ShipNetSim: A Multi-Ship Simulator for Evaluating Longitudinal Motion, Energy Consumption, and Carbon Footprint of Ship

By: Ahmed Aredah, Hesham Rakha

Charles E., Via, Jr. Department of Civil and Environmental Engineering

AhmedAredah@vt.edu, HRakha@vt.edu

VIRGINIA TECH.

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Motivation

- No integrated **cargo** ships simulator capable of
  1. simulating multiple ships,
  2. in a global setting, and
  3. mainly for energy consumption.

- Broader Goal:
  1. integrate within a larger scale simulator for agent-based container-level analysis and optimization.
     - Trains Simulator (NeTrainSim),
     - Ships Simulator (ShipNetSim),
     - Trucks/Traffic Simulator (Integration).

Scope

- Open-source simulator,
- Integrated simulator instead of sparse simulation efforts in the industry,
- Energy Consumption (EC) prediction tool,
- Fast but with high fidelity results.

Find routes by Traverse Points

- Build visibility graph (too many points & Earth Model),
- Use Quadtree for optimized map query performance, and
- Optimize trip travelled distance (could be altered).

Figure: Visibility Graph Sample

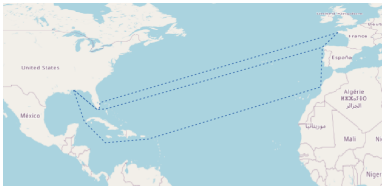
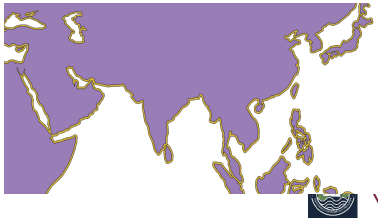
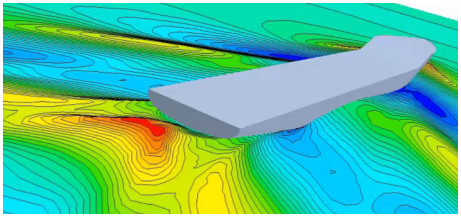


Figure: Edges Buffering



Estimate Resistance

1. Capture Full Scale Open-Seas Resistance
   1. Calm Water Resistance:
      - Frictional Resistance (R_F),
      - Wave-Making Resistance (R_W),
      - Bulbus Bow Resistance (R_B),
      - Transom Resistance (R_{TR}), and
      - Wind Resistance (R_{AA}) *,
      - Model Correction (R_A).
   2. Open Seas Resistance:
      - Wave Resistance, and
      - Wind Resistance *.



$\omega(t)$: Wave frequency, $\beta(t)$: Wave heading, $u(t)$: Wave speed.

$\psi(t)$: Wind heading, V_{WR}: Wind speed.

$$R_{t|n}(t) = R_{CALM}(t) + R_{AW}\left(\omega(t), u(t), \beta(t)\right) + R_{AA}(\psi(t), V_{WR}(t))$$

Estimate Resistance

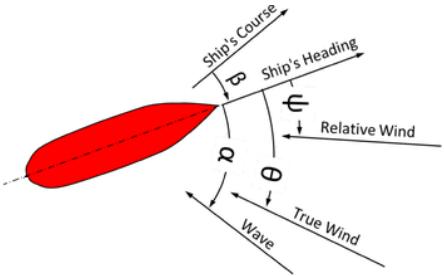


Figure: Wind and waves directions relative to ship's heading

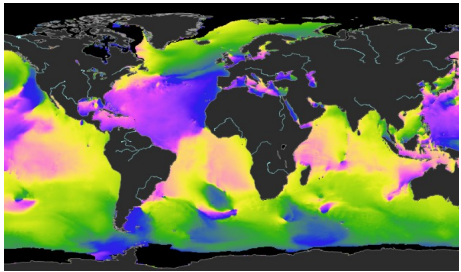


Figure: Attributes data as GIS TFF/SHP files

Estimate Propulsion Forces

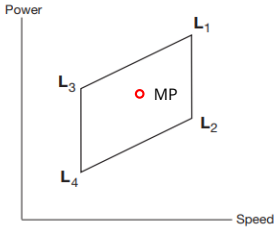


Figure: Engine Load Points

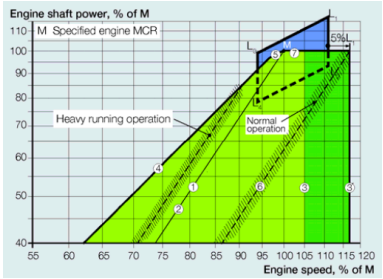


Figure: Engine Operational Limits

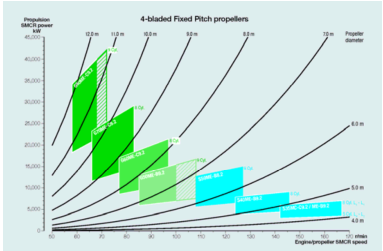


Figure: Engine Operational Limits

Estimate Propulsion Forces

2. Capture the Propeller Properties
   - Propellers' Efficiency vs. Speed of Advance,
   - Engine Efficiency vs. RPM.

$$K_T = \frac{T_p}{\rho_w n^2 D^4}$$

$$K_Q = \frac{Q_p}{\rho_w n^2 D^5}$$

$$\eta = \frac{K_t}{K_Q}\frac{J}{2\pi}$$

Figure: B-Series Propeller Thrust and Torque Coefficients and efficiency

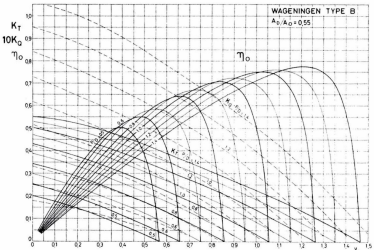


Figure 6.3.10. Results of open-water tests on four-bladed model propellers of the Wageningen B 4-55 type

Ship Dynamics

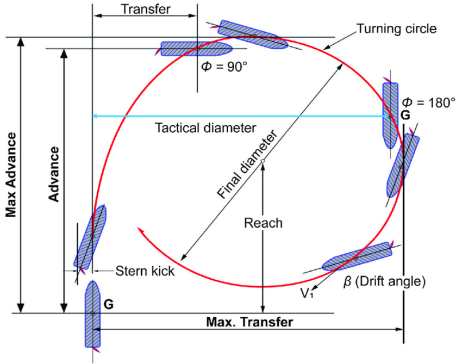


Figure: Ships' turning Circle

Ship Dynamics

Similar to the following model adopted in the train dynamics, albeit some changes:

- Spacing: $s_{lad} = s_{j_{n-1}} + x_{des}, \qquad x_{des} = \int_{v(t)}^{v(t)=0} (v(t) - d_{max} \cdot \Delta t) \cdot dt$
- Weight: $m_{total} = m_{\text{dead weight}} + m_{\text{surge added weight}}$

Stopping Distance

For ships, it is harder to predict in comparison to trains.

d_{max}: deceleration from resistance and reverse propeller (if applicable).

Energy Consumption Delimitation

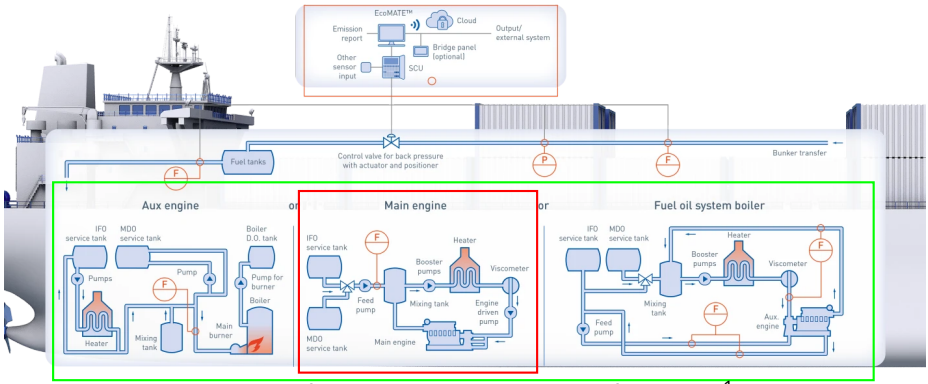


Figure: ShipNetSim Energy Considerations[1]

[1] Krohne n.d.

Emissions Limits

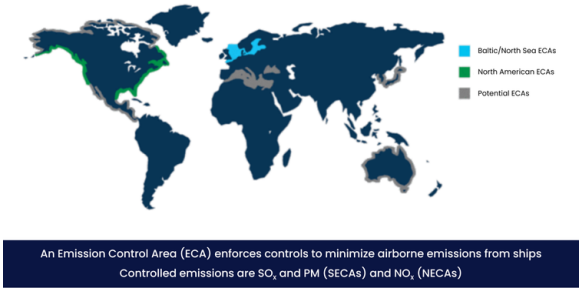
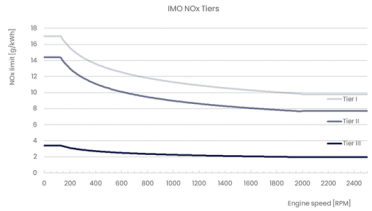


Figure: Emission Control Area (ECAs)[2]

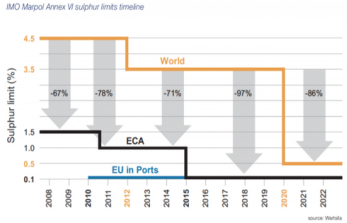
[2] sustainable ships n.d.

Estimating Emissions



Maximum NO_x limit [g/kWh] depends on vessel age and engine speed
Click here to determine your limit

Figure: Tier I, II, and III NOX restrictions[a]



Ships sailing in SECAs will have to use fuel oil with a sulphur content of 0.10% max (mass by mass)
Outside SECAs the maximum allowable sulphur content of fuel is 0.50%

Figure: Sulfur emissions world reduction goal[a]

[a] sustainable ships n.d.

ShipNetSim GUI

Figure: ShipNetSim GUI

Case Study

Table: Ship Characteristics used in the case study

Ship Characteristic	Value
Route	Savannah, U.S. to Algeciras, Spain
Length between perpendiculars (m)	175
Beam (m)	25.4
Average Draft (m)	9.5
Max Speed (knot)	20
Displacement (m^3)	24053
Block Coef	0.561
Prismatic coefficient	0.589
Position of LCG (m)	86.5
Fuel Type	**HFO**
Engine	6S60ME
Engine MCR @ L1 (kWh)	**14940**
Engine RPM @ L1	105
Engine Eff at L1	0.5018
Propeller Diam (m)	**6.5**
Propeller Pitch (m)	9.88
Propeller Blade Count	5
Propeller Expanded Area Ratio	0.8
Weight (ton)	**24610.0**

Fuel Types

- **MGO – Marine Gas Oil**
  Emissions: Low SOx, PM.
- **MDO – Marine Diesel Oil**
  Emissions: Moderate SOx, PM.
- **IFO – Intermediate Fuel Oil**
  Emissions: High SOx, PM.
- **MFO – Marine Fuel Oil**
  Emissions: High SOx, PM.
- **HFO – Heavy Fuel Oil**
  Emissions: Very high SOx, PM.

Results

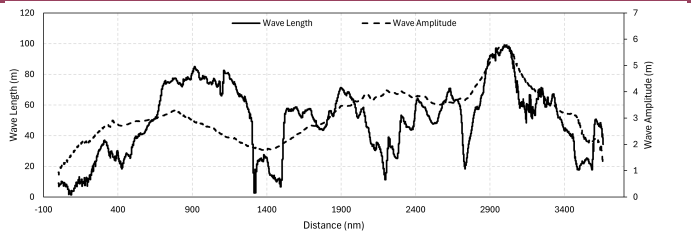


Figure: Wave Details.

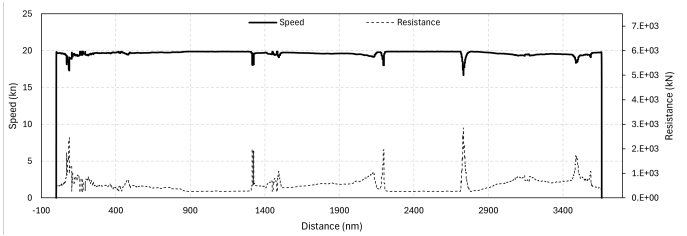


Figure: Speed vs Resistance Trajectories.

Results

With the delimitation of only allowing the ship to use HFO:

- **Simulation Time**: 6 min,
- **Trip Duration**: 7 Days,
- **EC**: 474 tons of HFO,
- **Emissions**: 1,495.305 tons of CO_2.

This result shows a 13% difference compared to the findings of Huotari et al. 2021, which reported a fuel consumption of 550 tons.

Conclusion

ShipNetSim is the first **Cargo/Bulk/Container Ship** simulator that:

- Integrates all aspects of ships analysis for energy consumption analysis,
- Applies location policy and geometrical restrictions on ships,
- Generates high fidelity forces estimations with low computational power.

Questions?

References I

- Huotari, Janne et al. (2021). “Convex optimisation model for ship speed profile: Optimisation under fixed schedule”. In: *Journal of Marine Science and Engineering* 9.7, p. 730.
- Krohne (n.d.). *Fuel consumption and bunker monitoring onboard a container ship Container ships — KROHNE USA*. URL: https://us.krohne.com/en/industries/marine-industry/container-ships/fuel-consumption-bunker-monitoring-container-ship (visited on 03/26/2024).
- sustainable ships (n.d.). *ECA (Emission Control Area)*. URL: https://www.sustainable-ships.org/rules-regulations/eca (visited on 07/23/2024).