A Ship Pickup and Delivery Model with Multiple Commodities, Variable Speeds, Cargo Inventory Costs and Freight Rates

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A synthesis of:

- Recent research in the area of pickup and delivery problems
- Recent research in the area of speed optimization in maritime transportation
- Recent research in the area of emissions from ships

The problem

- Graph G(N,A) with N={0,1,2,..,n} a set of ports
- Known inter-port distances s_{ij}
- Known O/D matrix, amount of cargo from i to j [d_{ij}]
- Each cargo a distinct commodity
- Cargoes cannot be split (as many as n(n-1))

- Ship is initially located at node 0 (home port)
- Capacity $Q \geq \max_{(i,j)} d_{ij}$
- Has to pick up and deliver all cargoes, and return to port 0
- Port dwell times proportional to cargo handled
- Visit each port as many times as necessary

O/D matrix

O/D matrix

i/j	1	2	3	4	5	6
1	-	4	5	6	3	1
2	5	-	3	2	9	5
3	3	7	-	4	7	3
4	8	3	2	-	5	4
5	2	4	4	2	-	2
6	4	3	5	7	2	-

Cost function

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

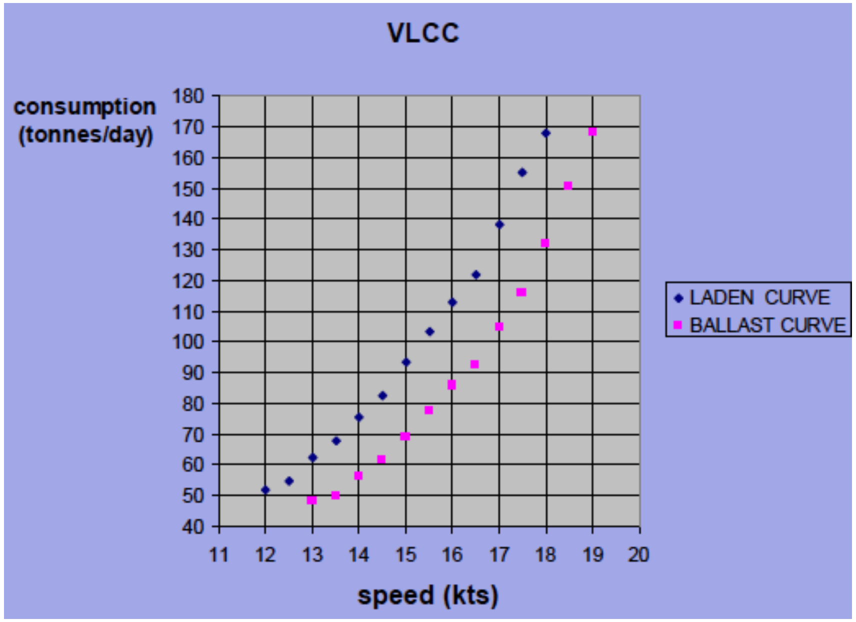
- Problem: FC depends on ship's loading condition

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

- Due to delay in delivery of cargo
- Per unit volume and per unit time cargo delay cost is equal to α for cargo waiting to be picked up (cost accrues from time 0 until cargo is on the ship)
- Such cost is equal to β for cargo within the ship (cost accrues from time cargo is on the ship until cargo is delivered).
- Both α and β are constants ≥ 0.
- Usually $\alpha=0$ for JIT systems
- These costs can be important if inventory costs are important (mainly for long-haul problems and/or high valued cargoes)

What are α and β?

- Lower bound in both α and β is PR/365

- Where P is CIF value of cargo
- R is cargo owner's cost of capital

- (α, β high for expensive cargoes)

Important observation

- Ship speed impacts all three categories of costs

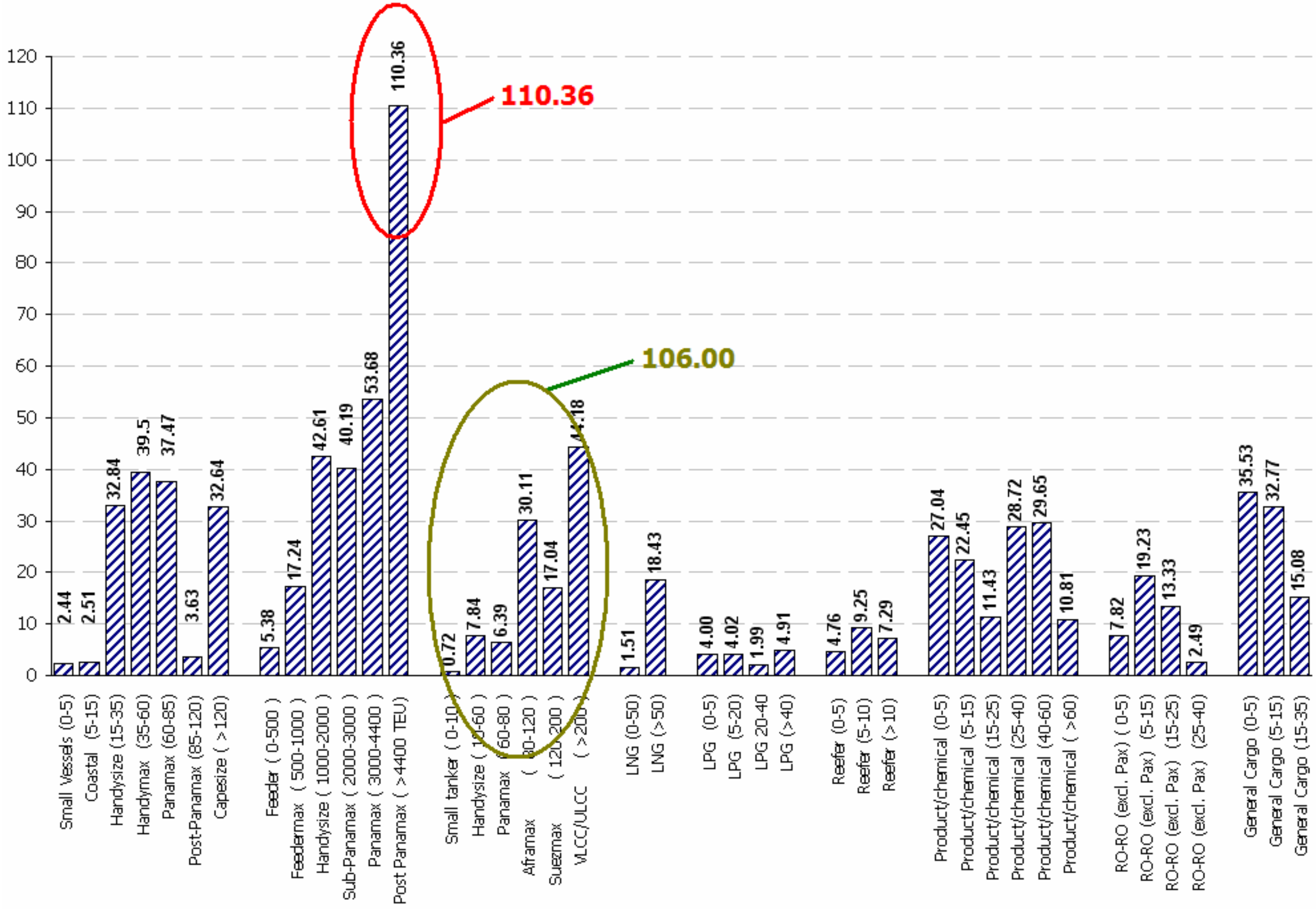
- Fuel costs in a positive way
- Time charter costs in a negative way
- Cargo inventory costs in a negative way

- What should the set of optimal ship speeds be?
- What should be the routing?
- What should be the sequence of pickups and deliveries?

Role of speed

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

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 CO_2 (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!

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

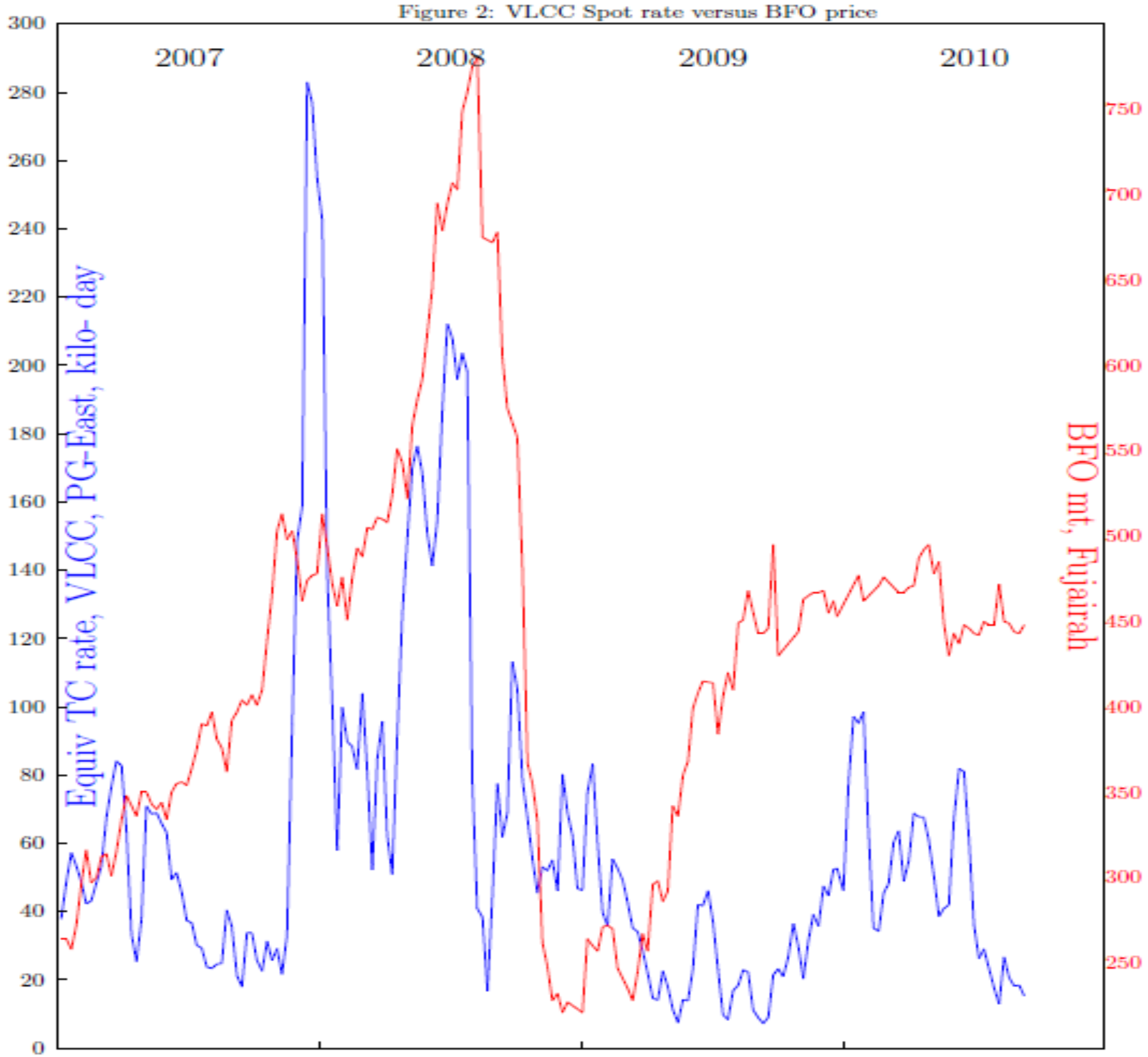


Figure 2: VLCC Spot rate versus BFO price
2007
2008
2009
2010
Equiv TC rate, VLCC, PG-East, kilo- day
BFO mt, Fujairah
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
750
700
650
600
550
500
450
400
350
300
250

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)

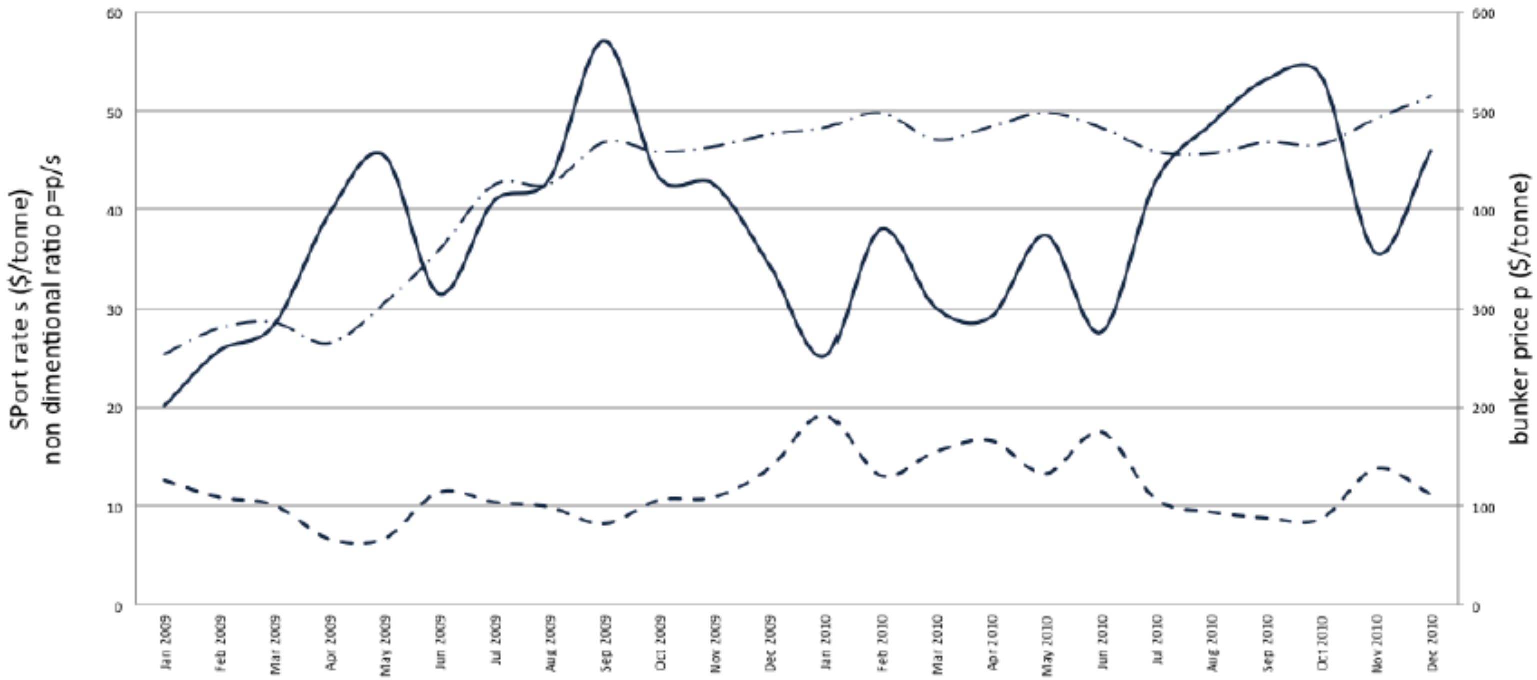
$$\min_{v} \left\{ s \left(R - \frac{C24v}{D} \right) + T + pF(v) \right\}$$

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
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).

Taxonomy of speed models

- Psaraftis & Kontovas (2012)

- Non-emissions related

- Emissions-related

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

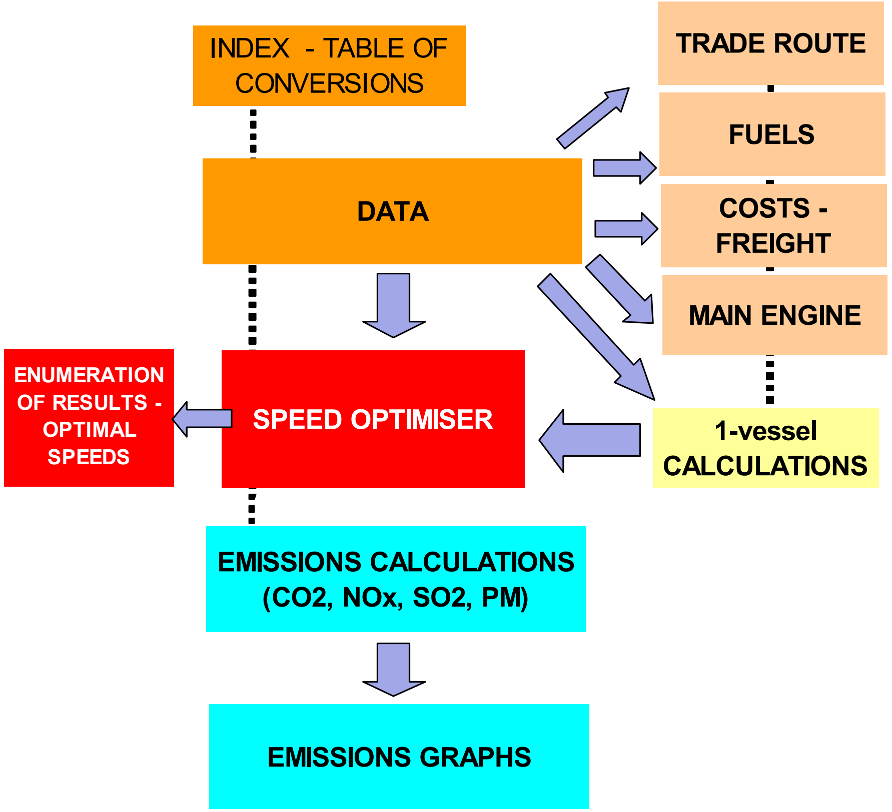
Taxonomy parameter \ paper	Alderton (1981)	Bausch et al (1998)	Benford (1981)	Brown et al (1987)	Cariou (2011)	Cariou and Cheaitou (2012)	Corbett et al (2010)	Devanney (2007)	Devanney (2010)	Eefsen and Cerup-Simonsen (2010)
Optimization criterion	Profit	Cost	Cost	Cost	Cost	Cost	Profit	Profit	Cost or 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

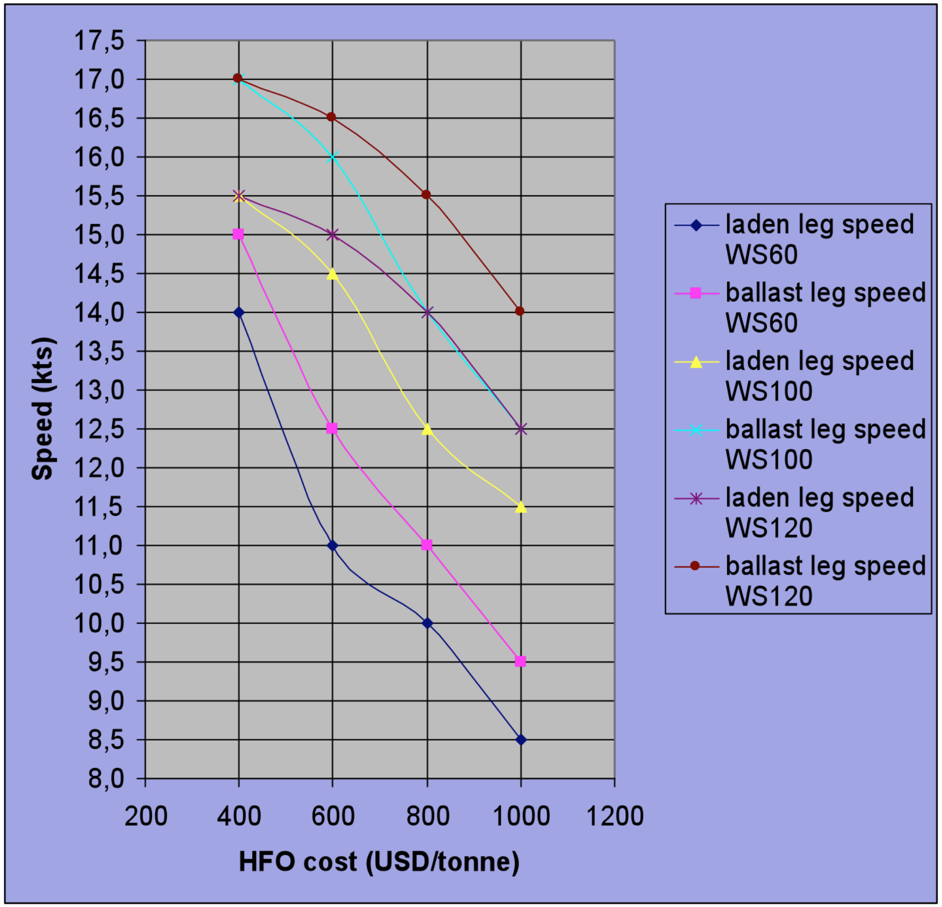
VLCC speed model

- Gkonis & Psaraftis (2012)



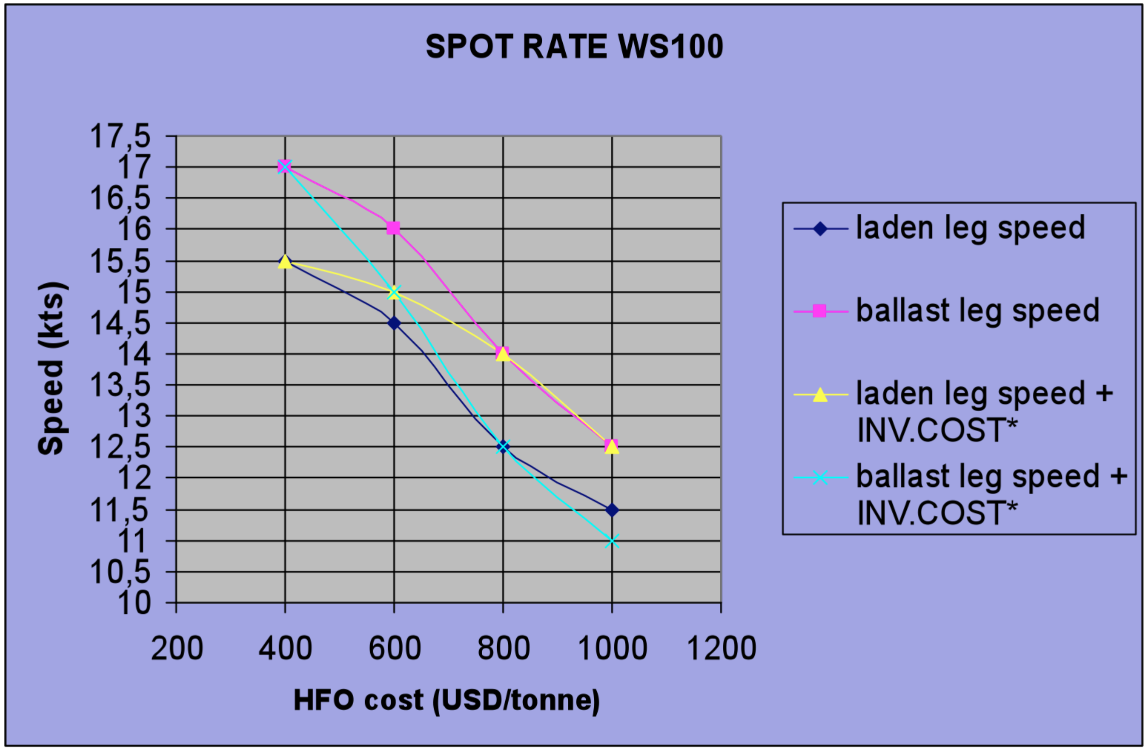
VLCC results

- 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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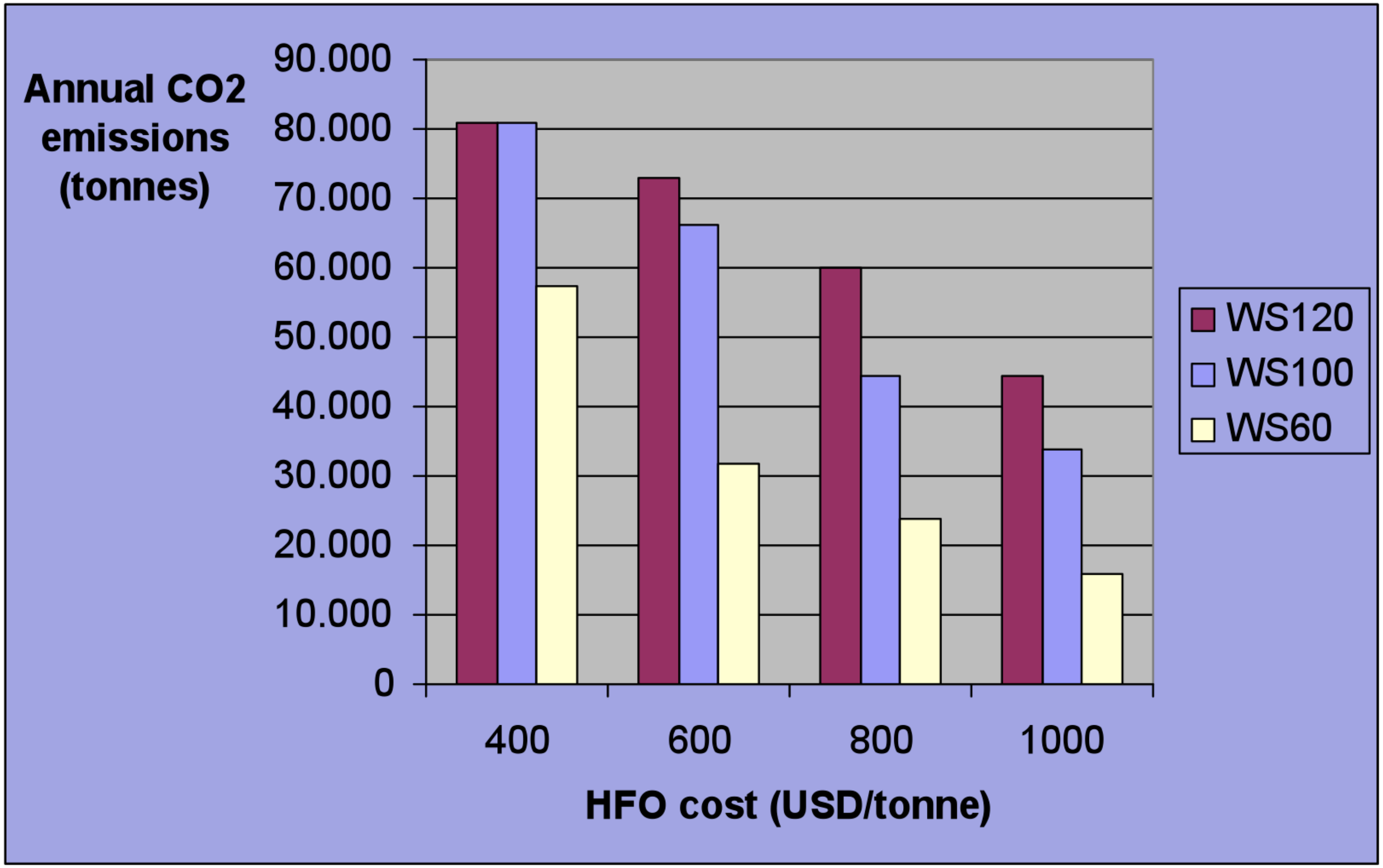


Speed decision can be decomposed from routing decision

- Assuming the ship is at port A and is set to sail to port B, the total cost on leg (A, B) is equal to

- $\text{COST}(A,B) = [P_{FUEL} f(v, w) + \alpha u + \beta w + F](s_{AB}/v)$,

Where:

- v: ship speed during leg
- w: ship payload during leg
- u: total weight of cargo not yet picked up during leg

Decompose speed cont'd

- Factor out s_{AB}
- $INCR(A,B) = \min_{v \in S} \{[P_{FUEL} f(v, w) + \alpha u + \beta w + F]/v\}$, with

with $S=\{v: v_{LB}(w) \leq v \leq v_{UB}(w)\}$

(per mile total cost)

- Observation: Speed decision is independent of A or B

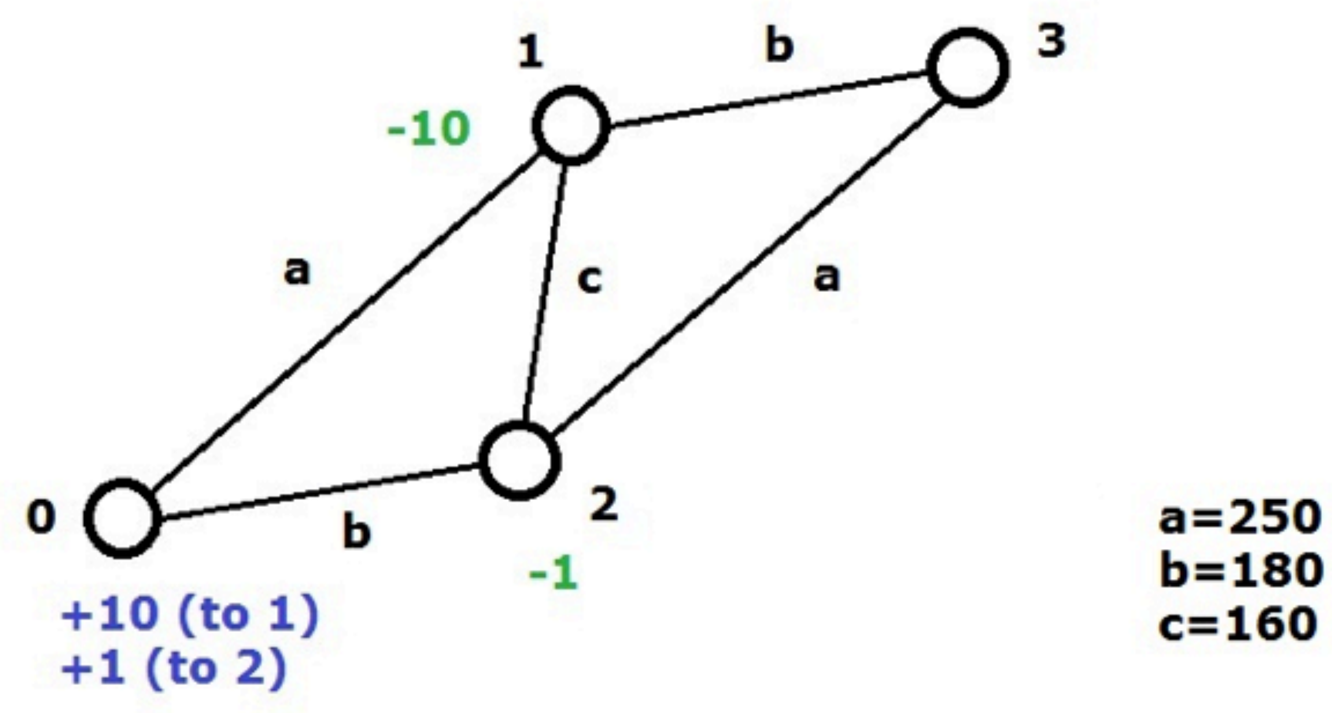
2^{nd} observation

- Input parameters $P_{FUEL,}$ F, α, and β are key determinants of the speed decision
- Higher values of P_{FUEL} would reduce optimal speed
- Higher values of F, α, or β would increase optimal speed

3rd observation

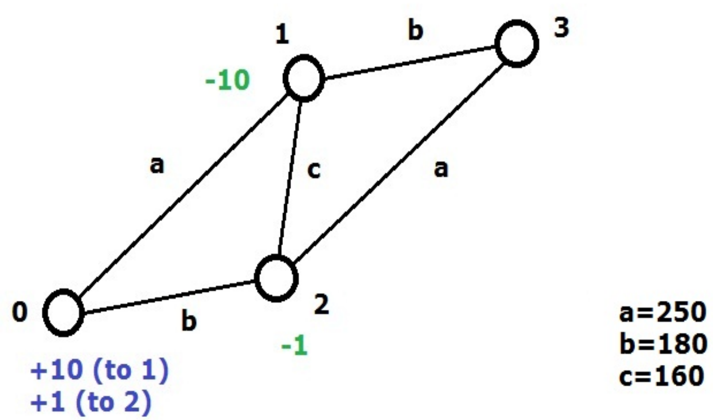
- Input parameters $P_{FUEL,}$ F, α, and β can also influence the ROUTING decision!

Example: ship of Q=11 (000 tons)



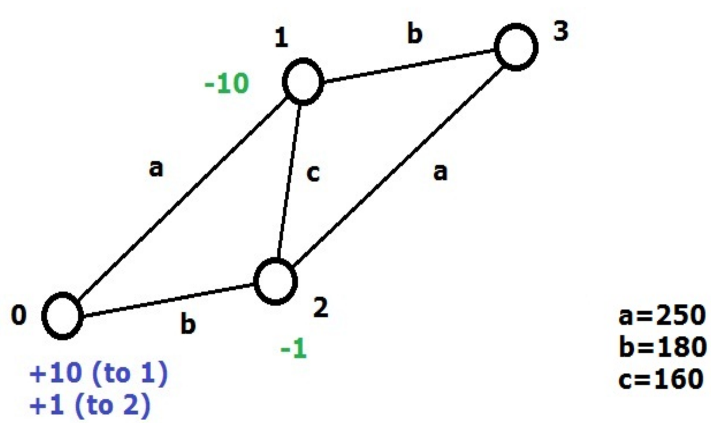
Minimum fuel cost (F=α=β=0)

- 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)

Embed within pickup and delivery algorithm

- Extension of:

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A multi-commodity, capacitated pickup and delivery problem: The single and two-vehicle cases

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Special case 1: dial-a-ride problem

- Psaraftis (1980, 1983abc), Desrosiers et al (1986), Cordeau (2006), Cordeau et al (2008)
- d_{ij}=1 for j=i+n only, 0 otherwise

Table 1: DARP O/D matrix (n=6)

i/j	1	2	3	4	5	6
1	-	0	0	1	0	0
2	0	-	0	0	1	0
3	0	0	-	0	0	1
4	0	0	0	-	0	0
5	0	0	0	0	-	0
6	0	0	0	0	0	-

Special case 2: vehicle routing problem with pickup and delivery

- Kalantari et al (1985), Desrosiers et al (1986), Ruland and Rodin (1997), Cordeau et al (2008), Berbeglia et al (2007).

Table 2: VRPPD O/D matrix (n=6)

i/j	1	2	3	4	5	6
1	-	0	0	5	0	0
2	0	-	0	0	10	0
3	0	0	-	0	0	7
4	0	0	0	-	0	0
5	0	0	0	0	-	0
6	0	0	0	0	0	-

Special case 3: all nodes feed into a depot and depot sends to all nodes

- Gribkovskaia et al (2006)
- Depot at one node Z

Table 3: VRPPD-II O/D matrix (n=6, Z=4)

i/j	**1**	**2**	**3**	**4**	**5**	**6**
1	-	0	0	5	0	0
2	0	-	0	4	0	0
3	0	0	-	7	0	0
4	8	3	2	-	6	5
5	0	0	0	2	-	0
6	0	0	0	9	0	-

Special case 4: unidirectional

- Hernandez-Perez and Salazar-Gonzalez (2009)
- If cargo from A to B, no cargo from B to A

Table 4: VRPPD-U O/D matrix (n=6)

i/j	1	2	3	4	5	6
1	-	0	0	0	0	0
2	5	-	0	0	0	0
3	3	7	-	0	0	0
4	8	3	2	-	0	0
5	2	4	4	2	-	0
6	4	3	5	7	2	-

DP approach

Define the matrix $[k_{ij}]$ and optimal value function V as follows:

$$k_{ij} = \begin{cases} 3 \text{ if cargo from i to j has not been picked up yet} \\ 2 \text{ if cargo from i to j is on board the ship} \\ 1 \text{ if cargo from i to j has been delivered.} \end{cases}$$

$V(L, [k_{ij}])$ = Minimum possible total cost to complete the trip from port L to port 0, by executing all pending actions on pickup and delivery of the cargoes, choosing optimal speeds and observing capacity constraints, given that the current status of the cargoes is described by matrix $[k_{ij}]$.

Recursion

Define set $R = \{(i,j): i \neq j, k_{ij} \neq 1\}$
Define M = large number
If $R = \emptyset$, $V(L, [k_{ij}]) = s_{L0} \min_{v \in S} \{[P_{FUEL} f(v, 0) + F]/v\}$ (boundary condition: ship returning to depot)
If $R \neq \emptyset$, then

$$V(L, [k_{ij}]) = \begin{cases} M \text{ if } w > Q \\ \min_{(x,y) \in R} \{ s_{LL'} \, INCR(L, L') + \lambda d_{xy} + (\alpha u + \beta w) + V(L', [k'_{ij}]) \} & \text{otherwise} \end{cases}$$

λd_{xy} : port dwell time

where for all pairs (i,j) with $i \neq j$, it is:

$$k'_{ij} = \begin{cases} k_{ij} - 1 \text{ if } i=x \text{ and } j=y \\ k_{ij} \text{ otherwise.} \end{cases}$$

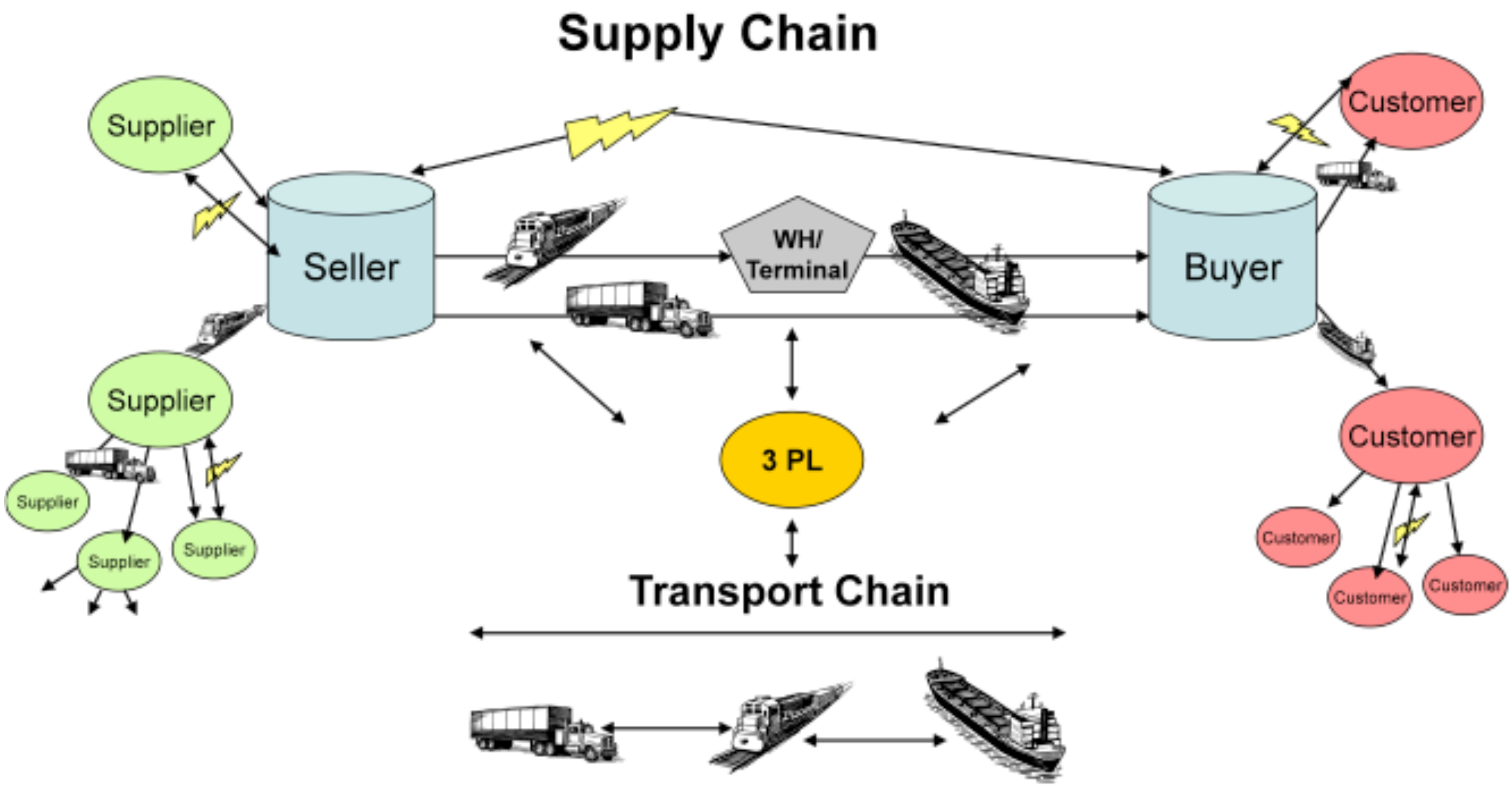
$$L' = \begin{cases} x \text{ if } k_{xy}=3 \\ y \text{ if } k_{xy}=2 \end{cases}$$

Status

- Developed combined algorithm
- Tested it on sample problems

- Developed NON-ROUTING speed models for tankers, bulk carriers, ro/ro carriers, LNG/LPG, container vessels

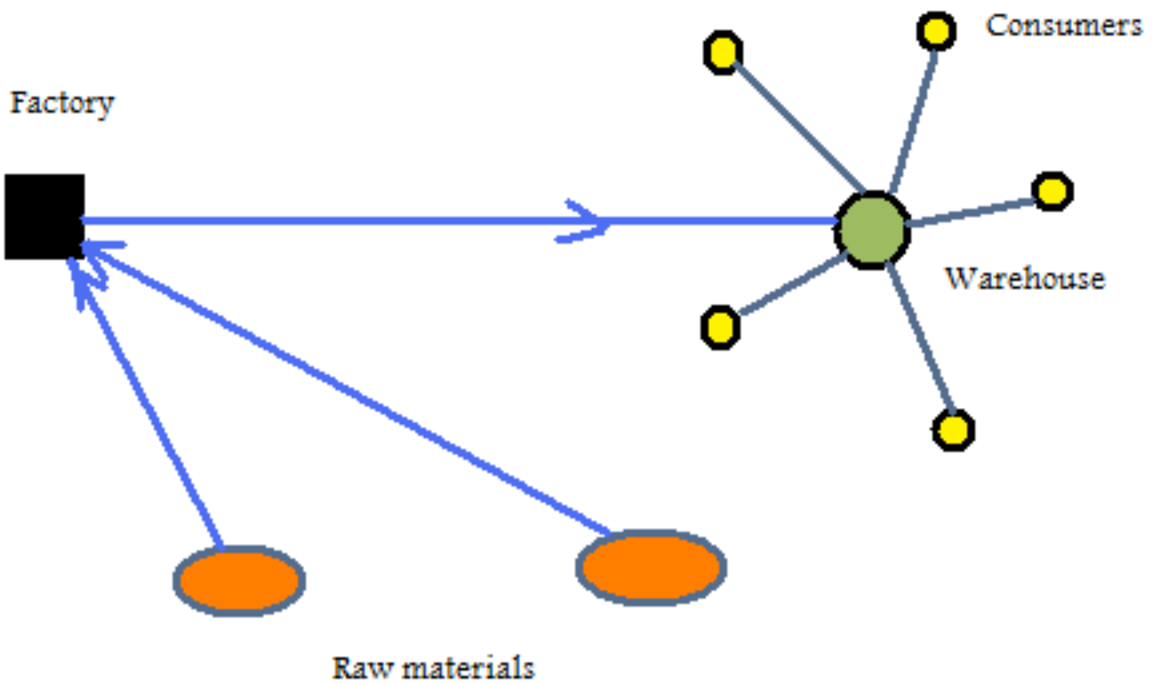
- Plans to integrate these models to fleet case



Part loads/Groupage: Line traffic - > terminals, consolidation, 3PL

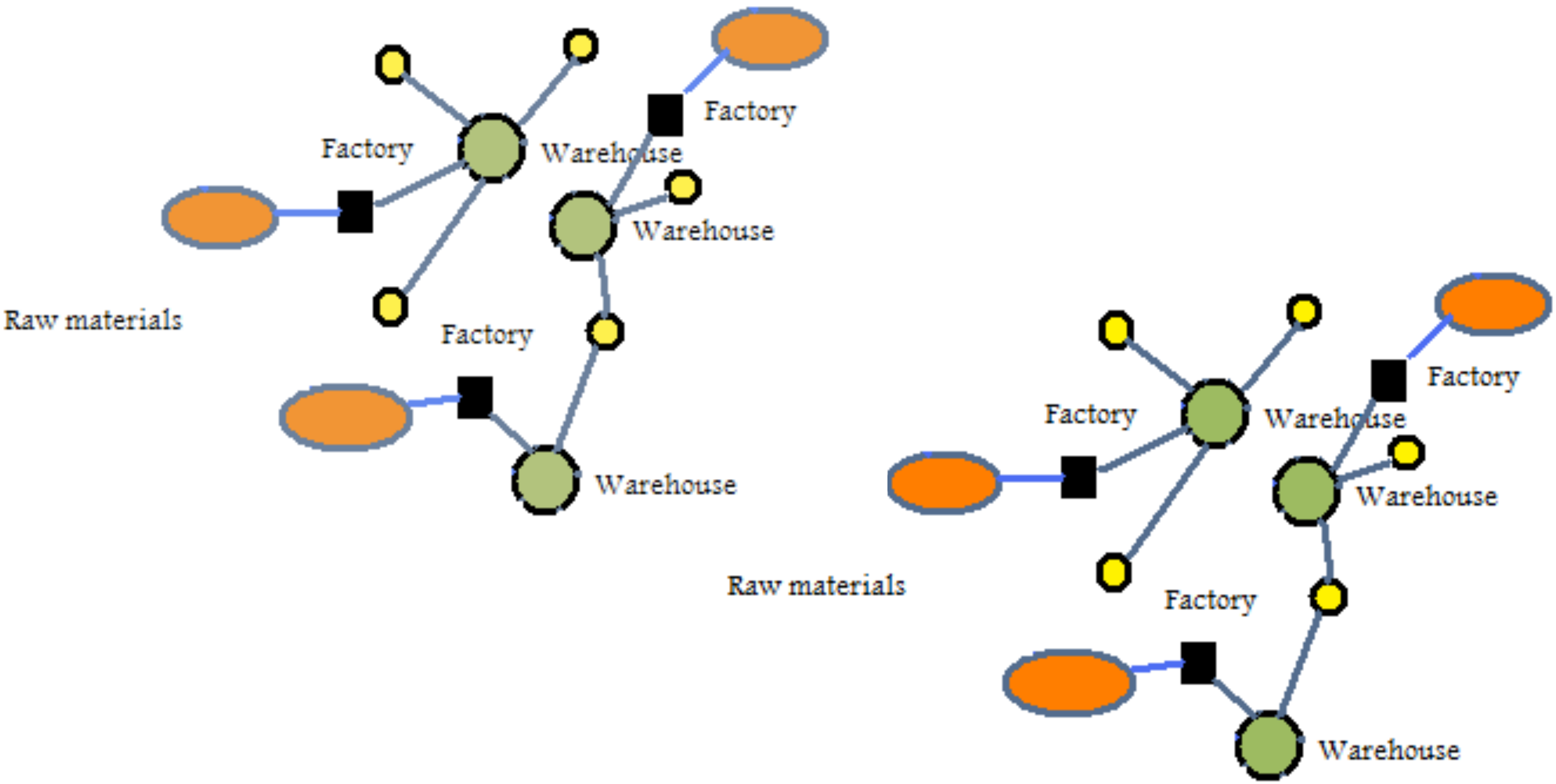
Full loads/ FTL,FCL: Bulk, Tramp Traffic, Contracted containers/tankers/rail cars

Which model?



- Long haul

Short haul (if price of emissions is high enough)



Is this green enough?

- Globally, ruminant livestock produce about 80 million metric tons of CH_4 annually, accounting for about 28% of global CH_4 emissions from human-related activities

(source: US EPA)

THANK YOU VERY MUCH!

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