Lindstad, E., Mørch, H., J., Sandaas, I., (2016) *Improving Cost and Fuel efficiency of short sea Ro-Ro vessels through more Slender Designs – a feasibility study. Society of Naval Architects and Marine Engineers TRANSACTIONS Volume 123, page 303 – 316*

THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS

Volume 123

2015

TRANSACTIONS Volume 123. Published in 2016 by SNAME, reports the activities of The Society of Naval Architects & Marine Engineers and a selection of the (best) publications presented at SNAME events in 2015.

This paper was first presented at the FAST ship conference 1st to 4th of September 2015 in Washington, D.C. It was there after selected for publication in the 2015 Transactions by the Society's Annual Meeting Paper Committee. The purpose of this front page is for any potential reader to familiarize themselves with the SNAME context and suggest how to quote the paper, including the ISSN and the ISBN references. Compared to the original submitted paper the page numbers are corrected to reflect the page numbers in Transactions 123. Compared to the printed version in Transactions 123 the main difference is that figures here are printed in colours

SNAME, 99 Canal Center Plaza, Suite 500, Alexandria, Virginia 22314 www.sname.org

ISSN 0081 1661 ISBN: 978-0-939773-17-6 (Hard cover)

Improving Cost and Fuel efficiency of short sea Ro-Ro vessels through more Slender Designs – a feasibility study

Elizabeth Lindstad [1], Hans Jørgen Mørch [2], Inge Sandaas [3]
[1]Norwegian Marine Technology Research Institute (MARINTEK), Trondheim, Norway
[2]CFD-Marine, Tvedestrand, Norway
[3]United European Car Carriers, Oslo, Norway
Email: Lindstad@sintef.no

Despite the political objective of decreasing road transport and transfer cargo to rail and sea, short sea shipping is struggling. There is therefore a need for development of new short sea Ro-Ro vessels which use significantly less fuel per ton transported and which can be built at a modest cost. This feasibility study has: Mapped the main characteristics of the current fleet; Investigated alternative combinations of main measurements to enable more slender hull forms to reduce power and fuel consumption per transported unit; Performed a case study to compare the economic and environmental performance of these slenderer designs with traditional designs and road only solutions. The results of this study indicate that significant fuel and cost savings can be achieved by designing and building more slender Ro-Ro vessels.

Keywords: Maritime transport; Energy efficiency; Vessel design; Multimodal transport; Transport Policy; IMO

INTRODUCTION

The European Commission (EC) has an active policy to promote Short Sea Shipping due to its high environmental performance and energy efficiency. In addition, Short Sea Shipping has the potential to solve road congestion problems affecting many parts of the European continent. Despite these political objectives of decreasing road transport and transfer cargo to rail and sea, short sea shipping is struggling. In Europe research projects funded both at national, regional and EU level have addressed these challenges, and the recommended solutions has been to focus on the whole supply chain, new or improved technologies or all of this in combination with larger vessels. In comparison, there has been little attention on the need for improving the cost competitiveness of short sea shipping versus road transport.

The vessel types in focus for this study are short sea Ro-Ro vessels. In a global setting Ro-Ro vessels including car carriers accounts for 1% to 1.5 % of the global sea freight work measured in ton nautical miles (nm) and in the range of 15% to 30% of total cargo values transported by sea, due to the high value of the transported goods (new cars, trucks, tractors, heavy machines and project cargoes). In Europe Ro-Ro vessels performs a significantly larger share of the sea freight work. The main explanation is that the Ro-Ro vessels provide relatively fast and reliable transport of trailers, other road units, cassette and mafi -stowed cargoes and even forest products stowed directly on the cargo decks. In total, short sea shipping, i.e. dry and wet bulk, container, general cargo and Ro-Ro accounts for 40% of the European freight work.

Increasing vessel size or reducing operational speeds are two well-known principles for reducing the fuel consumption and cost per transported unit. First; larger ships – and shipments - tend to be more energy efficient per freight unit transported than smaller (Cullinane and Khanna, 2000; Sys et al., 2008; Notteboom and Vernimmen, 2009; Stott and Wright, 2011; Lindstad et al., 2012; Lindstad 2013; Lindstad 2015). The key observation is that when the ship's cargo-carrying capacity is doubled, the required power and fuel use typically increases by about two thirds, so fuel consumption per freight unit is reduced. The vessel's building cost increases with about half of the increase in cargo capacity, and also costs of crew, maintenance and management rise less than proportionally with cargo capacity. However, in short sea trades available cargoes and the required frequencies will often limit the opportunities for increasing the vessel size, or vessel sizes might be limited due to port restrictions.

Second: reducing operational speeds – the power output required for propulsion is a function of the speed to the power of three and beyond, this implies that when a ship reduces its speed, the power required and therefore the fuel consumed per transported unit is considerably reduced (Corbett et al., 2009; Seas at Risk and CE Delft, 2010; Psaraftis and Kontovas, 2010; Lindstad et al, 2011: Psaraftis and Kontovas, 2013). Accordingly, average operational speeds have been reduced in the later years (Smith et al. 2014) due to higher fuel prices compared to in the nineties and early 2000's.

However, since Ro-Ro vessels compete with road transport both cost and time wise, this limits the opportunities for reducing their operational speeds (Pedersen et al 1999; Lindstad 2002; Lindstad and Pedersen 2009).

While speed reductions and economies of scale in vessel and shipment sizes often require changes in the supply chain due to longer transport times, port requirements and storage facilities, it is possible to introduce more energy efficient designs (we call these slender designs) without changes to the logistics. Traditionally, ships have been built to operate at their boundary speeds based on hydrodynamic considerations (Faltinsen et. al.1980). The boundary speed can be defined as the speed, at which for a given hull, the resistance coefficient starts to rise with increasing speeds (Silverleaf and Dawson, 1966). For an average bulk or tank vessel which has a block coefficient[1] in the 0.80 to 0.9 range (1.0 for a shoe box), the boundary speed area starts at 12 – 13 knots, with a gradual increase of resistance coefficient and hence power requirements which rise towards infinity for speed above 16 – 17 knots (Lindstad et al. 2014). For vessel types designed for higher speeds such as Ro-Ro and RoPax the block coefficient are much lower, i.e. typically in the 0.55–0.65 range. The core insight is that reducing the block coefficient, makes the hull form more slender and increases the boundary speed and enables higher operational speeds. See Larsson and Raven (2010) for a more extensive discussion of how hull resistance depends on speed and hull form.

The motivation for this feasibility study has been to investigate the opportunities for development of new Ro-Ro vessels which use significantly less fuel per unit transported and which can be built at a modest cost. This study has: First mapped the main characteristics of the current fleet, i.e. dimensions, capacities, installed power and designs speeds; Second investigated alternative combinations of main measurements to enable more slender hull forms to reduce power and fuel consumption per transported unit; Third, performed a case study to compare the economic and environmental performance of these slenderer designs, with traditional designs and road only solutions.

The employed model is described in the next section and the obtained results are discussed in the concluding section.

MODEL DESCRIPTION

The main objective of the model is to calculate emissions and costs for sea freight and road transport as a function of their characteristics and the transported cargo. The required power for the alternative vessel designs is based on traditional prediction methods (Holtrop and Mennen, 1984) while the boundary speeds for the alternative vessel designs are based on Silverleaf and Dawson (1966). These power and boundary speeds figures enable assessment of costs, fuel consumption and emissions. The applied assessment model consists of four main equations (see Lindstad et al., 2015).

The annual operational profile of a cargo carrier comprises cargo voyages, repositioning voyages and idle time as expressed by equation 1:

$$T = \sum_{i=1}^{N_c}\left(\frac{D_i^c}{v} + T_i^{l\&d} + T_i^w\right) + \sum_{i=1}^{N_b}\left(\frac{D_i^b}{v} + T_i^w\right) \quad (1)$$

Here, the first term on the right-hand side of the equation gives the annual number of days used on cargo voyages, where D_i^c is distance per voyage, v the speed per voyage, $T_i^{l\&d}$ the time used for loading and discharging cargo per voyage, T_i^w the waiting time and N_c the annual number of cargo voyages. The second term gives the annual number of days used on repositioning voyages, where D_i^b is the distance per voyage, v is the speed, T_i^w is the waiting time and N_b is the annual number of repositioning voyages. It should be noted that Ro-Ro vessels employed in scheduled European short sea trades will be partly or fully loaded on each sailing leg, while trailers units might be repositioned empty either by sea or by road pulled by their tractor units.

The annual fuel consumption F comprises the fuel used on cargo voyages F_c and that used on repositioning voyages F_b, and is given by equation (2):

$$F = F_c + F_b = \sum_{i=1}^{N_c}\left(K_f \cdot \left(\frac{P_i^{Mt\cdot v} \cdot D_i^c}{v}\right) + F_i^{l\&d} + F_i^w\right) + \sum_{i=1}^{N_b}\left(K_f \cdot \left(\frac{P_i^{Mt\cdot v} \cdot D_i^b}{v}\right) + F_i^w\right) \quad (2)$$

Here, the first term gives the annual fuel consumption for cargo-carrying voyages and the second term provides the annual fuel consumption for the repositioning voyages. N_c represents the number of cargo voyages, N_b the number of repositioning voyages, K_f the amount of fuel in grams per produced kWh, $P_{M_t \cdot v}$ the power required as a function of

---

[1] Block coefficient is defined as $C_B = \frac{\nabla}{L \cdot B \cdot T}$ where ∇ is the displaced volume, L is length, B is beam and T is draught

speed v and the total cargo carried M_t, including the fuel required, the empty weight of cargo containment units on board the cargo carrier and any other additional weight such as ballast water. D is the distance, $F_{l\&d}$ is the fuel used during loading and discharging and F_w is the fuel consumption while waiting.

The amount of CO_2, ε emitted per ton kilometer (ton km) or ton per nautical mile (ton nm) by the cargo carrier is calculated using equation 3:

$$\varepsilon = \frac{F}{\sum_{i=1}^{N_c}(D_i^c \cdot M_i)} \cdot K_e \quad (3)$$

where F is the annual fuel usage in tons, N_c is the number of cargo voyages, K_e is the emitted CO_2 per unit of fuel burnt, D_i^c is the distance per cargo voyage, M_i is the net cargo weight transported on a voyage.

The cost per ton km comprises the cost of fuel, the daily financial and operational costs of the cargo carrier, the port and road fees, and cargo handling, as expressed by equation (4):

$$\mathrm{C}_{D \cdot M} = \frac{1}{\sum_{i=1}^{N_c} D_i^c \cdot M_i} \cdot \left((F \cdot C_{Fuel}) + TC \cdot T + \sum_{i=1}^{N_c} C_i^{hpf} + \sum_{i=1}^{N_b} C_i^{pf} \right) \quad (4)$$

The first factor, transforms the cost from an annual cost to a cost per freight unit distance. Inside the main bracket, the cost of fuel is calculated by multiplying the annual quantity of burned fuel F (as determined by equation (2)) by the cost of fuel C_{Fuel}. TC is the daily operational and financial costs of the cargo carrier and T corresponds to the number of days per year or total days if the cargo carrier has been in service for less than a year. The two last terms summarize cargo handling, port and voyage fees C_i^{hpf} for the cargo voyages and the port and voyage fees C_i^{pf} for the repositioning voyages. To sum up, we can by combining equations 1, 2, and 3 describe the greenhouse gas emissions associated with a specific operational mode, while equations 1, 2 and 4 provide the costs.

THE EXISTING FLEET

Table 1 shows the key characteristics of the typical Ro-Ro vessels operating in European and Japanese waters. The data sources are: in house data; the Sea-web vessel database (www.sea-web.com); and the home pages of the operators. All the displayed figures are based on the designs conditions for each vessel, i.e. the design draught, the displacement at design draught, and design dead weight (dwt). All vessels have been anonymized, and the displayed figures for length, lane meters and power are rounded. Apart from vessel N, which is based on a high speed concept study, all vessels are currently in operation (2015).

The vessels are ranked from 1 to 37 based on emitted CO_2 per ton trailer cargo, i.e. the vessel with the lowest emission is number 1. For each vessel, we have also calculated the emissions if the vessel is employed in heavy cargo trades. These emission figures are based on net cargo weight, excluding the weight of the trailers, mafi-rolltrailers or cargo-cassettes to enable direct comparison with road transport. The trailer emission figures are calculated based on 24 tons of cargo plus 6 ton in empty trailer weight, i.e. 30 tons in total and 75% utilization of cargo positions. The remaining cargo positions will then be either empty or utilized to reposition empty trailers. It could be argued that 30 ton per trailer is low compared to maximum allowable trailer weights of 33 – 37 tons in main Western European countries. However a large share of the cargo flows is light-weighted, with cubic meter weights of less than 250 kg/m^3, which adds up to 18 tons or less of cargo in a fully loaded trailer. Our judgement is that with a mix of customers, cargoes and utilization percentages, it might therefore be sufficient to use 18 tons of cargo and 24 tons of total weight and 100% utilization as the design criteria for new Ro-Ro designs. In total this adds up to the same weight as what we get with 30 ton in total weight per trailer, 75 % utilization and the remaining 25 % positions filled with empty trailers. The heavy cargo emissions are based on typical industrial roundtrip trades where the front haul cargo weights add up to around 75 % of the dead weight capacity (The weights of the fuel, ballast water, the healing tanks, and cargo carrying units comes in addition to the cargo weights). The back haul utilization is typically quite low and 25 % might be a representative figure which gives 50% capacity utilization for the roundtrip.

The table displays the following columns: Vessel number; Length (LBP); Available lane meters with 3 meter width and the required high for trailers (Lane meters); block coefficient (Cb); Design speed (Vd); Froude number at design speed (Fn); Boundary speed (Vb); Design speed versus boundary, i.e. a positive number means that the design speed is higher than the boundary speed and a high fuel consumption when the vessel operates at the design speed; Installed POWER; Trailer capacity based on 13.6 meter trailer length; CO_2 emitted per ton trailer cargo and per ton heavy cargo.

Table 1: Key Characteristics existing fleet

Vessel	LBP	Lane meters	Cb	Design speed (Vd)	Fn	Boundary speed (Vb)	Vd versus Vb	Installed POWER	Trailer capacity	CO_2 emitted per ton trailer cargo	CO_2 emitted per ton heavy cargo
	meter	meter		knots		knots	%	kW	units	g/ton km	
1	190	3 900	0.56	18.5	0.22	22.7	-18%	10 800	276	32	27
2	190	3 700	0.61	19.0	0.23	20.9	-9%	12 000	262	37	29
3	220	4 700	0.63	21.8	0.24	22.1	-1%	20 100	327	43	41
4	180	3 700	0.59	21.5	0.26	21.4	0%	16 200	263	44	46
5	190	2 900	0.62	18.5	0.22	20.6	-10%	12 000	201	50	27
7	180	3 700	0.61	21.5	0.26	20.9	3%	18 000	258	50	40
8	190	3 800	0.56	22.8	0.27	22.9	-1%	20 100	270	50	40
9	180	3 200	0.57	21.6	0.26	22.2	-3%	16 200	226	51	59
10	190	3 800	0.59	22.3	0.27	21.7	3%	20 100	268	52	46
11	150	2 300	0.71	17.8	0.24	15.6	14%	9 800	163	52	31
12	180	2 500	0.66	20.0	0.25	18.9	6%	12 500	176	55	31
13	170	2 600	0.63	18.5	0.23	19.3	-4%	12 600	185	57	31
14	190	4 600	0.64	21.0	0.25	20.3	3%	21 600	324	57	39
15	180	2 600	0.60	18.0	0.22	21.2	-15%	12 600	184	58	38
16	180	2 600	0.57	21.6	0.26	22.2	-3%	16 200	186	62	54
17	170	3 300	0.69	20.0	0.25	17.2	16%	18 900	231	63	47
18	170	3 300	0.70	20.0	0.25	16.9	19%	19 200	234	63	47
19	170	3 300	0.68	21.0	0.26	17.7	19%	20 000	230	64	48
20	160	2 500	0.58	22.0	0.29	20.5	7%	16 800	176	67	46
21	150	1 900	0.68	20.0	0.27	16.4	22%	12 600	133	73	40
22	130	1 700	0.66	18.5	0.26	16.2	14%	10 700	119	75	69
23	140	1 600	0.71	16.5	0.23	15.4	7%	9 500	113	78	37
24	140	1 600	0.60	21.0	0.29	18.6	13%	12 600	114	81	50
25	120	1 400	0.60	17.0	0.25	17.2	-1%	8 600	96	81	47
26	160	1 900	0.47	21.7	0.29	23.5	-8%	16 700	135	88	68
27	130	2 200	0.61	21.0	0.30	17.7	18%	18 500	153	88	87
28	180	3 000	0.63	22.0	0.27	19.9	10%	27 000	211	89	75
29	150	1 800	0.51	21.2	0.28	21.9	-3%	15 900	126	91	59
30	170	2 700	0.66	22.0	0.28	18.2	21%	26 000	192	95	68
31	140	1 600	0.60	22.0	0.30	18.6	19%	15 600	113	96	61
32	130	1 600	0.60	20.5	0.30	17.6	16%	14 500	112	97	58
33	180	3 700	0.59	26.5	0.32	21.4	24%	43 200	258	97	96
34	130	1 800	0.61	22.0	0.31	17.7	24%	18 500	129	100	91
35	140	1 700	0.64	20.0	0.28	17.4	15%	15 600	119	101	49
36	190	3 500	0.60	26.5	0.32	21.4	24%	43 200	248	101	89
37	130	1 600	0.61	22.0	0.31	17.7	24%	18 500	115	112	91
N	170	1 400	0.43	38.0	0.48	26.0	46%	34 000	99	139	179

The main observations are: First, the top ten (10) vessels with the lowest emissions per ton trailer cargo have lengths above 180 meter, design speeds at or below their boundary speeds, and a large lane meter capacity; Second the bottom ten (10) vessels, with the highest emissions have design speeds significantly above their boundary speeds; Third apart from vessel 11, all vessels with lengths up to 150 are ranked in 21 to 37 group, i.e. the highest emissions; Fourth the most energy efficient vessels emit only a third (1/3) of what the least efficient vessels do; Fifth only 7 out 38 designs have block coefficients of 0.57 or less; Sixth, 8 out of 38 vessels have Froude numbers from 0.3 and higher; Seventh, only 4 out of

38 vessels loaded with trailers, emits less than 50 g of CO_2 per ton km, when operated at their design speeds.

In Comparison, recently published figures for road transport (European Environmental Agency, 2013; Persson and Zanganeh, 2012; Cefic and ECTA, 2011) indicate direct emissions levels in the range from 50 – 70 g CO_2 per ton km when the same cargo is transported in by road. Apart from the top ranked vessels the fuel consumption and emissions per ton transported by the existing short sea Ro-Ro fleet are at a comparable or higher level than road transport. It should be noted that these road emission figures, does not include the emissions from road maintenance and rebuilding. According to German figures, the wear and tear caused by one freight lorry (tractor and trailer unit) might equal the wear and tear caused by 3 – 400 ordinary cars. In comparison, sea-going vessels make little or no damage to supra and infrastructure. Adding it all up, it can therefore be concluded that if sea going vessels and road transport has similar fuel consumptions per ton transported, sea transport will still be more environmentally friendly with equal distances.

Independently of any comparisons with road transport there are strong arguments for the need to develop and build more energy efficient Ro-Ro vessels: First higher fuel cost, due to increased crude oil prices compared to 10 to 15 years ago; Second higher fuel cost due to the strict Sulphur limits when vessels operate in the maritime emission control areas (ECA) in Europe and North America. Third more public focus on maritime transport emissions; Fourth introduction of the Energy Efficiency Design Index (EEDI) applicable for new-built vessels, which requires that new-built vessels become significantly more energy efficient during the next 20 years.

MORE SLENDER VESSEL DESIGNS

The purpose of this section is to investigate alternative designs with focus on varying vessel length and width, to enable more slender designs and hence lower fuel consumption and emissions per transported unit, compared to more full body conventional Ro-Ro designs operating at similar speeds. The conventional Ro-Ro designs have typically been built to operate at or above their boundary speed, to maximize their cargo carrying capacity at the lowest building cost for the desired design speed. In comparison the slender designs investigated in this paper have been designed to operate at speeds bellow their boundary speeds to enable lower fuel consumption and cost and hence might come at a higher building cost per freight capacity unit.

Three conceptual designs have been investigated where the length is stepwise increased from the shortest version to the longest, which has a length too beam equal to 10. The first, which we have called the zero design (0), is a traditional full bodied Ro-Ro design similar to what is typical in the existing fleet, i.e. a block coefficient of 0.63. It has three cargo decks and a beam of 23meter. The first of the alternative designs, i.e. design one (1) has a block coefficient of 0.46 which is slender compared to the existing fleet, where only 7 out of 38 vessels have a block coefficient of 0.57 or less. It has three cargo decks and a beam of 23 meter. The second of the alternative designs, i.e. design two (2), has four cargo decks and a beam of 27 meter. The 27-meter conceptual design has a block coefficient of 0.565, to enable the carriage of cargo on four decks compared to three. The traditional design with lengths from 150 up to 230 meters has been numbered 0-B to 0-I, The alternative one design with lengths from 150 up to 230 meter has been numbered 1-B to 1-I, The alternative two design with lengths from 140 up to 270 meter are numbered 2-A to 2-W.

One of the main challenges when designing a Ro-Ro vessel is to avoid that the vessel throws the cargo in rough sea due to large accelerations and retardations caused by dimensional combinations which gives to much stiffness. Due to this, the three (3) deck vessels beam has therefor been limited to 23-meter beam. Both design one and two are designed for trailer traffic where the average weight of the trailer and its cargo is 18 tons of cargo plus 6 ton in empty trailer weight, i.e. 24 tons in total. Our judgement is that with a mix of customers, cargoes and utilization percentages this will give both sufficient vessel cargo carrying capacity and reduce the need for ballasting compared to traditional Ro-Ro vessels.

The table displays the following columns: Vessel design (DESIGN); Vessel length (LBP); The Froude number (Fn) at boundary speed followed by the Froude number with a design speed of 22 knots; Displacement (DEPL) at the design draught; Block coefficient (Cb); Boundary speed (Vb); cargo weight (CARGO) which includes the empty weights of the trailers; Trailer capacity (TRAILERS) based on 13.6 meter trailer length; Lane meter per vessel (LM); The length to beam ratio (L/B); The light displacement tonnage (LDT) which is the weight of water displaced by the ship when the ship is empty, i.e. it gives the mass of the ship excluding cargo, fuel, ballast, stores, passengers, crew, but with water in boilers to steaming level; The required power to achieve boundary speed at designs conditions (BOUNDARY); The required power to achieve 22 knots speed at calm water and design load (22 knots); The estimated new-building cost for each of the alternative designs based on the engine sizes which enables 22 knots speed at 70% of max continious engine rating.

Table 2: Main dimensions and characteristics for the alternative designs

Traditional Designs: Beam = 23 meter; 3 cargo decks; Built for heavy cargo

			Fn at 22									POWER		New building
Design	L	Fn	knots	DEPL	Cb	Vb	CARGO	Trailers	LM	L/B	LDT	BOUNDARY	22 knots	cost (MEuro)
0-B	150	0.244	0.295	15 597	0.63	18.2	6791	138	1965	6.5	7157	8 643	17 618	46
0-C	160	0.244	0.286	16 636	0.63	18.8	7244	148	2096	7.0	7634	9 958	17 809	48
0-D	170	0.244	0.277	17 676	0.63	19.4	7696	157	2226	7.4	8111	11 405	18 043	50
0-E	180	0.244	0.269	18 716	0.63	19.9	8149	166	2357	7.8	8588	12 764	18 313	53
0-F	190	0.244	0.262	19 756	0.63	20.5	8602	175	2488	8.3	9065	14 482	18 615	55
0-G	200	0.244	0.256	20 796	0.63	21.0	9054	184	2619	8.7	9542	16 265	19 183	57
0-H	210	0.244	0.249	21 835	0.63	21.5	9507	194	2750	9.1	10020	18 363	19 930	60
0-I	220	0.244	0.244	22 875	0.63	22.0	9960	203	2881	9.6	10497	20 687	20 687	63
0-J	230	0.244	0.238	23 915	0.63	22.5	10413	212	3012	10.0	10974	23 257	21 456	65

Alternative 1 : Beam = 23 meter; 3 cargo decks; Built for 24 tons trailers

			Fn at 22									POWER		New building
Design	L	Fn	knots	DEPL	Cb	Vb	CARGO	Trailers	LM	L/B	LDT	BOUNDARY	22 knots	cost (MEuro)
1-B	150	0.314	0.295	11 399	0.460	23.4	2944	123	1742	6.5	6555	18 077	10 693	42
1-C	160	0.314	0.286	12 159	0.460	24.2	3140	131	1858	7.0	6992	20 604	10 858	44
1-D	170	0.314	0.277	12 919	0.460	25.0	3337	139	1974	7.4	7429	23 367	11 049	46
1-E	180	0.314	0.269	13 679	0.460	25.7	3533	147	2090	7.8	7866	26 067	11 265	48
1-F	190	0.314	0.262	14 439	0.460	26.4	3729	155	2207	8.3	8303	28 997	11 497	51
1-G	200	0.314	0.256	15 199	0.460	27.1	3926	164	2323	8.7	8740	32 588	11 839	53
1-H	210	0.314	0.249	15 959	0.460	27.7	4122	172	2439	9.1	9177	36 396	12 251	55
1-I	220	0.314	0.244	16 719	0.460	28.4	4318	180	2555	9.6	9614	41 034	12 663	58
1-J	230	0.314	0.238	17 479	0.460	29.0	4514	188	2671	10.0	10051	45 594	13 078	60

Alternative 2 : Beam = 27 meter; 4 cargo decks; Built for 24 tons trailer

			Fn at 22									POWER		New building
Design	L	Fn	knots	DEPL	Cb	Vb	CARGO	Trailers	LM	L/B	LDT	BOUNDARY	22 knots	cost (MEuro)
2-A	140	0.270	0.305	15 362	0.565	19.5	4645	194	2748	5.2	8157	11 529	13 603	54
2-B	150	0.270	0.295	16 460	0.565	20.2	4977	207	2944	5.6	8740	13 439	13 756	57
2-C	160	0.270	0.286	17 557	0.565	20.8	5308	221	3141	5.9	9323	15 280	13 941	60
2-D	170	0.270	0.277	18 654	0.565	21.5	5640	235	3337	6.3	9905	17 586	14 153	63
2-E	180	0.270	0.269	19 752	0.565	22.1	5972	249	3533	6.7	10488	19 792	14 388	66
2-F	190	0.270	0.262	20 849	0.565	22.7	6304	263	3730	7.0	11070	22 182	14 644	69
2-G	200	0.270	0.256	21 946	0.565	23.3	6635	276	3926	7.4	11653	24 766	14 918	72
2-H	210	0.270	0.249	23 044	0.565	23.8	6967	290	4122	7.8	12236	27 149	15 208	75
2-I	220	0.270	0.244	24 141	0.565	24.4	7299	304	4319	8.1	12818	30 133	15 512	78
2-J	230	0.270	0.238	25 238	0.565	25.0	7631	318	4515	8.5	13401	33 344	15 828	81
2-K	240	0.270	0.233	26 336	0.565	25.5	7963	332	4711	8.9	13984	36 951	16 354	84
2-L	250	0.270	0.229	27 433	0.565	26.0	8294	346	4907	9.3	14566	40 914	16 896	88
2-M	260	0.270	0.224	28 530	0.565	26.5	8626	359	5104	9.6	15149	45 233	17 448	91
2-N	270	0.270	0.220	29 628	0.565	27.0	8958	373	5300	10.0	15732	49 934	18 010	94

The main observations are: First, the slender one design gives boundary speed in the range of 23 to 29 knots; Second, the shortest of the alternative one designs, i.e. the designs 1-B, 1-C and 1-D, has trailer capacities in 120 – 140 range, which enables serving ports with less dense traffic or length restrictions; Third, the alternative two designs gives capacities from 200 trailers upwards; Fourth, the increased cargo carrying capacity of the alternative two designs reduces the boundary speed with 15 – 20 % compared to the alternative one designs; Fifth the longest and largest of these designs, i.e. 2-L, 2-M and 2-N gives larger capacities than any of the reference vessels as displayed in Table 1.

All the investigated designs are feasible, however in the following sections we have chosen to focus on the longest and shortest version of the designs and the alternative two designs with similar length plus the longest vessel, i.e. 0-B, 0-J, 1-B, 1-J, 2-B, 2-J, and 2-N.

Figure 1 shows gram CO_2 per ton km as a function of speed for each of these designs based on18 tons of cargo per trailer unit and 24 tons in total with 100 % lane meter utilization. Here the power required to achieve speed above 24 knots for these designs will increase their new-building cost compared to the figures displayed in table 2.

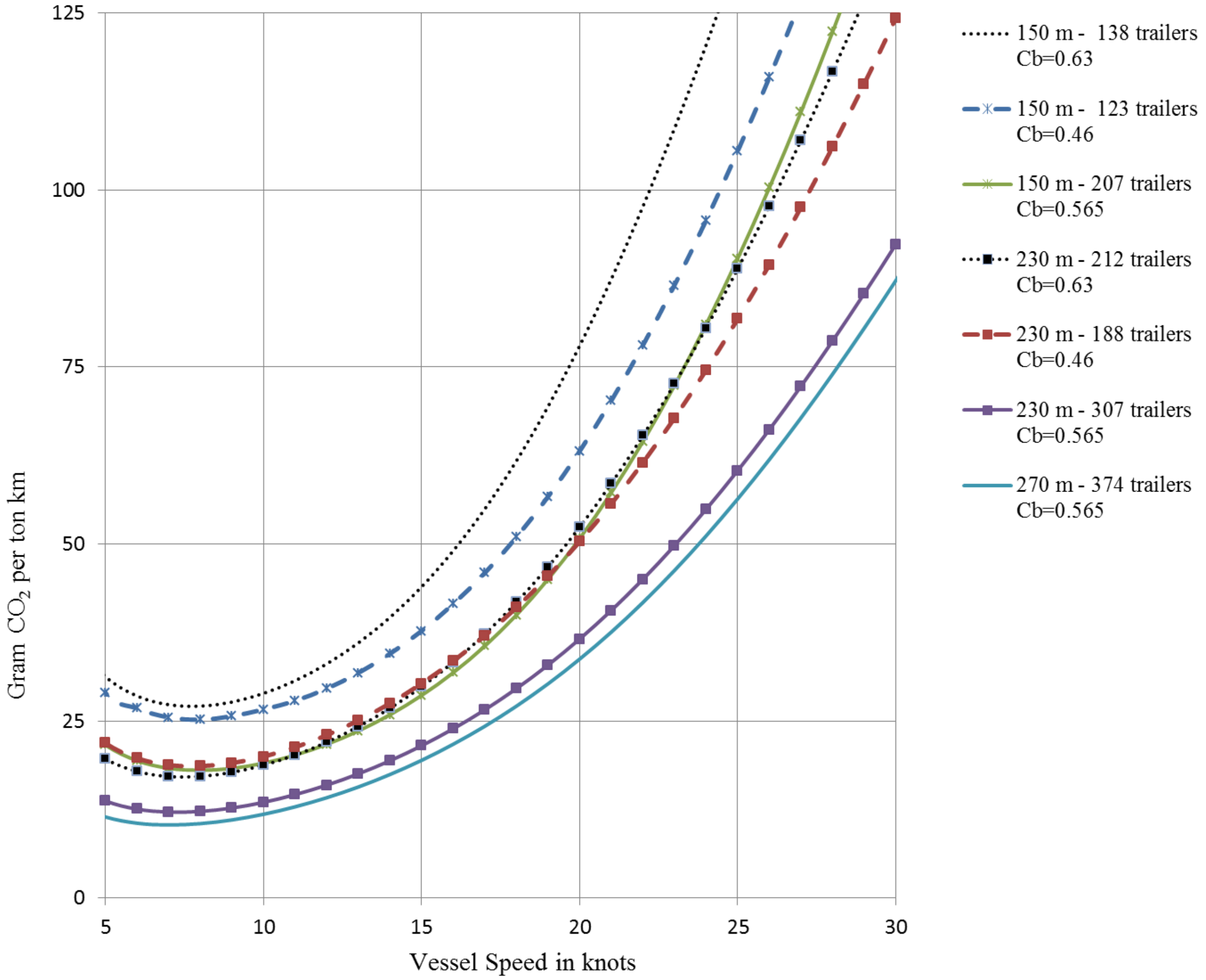

Fig 1: Gram CO_2 per ton km for alternative vessel designs as a function of vessel speed

The main observations are: First, when vessel increases, emissions per ton transported decreases if there are sufficient cargo amount to fill the larger vessels; Second, the lowest emissions are achieved at speeds in the 8 to 10 knots range; Third, the largest of the designs can operate at speeds of 22 – 24 knots with lower emissions than the direct emissions from comparable road transport.

In Figure 2 the designs: 1-B (150m-123 trailers); 1-J (230m-188 trailers); 2-J (230m-307 trailers), 2-N (270m-374 trailers) are compared with the emissions performance of vessels in the existing fleet. Each of these references vessels has numbers given by Table 1 and these numbers are plotted in the figure to indicate their emissions per ton transported when operated at their design speed.

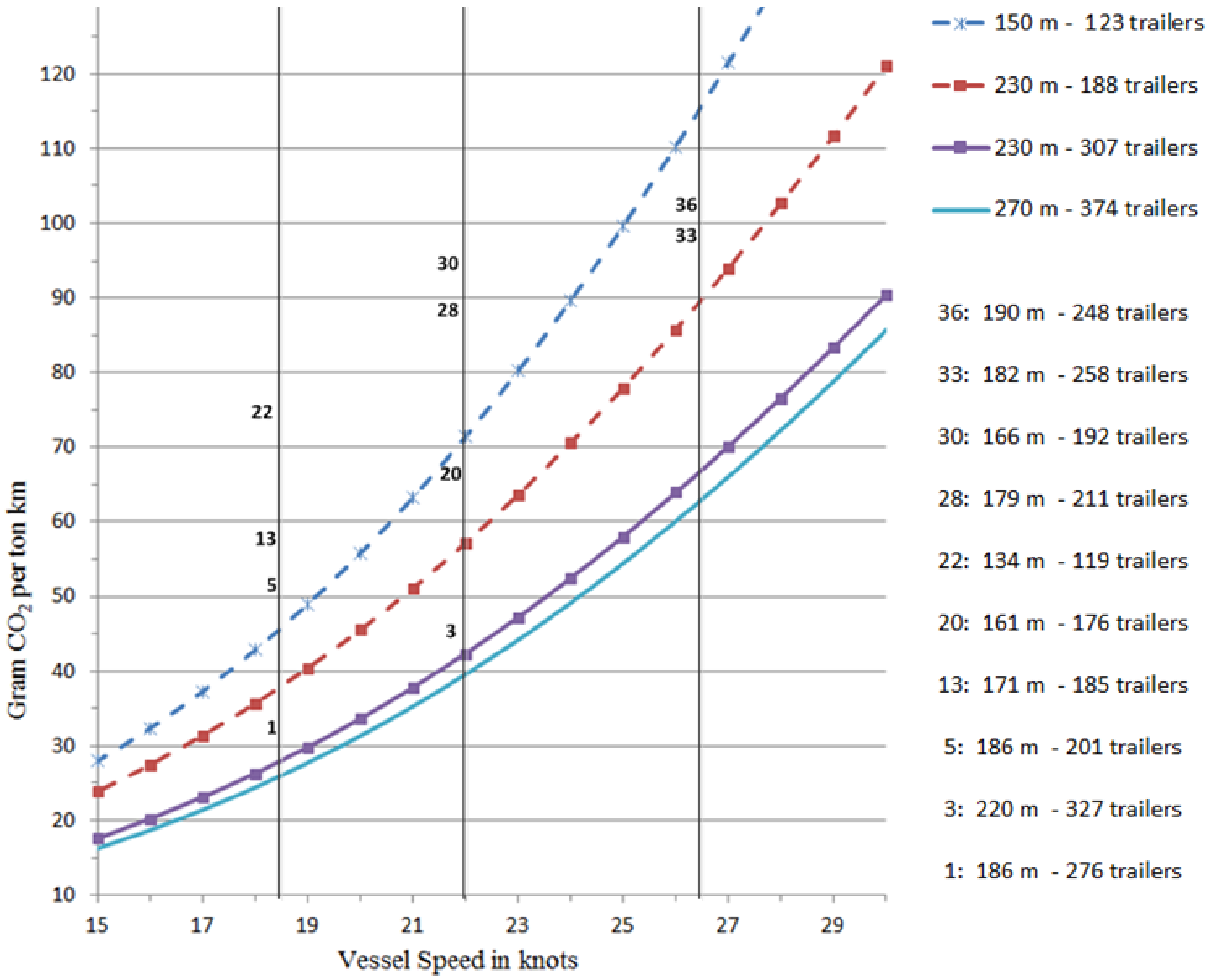

Fig 2: Gram CO_2 per ton km for alternative vessel designs as a function of vessel speed

The main observations are: First, apart from vessel 1 which is the best of the references vessels and which has a similar block coefficient (0.56) as the 2-a to 2-N designs, the existing fleet has high emissions per ton transported; Second, even the 123 trailer vessel achieves similar emissions levels as the best of the 50 % larger vessels in the existing fleet, i.e. vessel 5 and vessel 20; Third, the main explanation why eight of the ten plotted references vessels have higher emissions than the reference vessel with a 188 trailer capacity (1-J) is because their design speed is significantly above their boundary speed.

Based on these observations it can be concluded that replacing the existing fleet with more slender vessels will reduce fuel consumption and emissions per ton transported. Lower fuel consumption implies reduced fuel consumption per voyage and reduces total cost per voyage. Comparing new-building cost per lane meter for the slender designs with the conventional designs we find that they are of a similar magnitude. Combining the effects of lower fuel consumption with similar building cost, it can be concluded that the slender designs will be more cost competitive than the existing fleet. However, there are three additional questions to ask and investigate: First, what are the economies of scale effect by employing the larger of these slender designs; Second, how competitive are the smallest of these slender vessels versus road transport; Third, how will more expensive maritime fuels and constant prices for road fuel affect the competition between road and sea.

To answer these questions, we have chosen to calculate cost per trailer unit as a function of speed for two typical trades, i.e. 400 nm and 750 nm (750 km and 1400 km) and compare with road transport. The daily vessel cost is calculated based on vessel newbuilding cost and typical operational cost in line with standard accounting practice. Fuel cost is calculated based on consumption as a function of speed with two alternative fuel prices. The first is 300 Euro per ton to reflect 2015 crude oil prices of 50 – 60 USD per barrel. The second is 600 Euro per ton operating on distillate in European emission control areas (ECA) which reflect crude oil prices of 60 – 80 USD per barrel. Right now (August 2015) prices are closer to 250 Euro per ton for HFO and 400 per ton for MGO. See Lindstad et al. (2015) for an extensive discussion on cost as a function of abatement options in maritime emission control areas. The port and stevedoring cost are calculated to be around 200 Euro for a trailer one way. For road transport the cost including fuel and road taxes for the tractor unit pulling the trailer are estimated to be around 1 Euro per km based on present fuel prices of 1 Euro per litre and 3.5 liter per 10 km. In Europe fuel taxes on road fuels adds up to around 50 % of the price at the gas station, which implies that the price for road diesel varies much less than the fuel for the Ro-Ro vessels which is untaxed. The daily rental and maintenance cost for the trailers has not been included since both the sea and road solution will use the trailer as their cargo carrying unit.

Figure 3 shows the pure sea freight cost per trailer unit without port and stevedoring cost based on 100 % load meter utilization for each of the 5 alternative designs when the vessel is employed in a 400 nm trade (800 nm on a roundtrip basis) with a fuel cost of 300 Euro per ton.

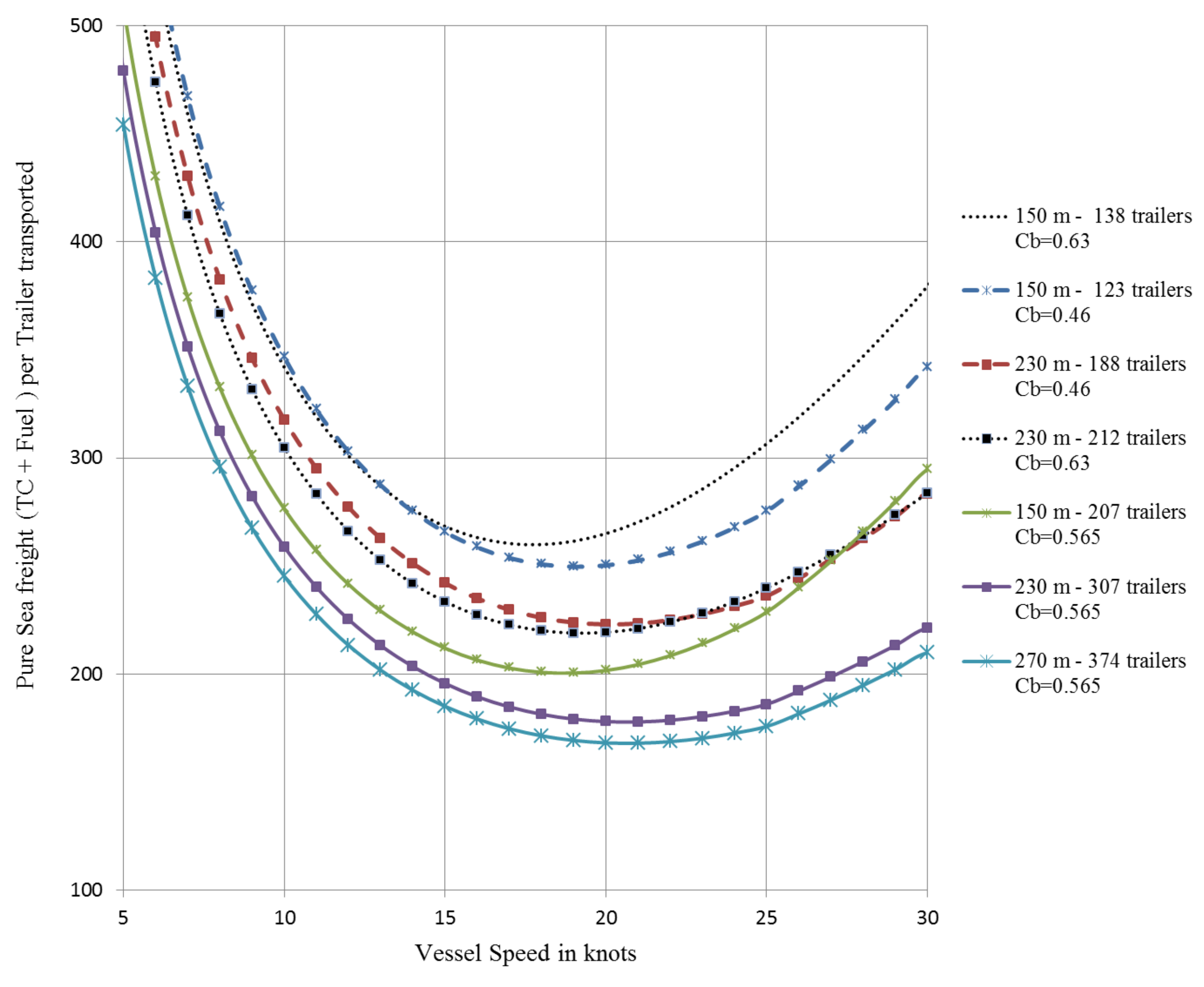

Fig 3: Pure Sea freight per trailer with a distance of 400 nm and a fuel price of 300 Euro per ton.

The main observations are: First, economies of scale are rewarded and employing the largest versus the smallest reduces the pure sea freight with 30 – 35 % per trailer based on equal capacity utilization; Second, all the investigated designs have cost minimizing speeds around 20 knots; Third the cost curves are rather flat for speeds in the 15 to 25 knots area, which implies that vessel speed can be increased or decreased to fit with 48 hours roundtrip for distances in the 300 – 500 nm range.

Figure 4 shows Euro per trailer including port and stevedoring cost based on 100 % load meter utilization for each of the assessed designs when the vessel is employed in a 400 nm trade (800 nm on a roundtrip basis) and a fuel cost of 300 Euro per ton. Plus the comparable cost figures for road transport to enable mode comparison.

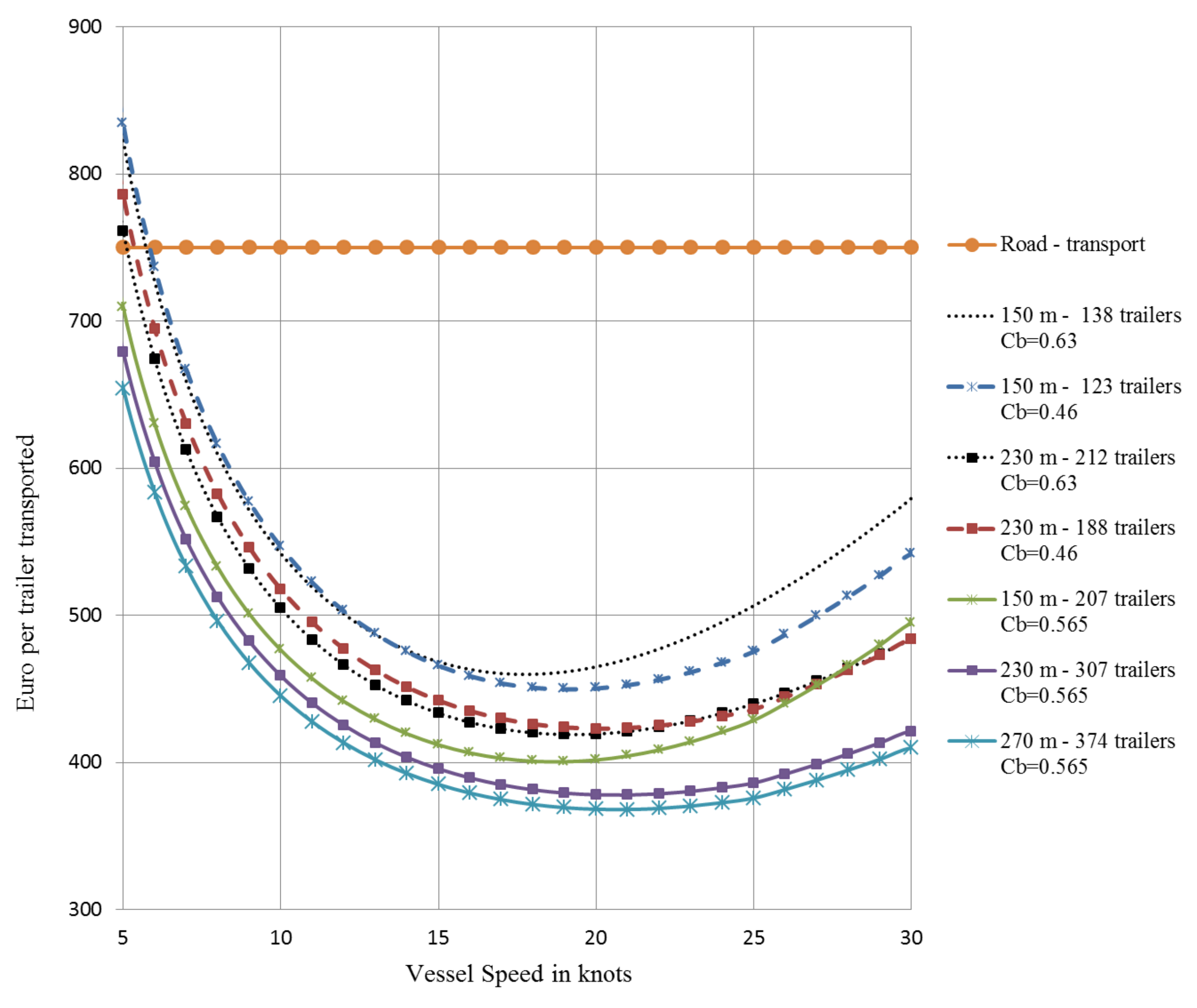

Fig 4: Cost in Euro per trailer with a distance of 400 nm and a fuel price of 300 Euro per ton.

The main observations are: First, economies of scale are rewarded, however when port and stevedoring cost is included the cost benefits is reduced to 15 – 20 % compared to 30 – 35 % per trailer as displayed in Figure 3; Second, including port and stevedoring cost do not change the cost minimizing speed, i.e. all the investigated designs still have cost minimizing speeds around 20 knots; Third the form of the cost curves are unchanged compared to figure 3 which implies that vessel speed can be increased or decreased to fit with 48 hours roundtrip for distances in the 300 – 500 nm range.

Figure 5 shows Euro per trailer including port and stevedoring cost based on 100 % load meter utilization for each of the 5 alternative designs when the vessel is employed in trades where the distance is 750 nm one way, i.e. 1400km. Examples of such trades are from North of Spain in Biscayan to southern UK or Belgium. We focus on the smaller vessels, i.e. the alternative 150 meter designs: 0-B; 1-B; and 2-B, which all give suitable cargo carrying capacity for these trades. We make the comparison with two fuel prices, i.e. 300 Euro per ton and 600 Euro per ton to investigate the impact of higher fuel prices due to stricter emissions rules set by IMO and EC. To keep it simple we have assumed that the ship has to operate on distillate instead of heavy fuel oil in emission control areas (ECA), but there are also other alternatives which might be less expensive (Lindstad et. al., 2015). In Europe with the current rules (2015) a Baltic trade operation will imply that the vessel will be in the ECA 100% of the time and the fuel cost will be 60 – 80 % higher than with heavy fuel oil. A Spain to UK or Belgium operation will imply that the vessels will be in the ECA part of the voyage. A Mediterranean operation will imply that the vessel can use heavy fuel oil on the whole sea voyage. The cost curves for a fuel price of 300 Euro per ton are plotted in black while cost curves with 600 Euro per ton are plotted with red colour. And since the maritime fuel regulations does not influence the price of the road fuel there are only one cost curve for road transport

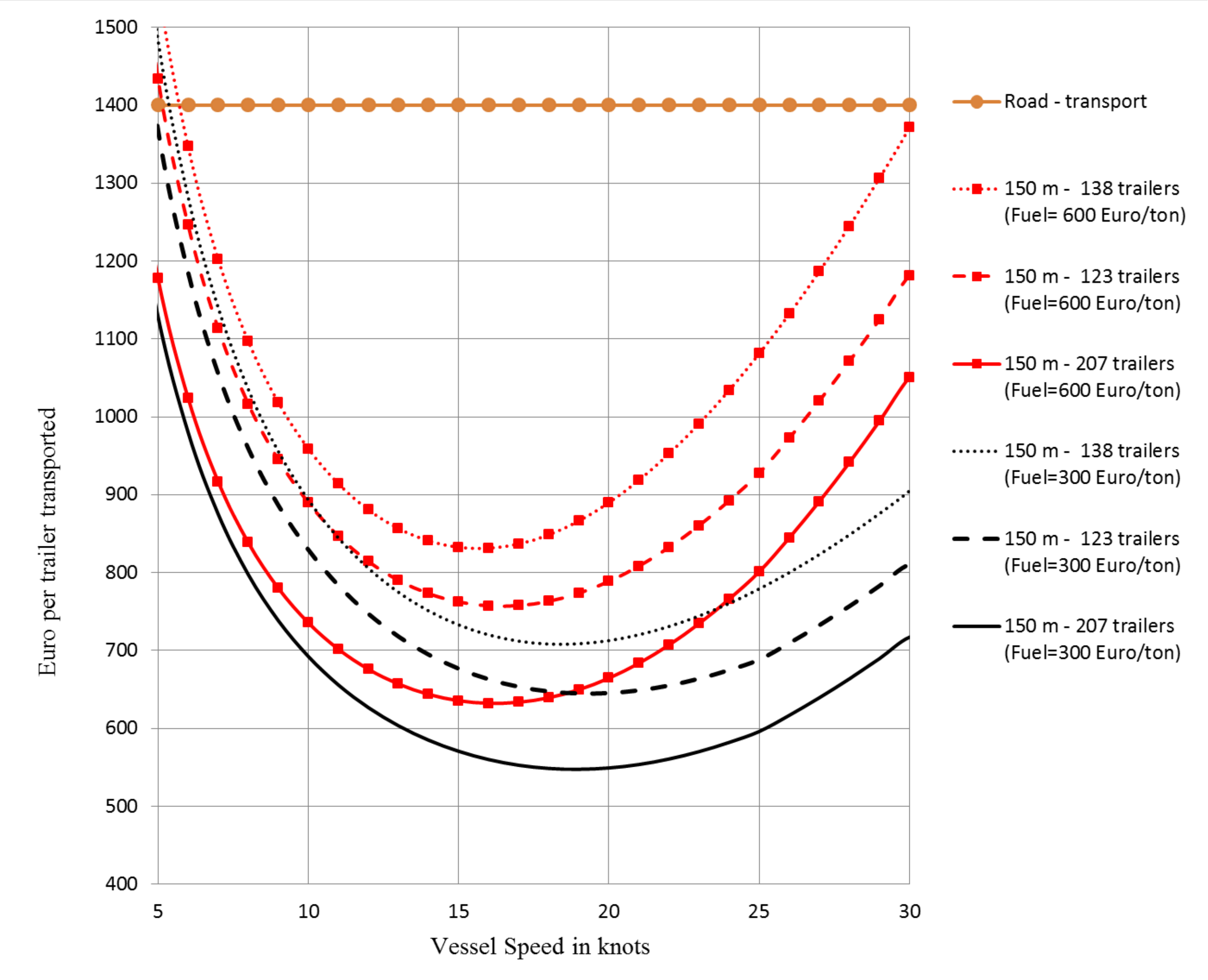

Fig 5: Cost in Euro per trailer with a distance of 750 nm and fuel prices of 300 and 600 Euro per ton.

The main observations are: First, the 207 trailer vessel with a block coefficient of 0.565 gives the lowest cost for both fuel prices; Second the conventional 138 trailer vessel gives the highest cost for both fuel prices; Third, when fuel price increases from 300 Euro to 600 Euro per ton, the cost minimizing speed is reduced from 19 to 20 knots down to 16 to 17 knots; Fourth our judgement is that the 138 conventional trailer vessel gives a cost level which is too high to compete with the trailer traffic, because parts of the cargo, has to be collected from a large hinterland, at an additional cost to generate sufficient tonnages to operate frequent liner traffic.

DISCUSSION AND CONCLUSIONS

This feasibility study has investigated the opportunities for development of new Ro-Ro vessels which use significantly less fuel per unit transported and which can be built at a modest cost. First we mapped the main characteristics of the current fleet; Second, we investigated alternative combinations of main measurements to enable more slender hull forms to reduce fuel consumption and fuel cost per transported unit; Third, we performed a case study to compare the economic and environmental performance of these slenderer designs, with traditional designs and road only solutions.

The results compared with existing vessels indicates that fuel cost and emissions can be reduced significantly by building more slender Ro-Ro vessels. With building cost at comparable levels this implies that more slender vessels achieve lower cost per trailer transported and hence becomes more cost competitive versus road transport. In Europe the European commission launched the Motorways of the Sea (MoS) initiative a decade in the early 2000's to transfer cargo traffic from road to sea. The core MoS concept was to provide high frequency connections operating at speeds enabling competition with road haulage. However, despite giving out subsidies to operators, the MoS concept has not been a success. One of the reasons for the lack of success is that the employed conventional tonnage has not given the required cost advantages versus road transport. Another is that the employed ships have struggled with keeping the schedule in rough, sea and hence has been perceived as less reliable than road transport solutions. In comparison, slender designs achieve lower cost and can operate at lower resistance at higher speeds in rough sea with less cargo damages. Slender designs are therefore more cost competitive and will achieve higher schedule adherence.

Present CO_2 emissions from maritime transport represent 3.0% of the world's total CO_2 emissions, and they are forecast to increase by 150% – 250% until 2050, on the basis of "business as usual" scenarios with a tripling of world trade (Smith et al 2014). In response to these challenges, the International Maritime Organization has introduced a mandatory Energy Efficiency Design Index (EEDI). The EEDI uses a formula to evaluate the CO_2 emitted by a vessel per unit of transport based on a fully loaded vessel as a function of vessel type and size. Common to all vessel types is that as vessel sizes increases, the EEDI thresholds require that emissions per transported ton decreases. Since slender vessels emit less per transported ton, they will more easily satisfy the requirement than conventional tonnage.

Comparing this study with conventional design practice, the largest difference is that starting with a feasibility study enables investigation of a large set of alternative designs in a cost and time efficient manner, while a conventional design process often starts with pre-defined external dimensions and cargo capacities. The best concepts identified through this feasibility study should be further investigated and improved with Computational fluid dynamics (CFD) software, followed by towing tank test of the final optimized hull.

ACKNOWLEDGEMENT

This study has been financially supported by the Norwegian Research Council project (Norges Forskningsråd) 245900 *Development of cost competitive and fuel-efficient short sea vessels.*

REFERENCES

Corbett, J, J. Wang, H, Winebrake, J, J. 2009. *The effectiveness and cost of speed reductions on emissions from international shipping*. Transportation Research D, 14, 2009, 593-598.

Cefic and ECTA, 2011 - *Guidelines for Measuring and Managing CO_2 Emission from Freight Transport Operations*

Cofret, 2014. *Allocation of the CO2 emissions – Road Freight Transport* http://www.cofret-project.eu/downloads/pdf/

Cullinane, K., Khanna, M. 2000. *Economies of scale in large containerships: Optimal size and geographical implications*. Journal of Transport Geography, 8 (3), Page 181-195.

European Environmental Agency (EEA), 2013. *Energy efficiency and specific CO2 emissions (TERM 027)* http://www.eea.europa.eu/data-and-maps/indicators/energy-efficiency-and-specific-co2-emissions

Faltinsen, O.M., Minsaas, K.J., Liapis, N., Skjørdal, S.O., 1980. *Prediction of resistance and propulsion of a ship in a Seaway*. In: Proceeding of the 13th Symposium on Naval Hydrodynamics, Tokyo, the Shipbuilding Research Association of Japan, 1980, pp. 505–529.

Holtrop, Mennen, 1984. *A statistical re-analysis of resistance and propulsion data.* ISP, Vol. 31, No. 363, November 1984

Larson, L., Raven, H., C., 2010. *The Principles of Naval Architecture Series: Ship Resistance and Flow.* SNAME 2010, ISBN 978-0-939773-76-3

Lindstad, H. 2002. *New Ro-Ro ship and barge designs promise great strides in handling efficiencies.* Ro-Ro 2002 Conference, The 16th biennial conference for the international RoRo industry, Lübeck Congress Centre, Germany 28-30 May 2002

Lindstad, H. Pedersen, J.T., 2009. *Using maritime transport to meet climate goals in Europe and challenges for the RoPax vessels.* Conference proceedings FAST 2009 Athens, Greece, October 2009

.

Lindstad, H. Asbjørnslett, B. E., Strømman, A., H., 2011. *Reductions in greenhouse gas emissions and cost by shipping at lower speed.* Energy Policy 39 (2011) 3456-3464

Lindstad, H. Asbjørnslett, B., E., Strømman, A., H., 2012. *The Importance of economies of scale for reductions in greenhouse gas emissions from shipping.* Energy Policy 46 (2012) 386-398

Lindstad, H. 2013. *Strategies and measures for reducing maritime CO2 emissions*, Doctoral thesis PhD. Norwegian University of Science and Technology – Department of Marine Technology. ISBN 978-82-461- 4516-6 (printed), ISBN 978-82-471-4517-3 (electronic).

Lindstad, H., Steen, S., Sandass, I. 2014. *Assessment of profit, cost, and emissions for slender bulk vessel designs*. Transportation Research Part D 29(2014) 32-39

Lindstad, H., Sandaas, I., Strømman, A.H., 2015 *Assessment of cost as a function of abatement options in maritime emission control areas*. Transportation Research Part D 38(2015), page 41-48
DOI information: 10.1016/j.trd.2015.04.018

Lindstad, H, 2015. *Assessment of Bulk designs Enabled by the Panama Canal expansion*. Society of Naval Architects and Marine Engineers (SNAME) *Transactions 121*, page 590-610, ISSN 0081 1661, ISBN 978-0-939773-95-4

Notteboom, T.E., Vernimmen, B., 2009. *The effect of high fuel liner service configuration in container shipping*. Journal of Transport Geography 17 (2009), Page 325–337.

Pedersen, J.T., Ottjes, J., Veeke, Lindstad, H. 1999. *IPSI – Improved Port Ship Interface, A Revolutionary Concept for Intermodal Transport.* European Commission.

Persson & Zanganeh, 2012. *A model for mapping carbon dioxide emissions during freight transports at Höganas AB, Sweden.* http://lup.lub.lu.se/luur/download

Psaraftis, H.N., Kontovas, C.A., 2010. *Balancing the economic and environmental performance of maritime transport. Transportation Research Part D*

Psaraftis, H, N. Kontovas, C, A. 2013. *Speed models for energy efficient transportation: A taxonomy and survey.* Transportaion research Part C, 2013

Silverleaf, A., Dawson, J., 1966. *Hydrodynamic design of merchant ships for high speed operation*. Summer meeting in Germany 12th – 16th of June, 1966. The Schiffbau-technische Gescaft E.V, The institute of marine engineers, The institute of engineers and shipbuilders in Scotland, The North East Coast Institution of Engineers and shipbuilders, The Royal institution of naval architects.

Sea at Risk and CE Delft, 2010. *Going Slow to Reduce Emissions*, www.seas-at-risk.org

Smith et al. (2014) *The Third IMO GHG Study*. Imo.org

Stott, P., Wright, P., 2011. *Opportunities for improved efficiency and reduced CO2 emissions in dry bulk shipping stemming from the relaxation of the Panamax beam constraint*. Trans RINA, Vol. 153. Part A4, Intl J Maritime Eng. Oct-Dec 2011

Sys, C., Blauwens, G., Omey, E., Van de Voorde, E., Witlox, F., 2008. *In Search of the Link between Ship Size and Operations.* Transportation Planning and Technology, August 2008. Vol. 31, No. 4 pages 435 – 463