Comparison study on moving and transportation performance of transportation modes

Wei Shi, Douwe Stapersma, and Hugo T. Grimmelius

***Abstract*—** The performance of a transportation mode is introduced as the moving (mechanical) performance and the transportation performance, in this paper represented by the mechanical index and the energy index. The paper gives a mathematical deduction of the relationship between the mechanical index and the energy index. In the mechanical point of view, the range of the mechanical index of different transportation modes is calculated. On the basis of a non-dimensional , in both full load and typical load conditions, a comparison of energy indexes of different transportation modes is presented. Then the fuel consumption and exhaust emissions of different transportation modes are compared by means of a "ton payload and distance specific factor" versus "Square-Froude number" diagram. Furthermore, the results of a case study demonstrate that low speed operational strategies could improve the mechanical efficiency and the energy efficiency of ships but both the fuel consumption and emission would deteriorate while sailing in part load condition or with fluctuating speed.

***Keywords*—** emission, energy index, fuel consumption, mechanical index, transportation modes.

I. Nomenclature

A	reference area	[m^2]
A_r	aspect ratio of the wing	
A_S	wetted hull surface of ship	[m^2]
B	beam of ship	[m]
C_1	friction coefficient	
C_2	fluid resistance coefficient	
C_A	non-dimensional factor of immersed area	
C_{A_0}	non-dimensional factor of immersed area of a specific transportation mode	
C_b	block coefficient of ship	
C_V	non-dimensional factor of volume	
C_{V_0}	non-dimensional factor of volume of a specific transportation mode	
C_{wetted}	friction coefficient of ship	
C_{wetted}	resistance coefficient of wetted surface	
D	covered distance	[m]
E	total consumed energy	[w]
F_n	Froude number	
I_E	energy index	
I_{E_0}	energy index of a specific transportation mode	
I_M	mechanical index	
I_{M_0}	mechanical index of a specific transportation mode	
L	characteristic dimension	[m]
L_s	wing span of the airplane	[m]
L_{wl}	water line length of the ship	[m]
$M_{(i)}$	moment of each particular propulsion component of the ship, such as the propeller, the shaft, the gearbox and the engine	[Nm]
P	consumed power	[W]
Q_{prop}	torque of the propeller	[Nm]
R	moving resistance	[N]
R_A	model-ship correlation resistance	[N]
R_{APP}	resistance of appendages	[N]
R_B	additional pressure resistance of bulbous bow of the ship near the water surface	[N]
R_F	frictional resistance of the ship according to the ITTC-1957 friction formula	[N]
R_{ship}	total resistance of the ship	[N]
R_{TR}	additional pressure resistance of the ship of immersed transom stern	[N]
R_w	wave-making and wave-breaking resistance of the ship	[N]
T	draught of ship	[m]
T_{prop}	thrust of the propeller	[N]
V	reference volume of the transportation mode	[m^3]
W	weight of transportation mode	[kg]
g	gravity acceleration	[m/s^2]
k_1+1	factor describing the viscous resistance of the hull form in relation of R_F	
m_{max}	mass of the maximum payload	[kg]
$m_{payload}$	mass of the payload	[kg]
$n_{(i)}$	rotate speed of each particular propulsion component of the ship, such as the propeller, the shaft, the gearbox and the engine	[rad/s]
v	moving speed	[m/s]
v_A	advance speed	[m/s]
v_{ship}	speed of the ship	[m/s]
w_v	width of the vehicle	[m]
x	loading fraction, the ratio between the actual and maximum mass of the payload	
x_b	benefit loading fraction of the ship, the ratio between the mass of transport cargo and the maximum payload of the ship	
ε	non-dimensional quantity of transportation mode	
η_{drive_train}	drive-train efficiency	

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$\eta_{propulsion}$ efficiency of propulsion system
$\eta_{transmission}$ efficiency of transmission system
$\eta_{transport}$ transport efficiency
$\rho_{()}$ density of individual fluid or transportation mode

II. Introduction

Industrialization and technological development cause people to use increasing quantities of energy and lead to increasing amounts of exhaust emissions, like CO_2 and SO_2. Among the human activities causing the energy consumption and corresponding exhaust emissions, the use of transportation systems and its associated burning of fossil fuel for energy are vital.

With the growing awareness of the environment impact of transportation systems, a lot of effort is undertaken to improve energy efficiency and to develop environmental-friendly transportation modes and operation strategies [1]-[3].

Three approaches may be taken to reduce the fuel-related impact of transportation modes. One is to improve energy efficiency. Another is to shift to alternative fuels, [4], [5]. The third is to control the amount of travel, including greater use of more energy-efficient modes of travel, in particular avoiding low-occupancy of transport vehicles.

In recent years, due to the difficulty to implement a consistent method to assess the energy efficiency of different types of transportation modes, the debate on energy demand is growing [6], [7]. For instance, in the intermodal transport industry it is of importance to find an optimum combination of different transportation modes, which lead to the lowest energy consumption.

In view of the environmental impact, an alternative method to reduce exhaust emissions from the transport industry is to shift the transport to less emitting transportation modes, thus leading to the shipping transportation, which, due to its large scale and low speeds, is considered basically as an environmental friendly transportation mode. But, unfortunately, there is an economic disadvantage of conventional ships as they sail at speeds that are much lower than those of other transportation modes. In order to improve the transportation quality, high-speed ships are required. However, whether a fast ship keeps the advantage over other transportation modes in being more environmental friendly is a controversial issue in recent years [8].

Meanwhile, it should be remembered that the high sulfur emission from ships is a consequence of the fact that residual oils used in ships contain much more sulfur than diesel used on land, or fuel oils used in airplanes.

In order to compare the performance of different transportation modes, the energy consumption and the exhaust emissions, in this paper a non-dimensional is generated by means of an empirical mathematical analysis. This is used to indicate the relationship between the mechanical index and the energy index. From this, the consequent comparisons of energy consumption and exhaust emissions of different transportation modes are made and presented from an engineering point of view.

The specific purpose of the case study is to investigate the issues that could influence both of the moving performance and the transportation performance of ships. On the basis of this case study, the influences of speed and loading condition on the energy consumption and exhaust emissions of ships are discussed.

III. Mathematical Analysis

A. Definition of Indexes

Von Karman and Gabrielli in their classic paper "What Price Speed?" [9] introduced a non-dimensional quantity ε , to indicate the transport performance of a transportation mode. Today this concept goes by the name "energy index" and in this paper will be designate by I_E:

$$\varepsilon = I_E = \frac{P}{W \cdot v} \tag{1}$$

Putting into words, this coefficient is the ratio between the consumed power and the transferred gross weight multiplied by the mean moving speed. It is apparent this coefficient is useful for the comparison of different types of transportation, since it gives an indication of the cost (the power) and the benefit (transport amount of weight at a particular speed).

The energy index is related to the energy efficiency and for a specific transportation mode, the energy efficiency could be derived in two parallel ways:

1. When considering the operation of a transportation mode from the outside of the propulsion system - in other words: from the viewpoint that considering the transportation mode as a “black box”, no matter which kind of propulsion system is implemented inside - then the energy efficiency is the ratio between the transferred weight times the covered distance (the benefit) and the consumed energy (the cost). This ratio is usually referred to as “transport efficiency” and is the inverse of the energy index:

$$\eta_{\text{transport}} = \frac{\text{weight} \cdot \text{distance}}{\text{energy}} = \frac{W \cdot D}{E} = \frac{W \cdot v}{P} = \frac{1}{I_E} \tag{2}$$

2. When looking at the propulsion system, the quality of the propulsion system can be indicated by the “drive-train efficiency”, defined as the ratio between the total moving resistance multiplied by the mean moving speed - the effective power (the benefit) and the required power (the cost). The drive-train efficiency relates to the losses in the propulsion system and its inverse will be designated by the mechanical index I_M:

$$\eta_{\text{drive train}} = \frac{\text{resistance} \cdot \text{speed}}{\text{power}} = \frac{R \cdot v}{P} = \frac{1}{I_M} \tag{3}$$

This drive train efficiency generally can be considered as the product of transmission efficiency and propulsion efficiency:

$$\eta_{drive\_train} = \eta_{transmission} \cdot \eta_{propulsion} \tag{4}$$

The $\eta_{transmission}$ is the efficiency of the transmission system, comprising the gearbox loss, the shaft loss and other transmission losses, whereas the $\eta_{propulsion}$ indicates the ability of the propulsion system to employ the delivered power for actually moving the platform against the resistance (the effective power)..

Now from s (2), (3) and (4) it can be concluded that the relation between energy efficiency and drive train efficiency is:

$$\eta_{transport} = \frac{W}{R} \cdot \underbrace{\eta_{transmission} \cdot \eta_{propulsion}}_{\eta_{drive\_train}} \qquad (5)$$

So transport efficiency is the overall system efficiency and it is proportional to drive train efficiency, comprising propulsion and transmission efficiency. Furthermore, transport efficiency is dependent on the Weight/Resistance ratio. In terms of indexes, the relation is:

$$I_E = \frac{R}{W} \cdot I_M \qquad (6)$$

Both the energy index and mechanical index are used to express the quality of a propulsion system but due to the presence of Resistance/Weight ratio, clearly the energy index is the overall system parameter. It is worth looking at this expression in detail.

B. Non-dimensional Deduction

In order to make comparisons of different transportation modes it is of importance to asses the influence of size, shape and the particular performance. The obvious way to accomplish this is the conversion from dimensional performance factors to non-dimensional factors.

Starting with the mechanical index (I_M), the motion of the transportation modes is considered. Generally speaking, the total resistance, generated by the motion of the transportation modes, could be divided into two parts: a non-speed dependent force and a speed dependent force. The first part is the friction, for instance between the wheel and the surface, which mainly depends on the weight of the transportation modes, the form and the type of the surface. The second part of the resistance is the fluid dynamic force, known as the drag, generated by a solid object moving through a fluid. The general consensus is to express the moving resistance through a fluid as a pressure times a reference area. Based on fluid dynamic theory, this pressure and the corresponding resistance force are dependent on the moving speed, the density of the fluid and a form related parameter. For instance, for a laminar flow in a non-compressible fluid, the relationship between resistance and speed is nearly linear, for a ship the resistance in calm water is proportional to the square of the speed. However, when taking into consideration waves, the resistance could be proportional to the 4th (or even higher) power of the speed. For an airplane, where the air is considered compressible due to the high Mach number, the relationship becomes even more complicated.

In this paper some empirical assumptions are made:

- Non-speed dependent force (friction) is proportional to the weight of the transportation modes and the friction coefficient, C_1;
- The speed dependent force (drag) is proportional to the density of the fluid, the speed squared and a reference area A. Deviations from this assumption are dealt with in a factor C_2.

Then, the total resistances of the transportation modes can be written as:

$$R = C_1 W + C_2 \rho_f A v^2 \qquad (7)$$

Inserting (7) into (3), the mechanical index (I_M) is written as:

$$I_M = \frac{P}{C_1 W v + C_2 \rho_f A v^3} \qquad (8)$$

Inserting (7) into (6), the energy index (I_E) is written as

$$I_E = \left(C_1 + C_2 \cdot \frac{\rho_f \cdot A}{W} \cdot v^2 \right) \cdot I_M \qquad (9)$$

As defined in (2), W is the transferred weight and it can be calculated by using a reference volume and a reference density of the transportation mode:

$$W = \rho \cdot V \cdot g \qquad (10)$$

Then the expression of the energy index becomes:

$$I_E = \left(C_1 + C_2 \cdot \frac{\rho_f}{\rho} \cdot \frac{A}{V} \cdot \frac{1}{g} \cdot v^2 \right) I_M \qquad (11)$$

As shown in (11), the energy index depends on the mechanical index and the properties of the transportation mode, the resistance coefficients, as well as on the density of the fluid.

One step further, with the regard to the non-dimensional conversion of the shape of the transportation mode, the reference volume and the reference area could be expressed in some linear size of the transportation mode (here for the moment designated by L):

$$V = C_V \cdot L^3 \qquad (12)$$

$$A = C_A \cdot L^2 \qquad (13)$$

The constants C_V and C_A are non-dimensional geometrical shape factors.

Finally, the non-dimensional relationship between the energy index and the mechanical index can be expressed as:

$$I_E = \left(C_1 + C_2 \cdot \frac{\rho_f}{\rho} \cdot \frac{C_A}{C_V} \cdot \frac{V^2}{g \cdot L} \right) I_M \qquad (14)$$

For a specific transportation mode, the ρ_f / ρ and the C_A / C_V are defined differently. The $v^2 / (gL)$, which represents the non-dimensional speed, also is different for each transportation mode.

For most ships, skin friction is the dominant part of resistance. Therefore, the area in (13) is taken as the wetted hull surface A_S. Empirical formulae exist to express this surface in the geometrical shape coefficients of the hull. For the volume the underwater displacement is taken, which can be expressed in the frequently used block coefficient:

$$\nabla = \frac{C_b}{\left(L_{wl}/B\right)^2 \left(B/T\right)} \cdot L_{wl}{}^3 = C_V \cdot L_{wl}{}^3 \qquad (15)$$

So the geometrical volume factor C_V for ships can be expressed in the block coefficient (C_b), L_{wl}/B ratio and B/T ratio. The same could be done for the geometrical area factor C_A.

The non-dimensional speed is known as Froude number (F_n):

$$F_n = \sqrt{\frac{V^2{}_{ship}}{g \cdot L_{wl}}} \qquad (16)$$

Note that the characteristic dimension L in (15) and (16) is set as the length of water line (L_{wl}). Then:

$$I_{E\_ship} = C_2 \cdot \frac{\rho_{water}}{\rho_{ship}} \cdot \frac{C_{A\_ship}}{C_{V\_ship}} \cdot F_n{}^2 \cdot I_{M\_ship} \qquad (17)$$

To calculate drag for land based vehicles (cars, trucks, trains and etc.), the cross sectional area is always used as the reference area. The width of the vehicle (w_v) is chosen as the characteristic dimension in this paper:

$$I_{E\_vehicle} = \left(C_1 + C_2 \cdot \frac{\rho_{air}}{\rho_{vehicle}} \cdot \frac{C_{A\_vehicle}}{C_{V\_vehicle}} \cdot \frac{v_{vehicle}{}^2}{g \cdot w_v} \right) I_{M\_vehicle} \qquad (18)$$

For airplanes the drag is normally expressed as a function of the wingspan (L_s), which is the obvious size parameter for that transportation mode. Then, the expression of the energy index for an airplane is:

$$I_{E\_airplane} = C_2 \cdot \frac{\rho_{air}}{\rho_{airplane}} \cdot \frac{C_{A\_airplane}}{C_{V\_airplane}} \cdot \frac{v_{airplane}{}^2}{g \cdot L_s} \cdot I_{M\_airplane} \qquad (19)$$

In this paper, the non-dimensional form $V^2 / (gL)$, with L chosen as indicated per transportation mode, is referred to as the "Square-Froude number". For ships it indicates the Froude number as normally used in resistance analysis. For other transportation modes it looks like a Froude number and it can be used to characterize the operational speed of that transportation mode.

IV. Calculation of Mechanical Index

As defined in (3), the mechanical index (I_M) is a function of the resistance, which is a mechanical force opposing the motion of the body of the transported object. However, when considering the different kind of transportation modes, the moving performance as well as the resistance varies, as defined in (7). In this paper, in order to compare the mechanical index of different transportation modes, general values of resistance coefficient (C_1, C_2) of each transportation modes are presented, as shown in Table I.

For ships, since they always sails at relatively low speed, the skin resistance dominates the magnitude and, depending on the speed range, the resistance coefficient is chosen as 0.04~0.065.

For land based vehicles, when moving at lower speed, the friction between the wheels and the road/rail surface is dominant, but when the speed is higher, the contribution of air resistance becomes the more dominant factor. Furthermore, special attention is needed for trains, which is a transportation mode that, using a locomotive, pulls several connected vehicles. Compared to the resistance of an automobile, the rolling resistance of its metal-rail system is much smaller than that of the rubber-road system of an automobile. Meanwhile, concerning the air resistance, the coefficient for the locomotive is at the same level as the automobiles, but is much larger than that of the following wagons, since the resistance from the headwind is of course less for the following wagons. The resistance of the following wagons is low due to the locomotive ahead, shielding the wagons behind it from the headwind.

For an airplane, the main drag is the aerodynamic resistance, including the form drag, the drag caused by the generation of the lift, the wave drag and the ram drag. Combining all sources of drag, when cruising at normal speed, the general fluid resistance coefficient of the airplane is set as 0.01~0.0125.

Combined with other parameters, such as the moving speed, the body form, the gross weight of the transportation modes, the general range of the mechanical index for each transportation mode is presented in Table II.

TABLE I
Moving Properties of Transportation Modes

				C_1	C_2	V
ship				NA	0.04 ~ 0.065	7 ~ 12.5
land based	Auto	car		0.018 ~ 0.025	0.14 ~ 0.19	16.5 ~ 27.5
		truck		0.02	0.38 ~ 0.47	16.5 ~ 25
	train	wagon	pass.	0.0046	0.06	25 ~ 41.5
			fri.	0.0028	0.09	
		loco.	stre	0.0022	0.314	
			norm.		0.462	
airplane				NA	0.01 ~ 0.0125	236 ~ 264

TABLE II
Mechanical Index of Transportation Modes

	ship	land based		airplane
		auto	train	
I_M	2~3	3~5	4~6	1.5~3

As shown in Table II, there is no large difference in terms mechanical index. In other words, from the mechanical point of view, although there are different transmission and propulsion systems for different kinds of transportation modes, the total mechanical efficiency is bounded.

However, one should notice that, since the moving resistance of most of the transportation modes is related to the body form and the moving speed, the mechanical index only represents the quality of the moving performance, but not the transport performance, since the outer shape of the body does not have a direct relationship with the cargo or passenger capacity. For instance, both the ship and the airplane could be treated as a solid object moving through a fluid. Because of the highly streamlined body design, the moving resistance of an airplane could be lower than that of a ship, in other words, the airplane has a better mechanical index than the ship. But, concerning the transported cargo or passengers, because of its big capacity, the ship still could perform much better than the airplane.

V. Comparison of Transportation Performance

A. Comparison of Energy Index

The performance of a transportation mode is to transfer a number of passengers or an amount of cargo from one place to another. In order to estimate the transportation performance of each transportation modes, in this paper the weight of the payload (not the total transferred weight) is used to define the energy index (I_E). By using the appropriate operational profile [10]-[12], the energy indexes of different transportation modes are calculated, based on the amount of payload and the mean transport speed. Meanwhile, combining the shape parameter of the transportation modes and the mean speeds (also presented in [10]-[12]), the Square-Froude number of each transportation mode is determined. Then the relationship between the energy index (I_E) and the operational performance of each transportation mode (indicated by the Square-Froude number) is presented in Fig. 1. A comparable result has been published by Von Karman and Gabrielli [9].

As illustrated in Fig. 1, the energy indexes of different transportation modes are comparable in this "energy index – Square-Froude number" diagram. It is worth looking at them in some detail.

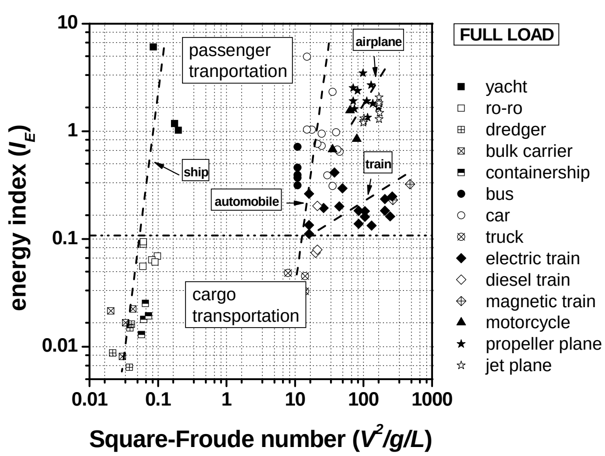

Fig. 1 Results of energy index in full load condition

Firstly, ships are well apart from the land based vehicles and the airplanes, due to their relative low sailing speeds and large sizes. Among all the transportation modes, the bulk carrier has the best energy index (the highest transport efficiency), but the smallest Square-Froude number, in other words: without regard to transport speed or cost of time, the bulk carrier is the most economical mode.

Secondly, because of lack of detailed information, it is hard to distinguish between propulsion energy consumption and auxiliary energy consumption. In this paper, the total energy consumption is used to calculate the energy index. The results show clearly that on the basis of the energy index as defined, the transportation modes which serve as passenger transport system consume more energy than cargo transportation systems. One reason for this is that, in passenger transport, a large amount of energy is needed to fulfil passengers' comfort needs. Taking ships as an example, the bulk carrier could have transport efficiency 1000 times higher than a luxury yacht, in spite of the fact that a comparable size and speed results in comparable propulsion energy consumption.

Thirdly, looking at passenger transport systems, the train provides higher speeds compared to the passenger ferry and the automobile, and consumes less energy, compared to the airplane.

Fourthly, when considering the relationship between energy index and the Square-Froude number within each category (the ship, the land based vehicle and the airplane), the results yield the broken lines shown in Fig. 1. The lines, which represent the low speed performance transportation modes, are steeper than those indicating high speed performance transportation modes. The main reason for deviation of the train transportation modes from the general trend is the fact that an increase of speed goes together with the application of low-drag body shapes, which dramatically reduce the air resistance.

Last but not least, the figure also shows the potential of fast transport and how to obtain fast performance for each transportation mode. Taking the ship as an example again, at high speed the wave resistance would rapidly increase. In order to remain the low energy index, the only effective remedy against this obstacle to the speed increase is to increase the length of the ship. However, this measure would be limited by several factors. In other words, without a new concept of ship body design, the fast ship is an uneconomical case.

Fig. 1 indicates the full load condition of each transportation mode, but, according to the commercial reality, this is rarely the case. A more logical way is to involve loading conditions.

In this paper, a loading factor x is introduced to indicate the loading conditions:

$$x = \frac{m_{payload}}{m_{\max}} \tag{20}$$

TABLE III
LOADING FACTORS OF TRANSPORTATION MODES

Mode	Container Ship	Bulk Carrier & Dredger	Ro-ro	Yacht	Car
Loading Factor *x*	80%	50%	50%	50%	35%
Mode	Bus	Truck	Train	Propeller Plane	Jet Plane
Loading Factor *x*	30%	80%	48%	60%	80%

Combining the assumption of typical loading conditions, as given in [13], with the author's experience, the loading factors used in the following discussion are shown in Table III. The results of the energy index in typical loading conditions are plotted in Fig. 2.

Comparing the results of typical loading conditions with those in full load conditions, the main trends are the same and leads to the conclusion that, for passenger transport, the public transportation modes (the bus and the train), which have a higher passenger occupancy and a better operation strategy, are more efficient than the corresponding private transportation modes.

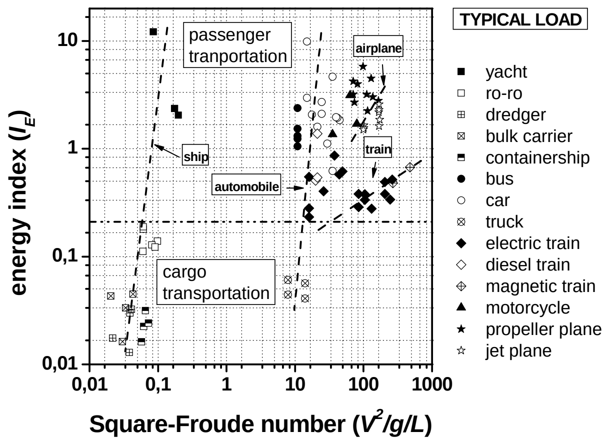

Fig. 2 Results of energy index in typical load condition

B. Comparison of Fuel Consumption and Exhaust Emissions

In this section, attention will be confined to compare the fuel consumption and exhaust emissions of different transportation modes, which cover a wide range of size and mass of payload - from a light motorcycle to a large bulk carrier, as well as a wide range of speeds - from about 25 km/hr for a bulk carrier to a speed of over 800 km/hr for a jet plane. The logical way to make a comparison is to use conversion factors from energy to fuel or emissions. This leads to the so-called "ton-kilometre" specific factors and yield the "consumed fuel (or emitted emissions) per payload per distance versus Square-Froude number" diagrams.

TABLE IV
PROPERTIES OF FUEL OILS

	ship		Land based vehicle		airplane
Fuel type	Residual Fuel	Marine Diesel	Land Diesel	Gasoline	Jet Fuel Oil
LHV (kJ/kg)	40000	42700	45400	44400	43700
Carbon content (mass)	82%	86%	86.2%	84.2%	84.2%
Sulfur content (mass)	3.5%	0.5%	0.035%	0.005%	0.4%

Due to economical reasons and operational requirements, different kinds of fuel oils are used in different transportation modes, see Table IV. In this paper, the consumption of every kind of fuel and the use of electric energy is corrected to the consumption of gasoline on the basis of the lower heating value. In order to simplify the comparison of exhaust emissions, only the CO_2 and SO_2 emissions are presented in this paper, and the general assumption is that the CO_2 and SO_2 emissions are inherent to the fuel properties and primarily a function of fuel consumption.

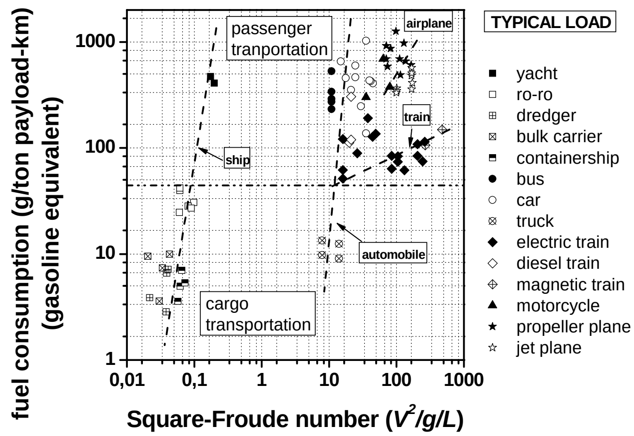

Fig. 3 Comparison of fuel consumption in typical load condition

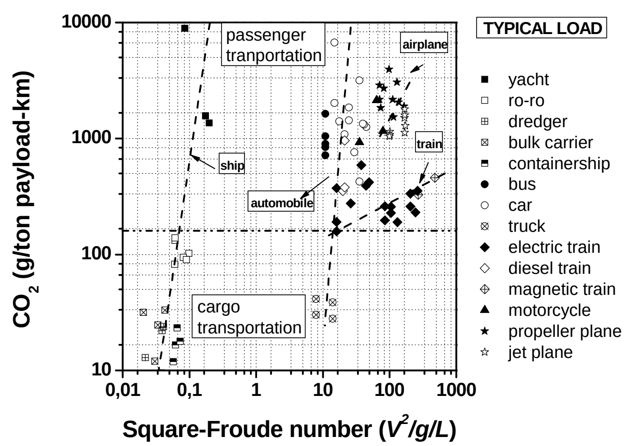

Fig. 4 Comparison of CO_2 emission in typical load condition

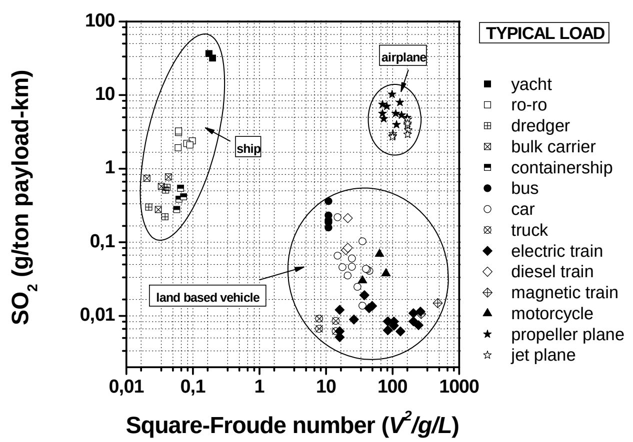

Fig. 5 Comparison of SO_2 emission in typical load condition

In typical loading conditions, the results of the fuel consumption and the exhaust emissions are shown in Fig. 3 – Fig. 5 respectively.

Since the carbon content of every fuel oil is only slightly different from each other, the main trends of fuel consumption and CO_2 emission show a great coherence, as plotted in Fig. 3 and Fig. 4. Although the loading factor of bulk carriers are about 50% when looking at their entire voyage they benefit from their large cargo capacities and their low auxiliary energy consumption. As a consequence they are still the best, both on the basis of ton-kilometre specific fuel consumption as well as on the basis of CO_2 emission,. On the other hand, yachts, passenger cars and propeller planes are at the highest level. The reasons are that for yachts a small loading factor is achieved, and large auxiliary energy consumption is required. For the passenger cars and the propeller planes the small passenger capacity and loading factor, as well as the large propulsion energy consumption render them relatively uneconomical and non-environmental friendly.

Regarding the SO_2 emission, the trends are very different compared to the fuel consumption and CO_2 emission. The fuel property dominates the picture, as illustrated in Fig. 5 Land based vehicles have the lowest specific SO_2 emission as a direct result from the use of low sulfur fuel oils. Due to the high sulfur contents of residual fuel and marine diesel, when looking at SO_2 emission, the advantage of the low fuel consumption of a cargo ship is counteracted, even for a bulk carrier. Because of the high fuel consumption and the relative high sulfur content of jet fuel oil, the SO_2 emission of airplanes are at a high level too.

As analyzed above, the energy efficiency and CO_2 emission of all types of transportation modes are dependent on their operational performances and on the markets they serve, but the fuel property dominates the SO_2 emission. In other words, ships win on fuel consumption but land based vehicles are superior on environmental impacts. Airplanes are neither economical nor environmentally friendly on a comparison basis.

VI. Case Study For Ships

In this case study, details are explored to estimate fuel consumption and the corresponding CO_2 and SO_2 emissions from ships. In the following discussion, four container ships, two bulk carriers and one cargo/passenger ferry are involved; see the APPENDIX for details of the reference ships. Because the auxiliary systems of a ship are mainly dependent on the ship type, in the analysis of the relationship between the energy index and operational shipping activities, the energy consumption of auxiliary system is excluded.

While sailing at a particular speed, the ship needs to overcome the resistance generated by both the air and the water. However, comparing the magnitude of these two forces, the general consensus is to neglect the air resistance when calculating ship resistance. On the basis of (7), the ship resistance can be described as:

$$R_{ship} = \sum 0.5 \cdot C_{wetted,i} \cdot \rho_{water} \cdot A_{S,i} \cdot v_{ship}^{\ 2} \qquad (21)$$

where the subscript i indicates each component of the total resistance.

In the ship design phase, there are different kinds of methods, refer to [14]-[17], to predict ship resistance and other factors, on the basis of ship dimensional parameters. In this paper, the Holtrop and Mennen method, presented in [16] and [17], is implemented to calculate ship resistance. In the Holtrop and Mennen method, the total ship resistance is divided into six parts:

$$R_{ship} = R_F(1+k_1) + R_{APP} + R_w + R_B + R_{TR} + R_A \qquad (22)$$

By calculating each part of the resistance separately, the total ship resistance can be achieved.

On the basis of [18]-[20], a simulation model was built in Matlab Simulink® to predict the propulsion power and the fuel consumption of the ship propulsion system. The block diagram is shown in Fig. 6.

This propulsion system model describes the dynamics of the ship propulsion plant by combining 4 subsystem models: a diesel engine & governor model, a transmission system model, a propeller model and a ship hydrodynamic force model. These 4 models are connected through 2 dynamic systems: a shaft rotation system and a ship translation system. [19] presents more details of this propulsion simulation model.

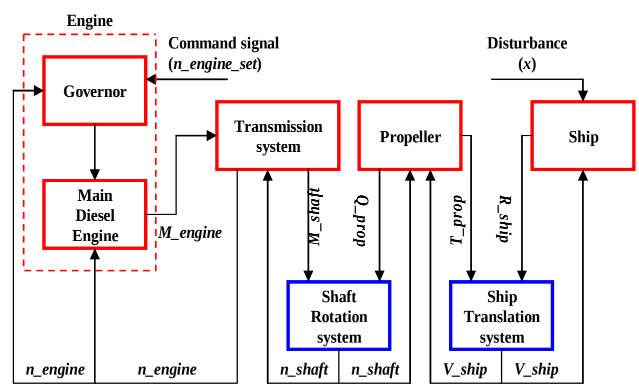

Fig. 6 Block diagram of propulsion system

In this case study, the command signal of the model is the engine speed (*n_engine_set*), which determines the ship speed. Another input is the actual loading fraction (x), which influences the ship resistance. The output data are the corresponding fuel consumption and exhaust emissions.

A. Energy Index at Low Speed

Referring to (17), regarding the influence of ship speed on the mechanical index (I_M), for a ship a rough estimate is that the energy index of a propulsion system should be proportional to the square of Froude number (F_n^2), as shown in Fig. 7. In a log-log figure, the slope of each line should be, and indeed is two.

However, at low speed, the square law is not valid anymore due to the decrease of some partial efficiencies, resulting in a change of the mechanical index (I_M) and of the energy index (I_E).

In order to investigate the influence of ship speed on the energy index (I_E), it is necessary to look at the power transmission through the propulsion system, from the engine brake power to the effective towing power, following the introduction in [18]. The whole power chain can be broken down into six parts, as shown in Fig. 8.

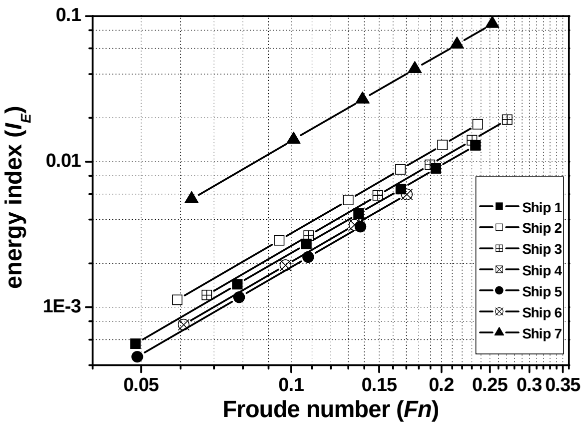

Fig. 7 Rough analysis of energy index

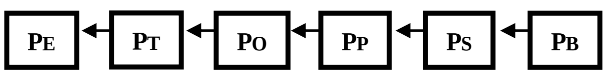

Fig. 8 power chain of propulsion system

With:

Engine brake power: $P_B = 2\pi \cdot M_{engine} \cdot n_{engine}$ (23)

Shaft power: $P_S = 2\pi \cdot M_{shaft} \cdot n_{shaft}$ (24)

Propeller power: $P_P = 2\pi \cdot M_{prop} \cdot n_{prop}$ (25)

Open water propeller power: $P_O = 2\pi \cdot Q_{prop} \cdot n_{prop}$ (26)

Thrust power: $P_T = T_{prop} \cdot v_A$ (27)

Then, a series of partial efficiencies are defined:

Hull efficiency: $\eta_H = P_E / P_T$ (28)

Open water efficiency: $\eta_O = P_T / P_O$ (29)

Relative rotative efficiency: $\eta_R = P_O / P_P$ (30)

Shaft efficiency: $\eta_S = P_P / P_S$ (31)

Gearbox efficiency: $\eta_{GB} = P_S / P_B$ (32)

By combining (28) - (32), the efficiency of the entire propulsion system is:

$$\eta_{drive\_train} = \eta_H \eta_O \eta_R \eta_S \eta_{GB} \quad (33)$$

Thus, the mechanical index (I_M) of the ship can be expressed as:

$$I_M = \frac{1}{\eta_H \eta_O \eta_R \eta_S \eta_{GB}} \quad (34)$$

In this section, in order to avoid the change of ship resistance caused by the change of loading condition, the loading factor (x) is set as 100%, which represents full load of the ship.

Take Ship 1 (large container ship) as an example. The influences of sailing speed on each part of the coefficient of the propulsion system are plotted in Fig. 9. As shown in this figure, all the coefficients change with sailing speed. When considering the overall drive-train efficiency, this kind of influence is amplified.

Meanwhile, the curve that indicates the relationship between the mechanical index (I_M) and the Froude number, illustrates that, at high speed (large Froude number), the mechanical index (I_M) only slightly changes, but at low speed, the curve becomes steeper. The mechanical index (I_M) increases fast for decreasing sailing speed. In other words, when sailing at very low speed, the ship propulsion system operates in relatively bad conditions.

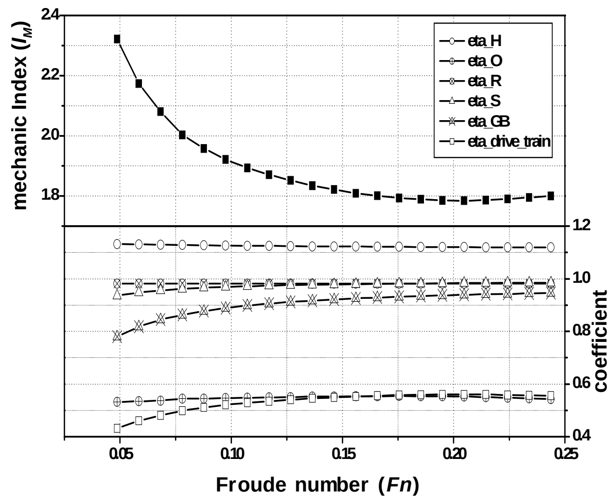

Fig. 9 Coefficients of propulsion system and the mechanical indices of Ship 1 at low speed

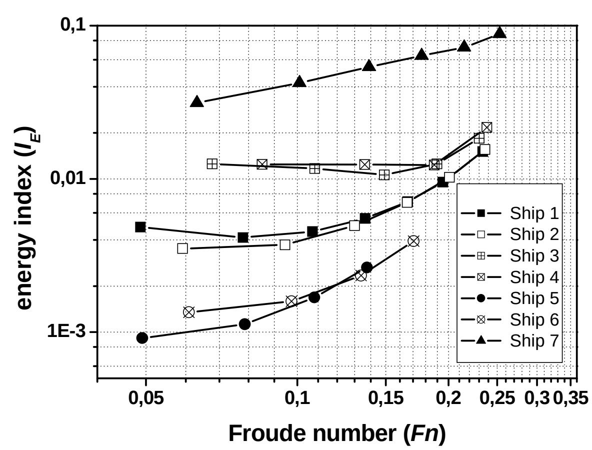

Fig. 10 Energy indices of reference ship

On the basis of the analysis of the mechanical index (I_M) in low speed conditions, the results for the energy index (I_E) are achieved: accordingly, the energy index also changes at low speed, as illustrated in Fig. 10. The general conclusion is that, the energy index decreases as a consequence of the sailing speed for all the reference ships and in low speed conditions the bulk carriers have the best energy index, followed by the container ships, while the ferry has the highest energy index.

When focussing on a particular ship, at high and medium speed, the energy index (I_E) is proportional to the square of the Froude number or the square of the ship speed. In Fig. 10, on a log-log scale, the slope of each line is approximately two at high F_n condition. In other words, ships could have higher transport efficiency when sailing at a lower speed. However, this advantage of low sailing speed on the energy index is limited, since at very low speed, other factors spoil the ship resistance, resulting in a relatively high energy index. Comparing the curves in Fig. 10 to those in Fig. 7, it reveals that, at lower sailing speed (smaller F_n), the curves in Fig. 10 are much gentler than those in Fig. 7. The energy index (I_E) decreases slower than the square of Froude number at low speed.

B. Influence of Speed Fluctuation

In this paper, mean speed is used in comparing the energy consumption and exhaust emissions of different transportation modes; however this simple assumption is not representative for real-life operation.

It is significant to look at some details of the influence of speed fluctuation on energy consumption and emission. A simple example, which is derived from the investigation of operational shipping activities, is presented in this case study.

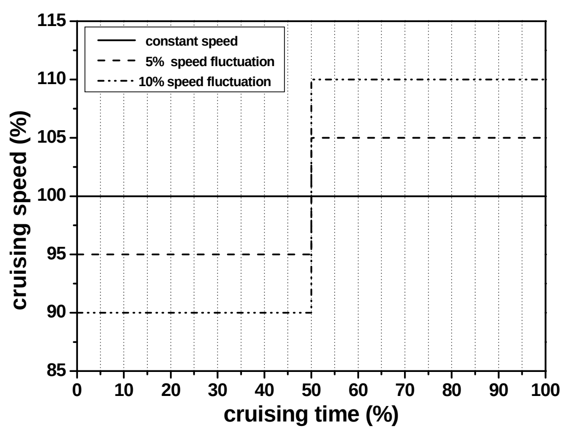

Fig. 11 Simple speed profiles of reference ships

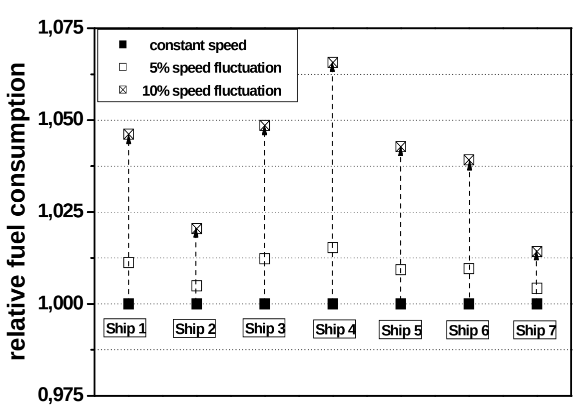

Fig. 12 Fluctuation of fuel consumption

When sailing at sea, the cruising speed of a ship could be different from the design speed, due to some unavoidable disturbance factors, like the weather conditions and the change of operational strategies. As an example, three scenarios are investigated: 1). the ideal case: the sailing speed remains constant during the whole voyage; 2). a small speed fluctuation case: during the first half of total time, sailing at a speed that is 5% higher than the sailing speed of case 1 and during the second half, sailing at a speed that is 5% lower than the sailing speed of case 1; 3). a large speed fluctuation case: during the first half of total time, sailing at a speed that is 10% higher than the sailing speed of case 1 and during the second half, sailing at a speed that is 10% lower than the sailing speed of case 1. It is also assumed that the operation mode for all the three scenarios is cruising. The speed profiles are illustrated in Fig. 11.

Fig.12 shows the results of these different speed profiles for seven reference ships by setting the fuel consumption of the constant speed operation strategy (case 1) at 100%. Evidently, as shown in Fig. 12, the bigger the speed fluctuation during the voyage, the higher the fuel consumption, in spite of the same mean speed.

C. Influence of Loading Conditions

For different loading conditions, the ship displacement is different too, resulting in a different wetted surface, which changes the ship resistance and thus the propulsion power and the fuel consumption [21].

As defined previously, the loading factor x is the ratio between the actual and maximum amount of payload. But with regard to real operation conditions, the mass displacement of a ship changes less than the payload, from full load to empty load, since in empty condition, for stability reasons ballast is taken on board. Thus, the payload is subdivided into two parts: the cargo (the benefit) and the ballast water (the penalty). In this case study, all the results are generated by using the actual loading factor x, and presented corresponding to the cargo load condition, the benefit loading factor x_b.

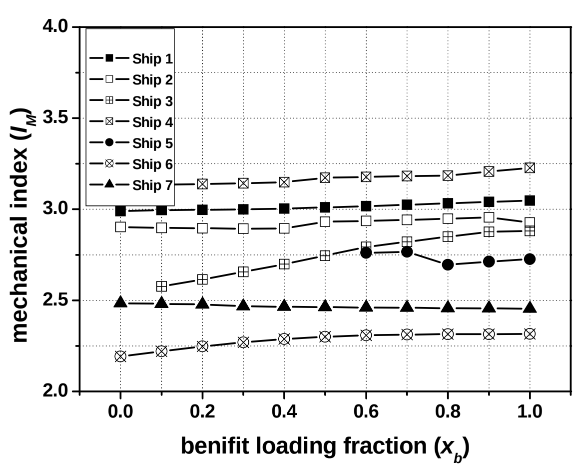

Fig. 13 Mechanical indices of ships

The range of the ships' mechanical index is 2~3 at service speed and full loading condition, as illustrated in Table II. In this case study, the mechanical indices in part loading conditions are estimated, as shown in Fig. 13. For each of the reference ship, the mechanical index remains almost constant for different loading conditions. In part load condition, both the ship resistance and the propulsion power change, with the ultimate result that the loading condition only has limited influence on ship moving performance.

When investigating the ship transportation performance in part loading conditions, the simulation results of Ship 1 (large container ship) are presented as an example in Fig. 14 – Fig. 16.

Looking at the absolute values in Fig. 14, it can be concluded that for sailing at low speed, the energy index (I_E) is lower than for sailing at high speed; these results agree with the previous analysis. Furthermore, at each sailing speed, the energy index (I_E) changes with loading conditions: the energy index (I_E) increases when the load decreases. In other words, when sailing in part load condition, in terms of transport efficiency, the ship has a worse transport performance than when sailing in full load condition.

Concerning the relative values, where the energy indices (I_E) in full load conditions are set at unity for each sailing speed, it is evident that the gaps of the energy index (I_E) between full load conditions and part load conditions increase when the sailing speed decreases. For Ship 1 (large container ship), at service speed (F_n = 0.234), the energy index (I_E) in 40% cargo load condition is about three times of that in full cargo load condition, whereas at low speed (F_n = 0.078) the energy index (I_E) in 40% cargo load condition is almost five times of that in full cargo load condition.

In Fig. 15 and Fig. 16, the curves that indicate the relationship between fuel consumption and sailing speed in different loading conditions, show that the more cargo load the ship takes, the steeper the curve is. Putting into words, these results are saying that in full load condition the influence of speed on fuel consumption is stronger than in part load conditions. Therefore, in part load conditions the advantage of low speed operation on fuel consumption is smaller than in full load condition. When looking at the ton-kilometre specific fuel consumption, as shown in Fig. 16, it can be seen that full load condition is more fuel efficient than part load condition and by decreasing the ship speed, the specific fuel consumption can be improved.

In this paper, the CO_2 and SO_2 emissions are primarily related to fuel properties and are considered as a function of fuel consumption. Thus, although all the presented results of this case study are focused on the fuel consumption, the conclusions also apply to the estimate of CO_2 and SO_2 emissions, since all the reference ships consume residual fuel in their propulsion system. Meanwhile, in a further precise prediction of ship fuel consumption and the corresponding exhaust emissions, the auxiliary system must be included, especially at low speed and berth conditions, when the auxiliary system may dominate the energy consumption.

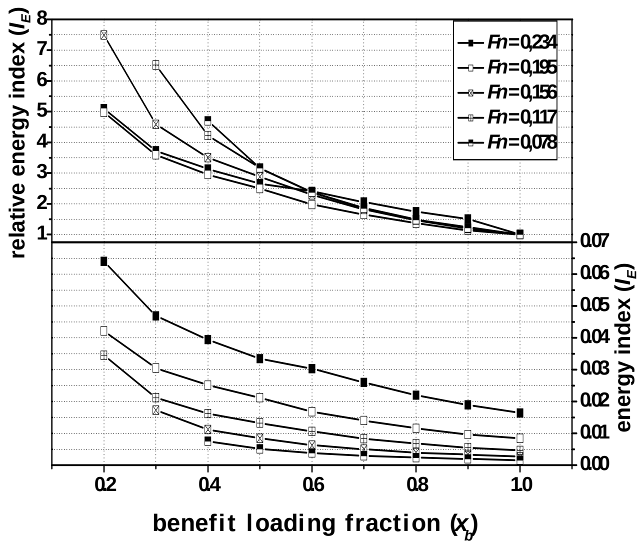

Fig. 14 Energy indices of Ship 1 in part loading condition

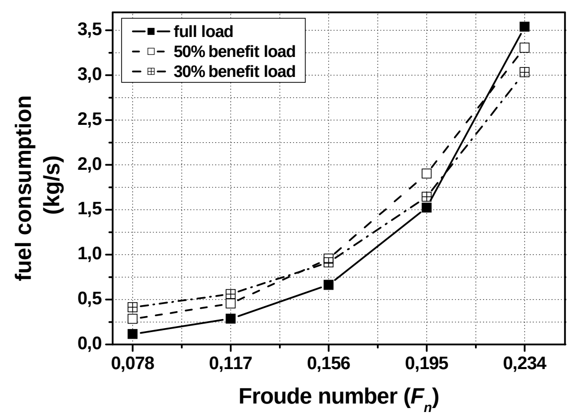

Fig. 15 Fuel consumption of Ship 1 in part loading condition in kg/s

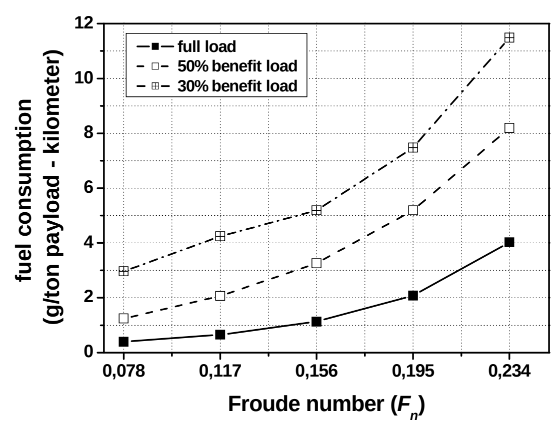

Fig. 16 Fuel consumption of Ship 1 in part loading condition in g/ton-km

VII. Conclusion

Both the mechanical index and the energy index are introduced, which represent the moving (mechanical) performance and the transportation performance of the transportation modes. By combining the definition of energy index and mechanical index, a non-dimensional is derived, which enables the comparison of results for different transportation modes.

It is demonstrated that, although there are different propulsion and transmission system in different transportation modes, from the mechanical point of view, the mechanical index, or the moving (mechanical) performance is similar.

On the basis of the mathematical description, the "energy index versus Square-Froude number" diagrams of different transportation modes in both full load and typical load conditions are presented. The comparisons of the results support the following conclusions:

1. Passenger transport systems consume more energy than cargo transport system on the basis of a energy index
2. Disregarding the cost of time, bulk carriers are the most economical transportation mode.
3. For high speed train transportation modes, the faster ones have a better energy index. For low speed transportation modes (ship, car, truck), increase of speed results in a rapid increase of energy consumption. Accordingly, the fast ship could be an uneconomical case.

In view of the ton-kilometre specific fuel consumption and CO_2 emission, it has been found that cargo ships are still superior as a low speed transport system, not only because of their good energy index, but also because of the large cargo capacities. However, when considering the SO_2 emission, the advantage of cargo ships is counteracted by the use of heavy fuel oils with high sulfur content and as a result the land based vehicles emit the least amount of SO_2.

By means of a case study of ships, some detailed results of the mechanical index and energy index are presented:

1. When sailing at low speed, the ship may have bad moving performance, whereas the part loading operation only makes a little contribution on the moving performance.
2. In view of energy index and fuel consumption, low speed operation strategy could bring benefits, whereas the part load operation strategy would result in penalties.
3. Considering the cruising part, a larger speed fluctuation causes higher fuel consumption.

Future research will focus on more details of the propulsion system and auxiliary system for each transportation mode and will include the transient operational conditions. Furthermore, for ships, more energy efficient and environmental friendly operational strategies should be explored.

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APPENDIX

Refer to [22]

	SHIP 1	SHIP 2	SHIP 3	SHIP 4	SHIP 5	SHIP 6	SHIP 7
Classification	**Large Container ship**	**Medium Container ship**	**Container feeder**	**Coastal feeder**	**Large Bulk carrier**	**Medium Bulk carrier**	**Ferry**
Name	Ned Lloyd Southampton	Dole Chile	Jork	Friesedijk	CKS Fortune	Jin Hui	Stena Jutlandica
Dimensions							
Length o.a., *m*	299.9	204.9	157.13	100.8	289	189.99	184.35
Length p.p., *m*	283.8	193.4	147	92.9	279	182	169.05
Beam mld, *m*	42.8	32.24	23.5	15.85	45	32.26	27.8
Draught, *m*	13.5	10.2	8.3	4.88	16.5	10.75	5.8
Depth, *m*	24.4	20.8	12.8	6.18	24.5	16.69	9.4
Cb	0.662	0.649	0.64	0.755	0.84	0.808	0.602
Cw	0.773	0.763	0.756	0.895	0.908	0.884	0.728
Tonnage							
DWT, *ton*	83826	30560	11870	3820	156300	44579	5640
Displacement, m^3	111825	42540	18903	5585	179250	52559	16903
Machinery							
Main engines							
Install power, *kW*	65880	23920	10920	3280	16858	8203	6480*4
Speed, *rpm*	100	97	135	750	91	118	550
Fuel type	HFO	HFO	HFO	HFO	HFO	HFO	HFO
Aux engines							
Install power, *kW*	3600*4	3840*3/2880*2	900*2	275*2	750*3	490*3	1760*4
Speed, *rpm*	600	600	900	1500	720	720	750
Fuel type	MDO	MDO	MDO	MDO	HFO	MDO	HFO
Propellers							
Type	Fixed pitch	Fixed pitch	Controllable pitch	Controllable pitch	Fixed pitch	Fixed pitch	Controllable pitch
Diameter, *,m*	8.75	6.65	5.1	3.2	8.1	6.35	4.8*2
Speed, *rpm*	100	97	135	184	91	118	150
Speed							
Service speed, *knot*	24.5	21	19	15	15	14	21.5