A CO_2 Index That Includes Hull and Propeller Condition (Propulsion Efficiency)

A Naval Architect's View

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Abstract. A CO_2 index for a transport vehicle should be a figure, which informs regarding the expediency of the transport with regard to CO_2 emission. It is therefore obvious to look at the associated CO_2 emission in relation to the quantity of transportation. This gives however rise to a number of questions:
1. How should "quantity of transportation" be defined?
2. For which situation should the index be calculated?
Many answers can be given to this, depending on the point of view and the type of transport. For general sea transport, taking all the technical aspects into account, it could be of interest to look at the matter mainly from a naval architect's position.

Quantity of transportation, definition of CO_2 index

Strictly speaking, transport capacity cannot be dealt with without knowledge of what is transported. The cargo capacity can be measured in tons, in square meters, in cubic meters, in cars, in meters of truck lanes, in containers and even in persons. It would however create a lot of confusion, if this diversity should be taken into account. Therefore, to make things simple, the naval architect would choose the displacement of a ship as a basis for an index. In the end, it is the total weight of a ship, including the cargo, which is transported, so there is a sort of logic in choosing the total transported weight, equal to the displacement, as a measure of the transported amount of goods.

An advantage of using the displacement is that it is a well-defined figure and that it is easy to determine. All that is needed is a draft/displacement table for the ship, and reading of the drafts fore and aft.

The transportation quantity of a specific sea transport can in this way be defined as the number of transported displacement tons times the distance for the transportation. Distances at sea are normally measured in nautical miles. A CO_2 index for a transport will then be the actually emitted weight of CO_2 divided by the corresponding quantity of transportation, measured as displacement tons times the transported distance in nautical miles:

$$\text{Index} = \text{g } CO_2 \,/\, (\text{tons displacement } \mathbf{x} \text{ transport distance in nautical miles}) \qquad (1)$$

It can be discussed if the ship's total emission of CO_2 should be used, or only the emission connected with the propulsion.

Conditions for calculation of the index

Again, different purposes require different views on the matter.

The simplest, and in certain connections also the most useful, method would be to calculate or measure the total emission of CO_2 over a certain time, for example one year, and for the same interval also measure or calculate the number of tons-nautical miles, which have been covered. An index found in this way may be used for general evaluation or for payment or taxation, but it is not suited for daily operation with the purpose of reducing the emission of CO_2.
A ship operator, who is dedicated to CO_2 reduction, will need a value, which can be used immediately as a benchmark for the actual operation and also as a tool for making decisions for future operation.

The naval architect's definition of an index

In order to calculate an immediate index value, both numerator and denominator in the expression (1) above could be divided by time:

Index = g CO_2/hour/(displacement **x** speed)

For this purpose, where the main goal is to arrange the transportation in such a way that the CO_2 emission is minimized, it is obvious only to use the CO_2 emitted by the propulsion machinery.
This index can easily be calculated, when the fuel consumption, the displacement and the speed is known.

Split-up of the index

For convenient all-round use, the index could be divided into 3 parts:

Total Index = Design Index + Operational Index + Maintenance Index

The Design Index is of course the index value corresponding to the design characteristics of the ship: Design draft and design speed. This part of the total index is useful at the design stage, as there could be a maximum design index value included in the design criteria.

The operational index is a correction to the design index, reflecting the effect of the actual values of draft and speed. In general, increased draft and reduced speed will reduce the index. It is quite easy to calculate this index from actual values of draft and speed, when the corresponding design values are known.

Finally, there is the Maintenance Index. This index reflects the effect of changes to the individual elements of the propulsion system: Engine, hull and propeller. This figure is what is left, when the Operational Index and the Design Index has been subtracted from the Total Index. It will immediately tell the technical manager, if repair or maintenance work is required in order to achieve a certain total index value. Alternatively, an excessive value of the maintenance index could be counterbalanced by a reduction of the operational index.

The Index used by the CASPER® program

The CASPER program determines the fuel consumption as a function of speed for certain loading conditions, certain weather conditions and (equally important) certain conditions of the surface of hull and propeller. Theoretically, CASPER could therefore easily calculate the indexes as described above. In the CASPER reports the design index and the operational index have however been added together, so that the total index consists of only two parts, a design/operational index and a maintenance index. The reason for this is that the design index, which may be of interest in connection with the planning, design and procurement of the ship, is of no interest for the operator. He will need indexes, which tell him, how the condition of the ships is, here and now. Further, it must be possible to identify precautions for an adjustment of the total index in relation to certain benchmark values.

A detailed description of the proposed index is given in the Appendix.

Acceptable values of the index

An overall target value of the CO_2 index could be calculated, if the total permissible CO_2 emission from shipping had been determined, and the total worldwide transport need, measured in tons-nautical miles was known.

Though such a figure would be of interest, it can only be used as a mean value for all shipping, because different types of ships will have different indexes. It appears from expression (A) in the Appendix, that the main contribution to the index is the used Froude's Number squared, "F_d^2",and as any naval architect will know, the Froude's Number, whether based on length or third root of displacement, varies greatly from a small, fast ferry to a ULCC. This is illustrated by the following example:

Fast Ferry, Length = 100 m, Displacement. = 4 500 t, Speed = 20 Knots, $F_d^2 = 24$

VLCC, Length = 335 m, Displacement. = 355 000 t, Speed = 15 Knots, $F_d^2 = 3$

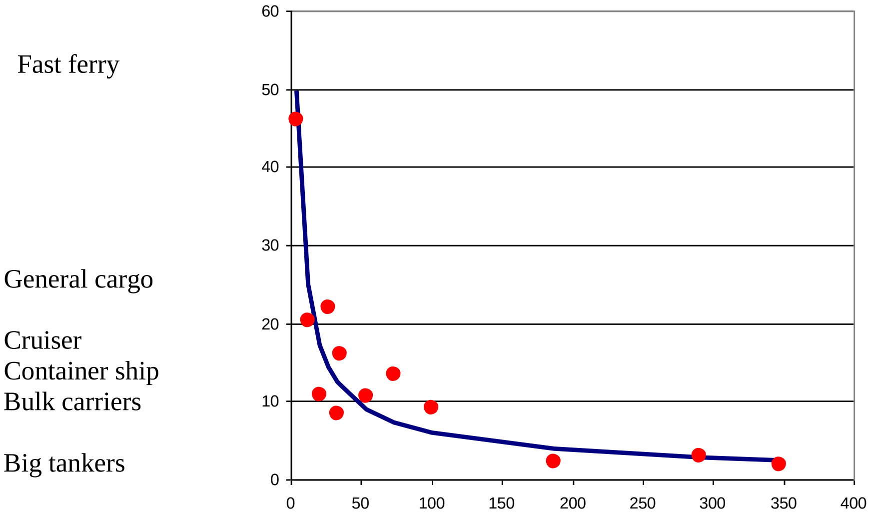
If the ferry should have approximately the same CO_2 index as a VLCC, the speed could only be 7 knots instead of 20 knots. This is of course unacceptable for practical reasons.

As another example, the following diagram shows the design CO_2 index calculated as described for a number of ships of different size and type. It is seen that the index is low for big ships and high for small ships.
It is therefore possible to draw a mean curve for the index, by the use of an expression of the form:

$$\text{Index} = a/(\text{Displacement})^b$$

Where a and b are constants.

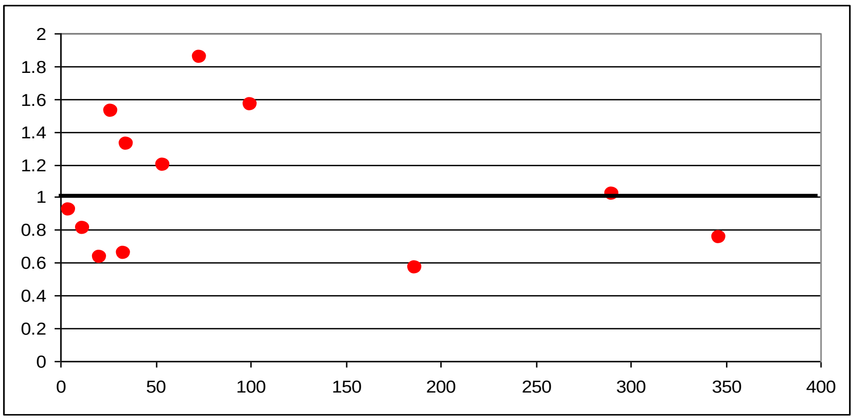
CO_2 index



1000 t displacement

An easy evaluation of the ships, independent of size, may be done by dividing the found indexes by the index from the mean curve. This is shown in the next diagram:

Modified CO_2 index



1000 t displacement

This is, as a matter of fact, a comparison of ships with equal displacement, but operating at different speeds. The deviation from the mean line can to a certain degree be caused by differences of the hull resistance and the propulsion efficiency, but the main reason for the deviation will no doubt be the Froude's Number, or the operational speed of the ship relative to the displacement as described in the Appendix.

Benchmarking

At this stage the naval architect will have to withdraw and leave the scene to the legislators. From what has been said up to now it is clear that the same criterion for a CO_2 index cannot be used for all ships. If a certain total mean value of the index is aimed for, it is obvious that some ships will have to be allowed an increased index value, while others will have to be further restricted. It has to be carefully considered, which ship types that are so important that a higher level of CO_2 emission can be accepted, and what cargo types there are of such a nature that delayed transportation is acceptable. This is a matter for regulating bodies, and no attempt will be made here to proceed further.

Note that the proposed CO_2 index can be used by ship owners internally to evaluate the individual ships. It is quite easy to calculate an "ideal index" for a specific ship or a series of ships, and the actual index of a ship can then be compared to this value. If it is found that a certain ship has developed a too high index value, precautions can be taken to reduce the value, either by enhanced hull and propeller husbandry, advanced coating systems or by an increase of the draft and a reduction of the service speed.

APPENDIX

Thoughts about a CO_2 index for ships

Nomenclature

D_d	Displacement at design draft
v	Design service speed (at design draft)
F_d	Froude's number, based on displacement ($F = v / D^{1/6}$)
c_t	Total resistance coefficient, design draft, design speed
η_{tot}	Total propulsion efficiency, (towing power / fuel power)
$k, k_1, k_2 \ldots$	constants

A CO_2 index is a measure of the relative CO_2 emission from a ship and can be defined as the ratio between the actual CO_2 emission, which is supposed to be directly proportional to the actual fuel oil consumption, and the actual transport capacity.

CO_2 index = $I_{CO}2$ = Fuel consumption / Transport capacity

Fuel consumption = k x Propulsion power $= k_1 \times D_d^{2/3} \times c_t \times v^3/\eta_{tot}$

Transport capacity = Displacement x speed $= D_d \times v$

$$\begin{aligned} I_{CO2} &= k_1 \times D_d^{2/3} \times c_t \times v^3/ \eta_{tot} / D_d/v \\ &= k_1 \times (v^2/ D_d^{1/3}) \times c_t / \eta_{tot} \\ &= k_2 \times F^2 \times c_t / \eta_{tot} \qquad \text{(A)} \end{aligned}$$

F is a measure of the relative speed
c_t is a measure of the expediency of the hull form
η_{tot} is a measure of the expediency of the propulsion system

As all parameters are valid for the design condition only, this could be called the CO_2 design index.

It may however be of interest to define a "Total CO_2" index" or "CO_2 service Index", too. This index should take the actual speed, the actual draft and the actual c_t (including propeller/hull roughness and marine fouling contributions) into account. The service CO_2 index would then be

$$I_{CO2,\ service} = I_{CO2,design} \times s$$

where s is a factor giving the relation between fuel consumption and transport capacity for the ship in the actual condition and for the ship in design condition.

$$s = D_d^{1/3} \times v_{actual}^2 / (D_{actual}^{1/3} \times v_d^2) \times (1+\text{actual virtual added resistance factor})$$

s can be calculated for a single service performance observation or can be calculated as a mean value for observations from a voyage or from a time period.

The “actual virtual added resistance factor” can be calculated by a propulsion performance monitoring program, as for example CASPER®.

Torben Munk graduated from the Danish Technical University in 1962 as Naval Architect, Marine Engineer and Mechanical Engineer. Some of his previous positions include: Head of the Department for Resistance and Propulsion of Ships and the Model Test Laboratory at the Danish Maritime Institute, Head of Ship Design, Klaus Dwinger, AS, Technical Director for the Danish Shipowners J. Lauritzen A/S and Knud I. Larsen A/S. Since 2002, he has been president for Propulsion Dynamics Inc., California, which provides CASPER®, a Hull Performance Monitoring service to shipowners and shipmanagers.