest ("6" lowest) emissions



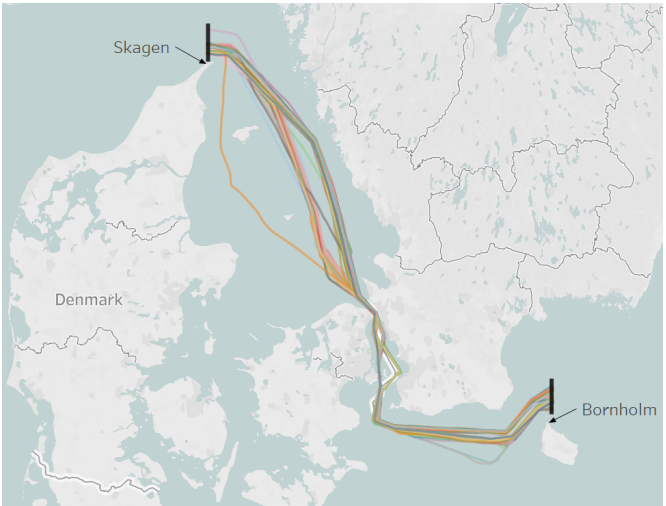
(a) Baseline

(b) GrossTonnage

Experiments: trajectory-based analysis

192 trips are selected travelling between Skagen and Bornholm

- the ship's DWT is larger than 2,000 tons.
- the trip is less than 600 kilometers.
- the avg. speed for each hour is larger than 5 knots.



Statistic of the 192 trips

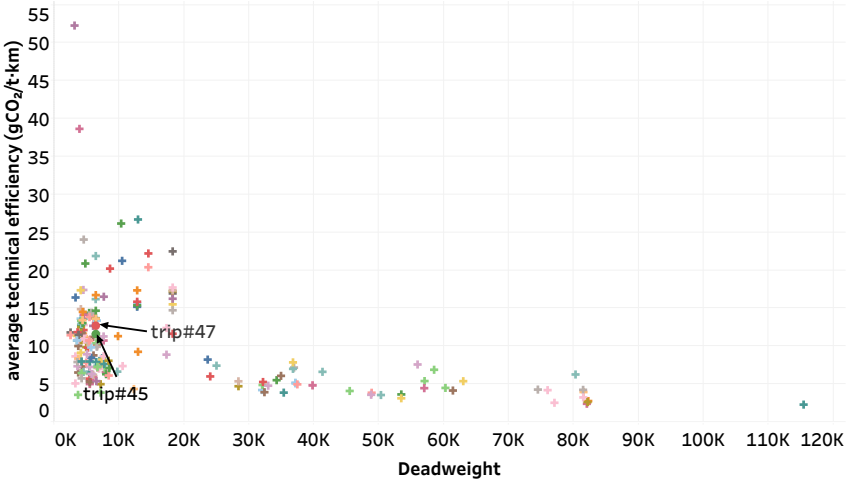
min. / avg. / max. length (km)	478.4 / 488.8 / 507.9
min. / avg. / max. duration (hours)	13.8 / 23.3 / 32.9
min. / avg. / max. passing speed (knots/hour)	8.0 / 11.7 / 19.0

Equivalent CO_2 efficiency for each trip

$$E_{CO_2,i} = \frac{CO_{2\_IMO}}{Cargo_i * Length_i}, 1 \leq i \leq 192$$

Experiments: trajectory-based analysis

Equivalent CO_2 efficiency of the 192 trips



trip#45 and trip#47 by the same ship (DWT = 6,410 t, S = 19 knots/h)

	trip#45	trip#47
length (km)	489.8	489.6
avg. passing speed (knots/hour)	13.17	14.15
CO_2 emissions (kg)	36,372	39,798
CO_2 efficiency (gCO_2/t·km)	11.58	12.68

A 5.2% decrease in speed leads to a 8.7% increase in CO_2 efficiency

- it suggests that shipowners can probably improve CO_2 efficiency of their fleet by speed optimization.

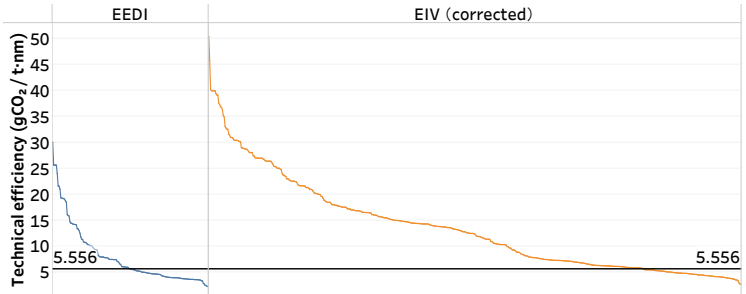
Experiments: MRV-based validation

The EU's Monitoring, Reporting and Verification (MRV) system

- ship above 5,000 gross tonnage should report CO_2 emissions data for their maritime transport activities in the EU waters.
- 760 out of the 1,571 ships have matching entries in the MRV dataset.

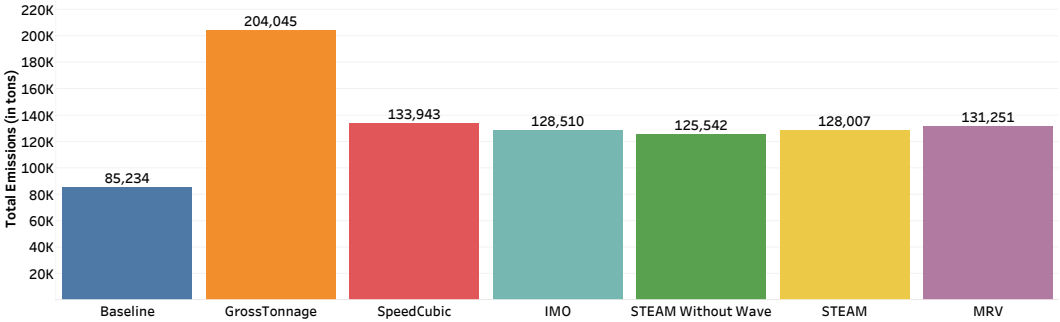
CO_2 efficiency of the 760 ships based on MRV

- - EEDI: Energy Efficiency Design Index
- - EIV: Estimated Index Values

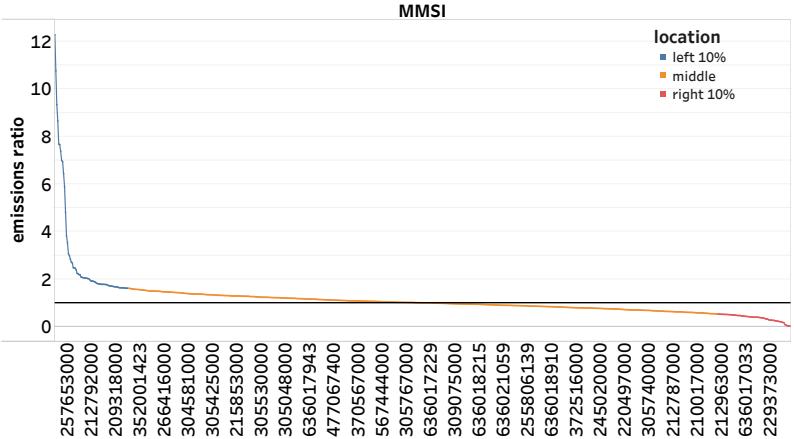


Experiments: MRV-based validation

Total CO_2 emissions of the 760 ships by each model



Ship-level CO_2 efficiency ratio between the IMO method and MRV dataset



Conclusions and Future Work

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- most of the CO2 emissions are located along the main sea routes.
- large ships tend to be more CO2 efficient than small ships.
- emission results from the three speed-based models are consistent with the MRV dataset.
- the comparison of two similar trips from the same ship suggests that a ship can probably improve its CO2 efficiency through speed optimization.

Future Work

- inclusion of more emission models.
- coverage of larger time periods and geographical regions
- investigation of a different movement profile, e.g. inter-continental voyages and other ship types.

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