Logistics-emissions tradeoffs in maritime transport

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OR 2008 Augsburg, Sep. 2008
Background

Drive for greener shipping:

- very high on IMO agenda
- very high on agendas of EU, individual coastal countries
- Reduction of ship emissions: top priority
Types of emissions

- Green House Gases- GHGs (mainly CO2, but also CH4 and others)
- Non-GHG (mainly SO2, but also NOx and others)
Kyoto Protocol

- Urgent measures to reduce CO2 emissions are necessary to curb the projected growth of GHGs worldwide.
- Shipping has thus far escaped being included in the Kyoto global emissions reduction target for CO2 and other GHGs
- Some regulation exists for SO2
Time of GHG non-regulation is rapidly approaching its end!

- Measures to curb future CO2 growth are being sought with a high sense of urgency.
- As CO2 is the most prevalent of these GHGs, any set of measures to reduce the latter should primarily focus on CO2.
- Message of EC to IMO: Act now, or we shall act instead!
Measures contemplated

Technological
- More efficient (energy-saving) engines
- More efficient ship hulls
- More efficient propulsion
- “Cold ironing” in ports
- Cleaner fuels (low sulphur content)
- Alternative fuels (fuel cells, biofuels, etc)
- Devices to trap exhaust emissions (scrubbers, etc)

Operational
- Speed reduction
- Optimized routing
- Other, logistics-related (eg, fewer, bigger ships)
- Protected areas (SECAs)
State of the art

R&D and studies on:

- Estimation of emissions
- Impact of emissions on world climate
- Technological means to reduce emissions
Remarks

- Even estimates of marine bunker sales are difficult to make
- Most global emissions estimates are based on modelling
- Not much on logistical dimension
Ship traffic densities (Endresen et al, 2003)

Figure 1. Vessel traffic densities for 1996 based on COADS [2001]. The integral over all grid cells equals 1.
Share of global emissions

Data: International Shipping: This study. Other IEA. Reference year: 2005
Comparison with other modes (2005)

Data: International Shipping: This study, Other IEA. Reference year: 2005
COMPARISON OF CO₂ EMISSIONS AMONG TRANSPORT MODES
(grams per tonne-kilometer)

Boeing 747-400³

Small Size Truck³

Heavy Truck¹

Rail (Diesel)¹

PS-type Container Vessel (11,000 TEU)²

VLCC/ULCC Crude Oil Carrier²

Capesize Bulk Carrier⁴

Units Relative

Sources:
1 Swedish Network for Transport and the Environment (NTM)
2 Maersk Line
3 MAN B&W Diesel
4 National Technical University of Athens (NTUA)

Produced by NTUA Laboratory for Maritime Transport www.martrans.org

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CO2 percentage per ship category

- Containerships: 32.08%
- Dry Bulk: 17.98%
- Ro-Ro (excl. Pass): 5.10%
- Reefer: 2.61%
- Crude oil: 12.65%
- Product/Chemical: 15.49%
- LNG: 2.37%
- General Cargo: 9.93%
- LPG: 1.78%
NTUA ship emissions study

www.martrans.org/emis/emis.htm

Ship Emissions Study

Download Ship Emissions Study (pdf format - 1.1 Mbytes)


Emissions Calculator (web tool)
Logistics trade-offs

- Reductions in emissions may have ramifications as regards the logistical supply chain.
- Measures such as speed reduction or others will generally entail costs, such as in-transit inventory and others (e.g., more ships to carry the same cargo).
Boomerang effect?

- Cleaner, low-sulphur fuel may make maritime transport (and in particular short-sea shipping) more expensive and induce shippers to use land-based alternatives (mainly road).
- That might increase overall GHG emissions!
Some basics

ONE tonne of marine bunker produces:

- 3.17 tonnes of CO2 (indep. of fuel type, engine type)
- 0.02*S tonnes of SO2, where S is the % of sulphur content in fuel (0.5 ≤ S ≤ 4.5)
- 0.057-0.087 tonnes of NOx (engine-dependent)
Simple model

- Fleet of $N$ identical ships, each of capacity (payload) $W$.
- Investigate impact of speed reduction
- Reduce speed, but add more ships to maintain same demand throughput
Fuel consumptions

- In port: f (tonnes per day)
- At sea: F (tonnes per day)
- Effect of speed change on fuel consumption: assumed cubic for same ship, ie

\[ \frac{F_{\text{new}}}{F} = \left( \frac{V_{\text{new}}}{V} \right)^3 \]
Basic question

- If all ships reduce speed uniformly, and number of ships is increased to match demand throughput, does this lead to a lower fuel bill? (and hence to reduced emissions?)

- Answer: YES
Example

- $L = 20,000 \text{ km (~11,000 miles)}$
- $V = 15 \text{ knots} = 668 \text{ km/day}$.
- Port time = 3 days
- $W = 100,000 \text{ tonnes}$
- $N = 10 \text{ ships (identical)}$
- Operational days/yr = 355
- BUNKER PRICE = $600/\text{tonne}$
Reduce speed by 1 knot (9.3%)

- From 668 to 624 km/day

- We would need 10.64 ships to satisfy same demand throughput per year

- Assume 11 ships (identical to original 10)
Net effect

- Per ship FC reduces from 2,413 to 2,108 tonnes per round-trip (13%)
- TOTAL FLEET FC reduces from 130k to 117k tonnes per year (10%)
- TOTAL FLEET CO2 reduces from 412k to 372k tonnes per year (10%)
- TOTAL FUEL BILL savings: $7.56M/yr (10%)
How many more ships needed?

- If speed $V$ is reduced to $v$,
  
  $$M = \frac{N(V-v)}{v} = \frac{NV}{v} - N = N\left(\frac{V}{v} - 1\right)$$

  Difference in fuel bills:

  $$= \text{Const} \times pNV(V^2 - v^2) > 0 \text{ always}$$
VESSEL DETAILS

AFRAMAX TANKER
modern D/H - 106,000 DWT
Payload : 80,000

Laden Leg
Speed : 14.5 Kn
Consumption : 49 tn/day

Ballast Leg
Speed : 14.5 Kn
Consumption : 40 tn/day

At port
Consumption : 116 tn/day

ROUTE DETAILS

Ras Tanura – Singapore

Distance : 3,702 nm

Voyage Time:
Sea Time : 21.3 days
Port Time : 4.0 days

no canal transit time
no port waiting
**Scenario:**
One fleet of one ten (10) aframax tankers
12 trips per year (oper. Days = 303,6 days)

<table>
<thead>
<tr>
<th></th>
<th>Bunkers (tonnes)</th>
<th>Cost ($)</th>
<th>CO2 emissions</th>
</tr>
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<tbody>
<tr>
<td><strong>Fleet of 10 ships</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Aframax tanker - Per trip</td>
<td>1,410.78</td>
<td>822,766.90</td>
<td>4,472.17</td>
</tr>
<tr>
<td></td>
<td>169,293.60</td>
<td>98,732,027.52</td>
<td>536,660.71</td>
</tr>
</tbody>
</table>

To satisfy the same demand i.e constant total payload within the same period of operation we need a number of additional ships. In this case we need 0,627 more ships thus we need one more ship.

For a fleet of 11 identical aframax vessels sailing with a reduced by 1 knot speed we obtain the following results:

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<td>1 Aframax tanker - Per trip</td>
<td>1,284.72</td>
<td>749,284.70</td>
<td>4,472.17</td>
</tr>
<tr>
<td></td>
<td>159,607.57</td>
<td>93,083,133.11</td>
<td>505,955.99</td>
</tr>
</tbody>
</table>

We see that we have a reduction in fuel consumption and, thus, in CO2 emissions

<table>
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<tr>
<th><strong>NET REDUCTION</strong></th>
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<tr>
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<td>9,686.03</td>
<td>5,648,894.41</td>
<td>30,704.72</td>
</tr>
</tbody>
</table>

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VESSEL DETAILS

PANAMAX BULK CARRIER (COAL)
modern D/H - 70,000 DWT
Payload : 66,000

Laden Leg
Speed : 13.5 Kn
Consumption : 32.5 tn/day

Ballast Leg
Speed : 14.0 Kn
Consumption : 30 tn/day

At port
Consumption : 2.5 tn/day HFO
1.0 tn/day DO

ROUTE DETAILS

Newcastle (AUS) – Japan
Distance : 4,287 nm

Voyage Time:
Sea Time : 26.0 days
Port Time : 4.0 days

no canal transit time
no port waiting
**Scenario:**
One fleet of one ten (10) Panamax bulk carriers
10 trips per year (oper. Days = 300 days)

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<tr>
<td><strong>Fleet of 10 ships</strong></td>
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</tr>
<tr>
<td>1 BC - Per trip</td>
<td>826.79</td>
<td>484,622.73</td>
<td>2,620.92</td>
</tr>
<tr>
<td></td>
<td>99,214.80</td>
<td>48,462,272.80</td>
<td>262,092.43</td>
</tr>
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</table>

To satisfy the same demand i.e constant total payload within the same period of operation we need a number of additional ships. In this case we need 0,627 more ships thus we need one more ship.
For a fleet of 11 identical aframax vessels sailing with a reduced by 1 knot speed we obtain the following results:

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<td><strong>Fleet of 11 ships</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1 BC - Per trip</td>
<td>712.45</td>
<td>417,939.64</td>
<td>2,258.47</td>
</tr>
<tr>
<td></td>
<td>73,402.59</td>
<td>42,808,391.26</td>
<td>232,686.21</td>
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We see that we have a reduction in fuel consumption and, thus, in CO2 emissions

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<td>25,812.21</td>
<td>15,053,680.10</td>
<td>81,824.70</td>
</tr>
</tbody>
</table>
However!

- STILL HAVE TO INCLUDE:
  - Ship operational costs (other than fuel)
  - Ship capital costs
  - Cargo in-transit inventory costs

- So final answer depends on the above
Containership example

- String of $N=100$ (identical) container ships
- Payload $W= 50,000$ tonnes
- Base speed $V= 21$ knots
- Fuel Consumption at 21 knots = 115 tonnes/day
- Assume fuel price $p= $600/tonne
- Fuel bill = $69,000/day/ship

- Reduced speed $v= 20$ knots
- FC at 20 knots = 100 tonnes/day (cube law vs. 21 knots)
- Fuel bill = $60,500/day/ship
For simplicity assume that

- These 100 ships go back and forth 2,100 miles full in one direction, empty in the other.
  - (if this is relaxed, analysis will be more involved, but will lead to similar results)

- Assume also zero loading and unloading times
  - (if non-zero, analysis will be more involved, but will lead to similar results).
AT FULL SPEED (case A)

- Transit time (one way) = 100 hrs = 4.17 days
- Round trip = 8.33 days
- Number of round trips per year (assuming 365 days operation): 43.8
- Tonnes carried each year (per ship): 43.8*50,000 = 2,190,000.
- Times 100 ships = 219,000,000.
- Total fuel burned/year/ship: 115 tonnes/day*365 = 41,975 tonnes
- Times 100 ships = 4,197,500 tonnes
- Total fuel cost (x$600) = $2,518,500,000.
AT REDUCED SPEED (case B)

- Transit time (one way) = 105 hrs = 4.375 days
- Round trip = 8.75 days
- Number of round trips per year (assuming 365 days operation): 41.714
- Tonnes carried each year (per ship): 41.714*50,000 = 2,085,714.

To reach the previous figure of 219,000,000 tonnes of cargo, we will need 105 ships.
- Times 105 ships = 219,000,000 tonnes.
- Total fuel burned/year/ship: 100 tonnes/day*365 = 36,500 tonnes
- Times 105 ships = 3,832,500 tonnes
- Total fuel cost (x$600) = $2,299,500,000, REDUCED.
BENEFITS

- Reduction of CO2 emissions: 
  \[3.17 \times (4,197,500 - 3,832,500) = 1,157,050\] tonnes.

- Fuel cost difference = $219,000,000 for 5 more ships, ie, $43,800,000 per ship.

- If we can charter each of these ships for less than $120,000 a day, then case B is overall cheaper!
Cost to avert one tonne of CO2

- BASIC QUESTION: HOW MUCH DOES IT COST TO AVERT ONE TONNE OF CO2?

- Reducing speed saves fuel costs, BUT:
- If C (cost of chartering a ship) is high, it is conceivable that having more ships will cost more, even though total fuel bill is lower.
\[ \Delta(\text{cost}) = NC(V/v-1) - 365kpNV(V^2 - v^2) \]

ON A PER TONNE OF CO2 BASIS:

\[ \text{CATC} = C/1,157kvV(V+v) - p/3.17 \]

(p= price of fuel)
CATC

- CATC = \( C/1,157kV(V+v) - p/3.17 \)

- Term \{- p/3.17\} is interesting.
- 1 tonne of fuel produces 3.17 tonnes of CO2.
- Term is the cost of the amount of fuel not spent that would produce one tonne of CO2.
- This amount would be saved if one tonne of CO2 is averted.
In-transit inventory costs

- Hauling cargo at a reduced speed will entail additional **in-transit inventory** costs for the shippers.
- Such inventory cost is incurred during the time that the cargo is in transit, and is equal to a factor of $t$ ($$/tonne/day), times the transit time, times the amount of cargo.
- $t$ is a function of the value of the cargo, interest rates, and other factors, value of time for the cargo, etc, and is assumed known.
Revised CATC

- CATC = \[
\frac{[C+182.5tW]}{1,157kvV(V+v)} - \frac{p}{3.17}
\]

- The higher t is, the higher CATC is.

- No examples fully worked out yet.
Effect of bigger ships operating at slower speed

- Base scenario: Fleet of N ships and capacity $W$, operating at speed $V$.
- Alternate scenario: Fleet of M bigger ships, of capacity $U (>W)$, operating at speed $v (<V)$.
- Both fleets achieve same throughput per year:
  - $M = N \left( \frac{VW}{vU} \right)$
Basic result (M=N)

- Substituting a string of ships with a string of bigger ships of same number, going at a slower speed so that total throughput remains the same, will reduce total fuel bill, hence total emissions.

- Speculate result also holds for M<N.
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)
How about speed reduction?

- Can speed reduction at SECAs work, as a measure to reduce SO2 emissions?
- An easy question, for which the answer is not so easy.
Scenario

- A ship that goes from A to B, distance L.
- At beginning or end of trip, there is a SECA, of distance d (<L).

2 options:
- A. go all trip at a constant speed of V.
- B. reduce speed to v (<V) within SECA, but go at a higher speed of V* (>V) outside SECA, so that total transit time is the same.
Ratio of fuel consumptions

- Ratio $R = \frac{FC(B)}{FC(A)} =$
  $= \frac{(L-d)^3}{L(L-d\frac{V}{v})^2} + \frac{(d/L)(v/V)^2}$

- Can be shown that always $R > 1$
Example

- L = 2000 nmiles
- d = 200 (SECA)
- V = 20 (knots)
- v = 18 within SECA

- \( V^* = \frac{1800}{(2000/20 - 200/18)} = 20.25 \) knots outside SECA.

- Then \( R = \frac{(1800)^3}{2000} \frac{(2000-200 \times 20/18)^2}{200/2000} \frac{(18/20)^2}{200/2000} \)

- \[ \frac{0.9226 + 0.081}{1.0036} \]
This means that

- Speed reduction in SECAs will result in **more total emissions** (of all gases, including SO2) and more total fuel spent if speed is increased outside SECA to make up for lost time.
- The reduced emissions within the SECA will be more than offset by higher emissions outside (for all gases).
- The fuel bill will also be higher.
Use cleaner fuels in SECAs

- If a ship is forced to use low sulphur fuel at a SECA, to reduce SO2 emissions.
- This fuel is more expensive than high sulphur fuel. Hence freight rates go up.
- This may induce shippers to use land transport alternatives (trucking), which will increase CO2 emissions thru the logistics chain!
How to find out?

- Develop a model that examines these tradeoffs.
- Use the concept of \textit{generalized cost} (taking into account value of time) and \textit{multinomial logit} model to determine modal split.
PLANS

- Get more real data to make realistic examples for these models (in progress)
- Develop modal split model (in progress).
- Refine the models.
- Run various scenarios
Acknowledgment

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Thank you very much!

- www.martrans.org