

Danish Shipowners' Association

CO₂ Indexing Principles and Historical Development of Energy Efficiency of Ships

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CO₂ indexing principles and
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1. Executive summary

The objective of this report is to provide a rational basis for the formulation of an alternative technical CO₂ index, which do not depend on operational measures, but on technical data obtainable at the delivery of the vessel. The purpose of this is to stimulate the development of more efficient ships. To do this the report presents some systematic data of CO₂ emission calculations for different ship types and gives some general background information and historical data about propulsion of ships, and fuel consumption of diesel engines.

The paper also highlights the most important parameters, which have an influence on the technical CO₂ index.

The results can be summarized as follows:

1. An alternative technical CO₂ index, which does not depend on operational measures, but on technical data obtainable at the delivery of the vessel, has been formulated.
2. Even without regulation of CO₂ emission from shipping the high fuel costs have provided a strong market driven pressure to develop engines operating almost as fuel efficient as physically possible, taking into account the trade off associated with the regulation of NO_x. The overall ship efficiency has also increased during the period from 1924 to 2006. This tendency is not so pronounced in the period from 1950 to the first oil crisis in 1973 because of relatively higher service speeds motivated by the low fuel prices at that time. The fuel prices provide a strong market drive towards increased efficiency because the fuel cost is a large proportion of the total cost associated with ship operation.
3. To provide an incentive for all ships to further improve their efficiency an individual CO₂ index has to be worked out for each ship type (container ships, bulk carriers, tankers, Ro-Ro cargo ships and Ro-Ro passenger ships).
4. The CO₂ emission is strongly dependant on the ship size and service speed. An attempt has been made to combine these parameters using the ships so-called Froude Number as a single non-dimensional parameter. However in doing so, it has become evident that large cargo ships such as container ships, bulk carriers and tankers will be favoured and loose incentive to improve because they obtain a lower CO₂ index more easily than the smaller cargo ships of the same type with low transport capacity. The dependency of the CO₂ index on deadweight should therefore be more pronounced.

2. Introduction

IMO Assembly Resolution A.963(23) on "IMO Policies and Practices Related to the Reduction of Greenhouse Gas Emissions from Ships" urged the Marine Environment Protection Committee (MEPC) to identify and develop mechanisms needed to achieve limitation or reduction of Greenhouse Gas (GHG) emissions from international shipping and, in doing so, to give priority to the establishment of a GHG baseline, and the development of a methodology to describe the GHG efficiency of a ship in terms of a GHG emission index. In developing the methodology for the GHG emission indexing scheme, the Committee should recognize that CO₂ is the main greenhouse gas emitted by ships.

As urged by the Assembly, MEPC 53 approved Interim Guidelines for Voluntary Ship CO₂ Emission Indexing for Use in Trials described in document MEPC/Circ.471. It was decided to update the Interim Guidelines at a later stage, taking into account operational experiences from trials of the

index for different ship types, as reported to MEPC by industry, organizations and Administrations, progress in ISO regarding ships' CO₂ performance, and any other relevant developments.

The interim guidelines presents the concept of an index for the energy efficiency of a ship in operation expressed in way of CO₂ emitted per unit of transport work. The index represents the efficiency of ship operation over a longer period of time and is based on recordings of the actual amount and type of fuel consumed, the actual distance travelled and the actual amount and type of cargo carried. The index will in this way depend on both technical and operational aspects, and it will require a huge amount of data collection, reporting, verification, processing and filing.

3. Objective

The objective of this paper is to provide a rational basis for the formulation of an alternative technical CO₂ index, which do not depend on operational measures. The purpose of this is to stimulate the development of more efficient engines and ships. To do this the paper presents some systematic data of CO₂ emission calculations for different ship types and gives some general background information and historical data about propulsion of ships, fuel consumption of diesel engines. The paper also highlights the most important parameters, which have an influence on the technical CO₂ index.

Focusing on various stakeholders, who have an influence on emissions, potential reductions can be divided in technical measures, which are in the hands of the engine manufacturer, the yard or the designer, and operational measures, which are in the hands of the ship operator. Technical measures include use of non-fossil fuels as well as further optimization of engines, hull and propeller. Operational measures include better utilization of cargo capacity, less time spent in port, better voyage planning to strike the right balance between the time spent underway and fuel consumption, and better linkage to the shore based part of the transport chain.

Drawing an obvious parallel to the car industry, the technical measures are clearly in the hands of the car manufacturer. The manufacturer can optimize the design for better fuel economy, test it under certain standardized conditions, label it and use this information to increase his sales. Only because technical and operational measures are separated, the consumer is able to compare the standardized fuel economy of various cars, when making a choice, and regulators are in a position to set minimum standards. Operational measures are in the hands of the consumer and stimulated by other means. Just imagine the enforcement problems and the bureaucracy involved, if everybody had to report fuel economy for every trip they made in their car.

4. Formulation of a technical CO₂ index

The car industry often refers to the CO₂ index for cars expressed as the CO₂ emission per km under some clearly defined conditions, as example at a constant speed of 90 km/hours. The same principle is suggested to be used for ships to stimulate development of more efficient engines and ships.

The technical CO₂ index is defined as:

CO₂ index = $m_{CO_2} / (\text{transport work})$, where

m_{CO_2} is the emission of CO₂ measured in gram per hour

transport work is the payload at design draught and trim measured in tonnes multiplied with the normal service speed at 85 % MCR measured in km per hour.

With the above mentioned definition it will be possible to compare the performance of different ships in a fair manner. In fact it would also be possible to compare with other modes of transport to identify the more efficient of a range of possible transport solutions.

In order to compare the CO₂ emission from ships, it is very important to state which reference is used when calculating the CO₂ emission per tonne kilometre, as different possibilities exist. Objectively the most correct weight reference is the payload of the ship, i.e. the weight of the actual cargo transported, but seen from a practical point of view; the payload is not very often published in connection with normal technical data for ships. A much more commonly used weight reference is the deadweight, which include both the payload but also the weight of consumerables (fuel oil, lub. oil and fresh water) plus the weight of necessary ballast water, spare parts, stores etc. When comparisons of CO₂ efficiency/index for different ship types shall be made at this preliminary stage, the deadweight is an acceptable weight reference, because this information is normally available for most ships. It is therefore technically the most convenient unit to deal with of which reason it will be used in most of the investigations presented in the following. But for an international final agreed CO₂ index, it is suggested to consider the use of payload as weight reference (as in figs. 12 to 14)

5. Historical development of the efficiency of marine diesel engines

As CO₂ emissions are directly proportional to the amount of fuel used for propulsion and for generation of electric power onboard, one of the key factors towards lower CO₂ emissions is to make the propulsion machinery more efficient. As diesel engines are the absolutely most dominating prime movers in ship propulsion it will be most relevant to look at the development of efficiency of diesel engines from the first time they were used for ship propulsion.

The efficiency of diesel engines has constantly grown since the first maritime diesel engine was introduced on an ocean-going merchant ship, SELANDIA in 1912. The improvement is shown in Fig. 1, showing the specific fuel oil consumption for two stroke engines based on actual data for MAN B&W engines during the years from 1912 until 2007.

As can be seen, the oil crisis in 1973 had a pronounced influence on the specific oil consumption which improved at a higher rate after 1973 down to approximately 170 g/kW/hour in 2000, when the new NO_x regulations MARPOL Annex VI entered into force. These regulations stopped the steady decrease of the fuel oil consumption quite distinctly, because the NO_x reducing measures had the general influence that they counteracted possible fuel oil savings. The steadily improved engine efficiency is thus counteracted by the negative influence from NO_x reducing initiatives, such that nearly constant specific fuel oil consumption has been observed since 2000.

However it is possible to decrease the specific fuel oil consumption even more than the general trend since 1973 by de-rating of the diesel-engines, which means that the engine is operated at its normal maximum cylinder pressure for the design continuous service rating, but at a lower mean effective pressure and shaft speed. According to information from MAN Diesel this feature has not yet found favourable – probably because these engines are more expensive and heavier. The specific oil consumption for de-rated two-stroke engines is also shown in Fig. 1.

For medium speed engines (400 – 1200 RPM) a similar tendency with respect to improved engine efficiency has been observed, however with a slightly higher specific fuel oil consumption of approximately 190 g/kW/hour in 2000.

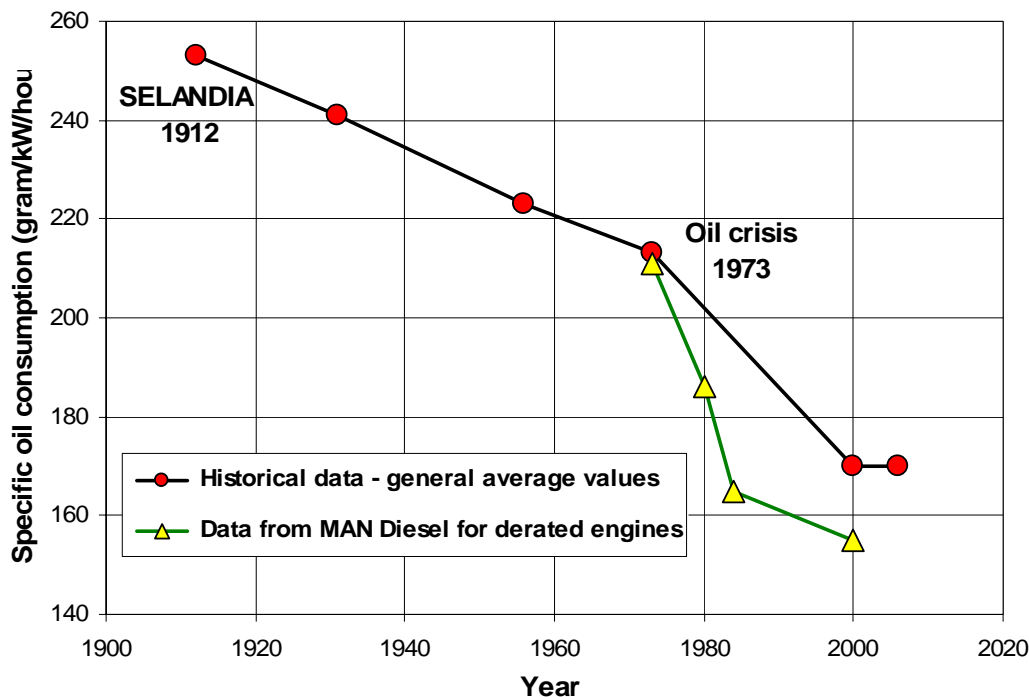


Fig. 1 General development of specific fuel oil consumption for 2-stroke diesel engines

From this historical analysis of the development of diesel engine efficiency it is concluded that without regulation of CO₂ emission from shipping, the high fuel prices have provided a strong market driven pressure to develop engines operating almost as fuel efficient as physically possible, taking into account the trade off associated with the regulation of NO_x.

6. The historical development of CO₂ index for ships

It might be interesting to look at the historic development of the CO₂ index for ships, because this is also the way to some basic considerations about the development of a CO₂ index. This will be done by looking at the development of the energy effectiveness of conventional cargo ships during the last 80 years. In that period these ships and the engine technology (diesel engines) has been under constant development in a transition period where container ships have nearly out ruled the general cargo ships.

Therefore a data survey has been carried out. For 212 ships built in the period from 1924 to 2006 data have been collected and analysed. The data has been taken from historical books about different shipping companies (Refs. 1 – 5) but also extensive use technical journals have been used, such as *Significant Ships* published by RINA, *Schiff und Hafen*, *HANSA*, *The Motor Ship* etc.

Only general cargo/container ships powered by diesel engines have been included in this historical study in order to get a homogeneous sample of ships. The reason for taking the data from different technical magazines (mainly *Significant Ships*) instead of using large ship data bases such as Lloyds

Register and/or Fairplay, is that some of the more technical details about the ships are only included in these magazines and not in the Lloyds Register and Fairplay data bases. Especially for the container ships from the period from 1992 to 2006 it is valuable to have more detailed data, as the trend in technical development within the last 15 years is important when a new proposal for a CO₂ index shall be discussed.

For all the ships the engine power, the deadweight and the service speed is known and additionally the oil consumption is available for some of the ships. Knowing the power, the building year, the deadweight, the service speed and the approximate specific fuel oil consumption determined from Fig. 1 it is possible to calculate the CO₂ emission per ton deadweight per kilometre assuming an engine loading of 85 % of the maximum continuous rating (MCR).

The average auxiliary power used at sea is assumed to be 10 % of the maximum installed main engine power. This assumption is based on a separate statistical analysis, but it seems to be a quite good assumption for general cargo ships and container ships.

These two assumptions about the main engine rating and the auxiliary power rating and the assumptions about specific fuel oil consumption (based on building year) are the greatest uncertainties. However as the total oil consumption per 24 hours is available for some of the ships, it has been possible to check the assumptions and this is done in Fig. 2 where the actual oil consumption compared with the calculated oil consumption used in the present analysis is shown for the ships where the oil consumption MCR data were available. Based on this comparison it is seen that the main engine loading of 85 % MCR and the auxiliary rating corresponding to 10 % MCR is quite reasonable of which reason these assumptions about engine loading have been assumed for all the analysed ships (Fig. 3)

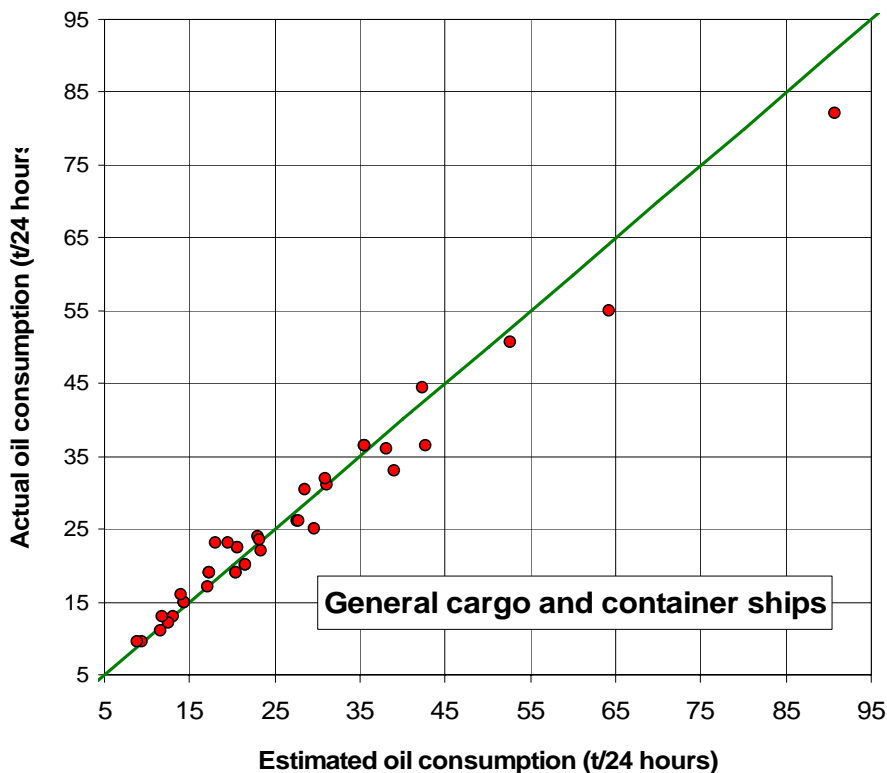


Fig. 2 Comparison of actual oil consumption and estimated oil consumption for the historic data sample based on an assumed engine loading of 85 % MCR and using the specific oil consumption shown in Fig. 1

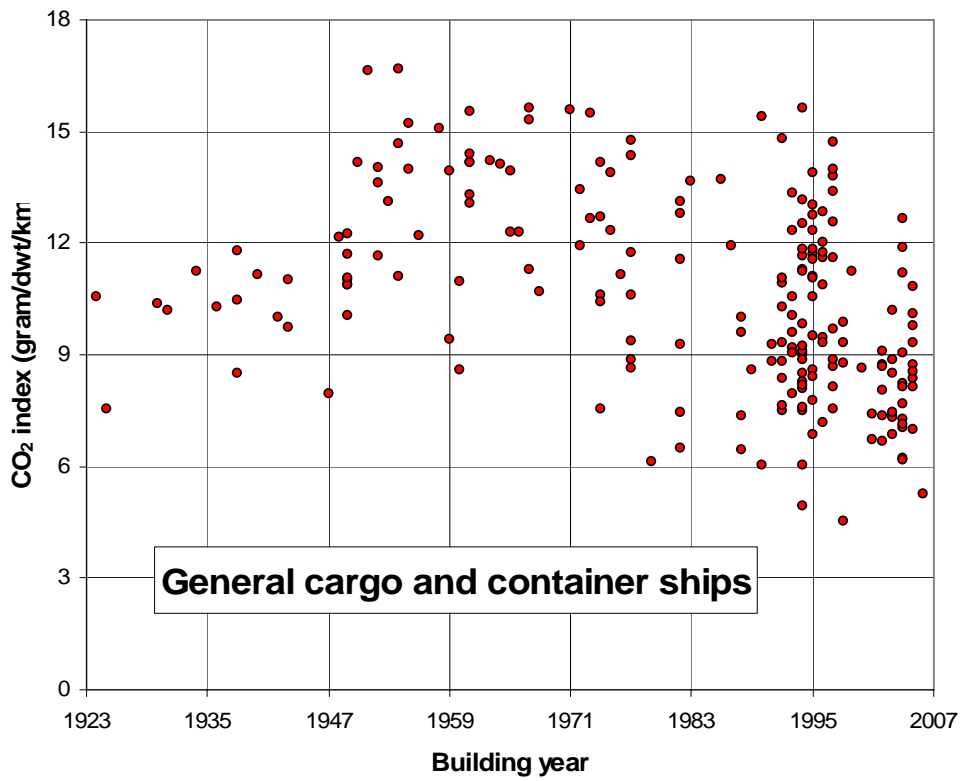


Fig. 3 CO₂ index for general cargo and container ships from the period 1924 – 2006

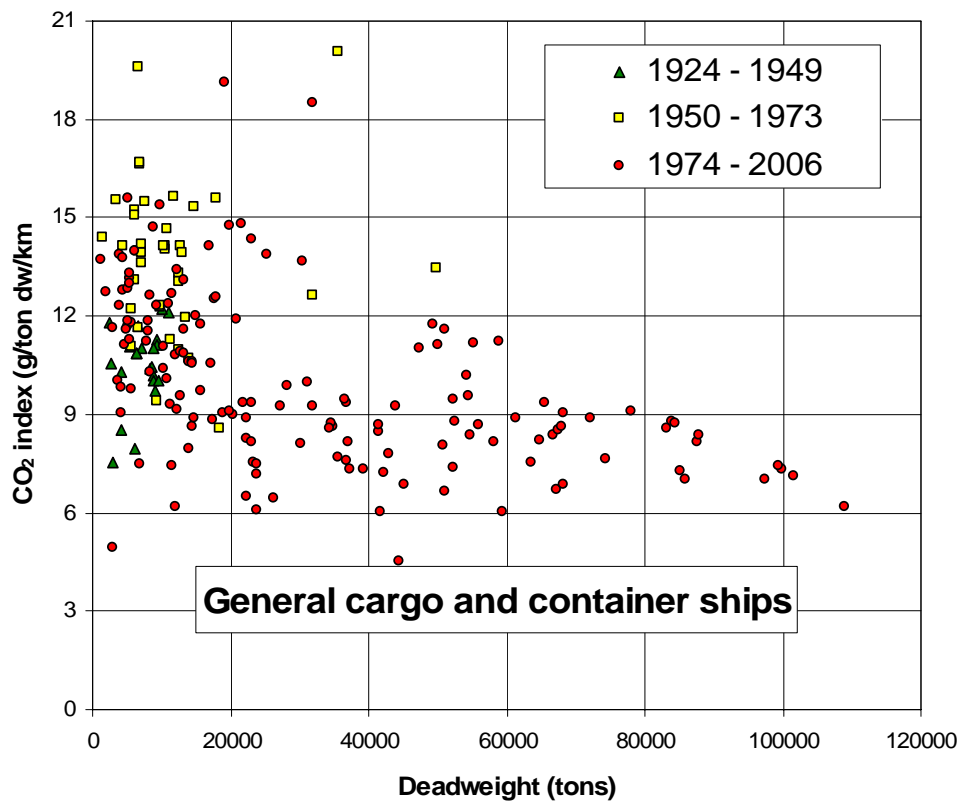


Fig. 4 CO₂ index for general cargo and container ships from the period 1924 – 2006

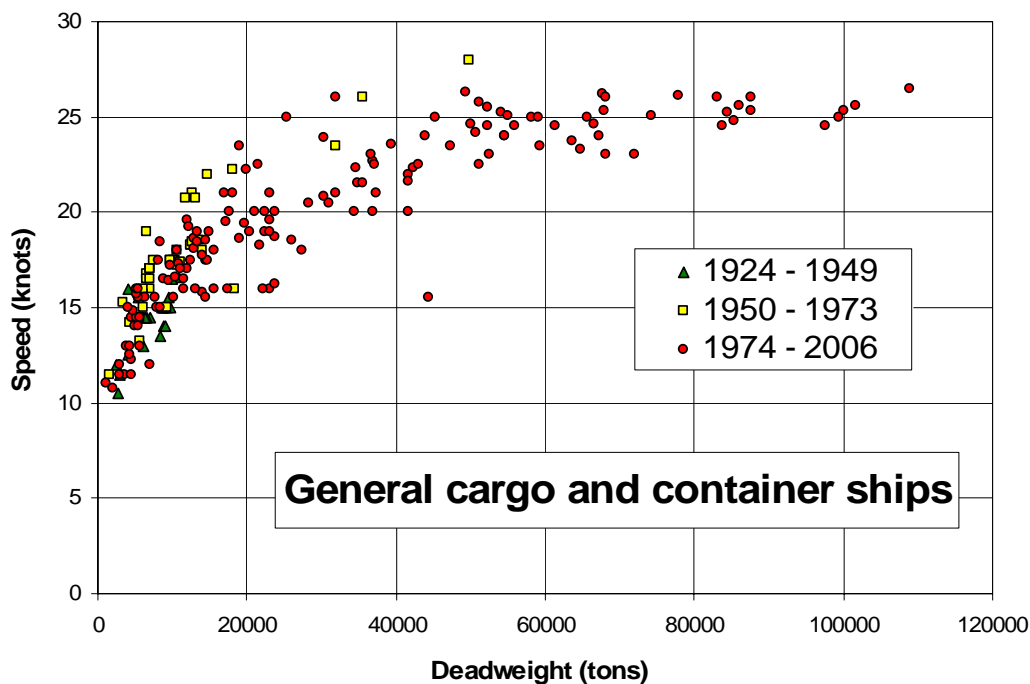


Fig. 5 Service speed as function of deadweight and building year

7. Conclusions about the historical development of the CO₂ index

The CO₂ indices shown in Fig. 3 show a relative large scatter. However it seems clear that the index has decreased in the period from the first oil crisis in 1973 to 2007. In the period from 1950 to the first oil crisis in 1973, the CO₂ index is in the upper range of indices which can be seen from Fig. 4. The reason for that increase of CO₂ index in the 50's and 60's can be explained by a relatively higher service speed (approximately 10 % increase compared to the cargo ships built before and after that period) as shown in Fig. 5.

Another interesting trend in the calculated CO₂ index is shown in Fig. 4, which clearly indicates that the index is strongly dependant on the ships deadweight, such that the index decreases with increasing deadweight. In order to get a more fundamental understanding/explanation of this development some basic facts about propulsion of ships will shortly be introduced, because this fundamental understanding is the key to be able to determine a rational target value for a new CO₂ index for different ship types.

8. Different payload on weight intensive or volume intensive ship types

It is a well known fact that shipping generally produces less CO₂ per tonne kilometre than any other form of transportation. However, the emission of CO₂ per tonne kilometre depends very much on the ship type, as some ships carry very much cargo at moderate speed (such as tankers and bulk carriers) while other ships carry a relatively low amount of cargo, in relation to the weight, but not necessarily in relation to the volume of the cargo (such as Ro-Ro ferries). Often these ships sail at a relatively high speed which also increases the CO₂ index.

In Fig. 6 is shown the typical approximate average payload (cargo weight) as function of the ship length for different ship types. The figure clearly illustrates the variation in cargo intensity for the 4 different ship types.

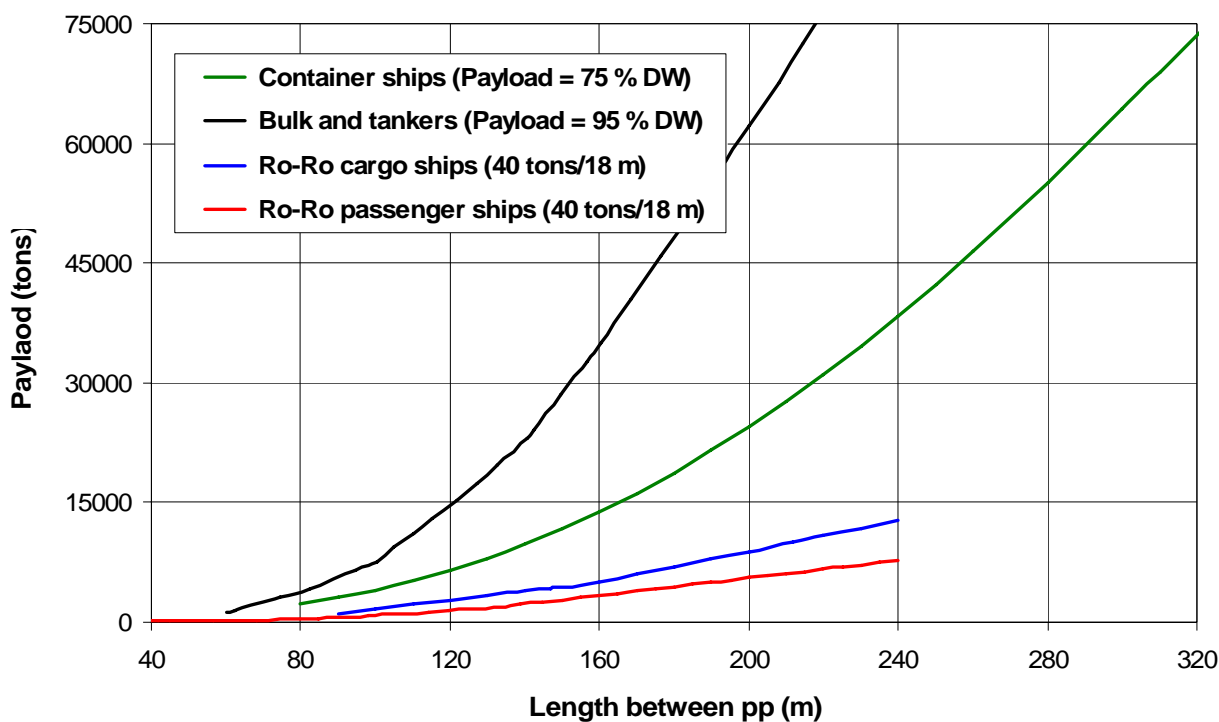


Fig. 6 Cargo weight i.e. payload as function of the ship length for different ship types (DW = deadweight which is the sum of payload, ballast water, fuel oil, lubrication oil, fresh water and other consumerables).

Table 1 CO₂ index for container ships calculated by a systematic computer model (Kristensen)

Capacity TEU's	Service speed (knots)	Deadweight (tons)	CO ₂ index (g/dwt/km)
1000	18,2	13699	11,7
2000	21,0	26725	10,5
3000	22,6	39104	9,4
4000	23,6	51282	9
5000	24,4	62500	8,9
6000	24,9	73182	8,6
7000	25,3	83333	8,2
8000	25,5	93023	7,9
9000	25,7	101315	7,5
10000	25,8	109925	7,2

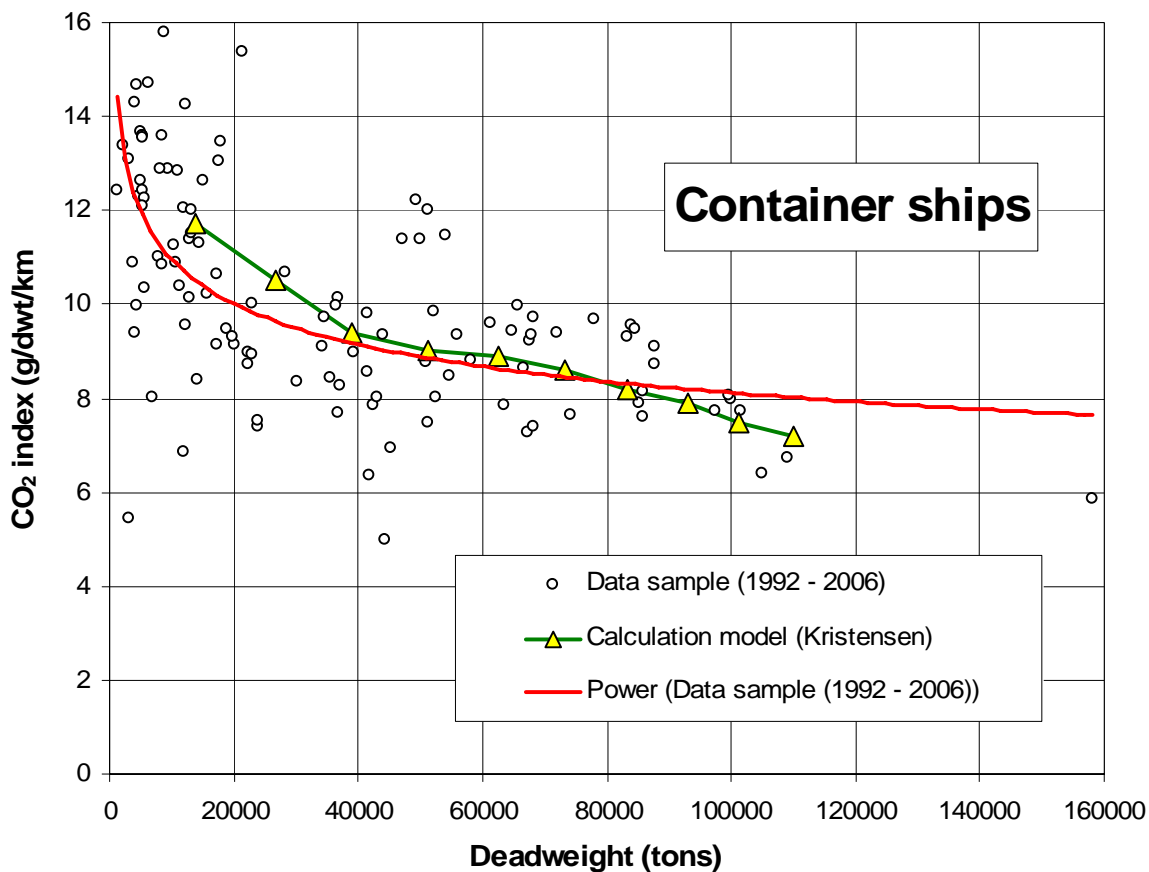


Fig. 8 CO₂ index for container ships built from 1992 to 2006, compared with systematic calculated CO₂ indices from a computer model (Kristensen). A curve fit of the data points is also shown in the diagram, but this curve is not well defined due to lack of ships above 120.000 tons deadweight.

Table 2 CO₂ index for bulk carriers calculated by a systematic computer model (Kristensen)

Payload (tons)	Service speed (knots)	Deadweight (tons)	CO ₂ index (g/dwt/km)
10000	12,9	10526	8,7
20000	13,6	21053	6,0
40000	14,2	42105	4,0
60000	14,7	63158	3,0
80000	15,0	84211	2,5
100000	15,2	105263	2,3
120000	15,3	126316	2,2
140000	15,4	147368	2,1
160000	15,5	168421	2,0
180000	15,6	189474	1,9
200000	15,8	210526	1,8

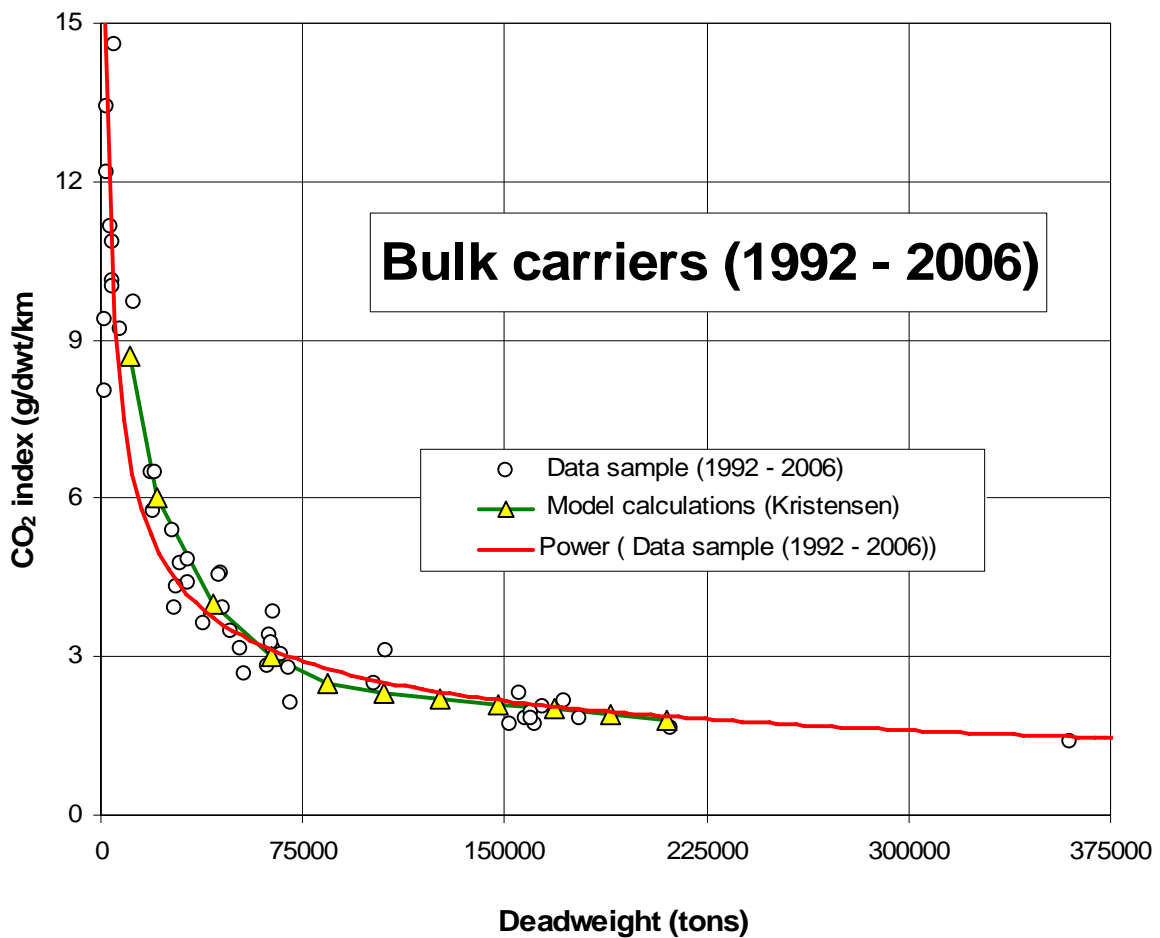


Fig. 9 CO₂ index for bulk carriers built from 1992 to 1998, compared with systematic calculated CO₂ indices from a computer model (Kristensen)

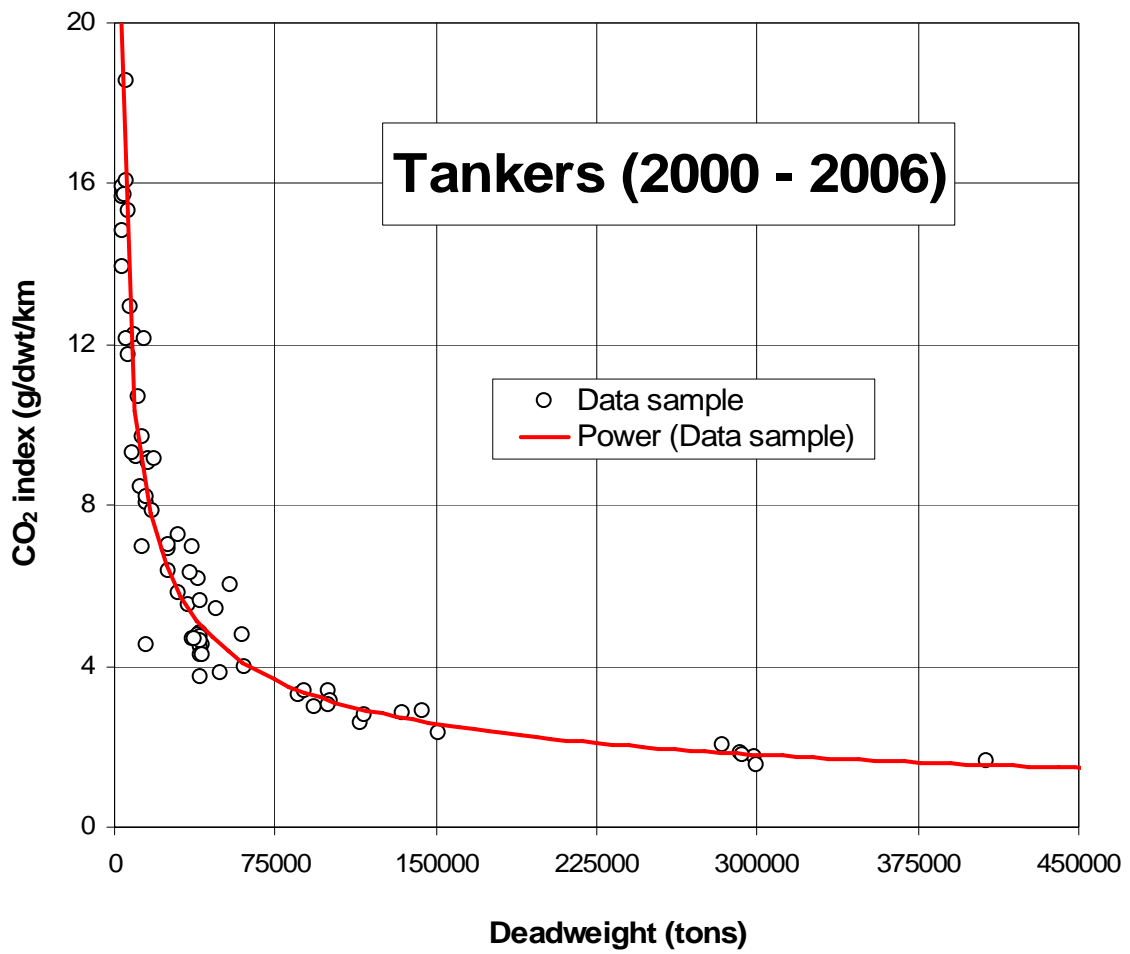


Fig. 10 CO₂ index for tankers built from 2000 to 2006

Table 3 CO₂ index for Ro-Ro cargo ships calculated by a systematic computer model (Kristensen)

Lanemetres (m)	Service speed (knots)	Deadweight (tons)	CO ₂ index (g/dwt/km)
1000	15,7	4469	19,6
2000	18,5	8938	20,8
3000	20,4	13406	21,3
4000	22,0	17875	21,9
5000	23,6	22344	22,6

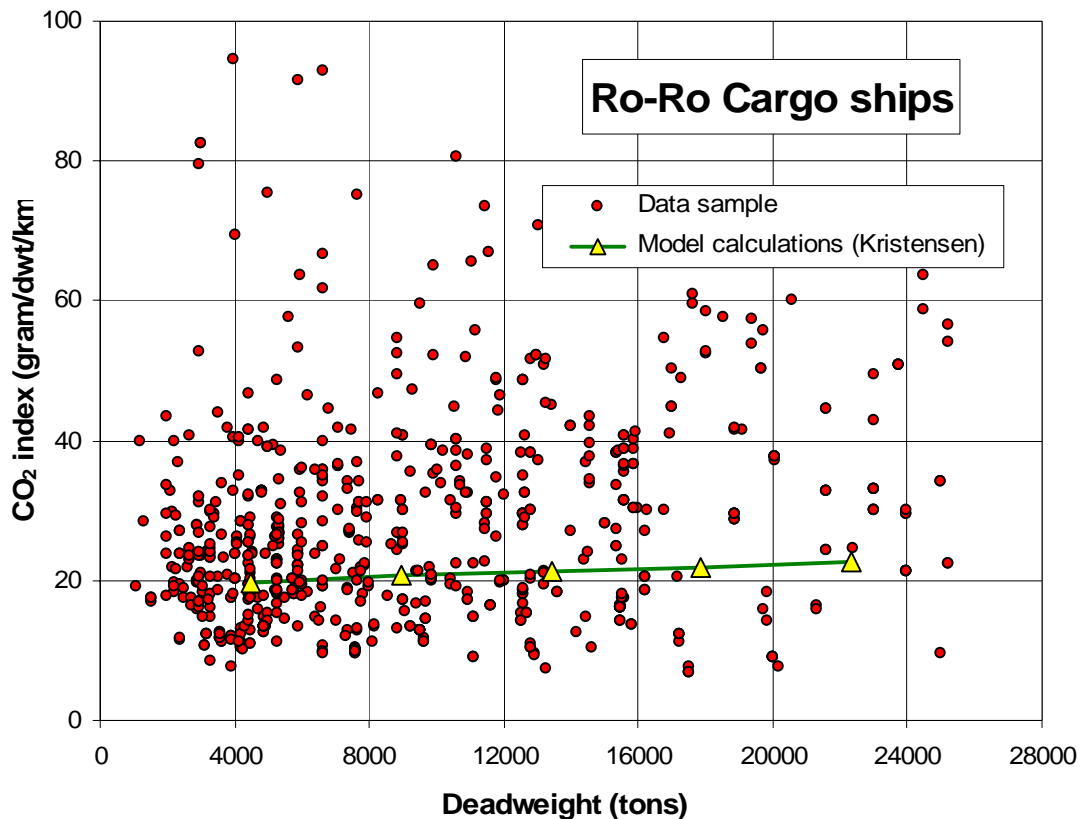


Fig. 11 CO₂ index for Ro-Ro cargo ships, compared with systematic calculated CO₂ indices from a computer model (Kristensen)

From this analysis it is concluded that the CO₂ index is strongly dependent on ship size.

11. Model calculations of CO₂ index versus deadweight and speed

With the systematic computer model previously mentioned, systematic calculations of the CO₂ index according to the proposed definition have been carried out, and the results of these model calculations are shown in Figs. 12 – 14. The calculations have been carried out to study the influence of ship size and speed on the CO₂ index, two parameters which need to be taken into account in the ongoing discussions of the CO₂ independently of which definition is finally accepted by the industry/IMO.

Except for Ro-Ro cargo ships it is seen that the CO₂ index decreases with increasing ship size for normal service speed as also found from historical investigation already described. The reason why Ro-Ro cargo ships do not show the same behaviour is that their service speed increases with a relatively higher rate (0.03 – 0.04 knots per 1 % cargo capacity increase) than for container ships (0.015 – 0.025 knots per 1 % cargo capacity increase) and bulk carriers (0.005 – 0.007 knots per 1 % cargo capacity increase).

Because of the relatively high service speed for Ro-Ro cargo ships, the CO₂ index is nearly constant irrespectively of the ship size. The service speed for app. 700 Ro-Ro cargo ships (Ref. 11) are shown in Fig. 15, from which the relation between capacity (in lane metres) and the service speed has been deducted.

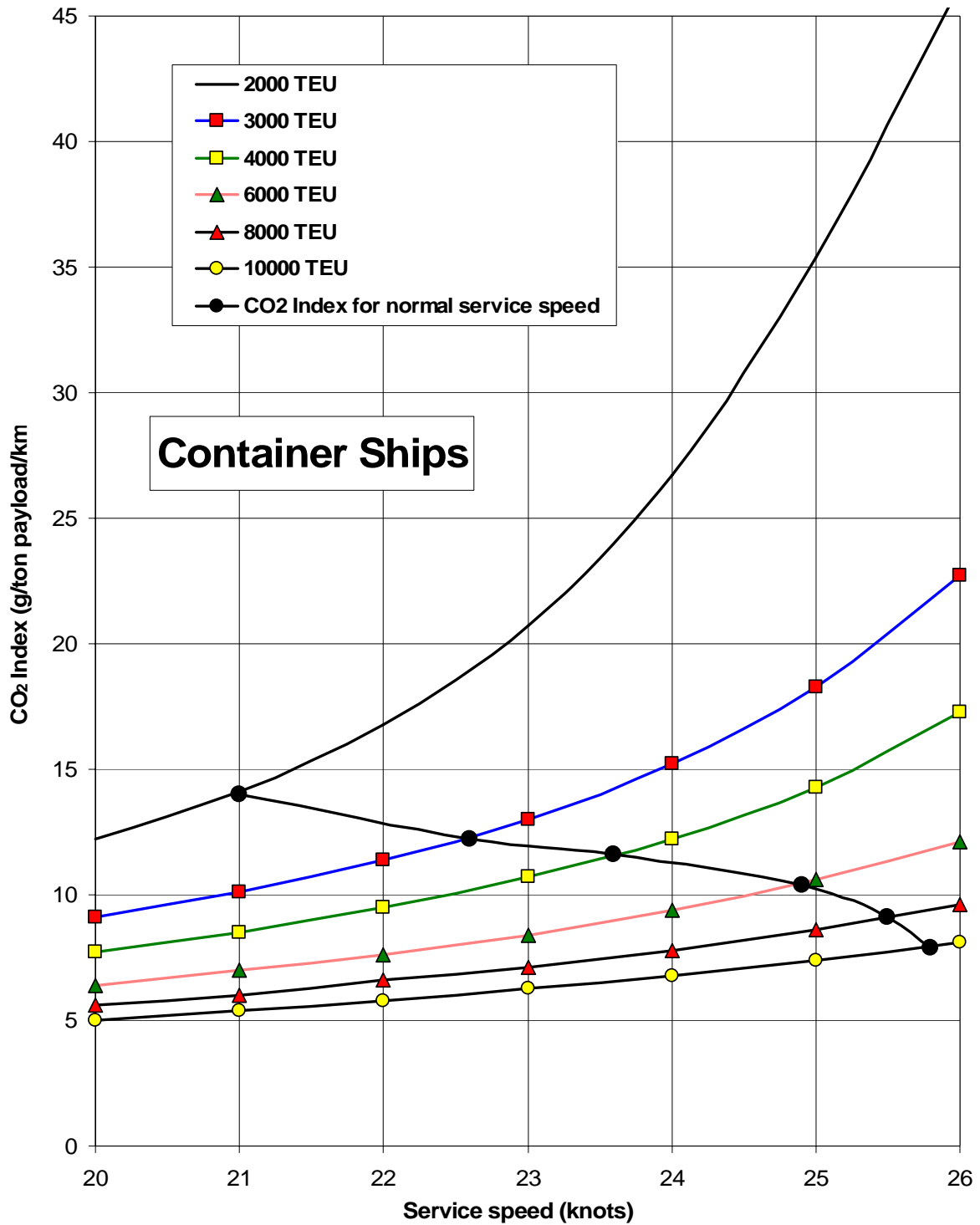


Fig. 12 Calculated average CO₂ index for container ships at full load (100 % utilisation)

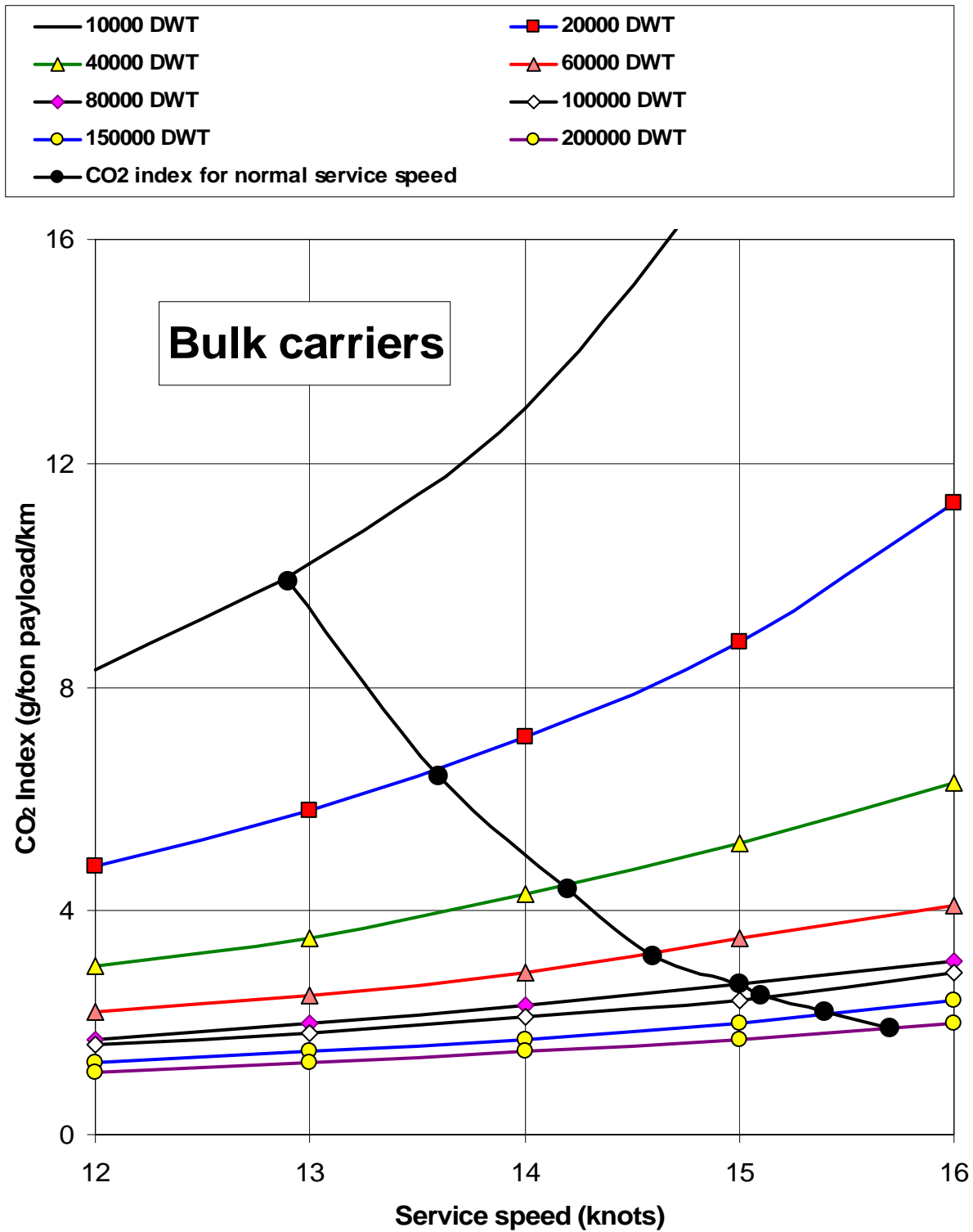


Fig. 13 Calculated average CO₂ index for bulk carriers at full load (100 % utilisation)

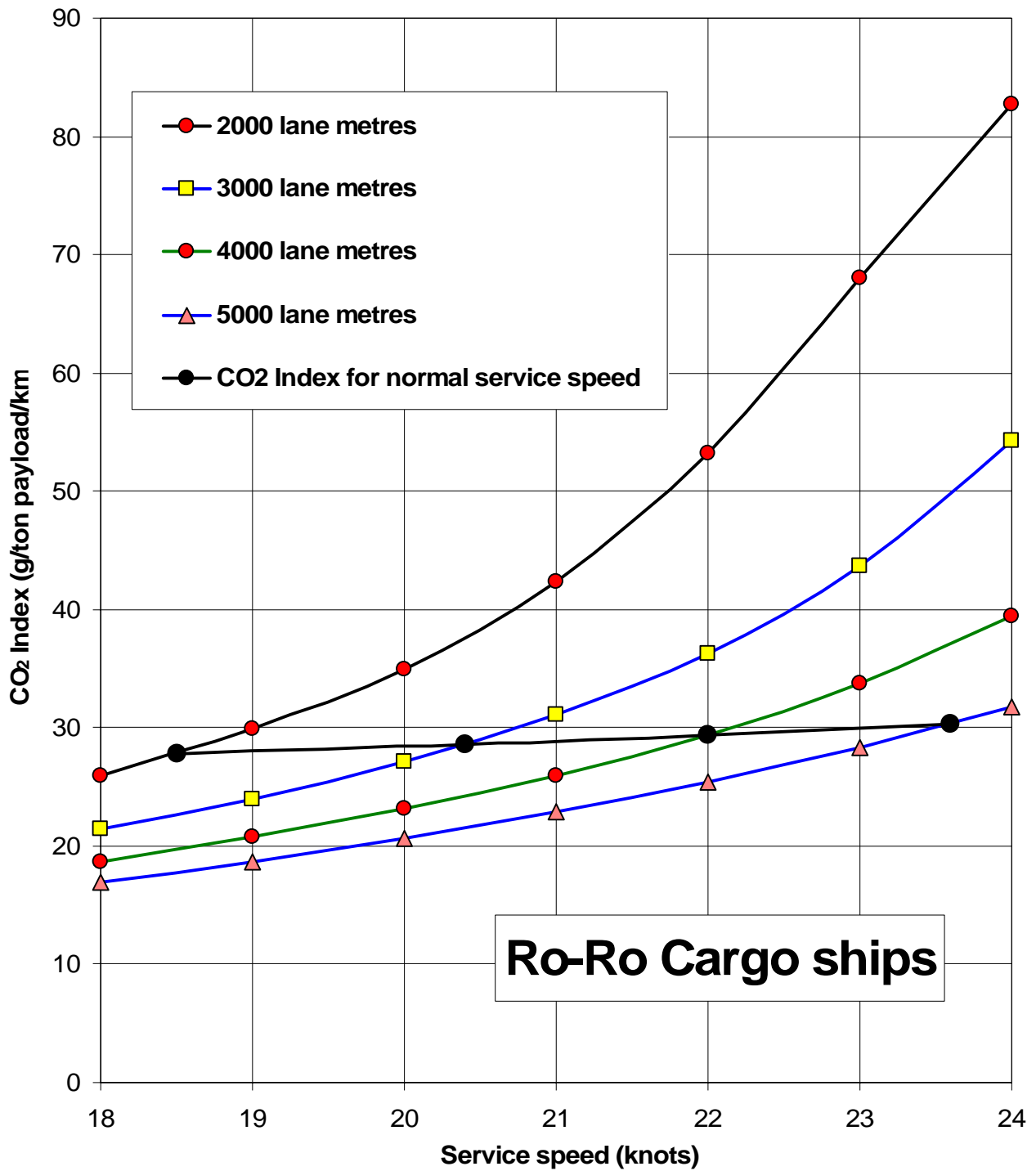


Fig. 14 Calculated average CO₂ index for Ro-Ro cargo ships at full load (100 % utilisation)

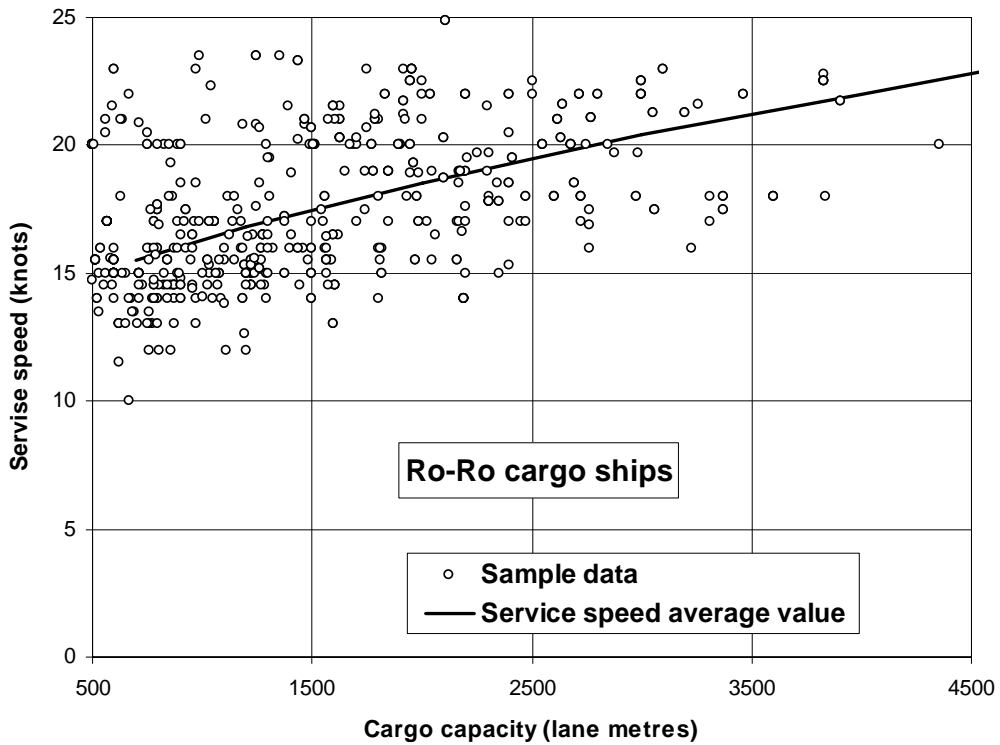


Fig. 15 Service speed for Ro-Ro cargo ships (from ShipPax database, Ref. 11)

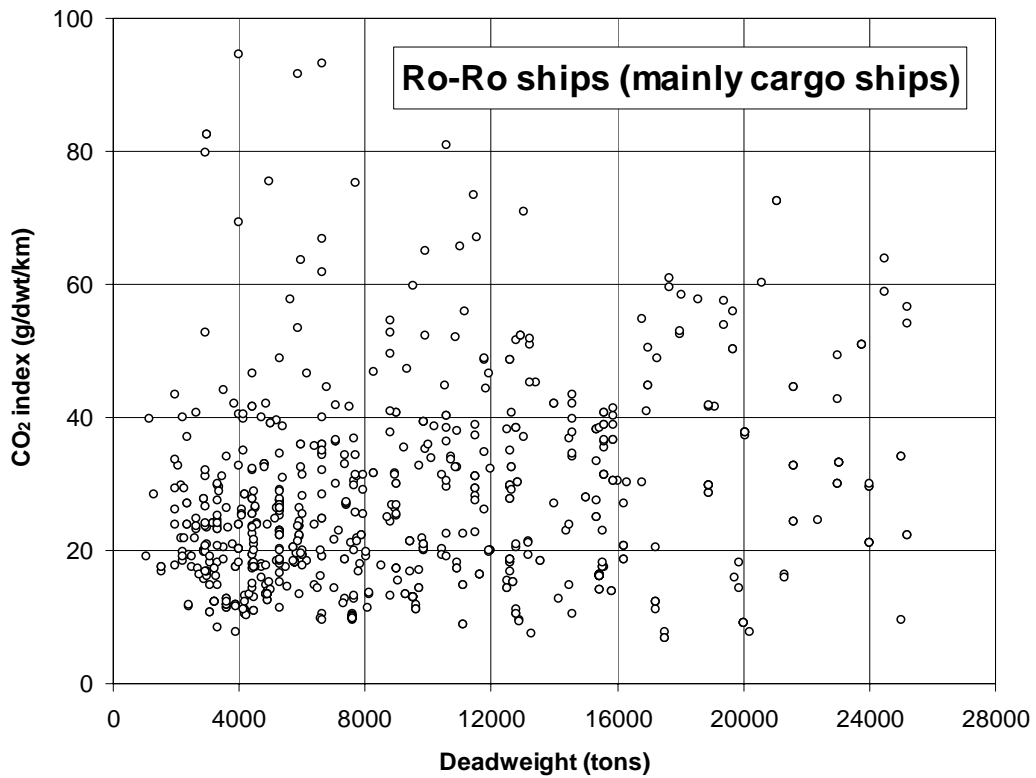


Fig. 16 CO₂ index (based on deadweight) for Ro-Ro cargo ships (from ShipPax database, Ref. 11)

From this analysis it is concluded that the CO₂ index is also strongly dependent on ship speed.

12. CO₂ index for Ro-Ro ships

As shown in Fig. 16 the scatter of the calculated CO₂ index is quite large for Ro-Ro cargo ships, which is due to the pronounced scatter of service speed (Fig. 15) but also due to the individuality of these ships. This tendency becomes even more pronounced for Ro-Ro passenger ships, i.e. conventional ferries as shown in Fig. 17.

Because of the large scatter in deadweight as function of the ship length for this ship type and due to large variation of the general lay-out of these ships, where some of the ships are large so-called cruise ferries with a huge passenger accommodation where others are only ferries for short domestic routes with a minimum amount of passenger facilities it will probably be better to use the volume of the ships as the transport unit for calculation of the CO₂ index, and therefore treat this ship type as “volume carriers”.

As the gross tonnage (GT) is a clear indicator of the passenger volume, Fig. 18 has been prepared where CO₂ emission per GT per km is shown as function of the ship size expressed in GT. This attempt seems more meaningful and it reduces the scatter considerably although there is still some scatter, which is still due to the large variation of the service speed.

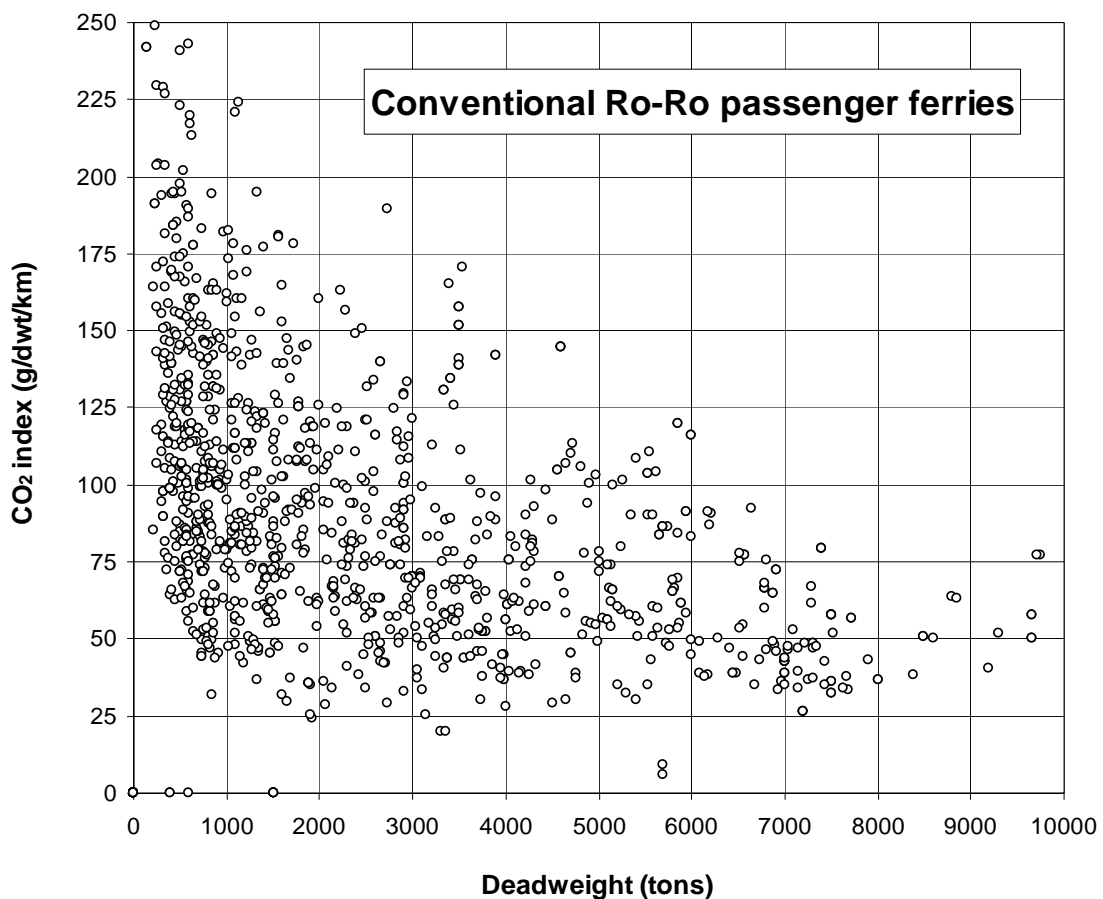


Fig. 17 CO₂ index (based on deadweight) for conventional Ro-Ro passenger ships (from ShipPax database, Ref. 11)

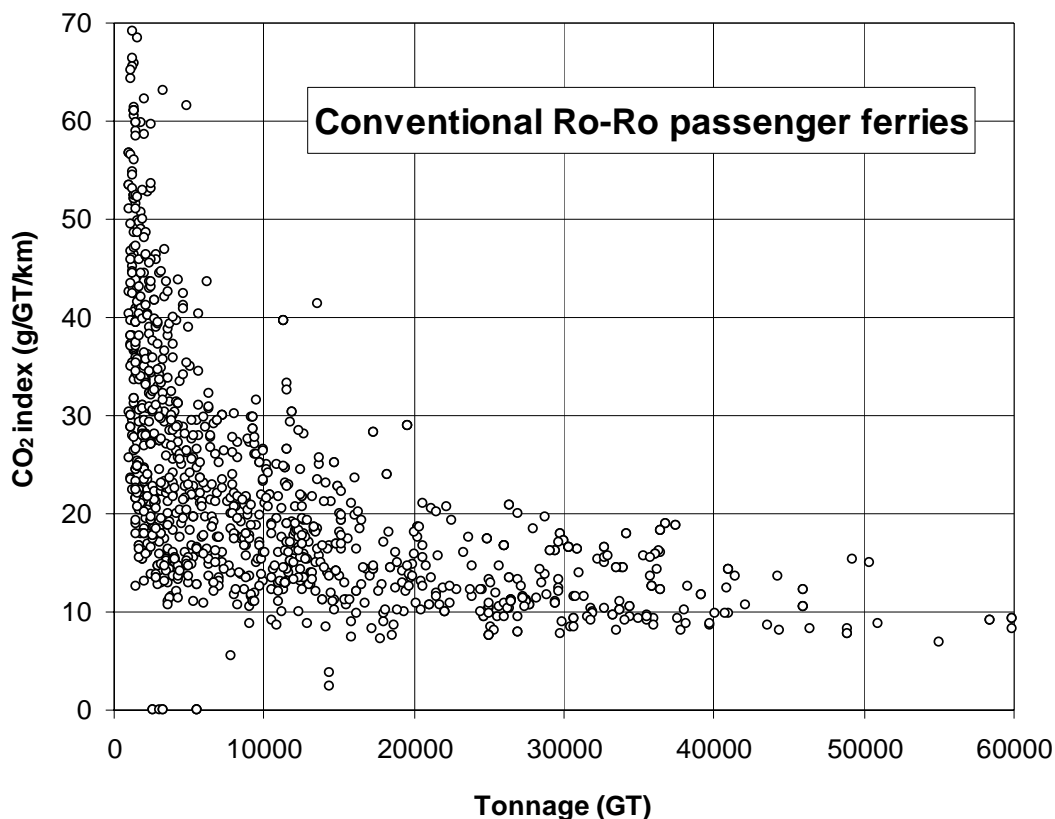


Fig. 18 CO₂ index (based on gross tonnage GT) for conventional Ro-Ro passenger ships (from ShipPax database, Ref. 11)

13. An attempt to combine the main parameters influencing the CO₂ index into a single parameter

The resistance of a ship depends on many factors but three non dimensional parameters are very important, namely following:

- 1) The Froude Number, $F_n = V/(g \times Lwl)^{1/2}$
- 2) The block coefficient, $C_b = Volume/Lwl/B/T$
- 3) The length displacement ratio = $Lwl/Volume^{1/3}$, where

V	=	ship speed in m/s
Lwl	=	waterline length in m
B	=	breadth in m
T	=	draught in m
Volume	=	displacement volume in m ³
g	=	gravitational constant (9.81 m/s ²)

These three factors will be discussed and illustrated in the following in relation to the CO₂ index calculations.

The Froude Number

Generally the resistance increases with increasing Froude Number, and above a certain limit the increase becomes very steep (this limit is often called "the critical Froude Number"). It can be shown that the CO₂ index will show the same steep increase as the resistance. Normally the ships maximum speed or service speed is selected such that the corresponding Froude Number calculated on basis of that speed is less than the critical Froude Number.

The development of the Froude Number (based on the service speed) for container ships built since 1992 is shown in Fig. 19. The tendency curve in this figure shows that the Froude Number has a slightly decreasing tendency with larger ship length, which is one of the reasons for the falling CO₂ index with increasing deadweight.

Fig. 20 showing the CO₂ index as function of the Froude Number supports the statement that the resistance and therefore also the CO₂ index increases with increasing Froude Number. In this figure are also shown the results of systematic model calculations for 4 container ships of different size (500, 2000, 6000 and 10000 TEU) where the Froude Number has been systematically varied stepwise from 0.18 to 0.28.

A generic computer model has been used for the systematic calculations. The generic model is described in APPENDIX A to this paper and descriptions and results by using the model are found in Refs. 6 – 10.

The results of the systematic calculations - which in this connection can be regarded as average values - seem to have the same increasing tendency as the data sample, which supports the statement that the CO₂ index increases with increasing Froude Number, with a rate which is similar for the 4 container ships. It is seen that for a Froude Number above approximately 0.25 the CO₂ index curves becomes rather steep. That illustrates the comments made about the critical Froude Number. Therefore most container ships are not designed to sail at a Froude Number of much more than 0.25 as indicated in Fig. 19.

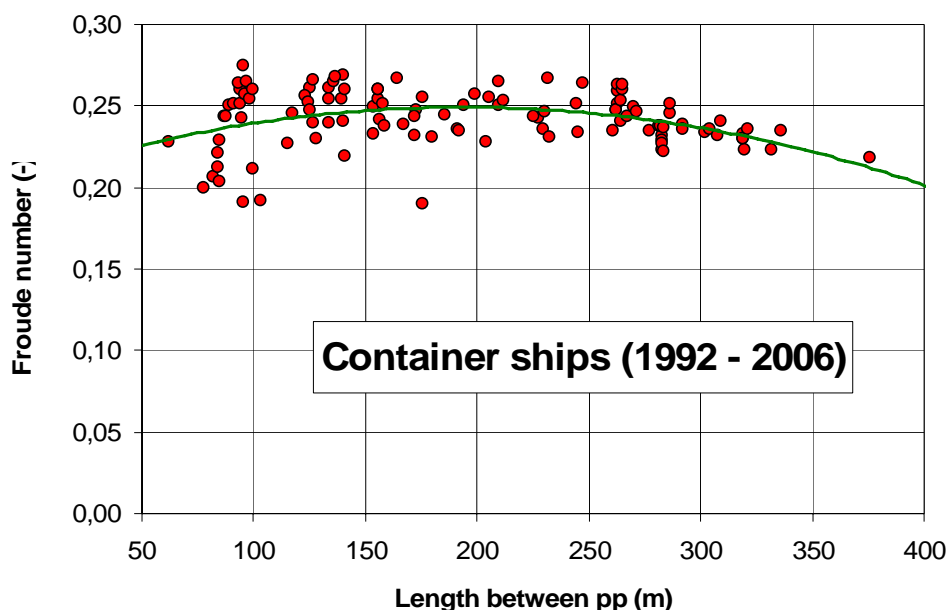


Fig. 19 Froude Number as function of the ship length for 115 container ships built from 1992 to 2006.

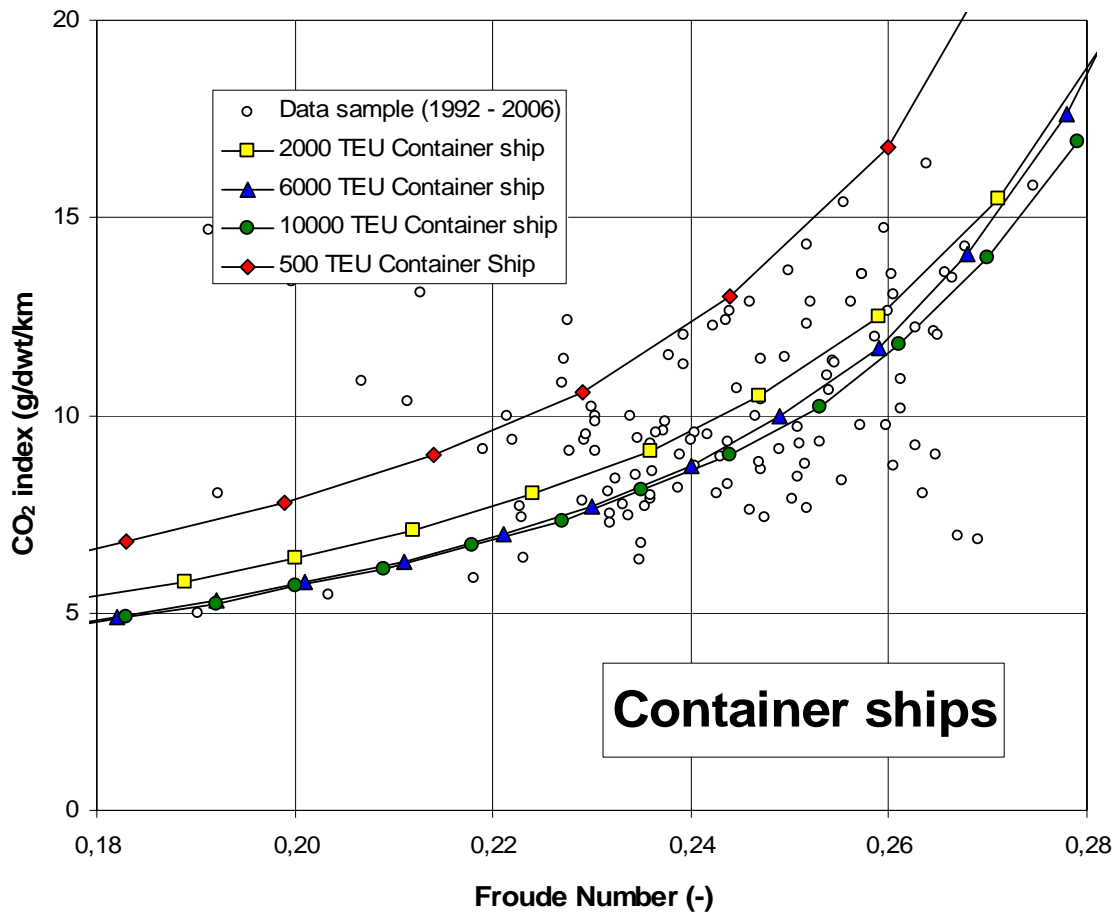


Fig. 20 CO₂ index as function of the Froude Number. The figure show results for 115 container ships built from 1992 to 2006 together with model calculations for 4 container ships sizes where the Froude Number has been systematically varied.

The block coefficient

The block coefficient has also a pronounced influence on the propulsion power and therefore on the CO₂ index. Statistical data for the block coefficient are shown in Fig. 21, which indicates that the block coefficient is large for small container ships ($L_{pp} < 150$ m), while it is nearly constant for container ships with a length of more than approximately 150 m (above 1000 TEU). Normally there is a clear relation between the block coefficient and the Froude Number (Fig. 22), such that for a given block coefficient it will not be advisable to sail faster than a certain Froude Number, as the power requirement will otherwise be very excessive. This is just another way to point out the problems about the critical Froude Number.

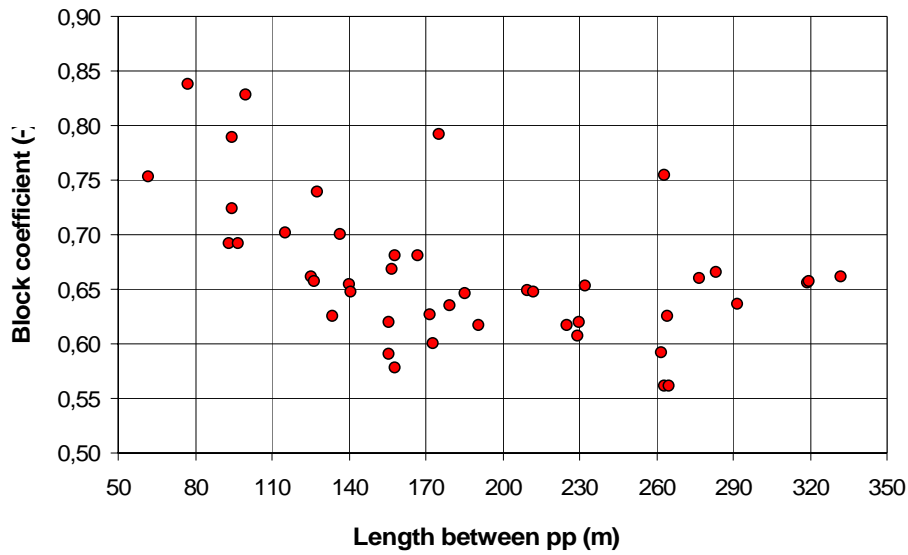


Fig. 21 Statistical data for the block coefficient for container ships built from 1992 to 2006

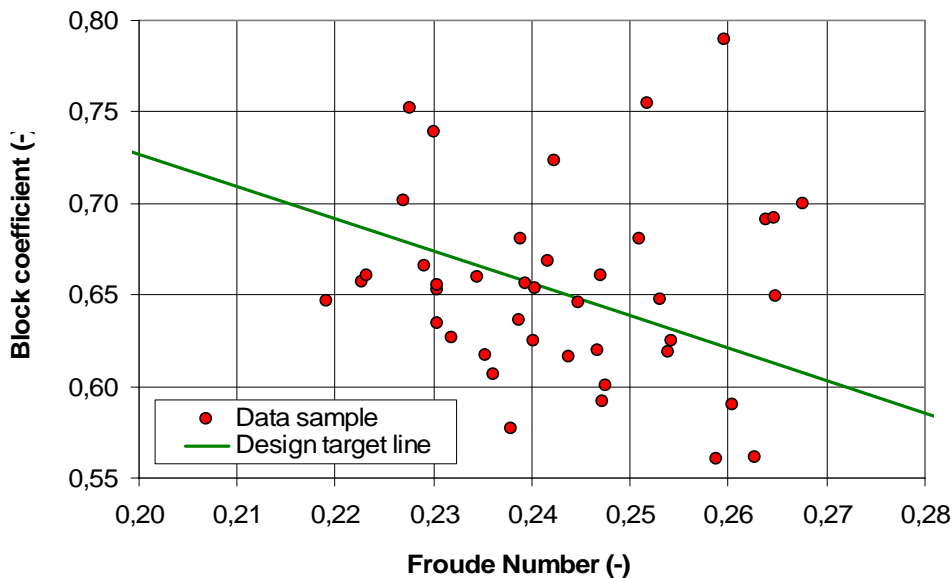


Figure 22 Relation between Froude Number and block coefficient for container ships built from 1992 to 2006. Also shown in the diagram is a design target line indicating the maximum advisable block coefficient for a given Froude Number

The influence of the block coefficient on the CO₂ index is illustrated in Fig. 23 where model calculations are shown for a 6000 TEU container ship, where the Froude Number has been systematically varied (identical to the curve in Fig. 20) and where the block coefficient has been systematically varied from 0.80 to 0.66 for a fixed Froude Number of 0.24. The block coefficient of 0.66 is typical for this size of container ships (Fig. 21 and 22).

Based on Fig. 23 it is very obvious that the CO₂ index increases with increasing block coefficient, which is also illustrated in Fig. 24, where some of the results from Fig. 23 (at fixed Froude number of 0.24) are plotted as function of the block coefficient.

Fig. 24 shows that the statistical block coefficient of 0.66 results in minimum CO₂ index, which of course is the reason why the block coefficient is on this level statistically for most container ships. The block coefficient 0.66 is also fully in line with the design target line in Fig. 22.

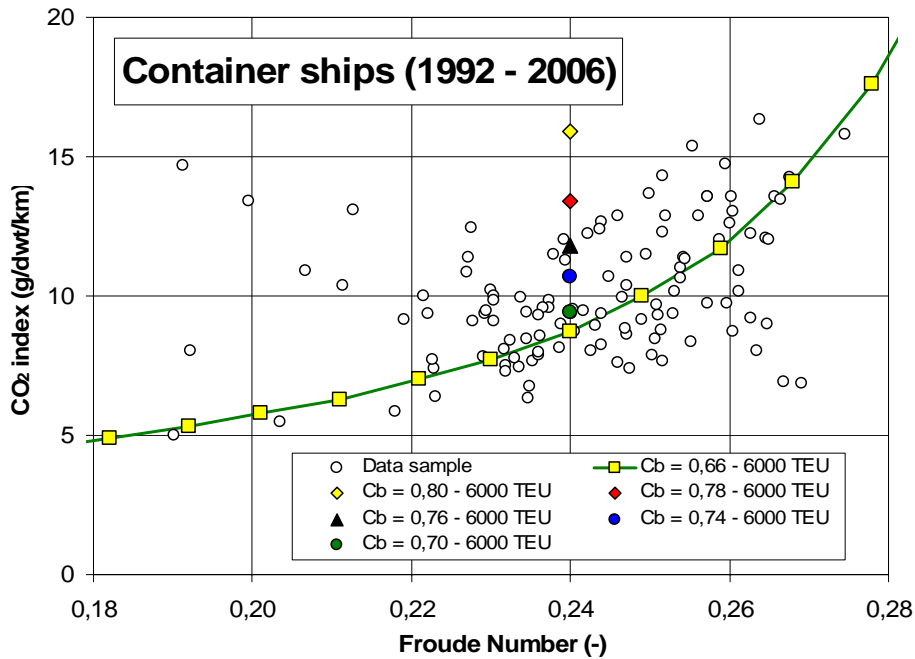


Fig. 23 The CO₂ index as function of the Froude number for the statistical sample of container ships built from 1992 to 2006 compared with model calculations for a 6000 TEU container ship with varying Froude Number and varying block coefficient.

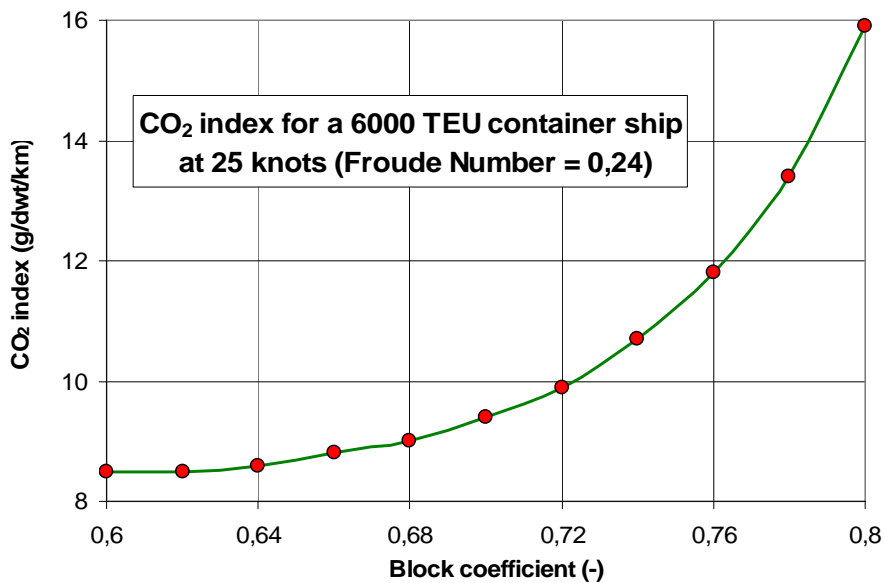


Fig. 24 The CO₂ index as function of the block coefficient. The block coefficient has been varied by changing the breadth of the ship such that the length displacement ratio has been kept nearly constant (6.37 – 6.47)

The length displacement ratio ($L_{wl}/\text{volume}^{1/3}$)

The length displacement ratio has also a pronounced influence on the propulsion power. The larger the ratio is the more slender is the ship, which is beneficial for the propulsion power requirement and therefore also for the CO₂ index. Statistical data for the length displacement ratio for container ships are shown in Fig. 25 which indicates that the ratio is lower for small container ships (below 25000 dwt ~ 2000 TEU), while it is higher and nearly constant above 50000 dwt.

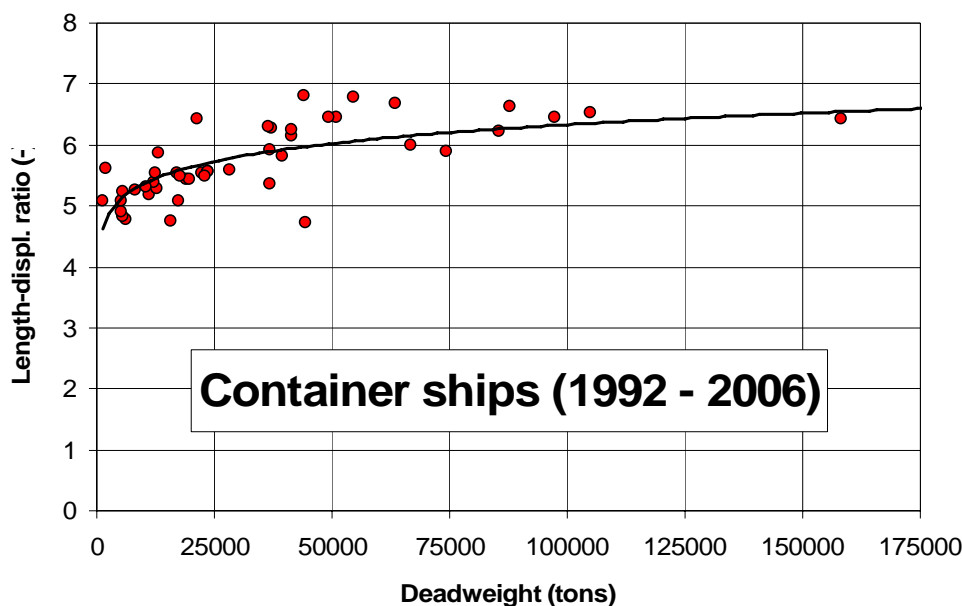


Fig. 25 Statistical data for the length-displacement ratio for container ships built from 1992 to 2006

Proposed parameters for a new CO₂ index for container ships

Based on the statistical data of the block coefficient, the length displacement ratio and the Froude Number for container ships built from 1992 to 2006, covering the whole capacity range from 100 to 10000+ TEU, it is obvious that the large container ships have the most beneficial combinations of all these 3 important parameters seen from a CO₂ index point of view. It is therefore quite evident that the CO₂ index will decrease with increasing deadweight or length. This statement is also confirmed by the statistically calculated CO₂ index of all the representative container ships analysed in this paper.

As the CO₂ index is strongly dependant on the ship size and service speed, an attempt has been made to combine these parameters using the ships so-called Froude Number as a single non-dimensional parameter disregarding the ship size. However in doing so, it is evident that large cargo ships such as container ships, bulk carriers and tankers will be favoured and loose incentive to improve because they obtain the target CO₂ index more easily than the smaller cargo ships of the same type with low transport capacity. Otherwise the curves in Fig. 20 would have merged into a single curve. In conclusion the dependency on deadweight should be more pronounced.

Based on the above mentioned analysis it must be concluded that the CO₂ index limit should be a function of the ship size, as example of the length, deadweight or the payload. It is also clear that the Froude Number has a pronounced influence on the CO₂ index, such that a CO₂ index limitation should also include this parameter.

14. References

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Appendix A

COMPUTER MODEL FOR CALCULATION OF ENERGY DEMAND AND EMISSIONS

COMPUTER MODEL FOR CALCULATION OF ENERGY DEMAND AND EMISSIONS

For ships, the energy demand varies very much from one ship type to another. Even for the same ship type, there can be great variations in energy demand per transported unit of cargo, depending primarily on the ship size and the ship speed. In general, for all means of transport the degree of utilization of the cargo capacity will also have a great influence on the energy demand per transported unit.

Professor Hans Otto Kristensen has developed a computer model which on basis of statistical data is able to calculate typical main dimensions for a given ship type based on the maximum cargo capacity for the ship. The theoretical background for the model has been described in Ref. 6.

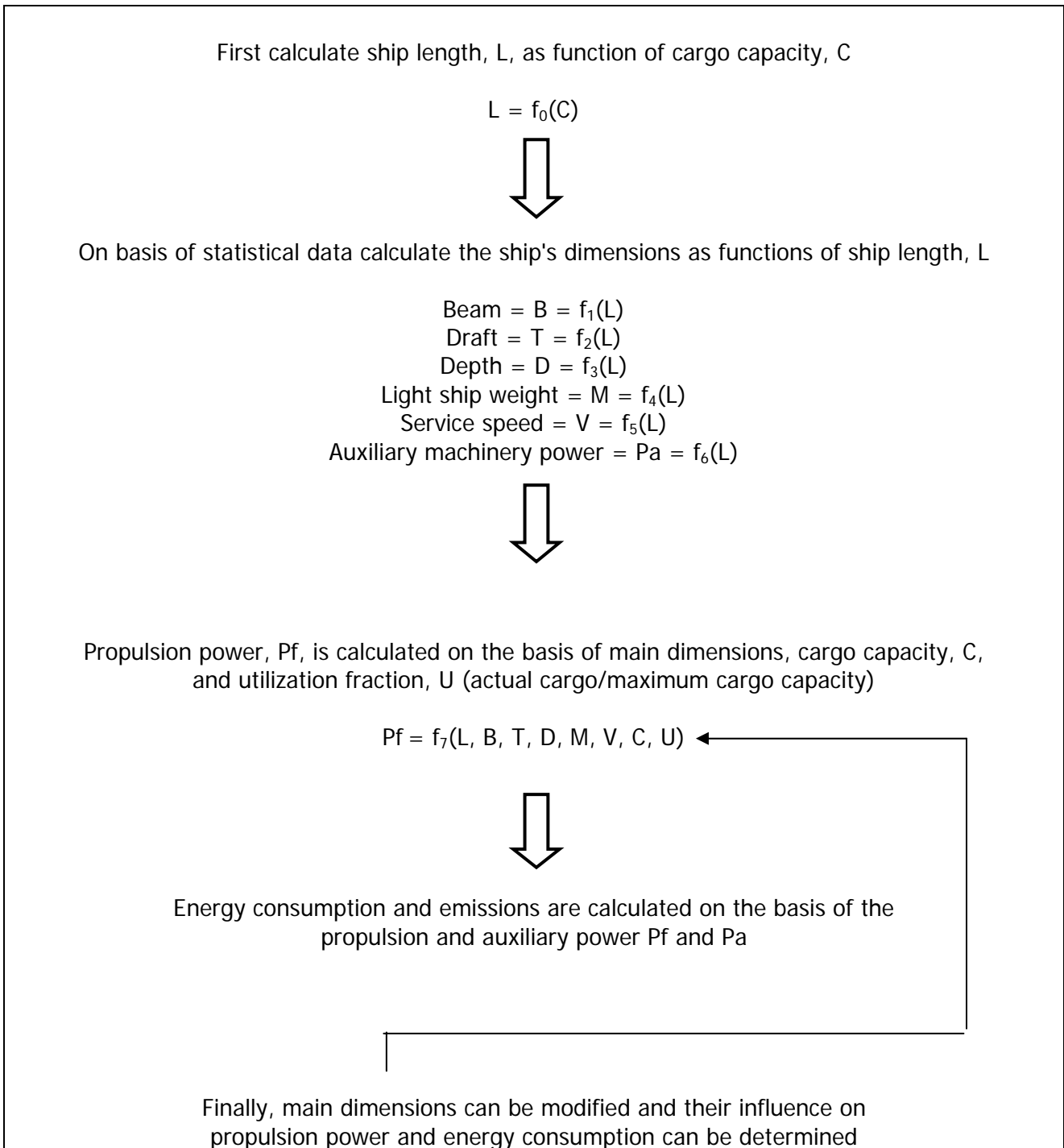
The structure of the calculation model is shown on next page, where the parameters of the calculation method can be seen. The model has been developed in order to get a more systematic insight into the parameters which have an influence on the energy demand and exhaust emissions.

On the basis of the suggested main dimensions by the calculation model, the energy demand and exhaust emissions are calculated by some empirical methods and formulas.

The main dimensions suggested by the program can be modified individually to show their influence on the propulsion power and the associated energy demand and exhaust emissions. Also, the influence of the speed and the cargo utilization can be investigated by the program as these are the two most important parameters in such investigations.

The calculation model includes the following ship types and sizes:

- Container ships: 100 - 10000 TEU (TEU = Twenty feet Equivalent Unit)
- Bulk carriers and tankers: 2000 – 200000 tons cargo capacity
- Ro-Ro cargo ships: 700 – 5000 lane metres
- Ro-Ro passenger ships (car ferries): 15 - 1400 PCU (PCU = private car unit)



Sketch showing the main principles for the calculation model for determination of energy consumption and emissions for different ship types.