A taxonomy and survey of speed models in maritime transport

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Role of speed in maritime transport

- Has always been important

- Increasingly important in recent years

- Economic considerations
- Operational considerations
- Environmental considerations

share of CO2 emissions

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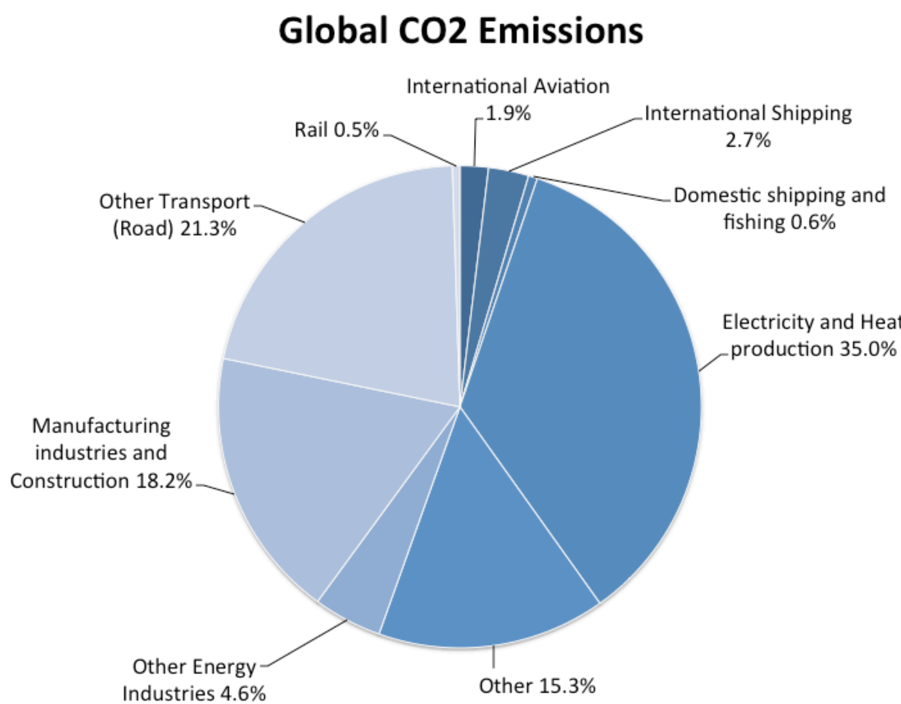
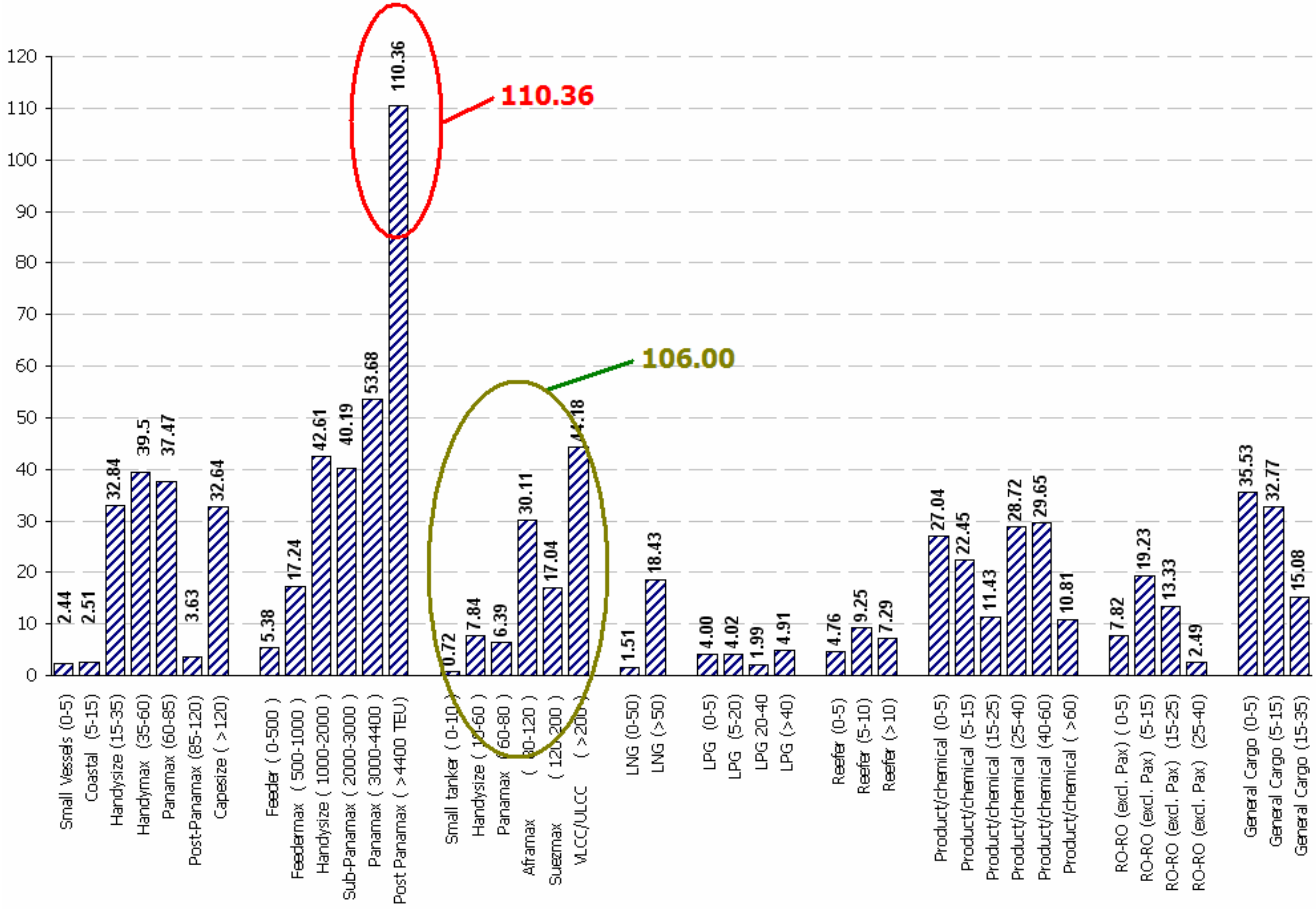


CO2 emissions per vessel category (million tonnes)



*Psaraftis, H.N. and C.A. Kontovas (2009), "CO2 Emissions Statistics for the World Commercial Fleet", WMU Journal of Maritime Affairs, 8:1, pp. 1-25.

Speed reduction

- An obvious way to reduce emissions

- Killing 3 birds with one stone?

- Pay less for fuel
- Reduce CO2 (and other) emissions
- Help sustain a volatile market

Dual targetting

- OPERATIONAL
- Operate existing ships at reduced speed (derate engines)
- Slow steaming kits

- STRATEGIC (DESIGN)
- Design new ships that cannot go very fast (have smaller engines)

How much slower?

- From 20-25 knots, go down to 14-18
- New Maersk 18,000 TEU ships: 19 knots
- Project ULYSSES:
  Go 5-6 knots!

In most OR/MS models

- Speed is NOT a decision variable
- Speed is only an IMPLICIT input
- (implicit in the sense that it is implied by other explicit inputs, eg times between ports)
- its potential impact on model outputs can only be considered indirectly

NOT including speed as a decision variable

- May in some cases remove flexibility in the overall decision making process.
- May render fixed-speed solutions subobtimal.

EXAMPLE 1

- A ship sailing at a prescribed speed to a certain port, only to have to wait there because the port is congested.
- May be a higher cost solution than one in which the ship is allowed to sail at a lower speed so as to arrive when the port is not congested any more.
- Overall emissions would be higher in that case as well.

EXAMPLE 2

- There are several models in the literature that include
  - port capacity constraints,
  - berth occupancy constraints,
  - time window constraints,
  - or other constraints that preclude the simultaneous service of more than a given number of vessels.
- Such constraints would conceivably be easier to meet if ship speed was allowed to vary.

Other fixed-speed models

- most emissions models assume fixed speeds
  - IMO GHG study (2009)
  - Psaraftis and Kontovas (2009)
  - others
- ship speed information is from databases and is of dubious quality
- Large distortions and wrong policies may be the result

Some basics

- Ships do NOT trade at predetermined speeds!
- Those who pay for the fuel, that is, the ship owner if the ship is in the spot market on voyage charter, or the charterer if the ship is on time or bareboat charter, will **choose an optimal speed** as a function of
  - (a) bunker price, and
  - (b) the state of the market and specifically the spot rate

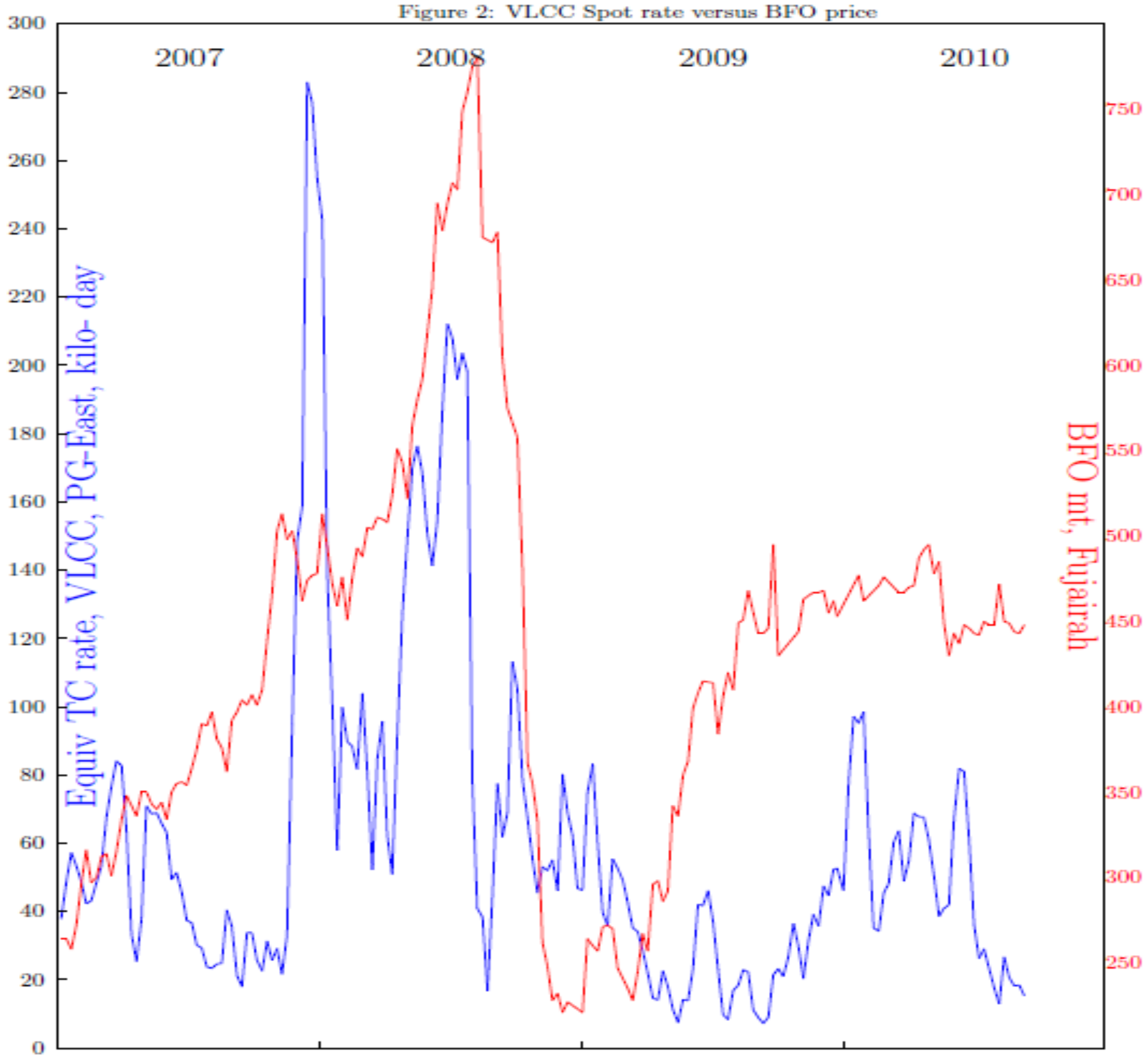


Figure 2: VLCC Spot rate versus BFO price
2007
2008
2009
2010
Equiv TC rate, VLCC, PG-East, kilo- day
BFO mt, Fujairah
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
250
300
350
400
450
500
550
600
650
700
750

Basic questions

- who is the speed optimizer?
- what is being optimized?
- owner in spot market: Max profit
- time charterer: Min cost

Basics ii

- Even though the owner's and time charterer's speed optimization problems may seem at first glance different, for a given ship the optimal speed (and hence fuel consumption) is in both cases the same.
- In that sense, it makes no difference who is paying for the fuel, the owner, the time charterer, or the bareboat charterer.

Owner in spot market

- OBJECTIVE: Maximize average per day profits
- s: spot rate ($/tonne)
- C: payload (tonnes)
- p: fuel price
- F(v): fuel consumption at speed v
- D: route r-trip distance
- E: OPEX ($/day)

$$\max_{v} \left\{ \frac{sC}{\frac{D}{24v}} - pF(v) - E \right\}$$

Time charterer

- OBJECTIVE: Minimize average per day costs
- R: demand requirements (tonnes/day)
- T: time charter rate ($/day)

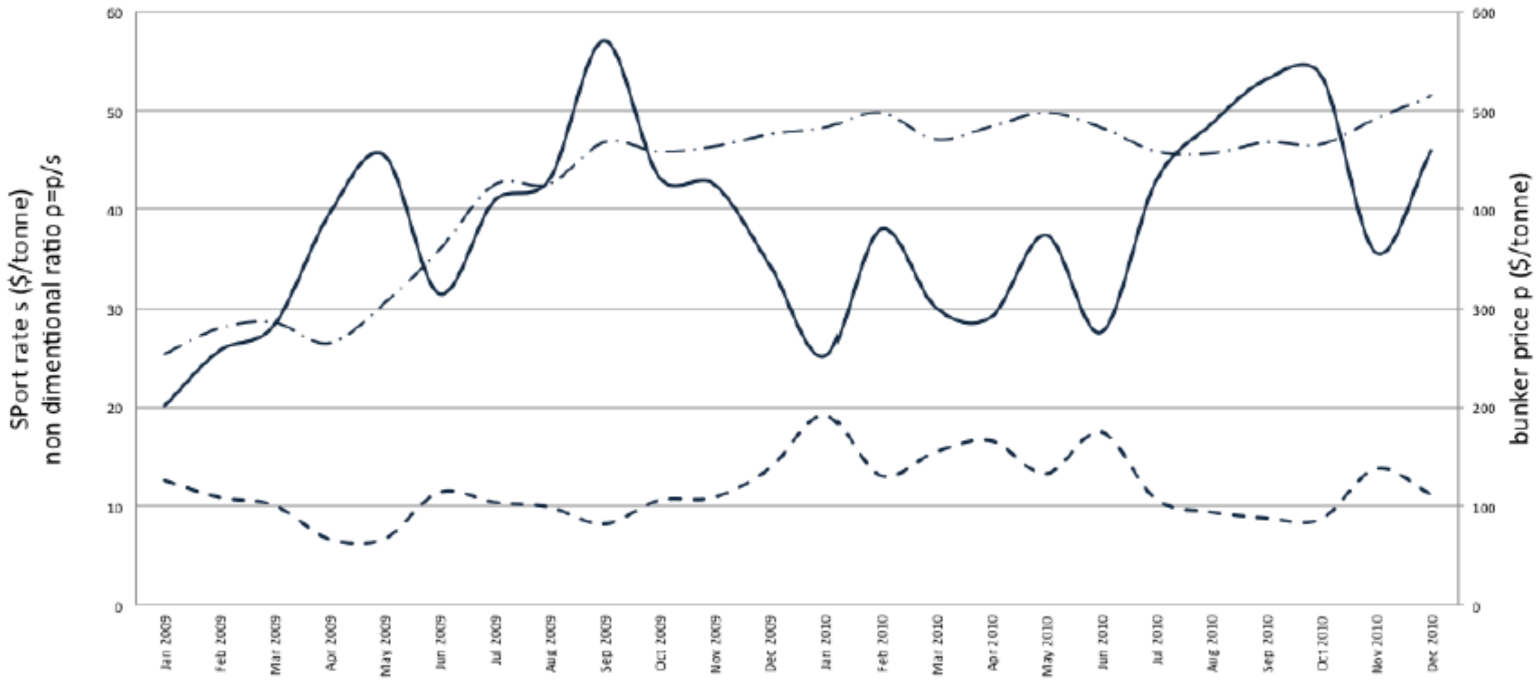
$$\min_{v} \left\{ s \left(R - \frac{C24v}{D} \right) + T + pF(v) \right\}$$

Role of ratio ρ= p/s

- Both problems reduce to:

$$\min_{v} \{ (p/s)f(v) - Cv/d \}$$

Ratio ρ=p/s



	Jan 2009	Feb 2009	Mar 2009	Apr 2009	May 2009	Jun 2009	Jul 2009	Aug 2009	Sep 2009	Oct 2009	Nov 2009	Dec 2009	Jan 2010	Feb 2010	Mar 2010	Apr 2010	May 2010	Jun 2010	Jul 2010	Aug 2010	Sep 2010	Oct 2010	Nov 2010	Dec 2010
s ($/tonne)	12.6	10.9	10.1	6.7	6.7	11.4	10.4	9.9	8.2	10.6	10.9	13.8	19.2	13.1	15.5	16.6	13.3	17.5	10.7	9.4	8.8	8.7	13.8	11.2
ρ=p/s	20.16	25.69	28.32	39.55	45.52	31.49	40.87	43.03	57.07	43.3	42.57	34.49	25.16	38.02	30.09	29.16	37.44	27.6	42.9	48.62	53.18	53.56	35.65	45.98
p ($/tonne)	254	280	286	265	305	359	425	426	468	459	464	476	483	498	471	484	498	483	459	457	468	466	492	515

Figure 4: Evolution of bunker price p, spot rate s and their ratio ρ=p/s. Data Source: Drewry's Shipping Economist (2009-2010).

Cost components

- Fuel costs
- Time charter costs
- Cargo inventory costs

Fuel costs

- On a leg from A to B of distance L
- If ship speed is v (n. miles/day)
- Fuel cost = P_{FUEL}*(L/v)*FC(v)
- Where FC(v) is the ship's daily fuel consumption

Fuel costs

- FC = kV^3 (cubic)
- Reasonable approximation in many cases

- Problem: exponent may be >3
- Problem: FC=0 for v=0

More general FC

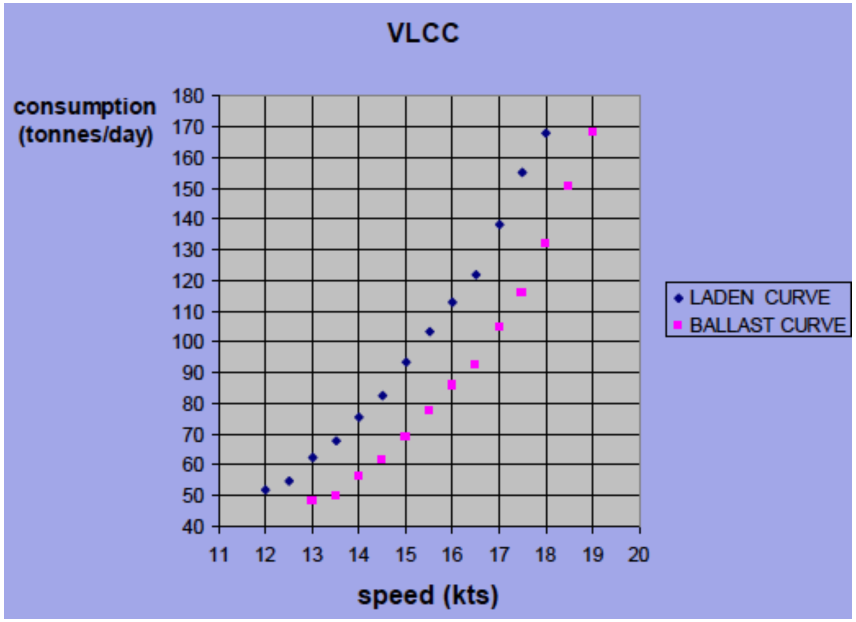
- $FC = a+bV^n$ ($n \geq 3$)

- Problem: FC depends on ship's loading condition

Even more general FC

- $FC = (A+BV^n)\Delta^{2/3}$

Δ= ship's displacement



- FC =f(V,w) (general)

- Depends on speed V and payload w

Time charter costs

- Assume ship on time charter
- Time charter rate F ($/day)
- F exogenous, determined by market conditions
- Cost proportional to overall time of trip (which depends on speeds of ship on each leg of route)

Cargo inventory costs (in-transit)

- Cargo inventory costs can be important, mainly in the liner business which involves trades of higher valued goods than bulk trades.
- The unit value of the top 20 containerized imports at the Los Angeles and Long Beach Ports in 2004 varied from about $14,000/tonne for furniture and bedding to $95,000/tonne for optic, photographic and medical instruments.
- Delaying one tonne of the latter category of cargo by one week because of reduced speed would cost some $91 if the cost of capital is 5%. For a $75,000/tonne payload this would amount to some $6.8 million.

Important observation

- Ship speed impacts all three categories of costs

- Fuel costs in a positive way
- Time charter costs in a negative way
- Cargo inventory costs in a negative way

Taxonomy of speed models

- 1st cut:
- Non-emissions related
- Emissions-related

Finer-grain classification according to

- Optimization criterion: cost, profit, or other
- Shipping market/context
- Who is the decision maker
- Fuel price an input?
- Freight rate an input?
- Fuel consumption function? Cubic/general
- Optimal speeds in various legs
- Logistical context

Classification ii

- Size of fleet? Single ship, multiple ships
- Adding more ships an option?
- Inventory costs included?
- Emissions considered?
- Modal split considered?
- Ports included in formulation?

Sample output

TABLE 3a: Taxonomy part I

Taxonomy parameter \ paper	Alderton (1981)	Bausch et al (1998)	Benford (1981)	Brown et al (1987)	Cariou (2011)	Cariou and Cheaitou (2012)	Corbett et al (2010)	Devanney (2007)	Devanney (2010)	Eefsen and Cerup-Simonsen (2010)
Optimization criterion	Profit	Cost	Cost	Cost	Cost	Cost	Profit	Profit	Cost or profit	Cost
Shipping market	General	Tanker/ barge	Coal	Tanker	Container	Container	Container	Tanker	Tanker (VLCC)	Container
Decision maker	Owner	Owner	Owner	Owner	Owner	Owner	Owner	Owner	Either	Owner
Fuel price an explicit input	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Freight rate an input	Input	No	No	No	No	No	Input	Computed	Computed	No
Fuel consumption function	Cubic	Unspecified	Cubic	Unspecified	Cubic	Cubic	Cubic	Cubic	General	Cubic
Optimal speeds in various legs	Yes	No	No	Only ballast	No	No	No	Yes	Yes	No
Optimal speeds as function of payload	Yes	No	No	No	No	No	No	No	No	No
Logistical context	Fixed route	Routing and scheduling	Fleet deployment	Routing and scheduling	Fixed route	Fixed route	Fixed route	World oil network	Fixed route	Fixed route
Size of fleet	Multiple ships	Multiple ships	Multiple ships	Multiple ships	Multiple ships	Multiple ships	Multiple ships	Multiple ships	One ship	Multiple ships
Add more ships an option	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Inventory costs included	Yes	No	No	No	No	Yes	No	Yes	Yes	Yes
Emissions considered	No	No	No	No	Yes	Yes	Yes	No	No	Yes
Modal split considered	No	No	No	No	No	No	No	No	No	No
Ports included	Yes	Yes	No	No	No	Yes	No	Yes	No	Yes

TABLE 3b: Taxonomy part II

Taxonomy parameter \ paper	Faber et al (2010)	Fagerholt (2001)	Fagerholt et al (2010)	Gkonis Psaraftis (2011abcd)	Kontovas Psaraftis (2011)	Lindstad et al (2011)	Norstad et al (2011)	Notteboom Vernimmen (2010)	Papadakis Perakis (1989)	Perakis (1985)
Optimization criterion	No/A	Cost	Cost	Profit	Cost	Pareto analysis	Cost	Cost	Cost	Cost
Shipping market	Various	General	Liner	Tanker, LNG, LPG	Container	All major ship types	Tramp	Container	Tramp	Tramp
Decision maker	No/A	Owner	Owner	Owner	Charterer	Owner	Owner	Owner	Owner	Owner
Fuel price an explicit input	No	No	No	Yes	Yes	Yes	No	Yes	Yes	No
Freight rate an input	No	No	No	Input	Input	No	No	No	No	No
Fuel consumption function	Cubic	Cubic	Cubic	General	Cubic	Cubic	Cubic	Unspecified	General	Cubic
Optimal speeds in various legs	No	Yes	Yes	Yes	Yes	No	Yes	No	Yes	No
Optimal speeds as function of payload	No	No	No	No	Yes	Yes	No	No	No	No
Logistical context	Fixed route	Pickup and	Fixed route	Fixed route	Fixed route	Fixed route	Pickup and	Fixed route	Fleet	Fleet

Highlights (sample)

- Alderton (1981) presents a variety of criteria to determine the speed that maximizes profit and discusses how sensitive these speeds are to such inputs as port time, voyage distance, freight rates and bunker costs. The influence of cargo inventory costs is also taken into account.

- Benford (1981) proposes a simple procedure to select the mix of available ships from a fleet and their speeds in order to achieve the best solution for a fleet owner. The approach is confined to non-liner trades (in fact his examples are from the coal trades in the Great Lakes).

More highlights

- Notteboom and Vernimmen (2010) deal with the impact of high fuel costs on the design of liner services on the Europe–Far East trade and discuss the way that shipping lines have adapted their schedules in terms of speed and number of vessels deployed for each loop.

- Devanney (2007) models the world's petroleum transportation network as a linear program, and simultaneously determines tanker optimal speeds in the laden and ballast legs, FOB and CIF prices of crude oil at origin and destination points, and the market equilibrium spot rates in various routes.

Even more..

- Norstad et al. (2011) present the tramp ship routing and scheduling problem with speed optimization, where speed is introduced as a decision variable. Although the main objective is to maximize profit by allowing the option of picking up spot cargoes, for the speed optimization subproblem the objective is to minimize costs on a certain leg of the route.

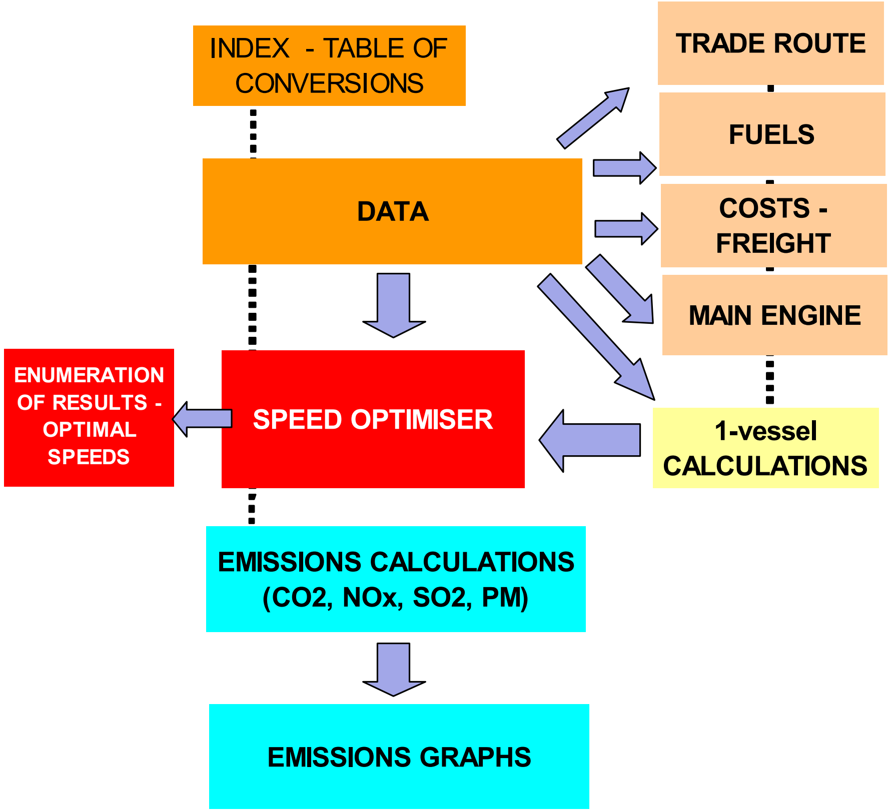
- Fagerholt et al. (2010) consider a single route speed optimization problem with soft-time windows and proposed a solution methodology in which the arrival times are discretized and the solution is based on the shortest path of the directed acyclic graph that is formed. Reduction in ship emissions are also computed.

and more..

- Cariou and Cheaitou (2012) investigate policy options contemplated by the European Commission and compare speed limits versus a bunker levy as two measures to abate GHGs, with a scenario from the container trades. They conclude that the latter measure is counterproductive for two reasons. First, because it may ultimately generate more emissions and incur a cost per tonne of CO_2 which is more than society is willing to pay. Second, because it is sub-optimal compared to results obtained if an international bunker-levy were to be implemented.
- Psaraftis and Kontovas (2010) look at the impact of speed reduction on modal split, in the sense that cargoes that go slower may choose alternative modes of transport, particularly if their inventory costs are high. This may be true not only for short sea trades, but for longer haul ones, for example using the Trans-siberian railway to move cargoes to or from the Far East. Multinomial logit models are introduced.

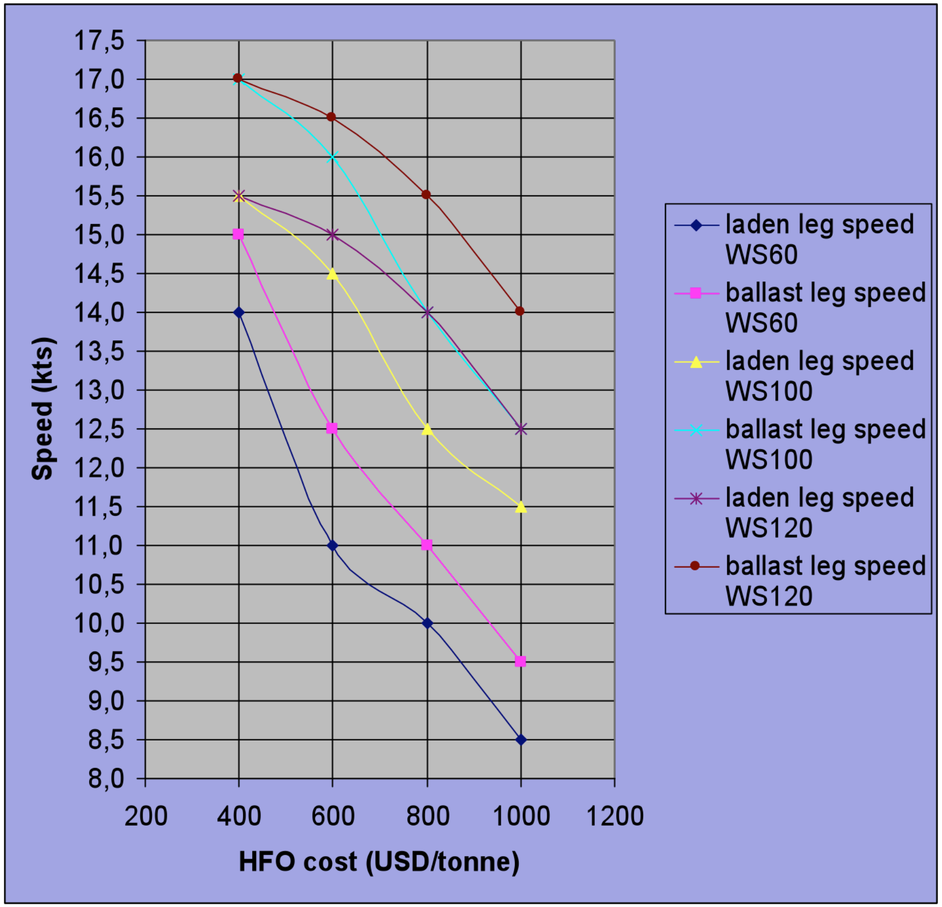
VLCC speed model

- Gkonis & Psaraftis (2012)



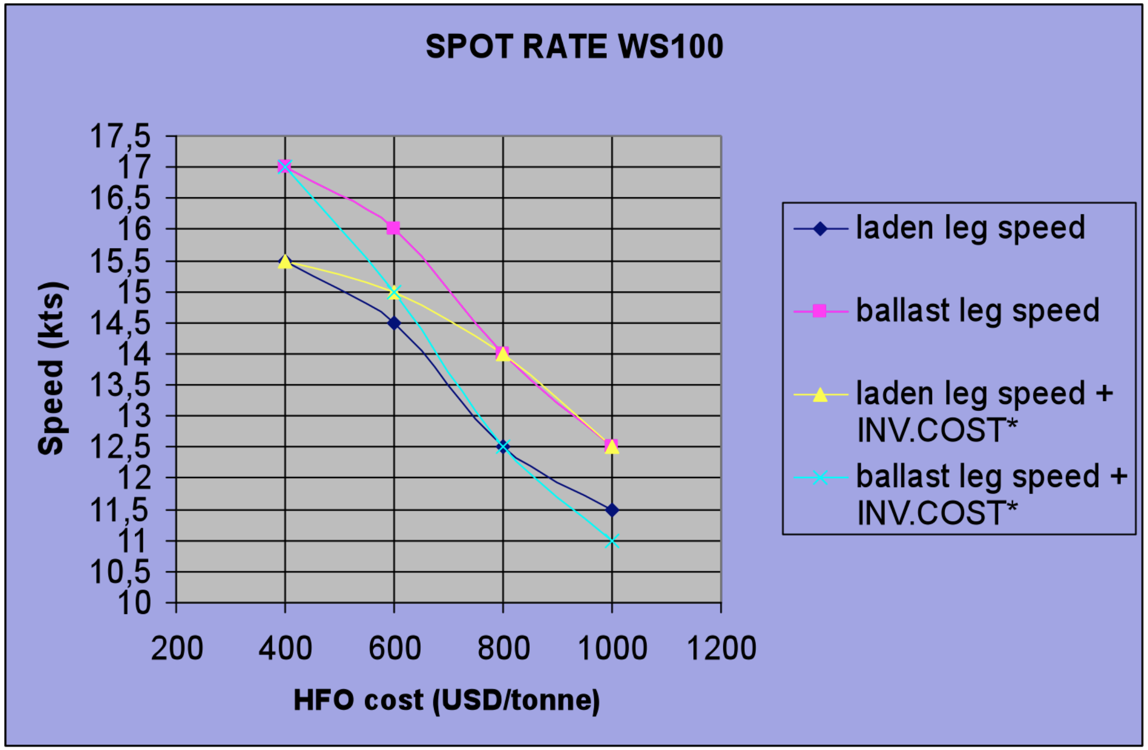
VLCC results

- Route: Gulf-Japan
- Optimize both laden and ballast speeds



VLCC cont’d

- Include cargo inventory costs



Effect of fuel price on emissions

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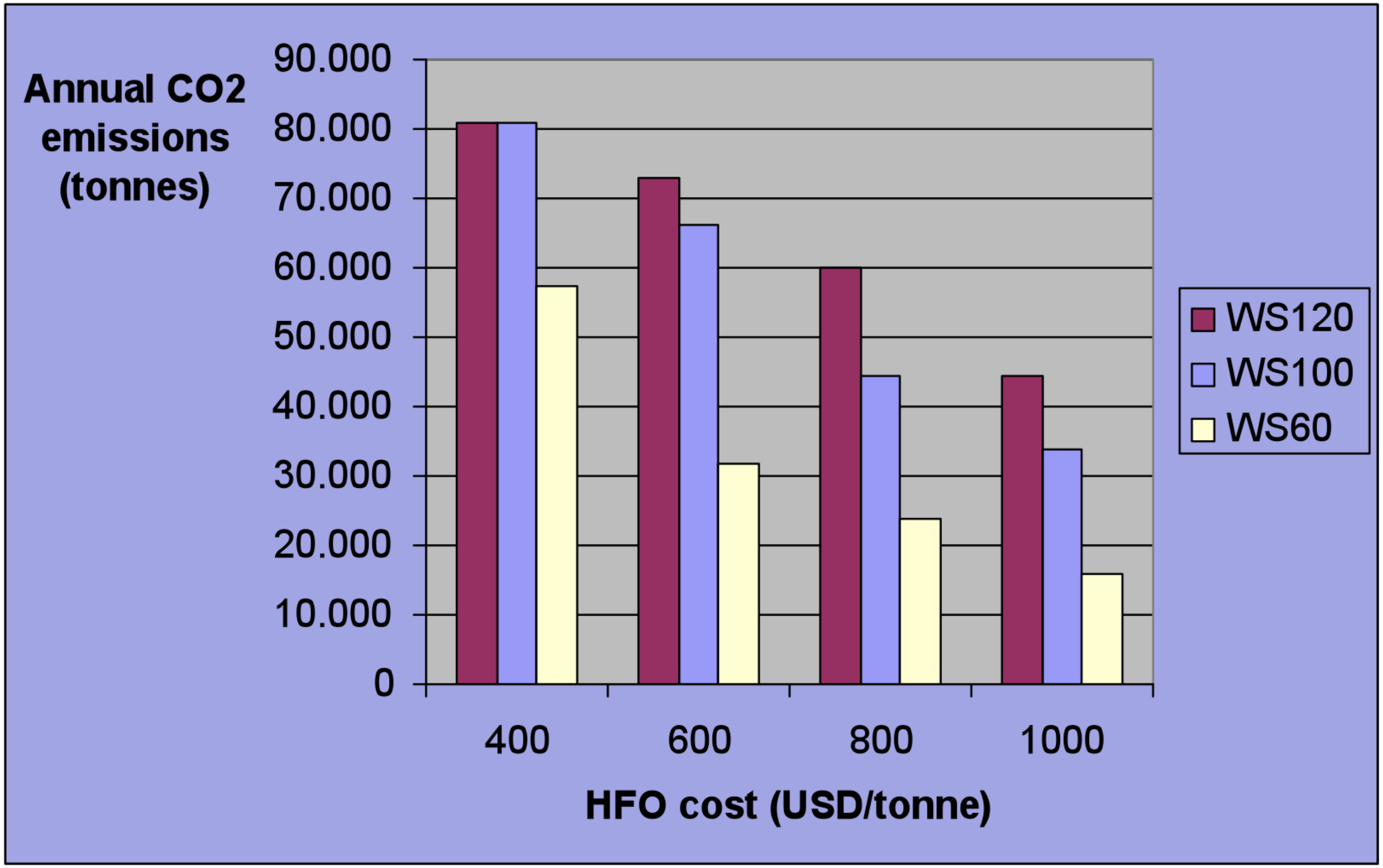
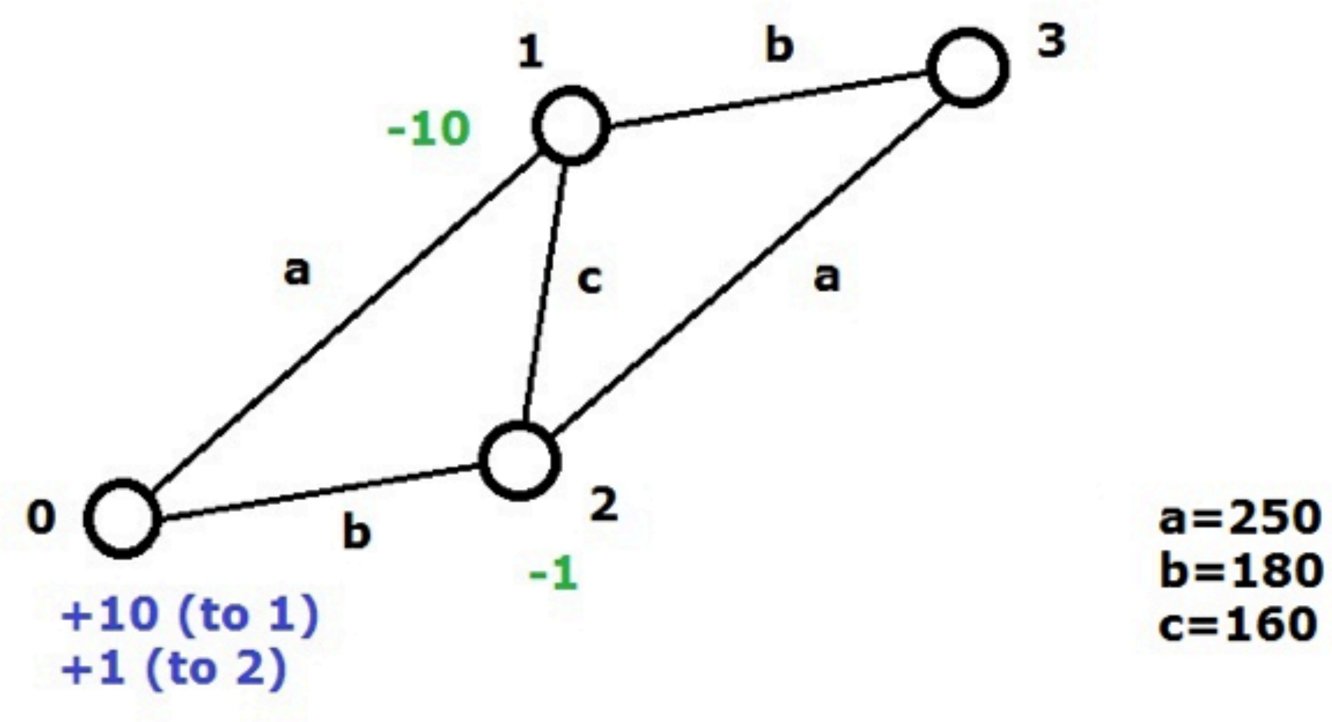


Combining speed and routing decisions

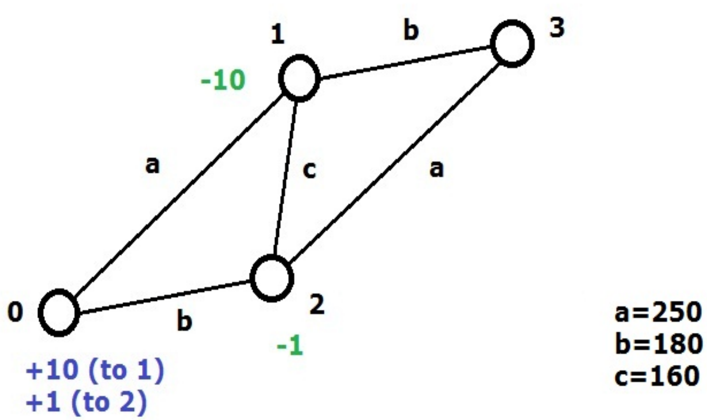
- Psaraftis (2012)
- Input parameters $P_{FUEL,}$ F, value of cargo can influence both ship speed and the routing decision!

Example: ship of Q=11 (000 tons)



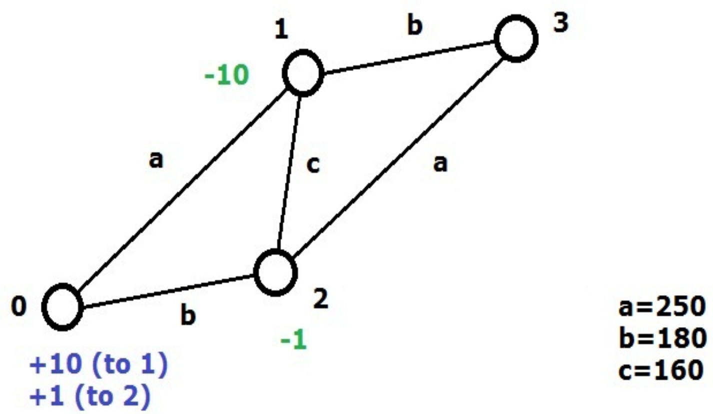
Minimum fuel cost (F=α=β=0)

- v between 8 and 14 knots
- Cubic FC function
- FC dependence on w
- Fuel price $600/ton



- Sail at minimum speed
- Optimal route: 0-1-2-3
- even though total distance sailed (660 nautical miles) is more than that of route 0-2-1-3 (480 nautical miles).
- Reason: heavier cargo is delivered first

If F > $450/day



- Optimal route: 0-2-1-3
- Different speeds in each leg
- Speeds depend on F (higher if F increases)

Policy aspects

- Numerous (IMO, EU, other)
- Impact of EEDI: indirect speed limits
- Speed limits lobbied for

Conclusions

- Ship speed is a key determinant to both shipping economics and the environmental sustainability of maritime transportation
- As the 'speed knob' is very much at play these days and will be more so in the future, we anticipate that research in this area will continue.
- In particular, we anticipate maritime logistics research to increasingly take into account environmental considerations.

THANK YOU VERY MUCH!

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