Froude-Limited Ships

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Richard Burke

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School of Engineering
Maritime College, State University of New York

Introduction

- Global warming is the current challenge for humanity
  - Since 1950 sea levels in New York City have risen more than 23 cm with more than a 100% increase in the frequency of flooding. The rate of sea level rise is increasing.
- International marine transportation accounts for about 4% of GHG emissions, more than commercial aviation
- In 2018 IMO issued the "Energy Efficient Design Index" (EEDI) rules, and followed with "Energy Efficient Existing Ship Index" (EEXI) rules in 2021

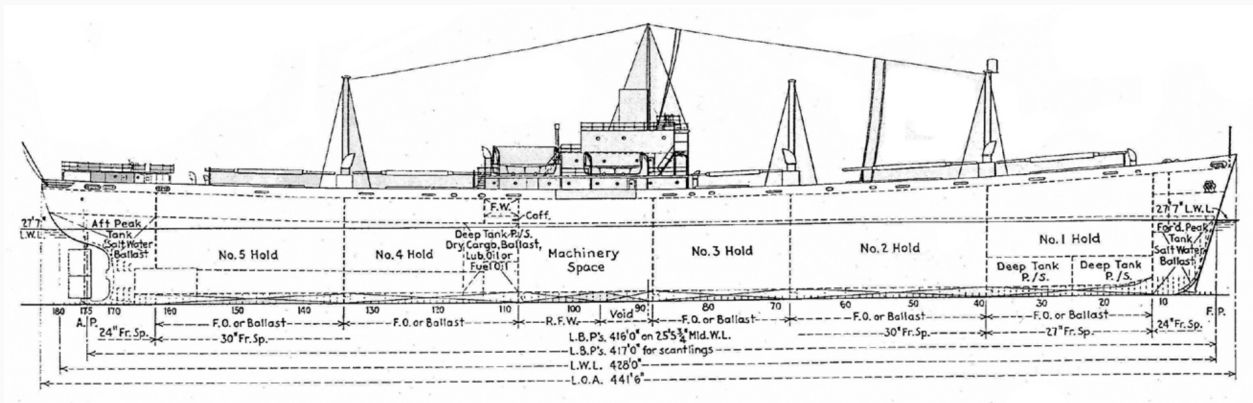
An Accidental Journey

My interest in this started accidentally:

- I was working with a student on a research project on *Expeditionary Logistics.* Unlike Underway Replenishment and Combat Logistics, Navy documentation states that expeditionary logistics is "... the responsibility of the Merchant Marine." The star of WWII expeditionary logistics was a ship called the EC-2. By 1945 2,710 of them were built. [Ref. 1]
- Then I received an email message from Kira Mendelsohn Matus, a friend at HKUST, asking why GHG discharges from ships were so high compared to aviation.
- Then I remembered some of the lectures given by Prof. Philip Mandel when I was a graduate student.

The Virtues of the Liberty Ship

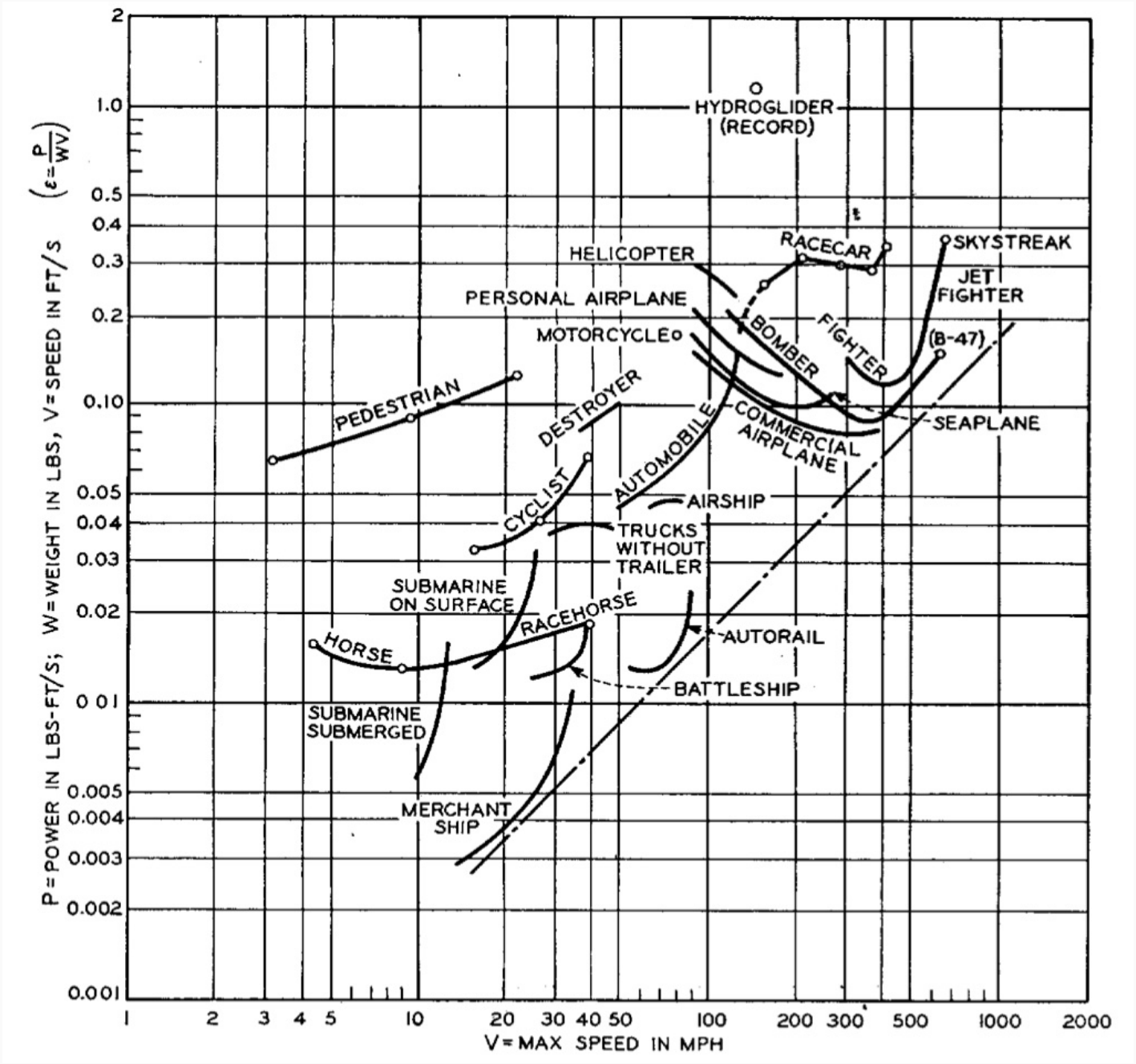
- They were simple to build using fully-welded modular construction, and they were simple and robust to operate.
- They were incredibly efficient to run, moving up to 10,845 dwt at about 11 knots with less power than found in a small tugboat today, approximately 1,500 kw. The Liberty Ship's Froude Number was only about 0.15.
- With a 17,000 mile range and flexible cargo arrangements, they could be utilized in many roles. Designed for a single wartime voyage with no commercial peacetime role, they became the backbone of world merchant shipping for a decade after 1945.



Efficiency of Ships

- In a famous 1950 paper, Gabrelli and von Kármán [Ref.2] defined an inverse measure of transport efficiency called *specific power*.
- Since the early 1870s when William Froude devised a means to segregate the elements of a ship's resistance to movement through the water, we have been able to assess and scale the effects of wave-making on ship's movement.
- All ships contend with viscous drag, but the choice to go fast means that much more power is needed to overcome wave-making drag.

Gabrelli and von Kármán have shown that low Froude Number ships are the most efficient means of transport available to humans


P = POWER IN LBS-FT/S; W = WEIGHT IN LBS, V = SPEED IN FT/S $(\epsilon = \frac{P}{WV})$
V = MAX SPEED IN MPH
HYDROGLIDER (RECORD)
HELICOPTER
RACECAR
SKYSTREAK
JET FIGHTER
PERSONAL AIRPLANE
MOTORCYCLE
BOMBER
FIGHTER
(B-47)
PEDESTRIAN
DESTROYER
AUTOMOBILE
COMMERCIAL AIRPLANE
SEAPLANE
CYCLIST
AIRSHIP
TRUCKS WITHOUT TRAILER
SUBMARINE ON SURFACE
RACEHORSE
HORSE
AUTORAIL
BATTLESHIP
SUBMARINE SUBMERGED
MERCHANT SHIP

Not Obvious: EEDI Was Initially Based on Specific Power

$$CO_2 Index = \frac{\sum_i FC_i * C_{carbon}}{\sum_i m_{cargo,i} * D_i}$$

$$I = \frac{AFC * Power * (0.85 + 0.10) * 3.17}{DWT * Speed}$$

$$\frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} C_{FMEi} SFC_{MEi} P_{MEi}\right) + P_{AE} C_{FAE} SFC_{AE} + \left(\sum_{i=1}^{nPTI} P_{PTIi} - \sum_{i=1}^{nWHR} P_{WHRi}\right) C_{FAE} SFC_{AE} - \left(\sum_{i=1}^{neff} f_{eff} P_{eff} C_{Feff} SFC_{MEi}\right)}{f_i Capacity \quad V_{ref} \quad f_W}$$

$$\frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{MEi} * C_{FME} * SFC_{ME}\right) + \left(P_{AE} * C_{FAE} * SFC_{AE}\right) + \left(\left(\prod_{j=1}^{M} f_j * \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} * P_{AEeff(i)}\right) C_{FAE} * SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} * P_{eff(i)} * C_{FME} * SFC_{ME}\right)}{f_i * f_c * fi * Capacity * f_w * V_{ref}}$$

An Indecent Proposal

Replace EEDI with a limit on Froude Number

- This would be entirely consistent with the current design of ships in the bulk trades, i.e., tankers and dry bulkers
- As for general cargo trades, the design of containerships would be significantly affected.
  - Speeds of main-line containerships were arbitrarily set to allow weekly sailings on North Atlantic routes and biweekly sailings on North Pacific routes.
  - Changes in design of large containerships might allow Froude-limited ships to come close to current speeds while perhaps improving cargo loss records.
- Some adjustment may be necessary for smaller ships, i.e., $L_{pp} \leq 150m$.

Froude-Limited Ship Speeds *v*. Length Between Perpendiculars

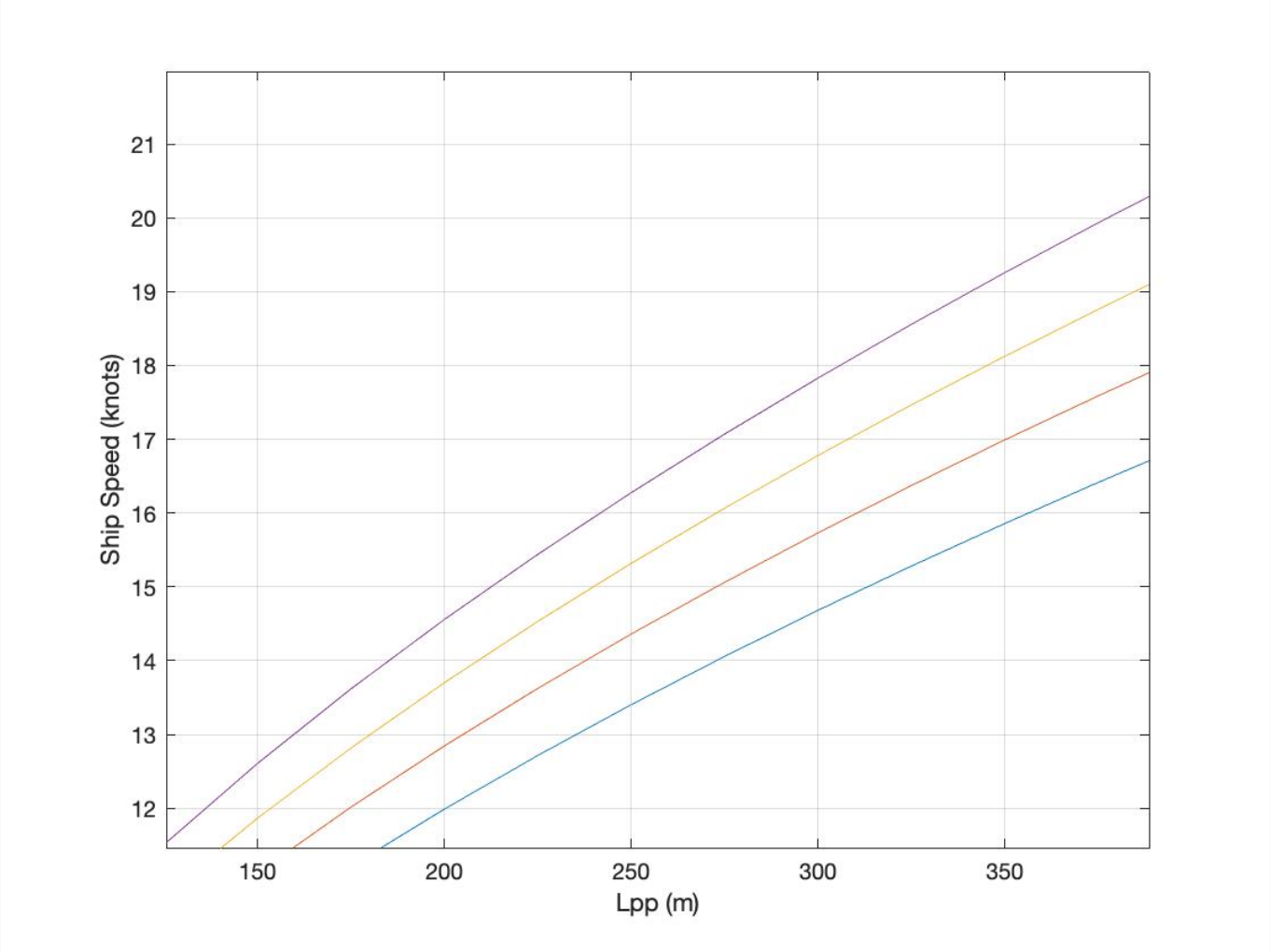


Figure 1: Froude Number: 0.14–Blue, 0.15–Red, 0.16–Yellow, 0.17–Purple

Some Recent Developments

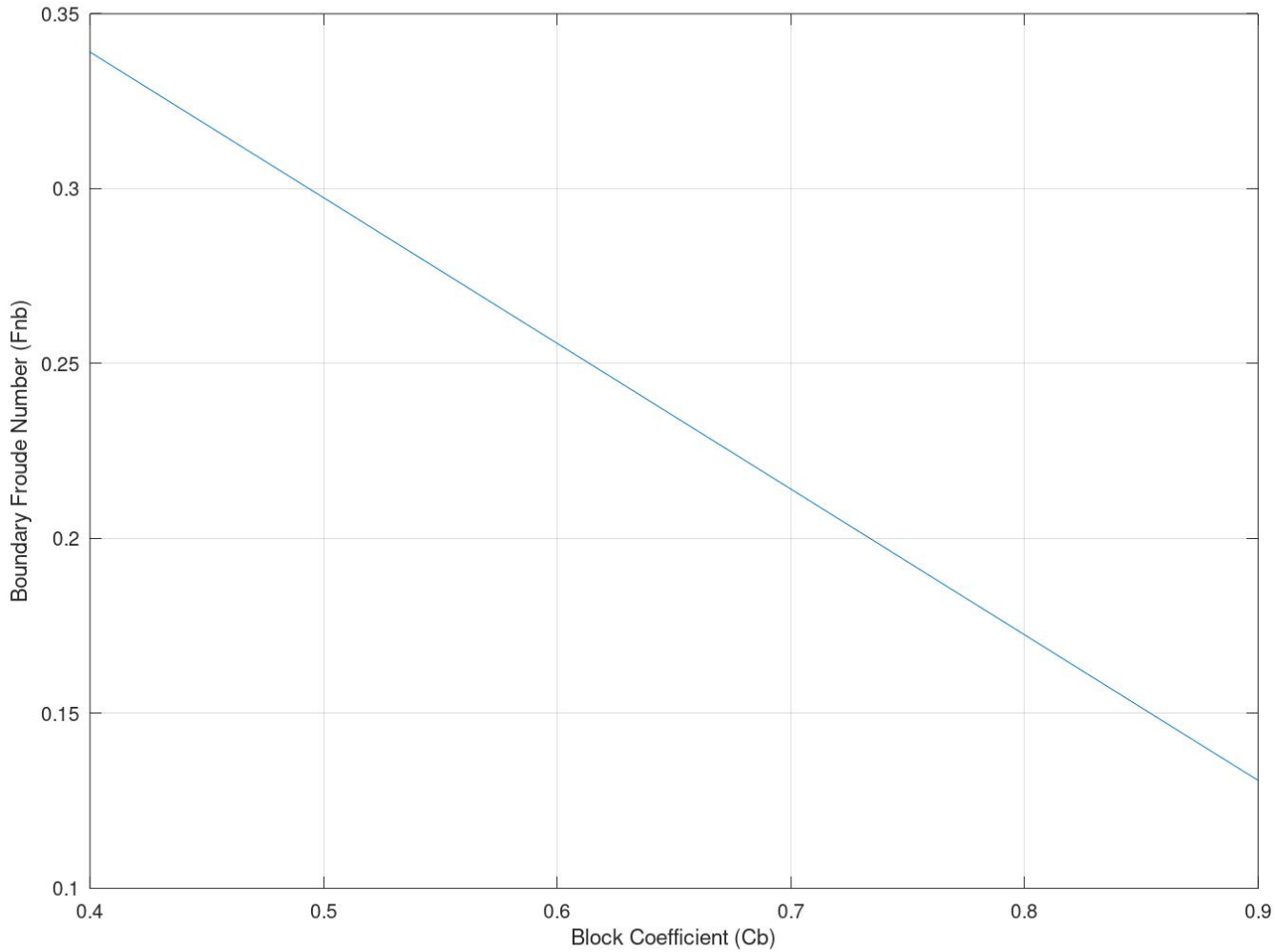
- Lindstad et al [Ref. 3] presented a compelling paper at SMC 2022. Although primarily concerned with wind assisted propulsion, they pointed out the benefits of hull slenderness in improving efficiency.
- They also discussed the concept of *boundary speed*, the speed at which significant wavemaking drag just begins to have an effect. This speed is given as

$$V_b = (1.7 - 1.4C_B)\sqrt{L}$$

  where length is in feet.
- This leads to the concept of *Boundary Froude Number*, which can be derived as

$$F_{Nb} = 0.5056 - 0.4164C_B$$

Boundary Froude Number as a Function of C_B



Some Conclusions

- First of all, if efficiency improves with reduction in speed, slow down; however, *Froude Number implies that length is also speed, thus providing a more intelligent standard.*
- Fineness of form can also improve efficiency by essentially increasing the permissible Froude Number.
- The assertion of Gabrelli & von Kármán that the price of speed is efficiency seems to be borne out for modern marine transportation. In the recent past efficiency has generally improved only when vessels were slowed [Ref.4]. Therefore, *Froude Limitation could be effective for existing ships.*
- *For general cargo trades ship speed is not a sufficient consideration;* optimization of the entire supply chain including ports, ships, land transport, and last-mile delivery is required.

Caveat Excogitatoris

- It is an axiom of operations research that the value of the objective function cannot be improved by adding a constraint, so the effect of GHG regulation is likely to be change of the shipping economy.
- Lindstad et al write of GHG evaluation in terms of "well to wake," but Matus, like other economists and policy makers, thinks about GHG in terms of product life cycles. This could result in more onshore manufacturing, reductions in general cargo movements, and more focus on shipment of raw materials.
- Initial results from GHG reduction efforts were promising [Ref. 5].This may be a short term problem if non-carbon based fuels emerge, but as Lindstad et al point out that could be misleading if fuels are being diverted from more effective uses.
- Ship owners will be sensitive to increases in both capex and opex relative to revenues, and will use their influence to change the development of standards. Simple standards are more resistant to influence.

References

1. *Workhorse of the Fleet - A History of the Liberty Ships*, G. Bourneuf Jr., American Bureau of Shipping, 1990, rev. 2008
2. "What price speed? Specific power required for propulsion of vehicles", G. Gabrielli and Th. von Kármán, *Mechanical Engineering* 72 (1950)
3. "Reaching IMO 2050 GHG targets exclusively through energy efficiency measures", E. Lindstad, D. Polić, A. Rialland, I. Sandaas, and T. Stokke, SNAME Maritime Convention, September 2022
4. "Historical trends in ship design efficiency", J. Faber and M. Hoen, CE Delft report to Seas at Risk and Transport & Environment, March, 2015
5. "Update of maritime greenhouse gas emission projections." David S. Lee, CE Delft report, January 2019