Slow steaming in maritime transportation: fundamentals, trade-offs, and decision models

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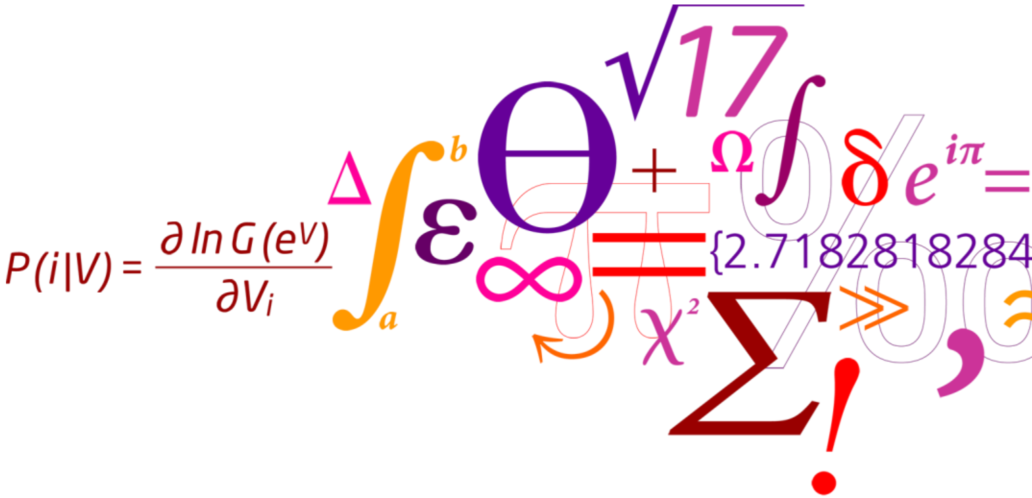

DTU Transport

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Scope

- Examine the practice of slow steaming from various angles
- Outline some fundamentals
- Analyse the main trade-offs
- Present some decision models
- Present some examples so as to highlight the main issues that are at play

Material taken from

- Psaraftis, H.N. and C.A. Kontovas, "CO2 Emissions Statistics for the World Commercial Fleet", WMU Journal of Maritime Affairs, 8:1, pp. 1-25, 2009.
- Psaraftis, H.N., C.A. Kontovas, "Ship Emissions: Logistics and Other Tradeoffs", 10th Int. Marine Design Conference (IMDC), Trondheim, Norway, 26-29 May 2009.
- Psaraftis, H.N., Kontovas, C.A., Kakalis, N., "Cost- effectiveness of Speed Reduction as an Emissions Reduction Measure for Fast Ships", Proceedings of the 10th International Conference on Fast Sea Transportation (FAST 2009), October 5-8, 2009, Athens, Greece.
- Kontovas, C.A., H. N. Psaraftis, "Reduction of emissions along the maritime intermodal container chain: operational models and policies," Maritime Policy and Management Vol. 38, No. 4, pp 451-469, 2011.
- Kontovas, C.A., H. N. Psaraftis, "Climate Change Policy in Shipping Focusing on Emission Standards and Technology Measures", Environmental Engineering and Management Journal, Vol. 10, Issue 10, pp.1589-1596., 2011.
- Kontovas, C.A., H.N. Psaraftis, "The link between economy and environment in the post-crisis era: lessons learned from slow steaming," Int. J. Decision Sciences, Risk and Management, Vol. 3, Nos. 3/4, 2011, pp. 311-326.
- Gkonis, K.G., H. N. Psaraftis, "Modelling tankers' optimal speed and emissions," Archival Paper, 2012 SNAME Transactions, Vol. 120, 90-115, 2012
- Psaraftis, H.N., and C.A. Kontovas, "Speed Models for Energy-Efficient Maritime Transportation: A Taxonomy and Survey," Transportation Research Part C, 26, 331–351, 2013.
- Psaraftis, H.N., and C.A. Kontovas , "Ship speed optimization: Concepts, models and combined speed-routing scenarios," Transportation Research Part C, 44, 52-69, 2014.

- **+SOME YET UNPUBLISHED STUFF**

Speed taxonomy paper (2013)

Transportation Research Part C 26 (2013) 331–351

Contents lists available at SciVerse ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Overview Paper

Speed models for energy-efficient maritime transportation: A taxonomy and survey

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Speed taxonomy paper

Purpose

- What has been done in this area?
- 42 papers reviewed

1st cut

- Non-emissions related (circa 1981)
- Emissions-related (circa 2009)

Table 2b
Taxonomy part II.

Taxonomy parameter/paper	Devanney (2007)	Devanney (2010)	Du et al. (2011) Wang et al. (2013)	Eefsen and Cerup-Simonsen (2010)	Faber et al. (2010)	Fagerholt (2001)	Fagerholt et al. (2010)	Gkonis and Psaraftis (2012)
Optimization criterion	Profit	Cost or profit	Fuel consumption	Cost	N/A	Cost	Fuel consumption	Profit
Shipping market	Tanker	Tanker (VLCC)	Container	Container	Various	General	Liner	Tanker, LNG, LPG
Decision maker	Owner	Owner or charterer	Owner	Owner	N/A	Owner	Owner	Owner
Fuel price an explicit input	Yes	Yes	No	Yes	No	No	No	Yes
Freight rate an input	Computed	Computed	No	No	No	No	No	Input
Fuel consumption function	Cubic	General	Non-linear	Cubic	Cubic	Cubic	Cubic	General
Optimal speeds in various legs	Yes	Yes	Yes	No	No	Yes	Yes	Yes
Optimal speeds as function of payload	No	No	No	No	No	No	No	No
Logistical context	World oil network	Fixed route	Berth allocation	Fixed route	Fixed route	Pickup and delivery	Fixed route	Fixed route
Size of fleet	Multiple ships	One ship	Multiple ships	Multiple ships	Multiple ships	Multiple ships	One ship	Multiple ships
Add more ships an option	Yes	Yes	No	Yes	Yes	No	No	Yes
Inventory costs included	Yes	Yes	No	Yes	No	No	No	Yes
Emissions considered	No	No	Yes	Yes	Yes	No	Yes	Yes
Modal split considered	No	No	No	No	No	No	No	No
Ports included	Yes	No	Yes	Yes	No	No	No	Yes

How many?

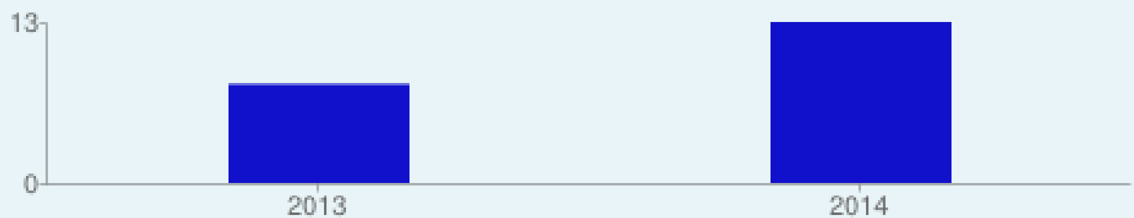
- 1981-2013 (32 years): 42 papers

- 2013-2014 (<2 years): ?

- ≥21 new publications in 2013 and 2014 alone

Total citations — Cited by 21

Citations per year



Scholar articles — Speed models for energy-efficient maritime transportation: A taxonomy and survey
HN Psaraftis, CA Kontovas - Transportation Research Part C: Emerging ..., 2013
Cited by 21 - Related articles - All 5 versions

Topics include

[Containership routing and scheduling in liner shipping: overview and future research directions]
Q Meng, S Wang, H Andersson... - Transportation ..., 2013 - pubsonline.informs.org
This paper reviews studies from the past 30 years that use operations research methods to tackle containership routing and scheduling problems at the strategic, tactical, and operational planning levels. These problems are first classified and summarized, with a ...
Cited by 14 Related articles Cite Save

[Bunker consumption optimization methods in shipping: a critical review and extensions]
S Wang, Q Meng, Z Liu - Transportation Research Part E: Logistics and ..., 2013 - Elsevier
It is crucial nowadays for shipping companies to reduce bunker consumption while maintaining a certain level of shipping service in view of the high bunker price and concerned shipping emissions. After introducing the three bunker consumption ...
Cited by 6 Related articles All 4 versions Cite Save

[Global intermodal liner shipping network design]
Z Liu, Q Meng, S Wang, Z Sun - Transportation Research Part E: Logistics ..., 2014 - Elsevier
Abstract This paper presents a holistic analysis for the network design problem of the intermodal liner shipping system. Existing methods for liner shipping network design mainly deal with port-to-port demand. However, most of the demand has inland origins and/or ...
Cited by 1 Related articles All 4 versions Cite Save

[Maritime fleet deployment with voyage separation requirements]
I Norstad, K Fagerholt, LM Hvattum, HS Arnulf... - Flexible Services and ..., 2013 - Springer
Abstract A dry bulk shipping company is operating its fleet on a number of trade routes and is committed to sail a given number of voyages on these trade routes during the planning period, while trying to derive additional revenue from chartering out ships on short term ...
Cited by 2 Related articles Cite Save

[Effect of a speed reduction of containerships in response to higher energy costs in Sulphur Emission Control Areas]
M Doudnikoff, R Lacoste - Transportation Research Part D: Transport and ..., 2014 - Elsevier
Abstract The objective of this paper is to explore the possible consequences of the future low-sulphur fuel requirements in Sulphur Emission Control Areas (SECA) on vessel speed, from the standpoint of the container shipping industry. Rational energy use, speed reduction, ...
Related articles Cite Save

[The feeder network design problem: Application to container services in the Black Sea region]
O Polat, HO Günther, O Kulak - Maritime Economics & ..., 2014 - palgrave-journals.com
Abstract Global containership liners design their transportation service as hub-and-spoke

Latest citation

Meat Science

Volume 98, Issue 1, September 2014, Pages 71–80

Review

Factors affecting microbial spoilage and shelf-life of chilled vacuum-
d lamb transported to distant markets: A review

ls[a], Andrea Donnison[a], Gale Brightwell[b,]

Ship speed

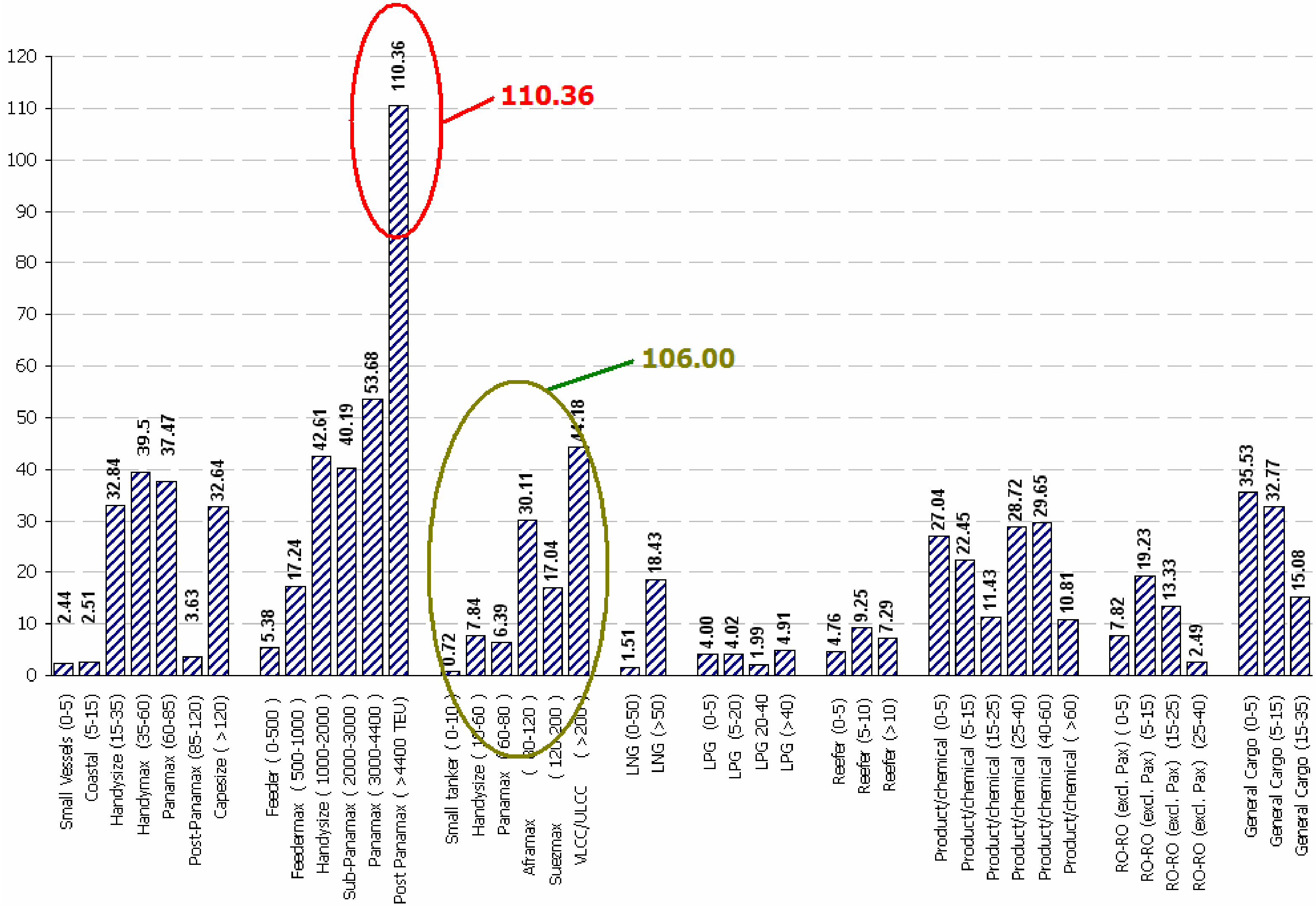
- Has always been important
- Increasingly important in recent years
- Economic considerations
- Operational considerations
- Environmental considerations

Rationale

- Need to optimize ship economic performance in these difficult times (high bunker prices and low freight rates)
- Important byproduct: reduce emissions

- ---> Slow steaming

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

- Win-win-win?

Is it always win-win?

- NOT NECESSARILY!

- Adding more ships to maintain same throughput will entail a cost
- Delaying cargo delivery will increase (in transit) inventory costs
- Shrinking fleet supply may increase freight rates
- Ships going slower may shift cargo to other modes, possibly increasing overall CO2
- Building more ships to match throughput will increase CO2 due to shipbuilding and scrapping!

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

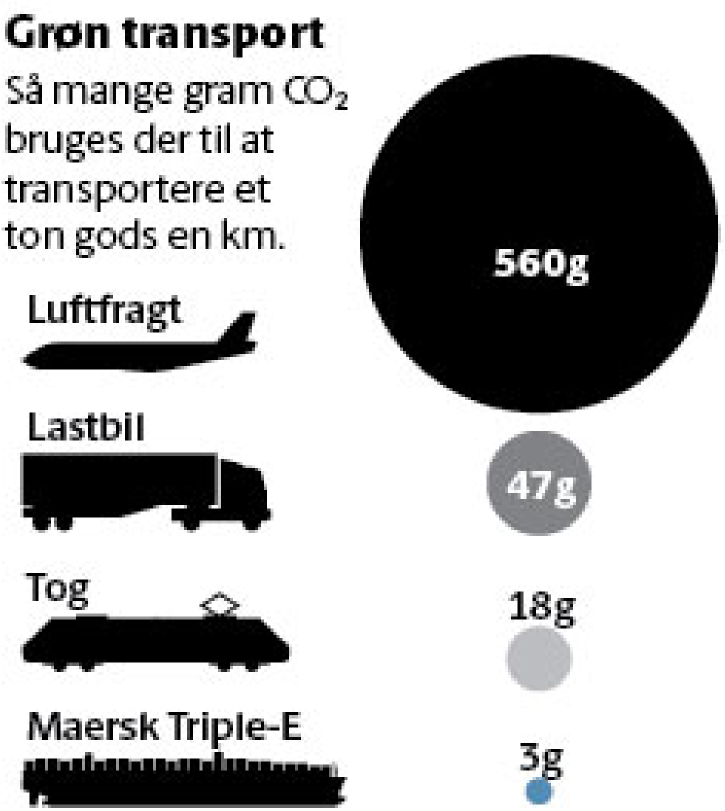
- New Maersk 18,000 TEU ships: 17.8 knots

- Project ULYSSES:
  Go 5-6 knots!

Maersk 3E: 18,000 TEU

- Economy of scale, Energy efficiency and Environmentally improved performance

3E is green


Grøn transport
Så mange gram CO₂ bruges der til at transportere et ton gods en km.
Luftfragt
560g
Lastbil
47g
Tog
18g
Maersk Triple-E
3g


Find den rette kø
Tidspunkt >
:00
:15
:30
:45

In many OR/MS maritime 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.

EXAMPLES

- There are several fixed-speed models in the literature that include
  - port capacity constraints,
  - berth occupancy constraints,
  - time window or other constraints that preclude the simultaneous service of more than a given number of vessels
  - disruption scenarios that call for remedial action
- Better solutions to these problems could conceivably be obtained if ship speed was allowed to vary

Shipping market behavior

- If state of the market is up, ships tend to speed up, else they slow steam
- If bunker prices are up, ships tend to slow steam, else they go faster.

- (Intuitively) the ratio of (bunker price/freight rate) seems to be an important parameter

Some fundamentals

- Ships do NOT trade at predetermined speeds!
- Those who pay for the fuel will **choose an optimal speed** as a function of basically 2 things:
  - (a) bunker price, and
  - (b) the state of the market and specifically the spot rate

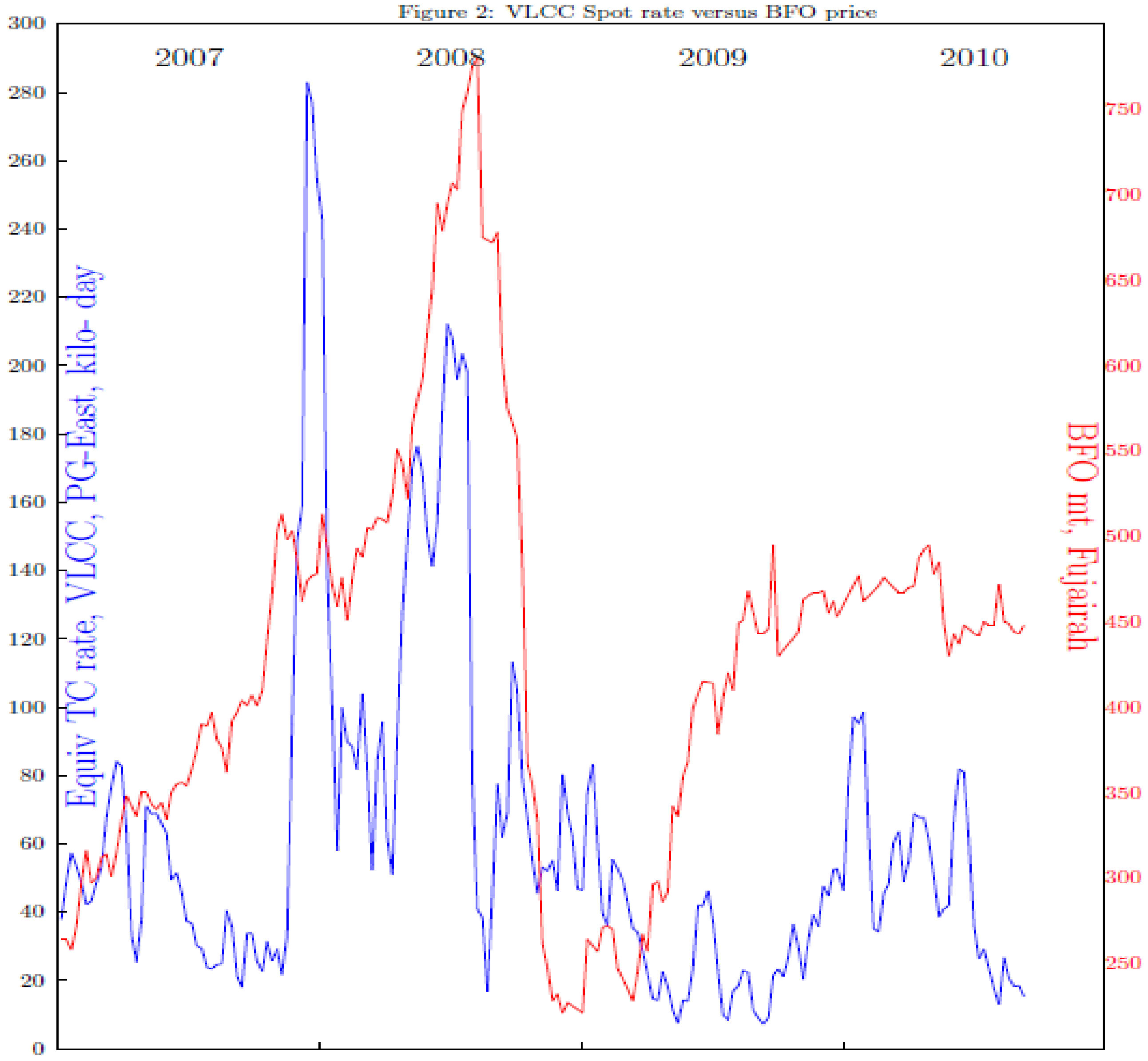


Figure 2: VLCC Spot rate versus BFO price
2007
2008
2009
2010
Equiv TC rate, VLCC, PG-East, kilo-day
BFO mt, Fujairah
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
250
300
350
400
450
500
550
600
650
700
750

Who pays for the fuel?

- the ship owner if the ship is in the spot market on a voyage charter
- the charterer if the ship is on a time or bareboat charter

Who and what

- who is the speed optimizer?

- what is being optimized?

- owner in spot market: Max profit
- time charterer: Min cost

Fundamentals 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 problem
source: Devanney (2010)

- OBJECTIVE: Maximize average per day profits
- s: spot rate ($/tonne)
- C: payload (tonnes)
- p: fuel price ($/tonne)
- F(v): daily 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 problem

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

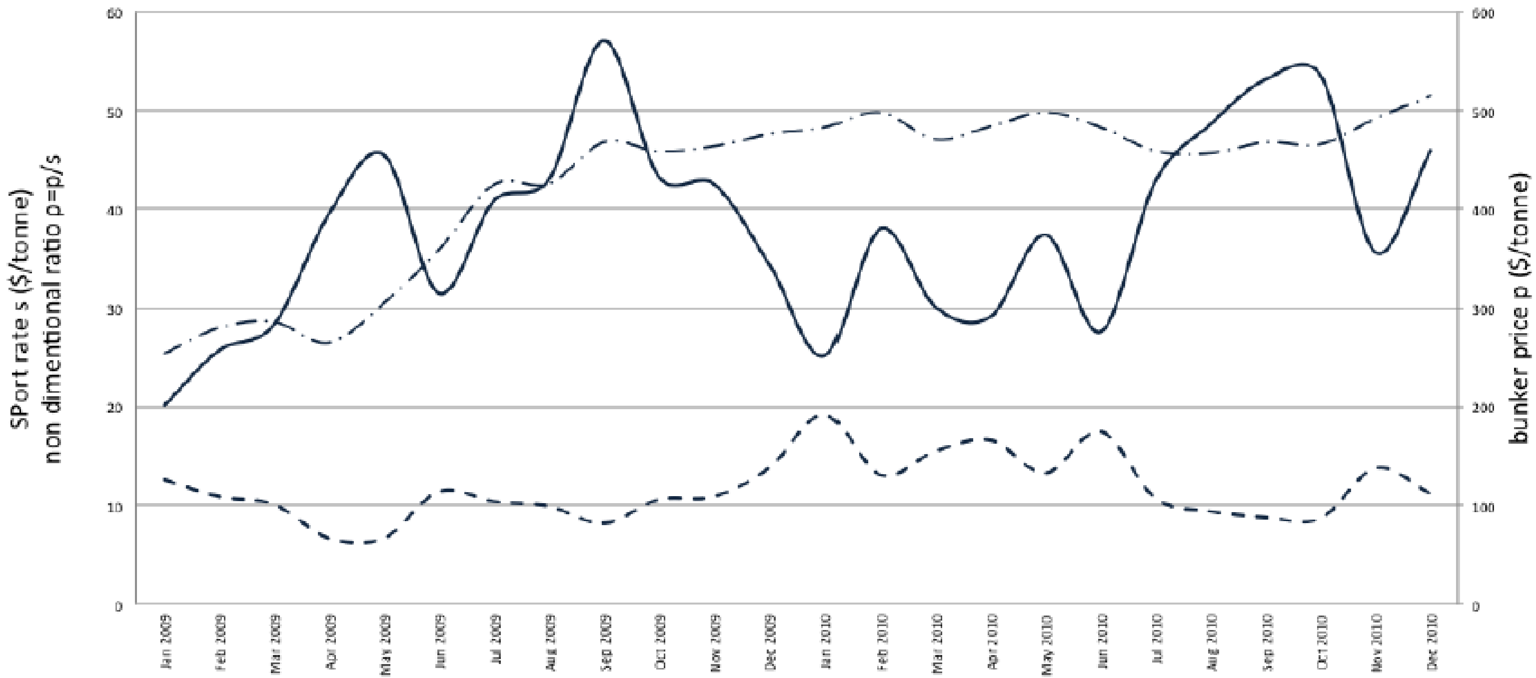
$$\min_{v} \left\{ s \left(R - \frac{C24v}{D} \right) + T + pF(v) \right\}$$

Role of ratio ρ= p/s
(fuel price to spot rate)

- 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
s ($/tonne)	12.6	10.9	10.1	6.7	6.7	11.4	10.4	9.9	8.2	10.6	10.9	13.8
ρ=p/s	20.16	25.69	28.32	39.55	45.52	31.49	40.87	43.03	57.07	43.3	42.57	34.49
p ($/tonne)	254	280	286	265	305	359	425	426	468	459	464	476

	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 ($/tonne)	19.2	13.1	15.5	16.6	13.3	17.5	10.7	9.4	8.8	8.7	13.8	11.2
ρ=p/s	25.16	38.02	30.09	29.16	37.44	27.6	42.9	48.62	53.18	53.56	35.65	45.98
p ($/tonne)	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).

Exceptions

- If ship on voyage charter, speed in **laden leg** may be specified in the charter party agreement
- That speed may not be equal to the optimal speed the owner would choose
- In this case, there is no optimization involved in the laden leg

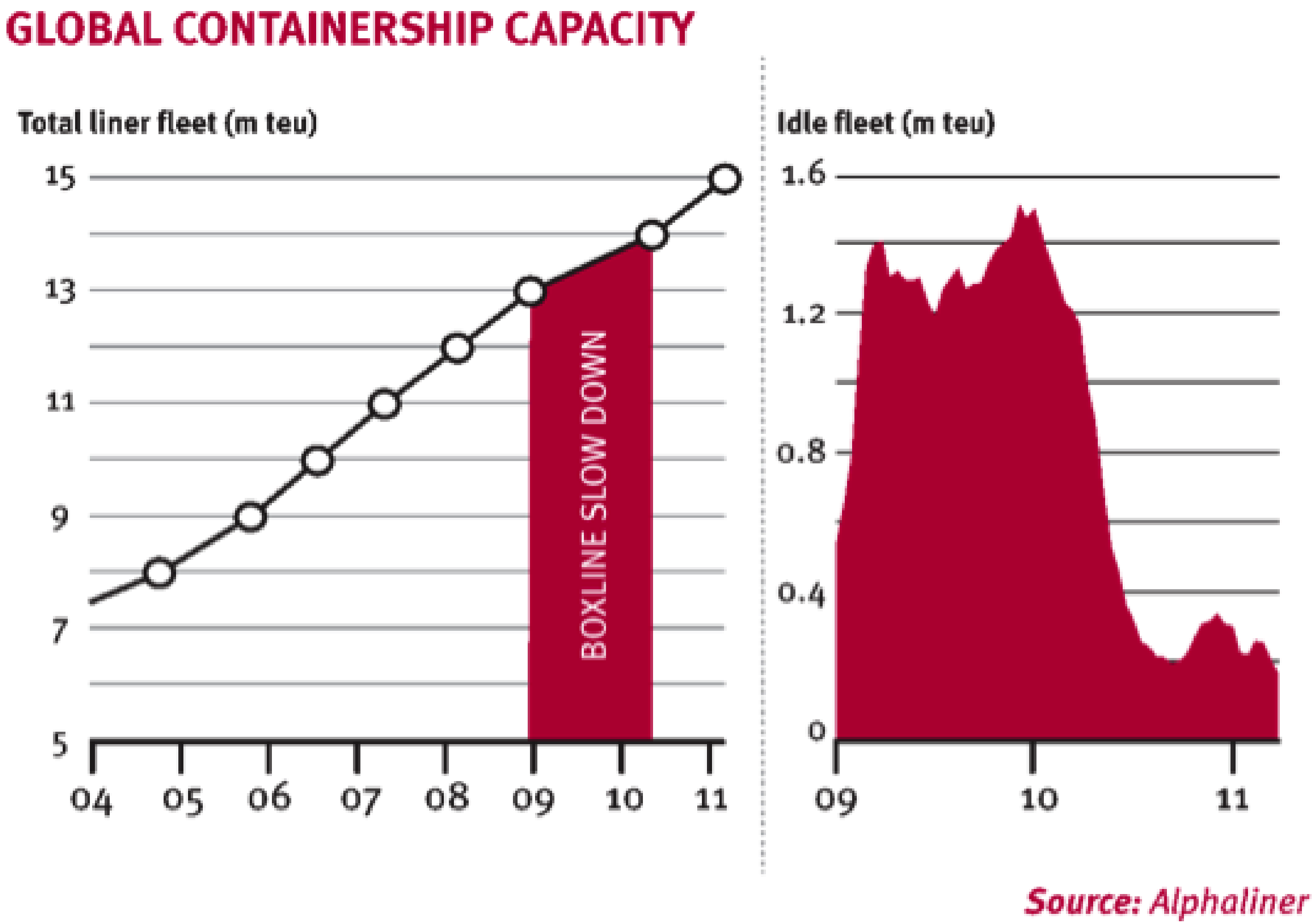
- Time windows on delivery may also implicitly determine laden speed

Is slow steaming being practised today?

OF COURSE!

- Practically 0 tanker and bulk carrier lay up
- 0.2 mm tons of bulkers laid up out of 564.1 mm afloat*
- 2.6 mm tons of tankers out of 440.1 mm tons afloat*

*Clarksons Shipping Intelligence Weekly, 2011-06-03,


GLOBAL CONTAINERSHIP CAPACITY
Total liner fleet (m teu)
15
13
11
9
7
5
04
05
06
07
08
09
10
11
BOXLINE SLOW DOWN
Idle fleet (m teu)
1.6
1.2
0.8
0.4
0
09
10
11
Source: Alphaliner

Fuel consumption function

- MOST MODELS ASSUME

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

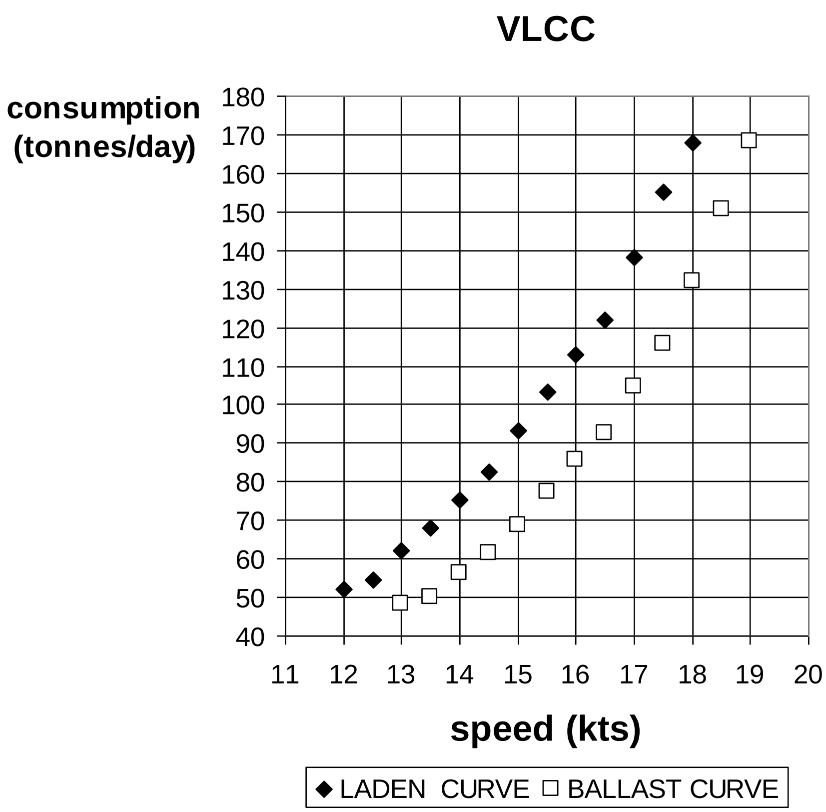
- Problem: exponent may be >3 for some ships
- Problem: FC=0 for v=0
- Problem: FC may depend on payload

More general FCs

- $FC = (A+BV^n)\Delta^{2/3}$
  Δ= ship's displacement

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

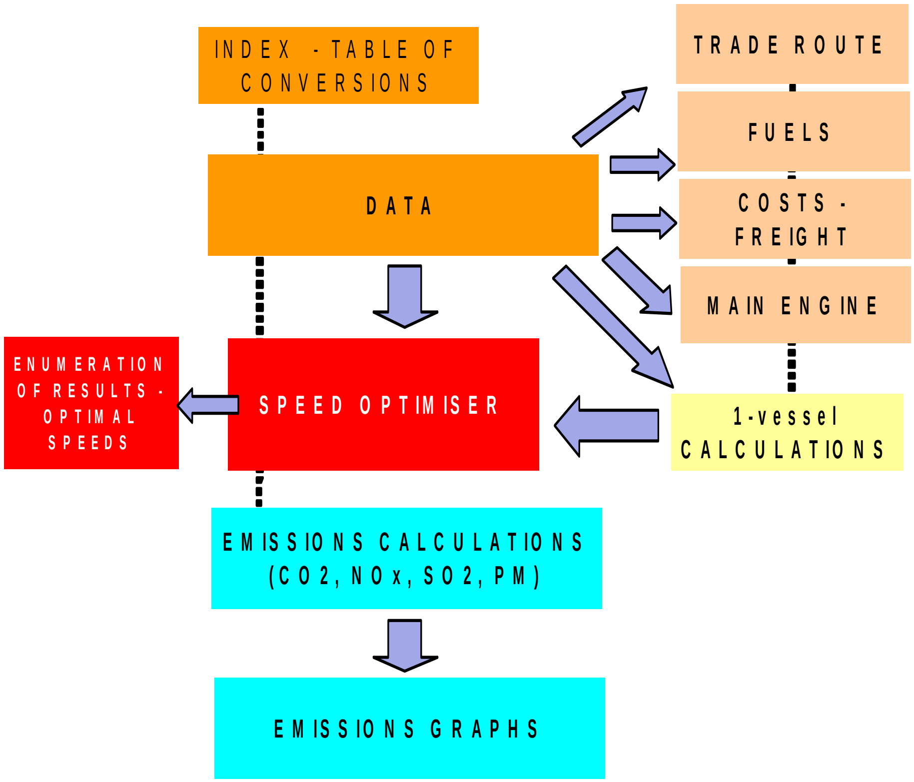
- Depends on both speed V and payload w



Gkonis and Psaraftis (2012): a 2-level approach

Level 1: speed optimization for **single tanker** over a defined route

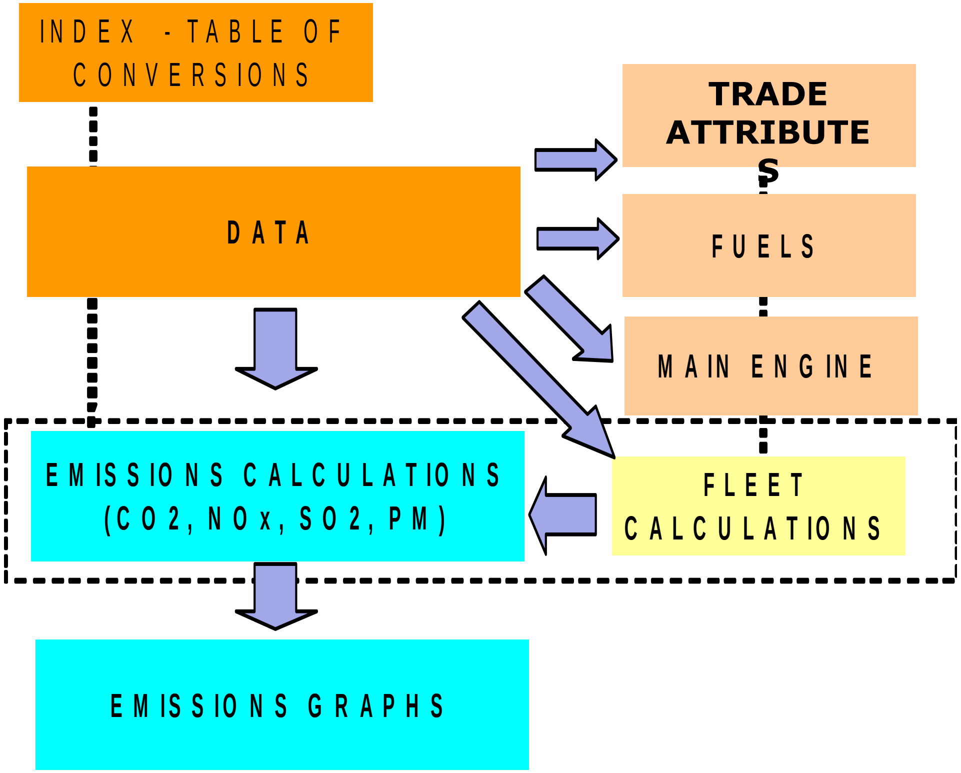
- Typical ship / trading routes
- defined scenario (e.g. freight rate levels & bunker prices)
- Output: laden and ballast leg speeds / emissions



Gkonis and Psaraftis (2012) cont'd

Level 2: calculation of emissions for **a segment of the global tanker fleet**

- does not refer to a specific route / basis: annual tonne*miles throughput of the fleet / speeds from Step 1
- Output: annual emissions / operational aspects (e.g. fuel consumption)



2 cases

Case 1:

Laden leg speed constrained around (+/- 1 kt) of average service speed

(speed at ~ 90% MCR)

Ballast speed free

Case 2:

No operational restrictions imposed on either speed (other than technical limits)

General trend

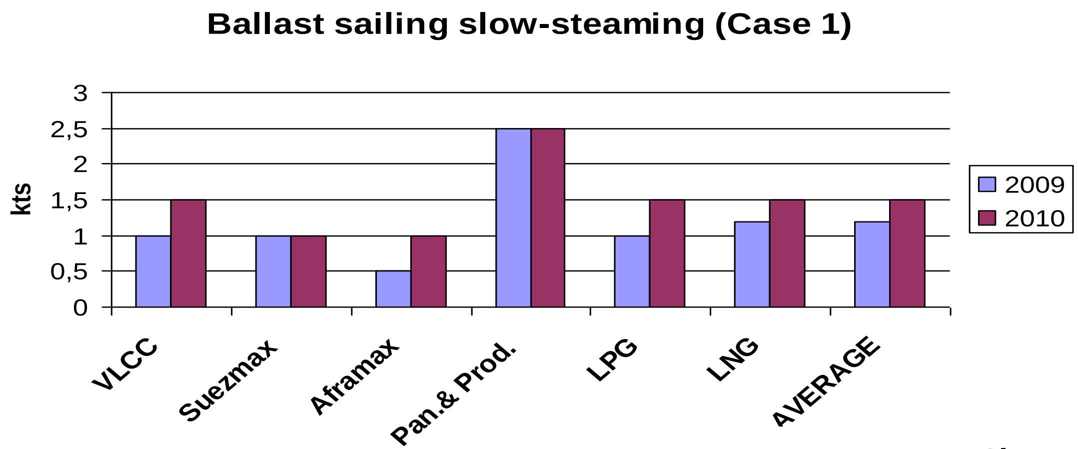
- Case 1 (Laden speed restricted, ballast speed free):

  Laden speed > ballast speed

- Case 2 (both speeds free):

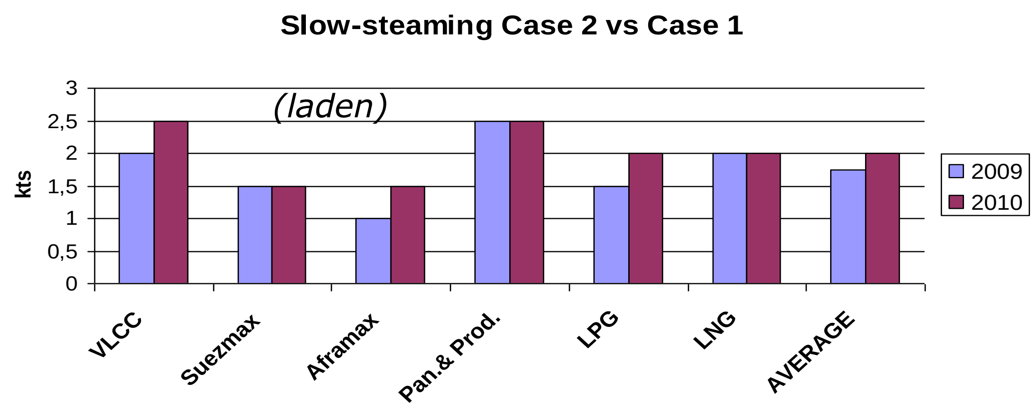
  Laden speed < ballast speed

Speed differentials, all tanker types



- Δ1 =[Laden-ballast] (case 1)

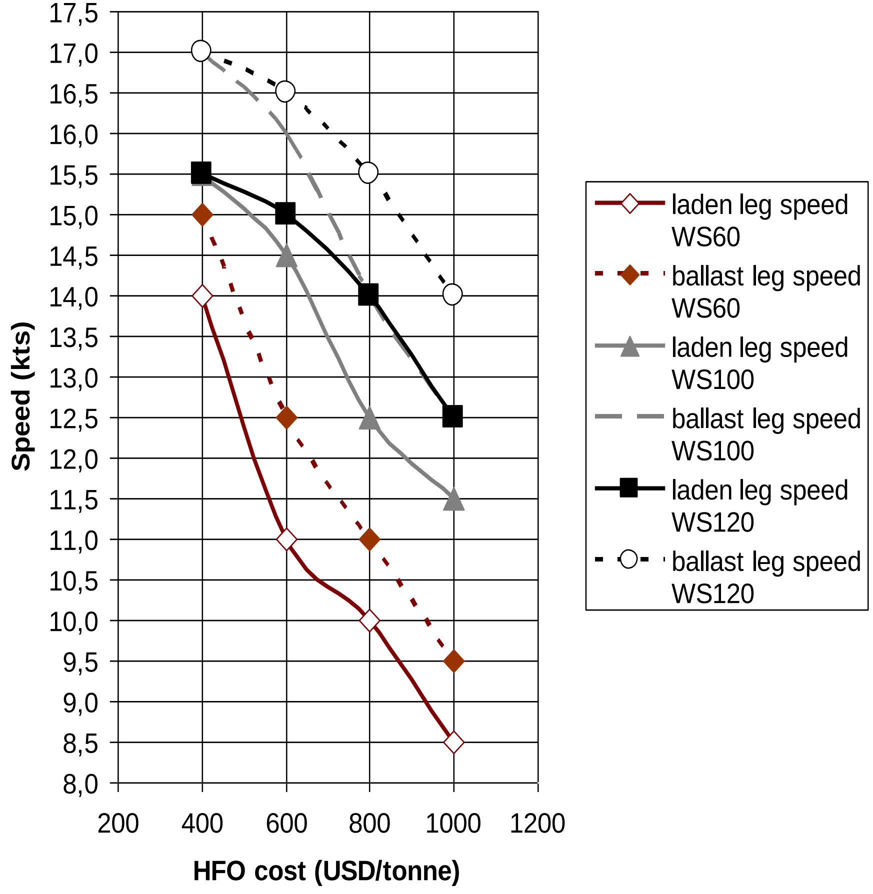
- Δ2=[case 1-case 2] (laden speed)



SENSITIVITY ANALYSES (VLCC)

Impact of higher freight rates

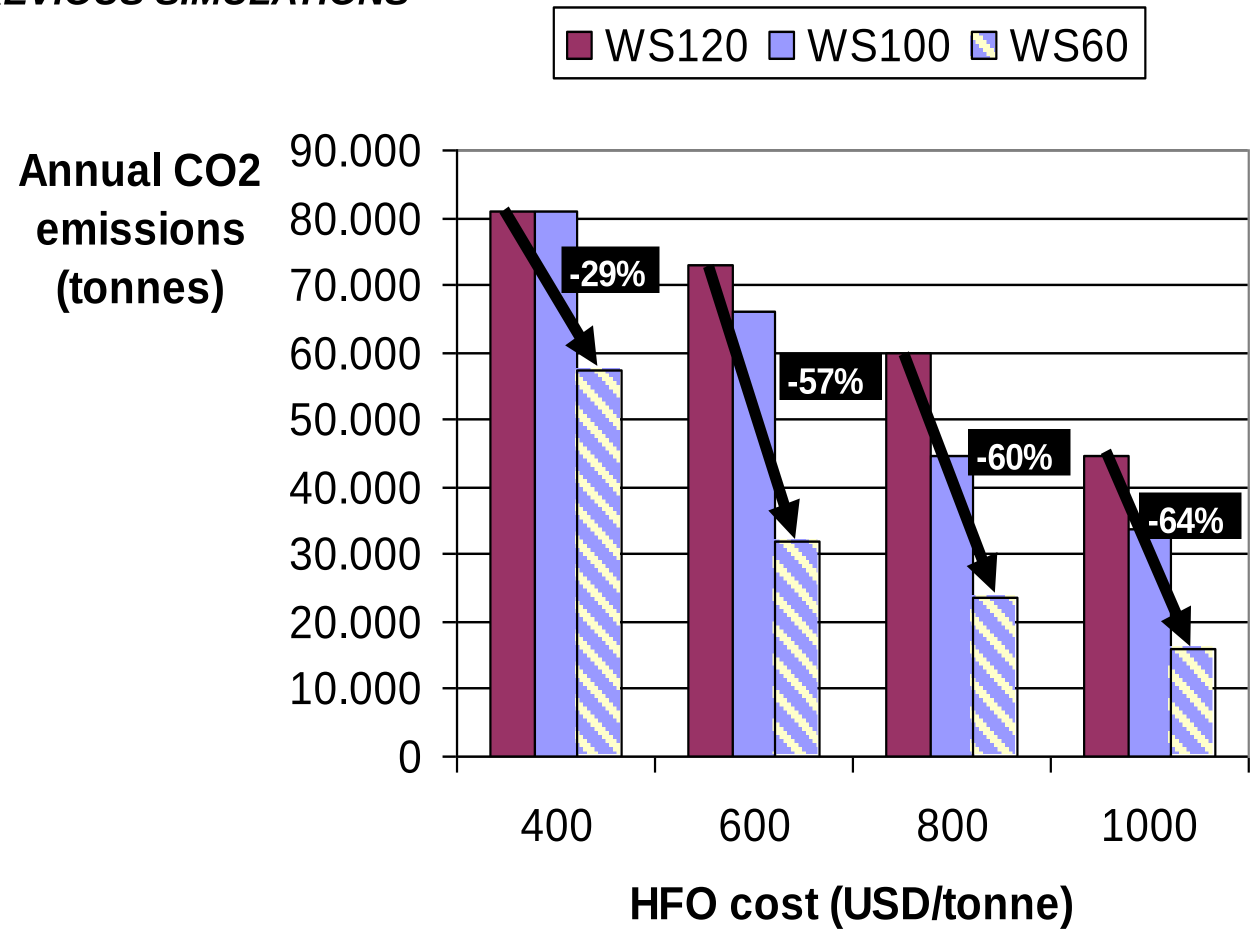
BASIS: PREVIOUS SIMULATIONS



SENSITIVITY ANALYSES (VLCC)

Impact of higher freight rates cont’d

BASIS: PREVIOUS SIMULATIONS

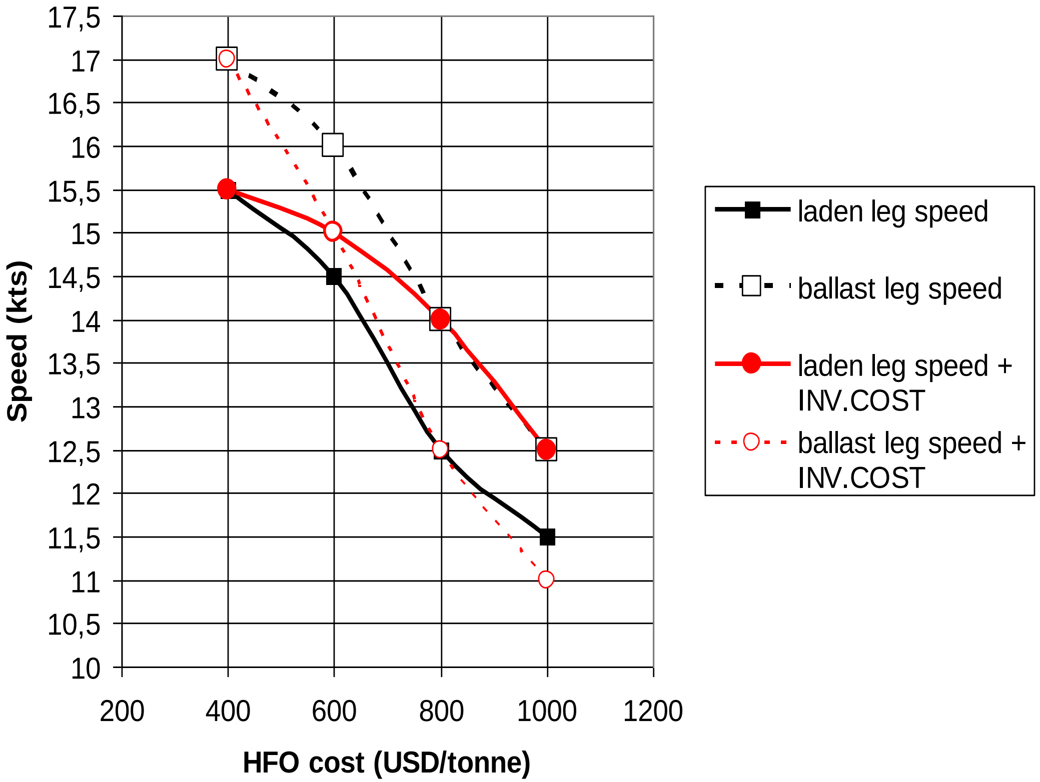


SENSITIVITY ANALYSES (VLCC)

Impact of inventory costs

'IN TRANSIT' INVENTORY COSTS INCLUDED IN COST EQUATION

SPOT RATE WS100



If inventory costs are factored in

- Generally laden speed goes up
- Generally does not reach the level of Case 1 (laden speed restricted)

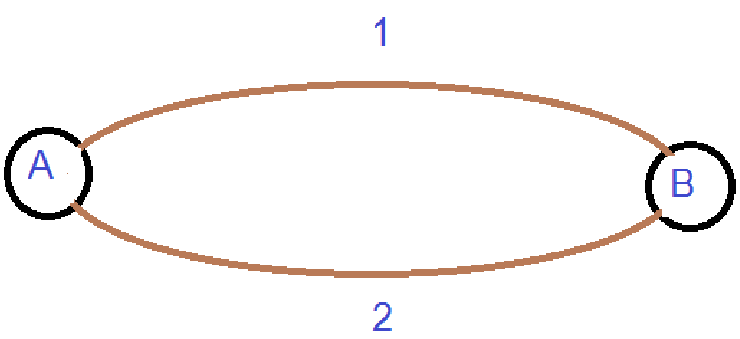
- Daily inv. cost ($/tonne/day) = P*R/365

  P=CIF value of cargo

  R: cargo owner's interest rate

Inventory costs can be important for high-valued cargoes

Impact on modal choice



- Mode 1: ship
- Mode 2: land-based mode (eg, rail or road)
- Ship’s speed reduced from V to V-ΔV due to slow steaming

Multinomial logit model

- 2 modes i=1,2

$$x_i = \frac{e^{-\lambda C_i}}{e^{-\lambda C_1} + e^{-\lambda C_2}}$$

Generalized cost

- $C = p + kt$

- p: freight rate
- t: transit time (door to door)
- k: unit cargo inventory cost = PR/365

Possible modal shifts: Tran-siberian railway example

•

TEE TRANS EURASIA EXPRESS

Scenario

Ships reduce speed due to higher fuel prices and fleet overcapacity

Result: Reduced CO2, less fuel

Side-effects: Inventory costs, potential cargo shifts

Question: how much cargo will shift to the railway mode?

Reference: Psaraftis and Kontovas (2010)

Changing proportions

$$\frac{x_1^*}{x_2^*} = \frac{x_1}{x_2} e^{-\lambda\left(p_1^* - p_1 + k\frac{L_1 \Delta V}{V(V-\Delta V)}\right)}$$

$$\frac{x_1^*}{x_2^*} = \frac{x_1}{x_2}\left(1 - \lambda\left(p_1^* - p_1 + k\frac{L_1 \Delta V}{V(V-\Delta V)}\right)\right)$$

Trans-siberian railway cont’d

- Far East to Europe by boat

- 43,000 km
- FC=7.8 gr CO_2/tkm at full speed
- V = 800 km/day (abt 18 knots)
- $\Delta V = 0.3V$ (reduction to abt 12.6 knots)
- FC reduced in a quadratic fashion
- Hauling 150,000 tons of cargo produces 18,000 tons of CO_2

Trans-siberian railway cont'd

- Far East to Europe by rail

- 12,000 km (10,000 +2,000)
- Cargo arrives 26 days earlier
- Lower inventory costs, depends on value of cargo
- 18 gr CO_2/tkm for electric traction
- Hauling 150,000 tons of cargo produces 32,000 tons of CO_2

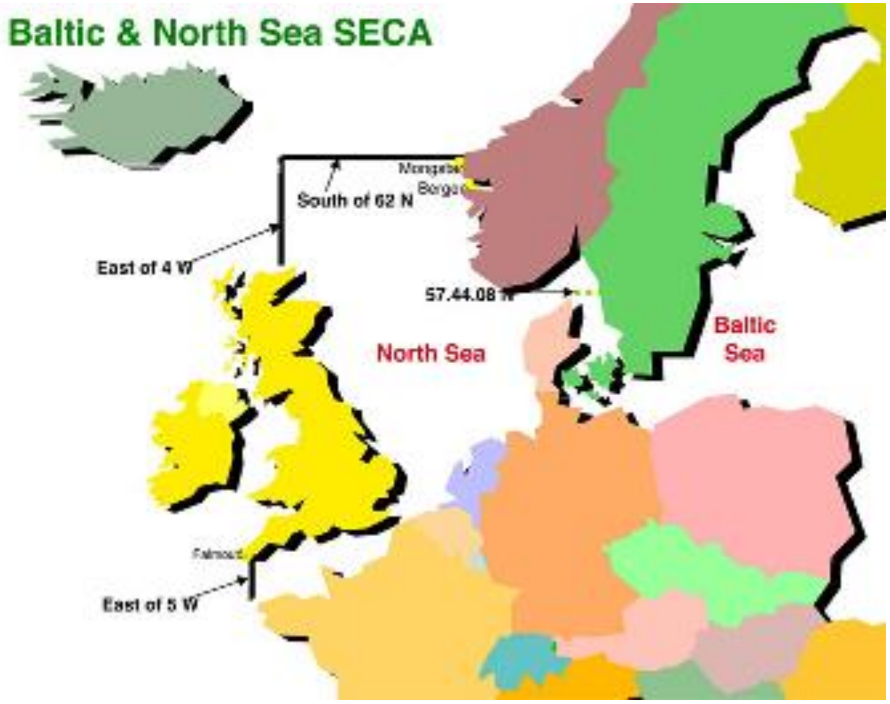
Possible shifts

Table 2
x_1^*/x_1 as a function of k and the price difference.

$k/(p_1^* - p_1)$	0	–\$100/tonne	–\$200/tonne
\$2/day/tonne	0.999	1.003	1.007
\$5/day/tonne	0.994	1.000	1.004
\$10/day/tonne	0.988	0.994	1.000

Sulphur Emissions Control Areas: SECAs

- SO2 reduction: high on IMO agenda
- Regional policies
- Big question: how to limit SO2 emissions
- Various measures (cleaner fuel, scrubbers)



EU new sulphur directive

DIRECTIVE 2012/33/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 21 November 2012

amending Council Directive 1999/32/EC as regards the sulphur content of marine fuels

- Mandates 0.1% S fuel in SECAs as of 1/1/2015
- Big problem for competitiveness of Ro/ro carriers in Baltic and North Sea
- May lose traffic to land based modes
- Some routes become unprofitable and shut down
- Serious side effects for many other industries (forest, mining, etc)
- Industry is striving to seek solutions

Low S-fuel vs scrubber

Low S-fuel

- 0.1% as of 1.1.2015
- $876/tonne
- All of extra costs are speed dependent
- Optimal speed will be reduced

Scrubber

- Can still burn HFO ($600/tonne)
- Very expensive capital investment
- Extra operational cost per fuel burned
- Most of extra costs are fixed

Same ship will have a different optimal speed in each of 2 cases (lower for low-S fuel case)

Result (Psaraftis and Kontovas, 2009)

- A deep sea ship may slow down within a SECA to save fuel costs
- If ship speeds up outside the SECA to make up for lost time within the SECA,
- This will result in **more total emissions** (of all gases, including SOx) and more total fuel spent.

Combining speed and routing decisions

- Psaraftis & Kontovas (2014)
- Pick up and delivery setting

- Input parameters fuel price, charter rate & value of cargo can influence both ship speed and the routing decision!

Cost components

- Fuel costs (<--> emissions)
  - *FC depends on both speed and payload*

- Time charter costs

- In-transit cargo inventory costs

Solution by DP

$$V\left(L,\left[k_{ij}\right]\right)=\begin{cases} M & if\ \ w>Q \\ \min\limits_{(x,y)\in R}\left\{s_{LL}C^{*}+/\,d_{xy}(au+bw)+V\left(L',\left[k'_{ij}\right]\right)\right\} & otherwise \end{cases}$$

$$C^{*}=\min_{v\in S}\left\{\frac{P_{FUEL}f(v,w)+au+bw+F}{v}\right\}$$

$$S=\left\{v:v_{LB}(w)\le v\le v_{UB}(w)\right\}$$

Min emissions vs min cost

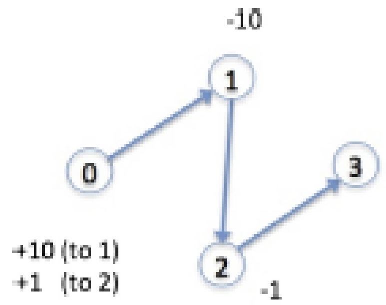


Fig. 3. Optimal route to minimize total emissions.

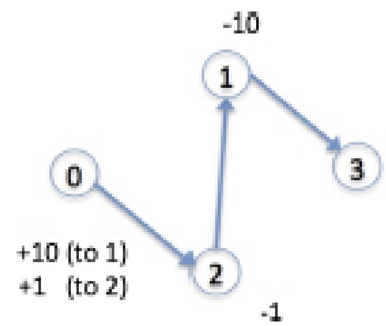


Fig. 4. Optimal route to minimize total cost.

Table 3
Minimum emissions solution (optimal speed = 8 knots).

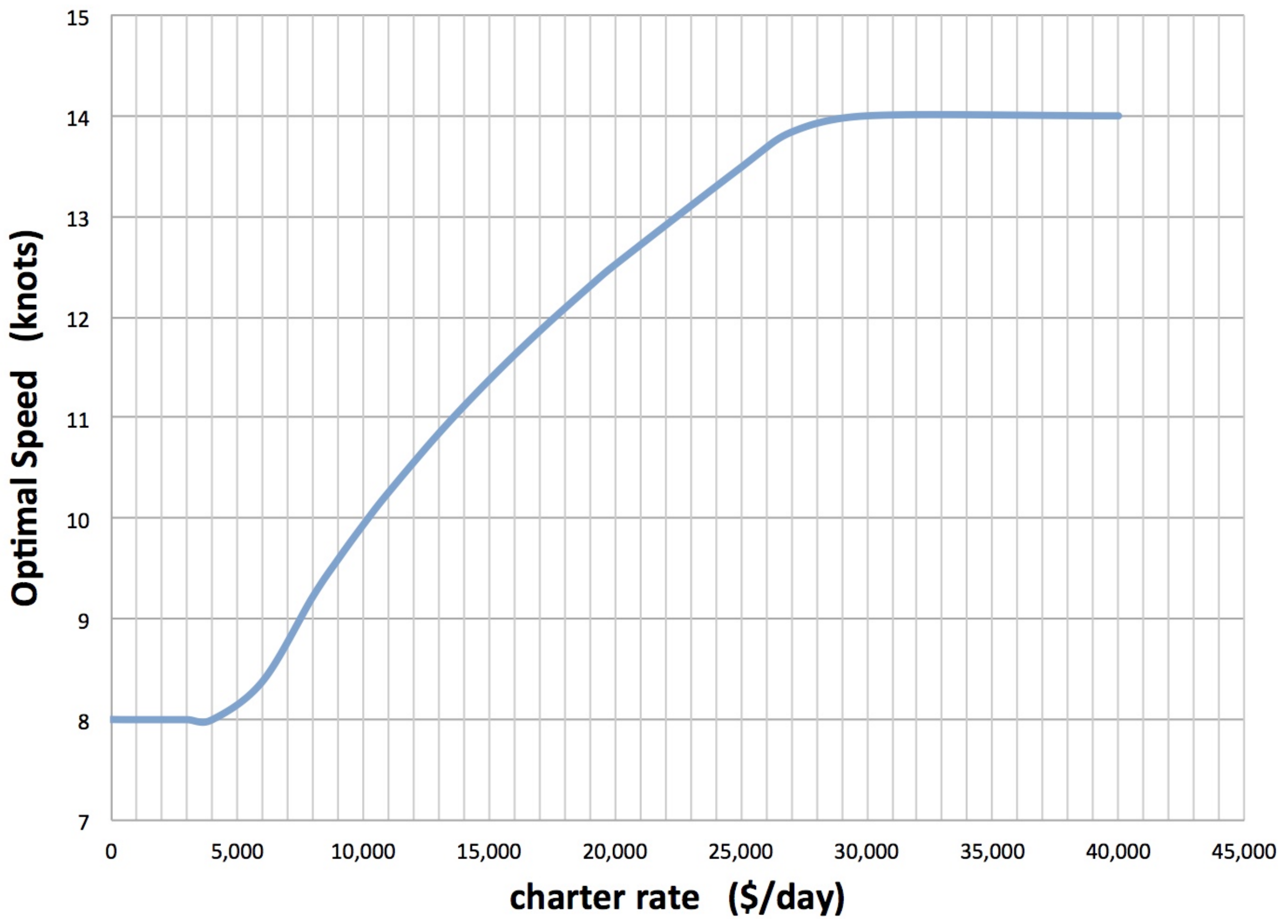
	Fuel consumption (tonnes)	Fuel cost ($)	Trip time (days)
Route 0–1–2–3			
Leg 0–1 (200 nm)	5.83	3499	1.04
Leg 1–2 (160 nm)	2.43	1455	0.83
Leg 2–3 (200 nm)	2.69	1611	1.04
Total (560 nm)	10.94	6565	2.92
Total CO_2 emissions (tonnes)	34.02		
Route 0–2–1–3			
Leg 0–2 (180 nm)	5.25	3149	0.94
Leg 2–1 (160 nm)	4.47	2681	0.83
Leg 1–3 (180 nm)	2.42	1450	0.94
Total (520 nm)	12.13	7280	2.71
Total CO_2 emissions (tonnes)	37.72		

Moreover

- **Sailing the minimum distance route at minimum speed may not minimize emissions**

- Paradox?
- No. This may involve a heavier load profile which would result in higher fuel consumption (and emissions) overall, even though the route may be shorter.

Optimal speed vs charter rate



Impact of inventory costs

- **Expensive cargoes sail faster and induce more CO2**

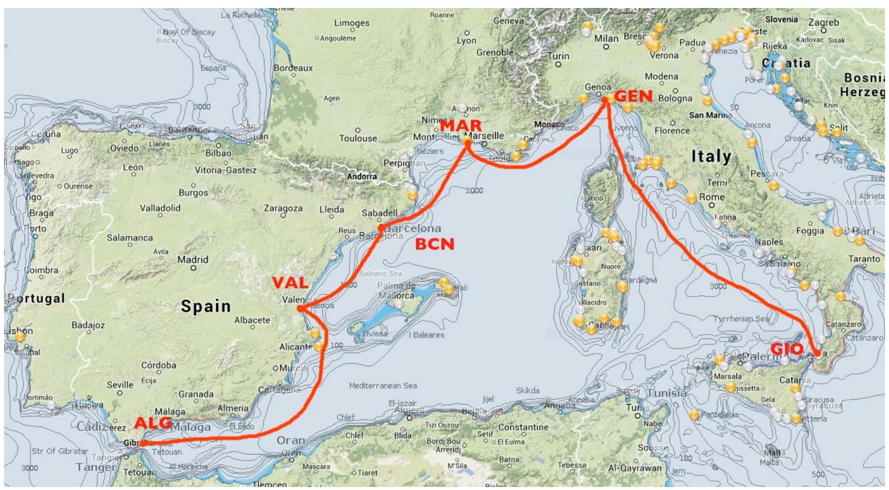


Table 7: Variation of optimal speed with value of cargo

VALUE OF CARGO ($/tonne)			0	5,000	10,000	15,000	20,000	25,000
		Payload (000 tonnes)	Speed (knots)					
Leg	ALG-VAL	0	13.54	13.54	13.54	13.54	13.54	13.54
	VAL-BCN	5	11.61	12.12	12.58	13.02	13.43	13.81
	BCN-MAR	6	11.36	11.96	12.49	12.99	13.45	13.88
	MAR-GEN	8	10.95	11.70	12.36	12.96	13.51	14.00
	GEN-GIO	11	10.46	11.42	12.24	12.96	13.61	14.00
FUEL COST ($)			39,751	44,433	48,808	52,945	56,890	59,854
CHARTER COST ($)			79,502	75,324	72,136	69,580	67,461	65,996
INVENTORY COST($)			0	13,542	25,480	36,310	46,318	56,189
TOTAL COST ($)			119,253	133,299	146,424	158,835	170,669	182,039
CO_2 EMITTED (tonnes)			206.04	230.31	252.99	274.43	294.88	310.24
TRIP TIME (days)			5,30	5,02	4,81	4,64	4,50	4,40

Conclusions

- Slow steaming is a key determinant to both shipping economics and the environmental sustainability of maritime transportation
- We anticipate that research in this area will continue.
- In particular, we anticipate research in this area to increasingly take into account environmental considerations.

THANK YOU VERY MUCH!