A Report on Research Concerning the Reduction of CO_2 Emission from Vessels

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Ship & Ocean Foundation

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CO_2 Emission from Vessels

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Preface

This report is a compilation of the result from the “ Research Concerning the Reduction of CO$_2$ Emission from Vessels “ project, which was implemented with the financial assistance of the Nippon Foundation, from the proceeds of motorboat racing.

Since the Third Conference of the Parties to the UN Framework Convention on Climate Change (UNFCCC) held in Kyoto in December 1997, the International Maritime Organization has maintained its demand for an investigation into the current amount of emission released from ocean going vessels, of such global warming gases as CO$_{2,}$ and the development of plans to reduce such emissions. With a view to this, through the Maritime Environment Preservation Committee, IMO has begun an extensive research investigation into global warming gases.

This research project, in line with the movements of the above organizations, investigation, investigates the amount CO$_2$ emissions by vessel size and type, while also researching potential CO$_2$ reduction plans. This includes plans such as improving vessel engine heat efficiency and propulsive performance, as well as operational efficiency options such as the research into ocean going vessel operating speed and weather routing (optimal route selection procedures based on atmospheric and oceanographic conditions).

This study could not have been completed without the devoted assistance and guidance of the members of the “Investigative Committee on Research Concerning the Reduction of CO$_2$ Emission from Vessels”, chaired by Prof. Masasu Hirata of Shibaura Institute of Technology, immeasurable support from the Japan Ministry of Transport and the extensive cooperation of many other related individuals. We would like to express our deepest gratitude for your enormous contributions.

In addition to helping reduce the emissions of global warming substances and thereby contributing to the preservation of the global environment, we hope that this report will be of great help to many people.

March 2000
Kensaku Imaichi
Chairman,
Ship & Ocean Foundation

※ Please note that this is the English version of the Japanese Research Report that was issued in March of 2000.

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1. Executive Summary

1.1 Investigation Objective

Recently, as part of its concern for environmental problems, the International Maritime Organization (IMO) has taken actions to counter such air pollutants as NOx, SO_X and CFCs/PPCs by developing a new appendix to the MARPOL 73/78 convention. The Organization has also expanded its attention on the global environment in the appendix to stress that increases of greenhouse gases such as CO_2 should be kept at a minimum.

Since the COP3 conference held in Kyoto by the parties to the United Nation Framework Convention on Climate Change, the IMO has been required to study current CO_2 emission amount from ocean vessels and to develop solutions.

The protocol under this framework omits CO_2 emissions by international navigation from country-specific emission volumes of both member and non-member countries. Thus, the emission reduction efforts related to bunker oil consumption have not been properly shared and the study of bunker oil consumption has not been adequately performed. The UNFCCC has requested the IMO to conduct a global-level study of greenhouse gas emissions that are attributable to ocean vessels and to take actions necessary. In response to this growing awareness, this year the MEPC launched a research initiative of global warming gases.

Appropriate solutions require improvements to engine heat efficiency and operating efficiency, as well as long-term R&D on CO_2 reduction technologies including operating patterns and increased cargo occupancy. This project studies CO_2 emissions by vessel size and type, specifies possible solutions and finally calculates emission reductions possible in the future.

1.2 Investigation Procedure

The project this year has been conducted as follows.

1999

August 2	First Investigation Committee
September 7	Interview with the Maritime Industry Institute
October 26	Interview with Mitsubishi Heavy Industries at its Kobe Dockyard
November 22	Interview with Ship Machinery Industry and Shipbuilders' Association of Japan
November 24	Interview with Japan Naval Engineering Center
December 13	Second Investigation Committee

2000

February 29	Third Investigation Committee

1.3 Investigation Methods

This investigation deals specifically with CO_2 emissions from ocean vessels and omits emissions from domestic vessels, inner bay cargo ships, fishery boats, and harbor cargo handling machinery. This is because the Japanese government has set emission reduction targets for the non-ocean vessel group and its reduction plans have been subject to overall reviewed.

COP3 specified reduction targets for six global warming substances: CO_2, CH_4, N_2O, HFC, PFC and SF6. Among the substances attributable to ocean vessels, an enormous amount of CH4 emissions originate from vessel engines under low load and from evaporation from crude oil tankers. HFC is a substitute for CFC and believed to leak from refrigerated cargoes ships. However, this investigation primarily targets CO_2 emissions and reduction solutions.

1.3.1 Investigation of CO_2 emissions from vessels

(1)Investigation of calculation methods for CO_2 emissions

Global CO_2 emission have been calculated indirectly based on the shipped volume of bunker oil. However, shipping locations and actual oil consumption routes are not necessarily consistent. It is still not possible to specify regional emission amounts or consumption distributions by vessel type. Calculation methods of fuel consumption by area and vessel type have been reviewed. Required parameters and reference values were organized using an estimation of cargo movement method to study the accuracy of the calculation methods.

(2)Questionnaire Survey

As discussed in (1), accurate estimates of fuel consumption per freight transportation volume would help improve numerical accuracy and enable the calculation of CO_2 emissions by area or vessel type.

The fuel consumption amounts described in Japanese vessel specifications have been exhaustively studied to identify catalog values of fuel consumption over the past 10 years and to organize values by vessel type and size. In addition, members of the Shipowners' Association of Japan and others were interviewed concerning operation modeling to develop a global standard operation model.

(3)Assessment of CO_2 emissions by vessel type and operation pattern

CO_2 emission amounts by ship type and operation pattern were estimated based on the calculation methods described in (1) and the survey result and statistical materials in (2). In this assessment, temporary fuel consumption amount is defined by cataloged figures of fuel consumption based on the fuel consumption or deadweight given in the specifications for each vessel size, engine model, model year and vessel age. These were provided by vessel specifications of the vessels under Japanese control.

1.3.2 Investigation of solutions for vessel

By studying existing documentation, improved model development technologies, engine efficiency refitting and fuel conversion were identified as means of improving the efficiency of the hardware aspects of vessels. Interviewing members of the Shipbuilders' Association of Japan and academics helped to further review the reduction impact of these technologies.

Issues were broadly classified into two categories based on the length of time for implementation. Short-term issues included improved model development, while long-term projects included fuel conversion to Type-C heavy oil or LNG.

Short-term projects were reviewed to roughly quantify their reduction impact and cost, whereas long-term items were studied for their technological limitations such as the reducible amount of CO_2.

1.3.3 Investigation of solutions for vessel operation

Possible actions to improve vessel operation efficiency were selected from existing documentation and studied for their reduction effectiveness. The best and most cost effective option, slow steaming, was studied in terms of consumer demand for transport speed and classified by load type. Interviews were conducted to assess further implementation and to specify any improvement possibilities of weather routing.

One long-term solution is a modal shift from air-freight transportation to marine transportation. However this issue was reserved for future review.

1.3.4 Review of solution implementation methods

(1)Options to reduce CO_2 emissions

The effectiveness of reduction options was roughly quantified by combining the CO_2 emission amounts calculated in 1.3.1 and the options for emission reduction specified in 1.3.3.

(2)Implementation framework for options to reduce CO_2 emissions

Information of such government incentives as the introduction of a CO_2 emission tax for surface transportation, Activities Implemented Jointly (AIJ) and Clean Development Mechanism (CDM), as well as the possibility of joint implementation for flags of convenience vessels were organized by analyzing the business climate of COP4 and COP5.

1.4 Investigation result overview

1.4.1 Investigation of CO_2 emissions from vessels

(1)Investigation of calculation methods of CO_2 emissions

Based on statistical analysis, annual bunker oil consumption is estimated at 131.8×10^6 t/y (CO_2 emission equivalent of 3.95×10^8 t/y). A navigation speed category was established based on vessel size and age to allocate the world transportation tonnage mile recorded amounts.

(2)Questionnaire Survey

Fuel consumption amount per transportation tonnage mile was calculated for vessel type, size and age by combining fuel consumption amounts specified in vessel specifications and size figures of actual navigation speed, cargo loading rate and engine unit deterioration over time that were developed from interviews. Vessels built in the 1990s are estimated to be 70% to 80% more efficient in gas mileage performance than equivalent models made in the 1970s.

(3)Assessment of CO_2 emissions by vessel type and operating pattern

Annual fuel consumption by vessel type is distributed as tankers 31%, bunkers 29%, and container vessels 33%. However, the actual operating conditions of container vessels are not clear and the figures presented should be assumed to be less accurate. The fuel consumption distribution for the vessel types based on accumulated data is approximately the same as the values above.

1.4.2 Investigation of solutions for vessel engines

Heat efficiency of Vessel main engines improved 20% during the 1990s. However, efficiencies have stayed unchanged for the past few years. Heat efficiency is expected to rise by 4% to 6% for 2 cycle engines and 4% to 8% for 4 cycle engines due to computerized fuel injection systems. But it should be noted that heat efficiency improvements come at the cost of increased NOx emissions. Engine energy consumption has improved by 15% due to improved model development over the past 20 years. Model modifications are expected to provide up to 5% further improvement. Potential fields of technological improvement are PBCF, counter-rotating propellers and ship bottom coatings (excluding organic tin compounds). Some of these have already been put into practical use. However, cost issues must be addressed before these technologies become widely popular.

1.4.3 Investigation of solutions for vessel operation

Slow steaming and weather routing were examined as potential solutions for vessel operation.

Reducing navigation speed by 10% would lessen fuel consumption by 10% to 20% even with the prolonged traveling time required to cover the same distance. Though, it is not necessarily consistent with the growing demand for faster transportation service in the modern society.

Navigation time reduction impact by WRS, for example in the North Pacific Route (which takes a rapid ship 10 days), is estimated at 5% to 10% per voyage according to our investigation. With anticipated development in both quantity and quality of available observation data, forecastable time period can be extended to help expand the WRS effectiveness and its popularity.

1.4.4 Review of solution implementation methods

(1)Options to reduce CO_2 emissions

Transportation volume forecasts are based on the volume variation by age for each vessel type. The total amount of annual fuel consumption was calculated using this forecast. The calculation indicates that refitting older vessels would decrease annual consumption only slightly with a constant vessel transportation volume. Refitting of older vessels would cause no change or a slight increase to annual consumption with some increase in the transportation volume. However, implementation of both refitting older vessels and a 10% to 20% reduction in operating speed would immediately decrease annual consumption, followed by a continuous small decreases.

(2)Implementation framework for options to reduce CO_2 emissions

Land-based transportation emissions have been discussed at COP with regard to the regulatory issues associated with carbon taxes and emissions trading systems. Demand is growing for the establishment of private CO_2 emissions trading systems in Chicago and London markets. Supposedly, a similar framework could be implemented for global marine transportation. Close attention needs to be paid to actions by international organizations regarding surface transportation emissions.

2. Investigation Overview

The flowchart below provides an overview to the investigation.

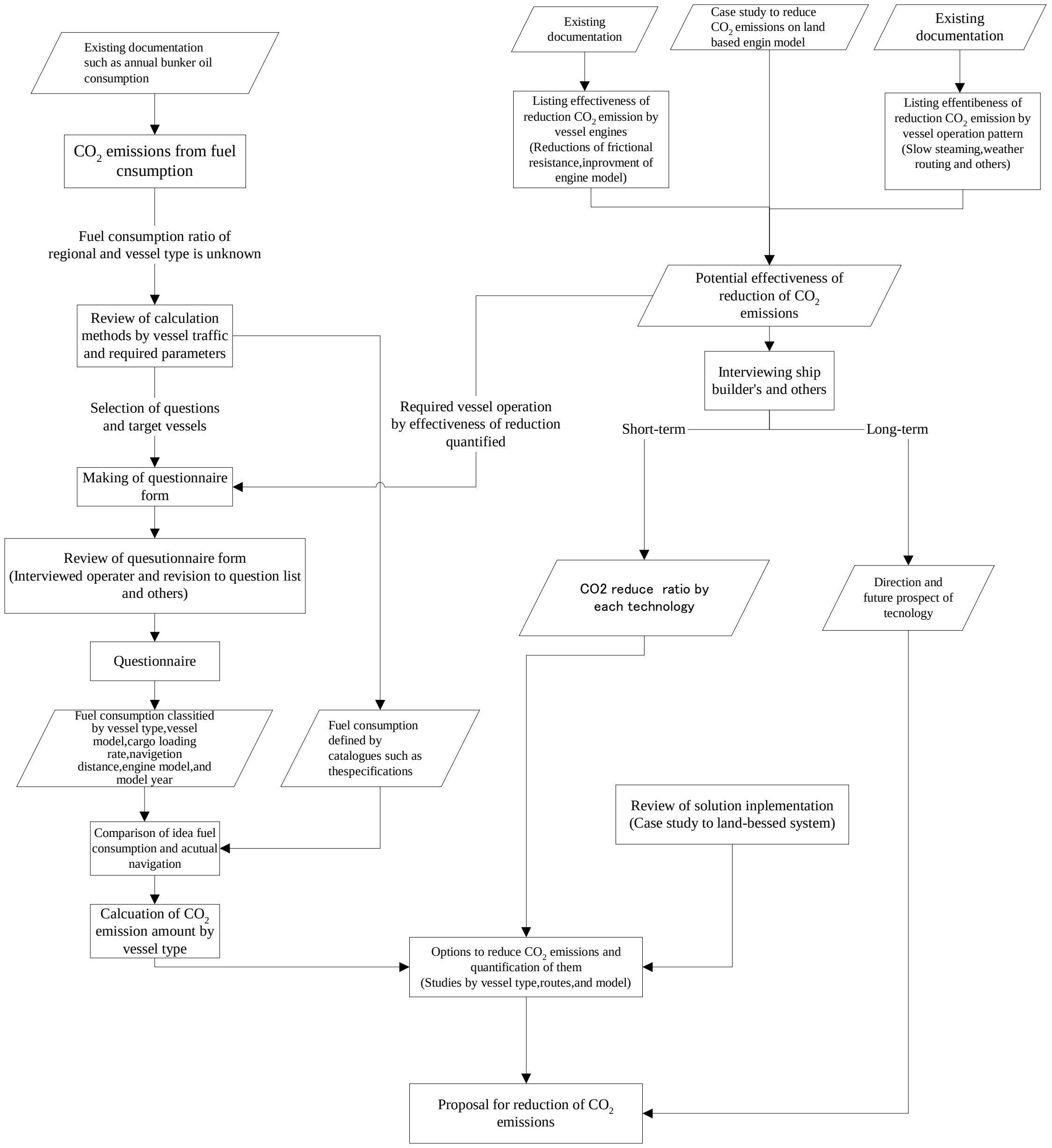


Figure A 1999 Investigation procedure of vessel CO_2 emission containment

3. Investigation Details

3.1 Investigation of CO_2 emissions from vessels

3.1.1 Investigation of calculation methods of CO_2 emissions

(1)Macro level CO_2 amount generated from fuel consumption

Table 1 shows the findings of the 1998 Ship and Ocean Foundation study on CO_2 emissions from vessels. Included are both statistical figures with specific fuel consumption amounts and estimates based on transportation records. For example, global domestic trading is extrapolated from OECD shipping fuel amounts. The global consumption by fishery and leisure vessels is extrapolated from Japanese domestic fuel consumption based on the number of ships in service as well as actual consumption findings.

The table shows all amounts of vessel-related CO_2 emissions. However, emissions classified as sourced from domestic trading, fishery and leisure vessels are subject to national reduction targets by each UNFCCC member nation and thus are not dealt with by this investigation.

Table 1 1995 CO_2 emissions from vessels (10^3t-CO_2)

	Gas/Diesel oil	Heavy Fuel Oil	Motor Gasoline	Total emission	Percentage
Domestic Trading	48,136	25,791	17,199	91,127	16%
Fishery	34,952	300	4,459	39,711	7%
Leisure	-	-	28,665	28,665	5%
Marine Bunker	88,230	271,673	-	359,904	69%
Total	171,318	297,764	50,323	519,407	100%

Marine bunker emissions are an adjusted total of OECD and Non-OECD member nations based on the 1998 Ship and Ocean Foundation study.

Table 2 indicates the discrepancies among marine bunker statistical amounts released. The table shows a difference of approximately 20% among the totals. However, a reasonable amount for the global consumption of marine bunker fuel would be approximately 100×10^6 t. This study assumes a robust amount (a larger emission amount) for the global consumption of marine bunkers.

Table 2 Statistical discrepancies of marine bunker fuel consumption (1995)

10^6t

	Gas/Diesel Oil	Heavy Fuel Oil	Motor Gasoline	Total
Marine Bunker Total of OECD and Non-OECD member nations	30.0	101.8		131.8
Bunkers in UN Material (for reference)	28.8	90.6	-	119.4

Based on Energy Statistics of OECD Countries 1994-1995 (OECD/IEA, 1997) and Energy Statistics and Balances of Non-OECD Countries 1994-1995 (OECD/IEA, 1997).

Excerpt from the 1996 Energy Statistics Yearbook (UN, 1998). Heavy Fuel Oil volume for marine bunkers is taken from the Residual Fuel Oil classification in UN material.

Gas/Diesel Oil is equivalent to MDO. Heavy Fuel Oil corresponds to MFO.

Table 3 shows a comparison of vessel emissions and land-based transportation emissions included in Table 2. The Oak Ridge Laboratory calculates a global emission total, including the amount of CO_2 emissions, corresponding to bunker oil consumption. As indicated in the table, vessel-based emissions comprise 2.2%, of which bunker oil accounts for 1.5% and almost equals the national total CO_2 emissions of France.

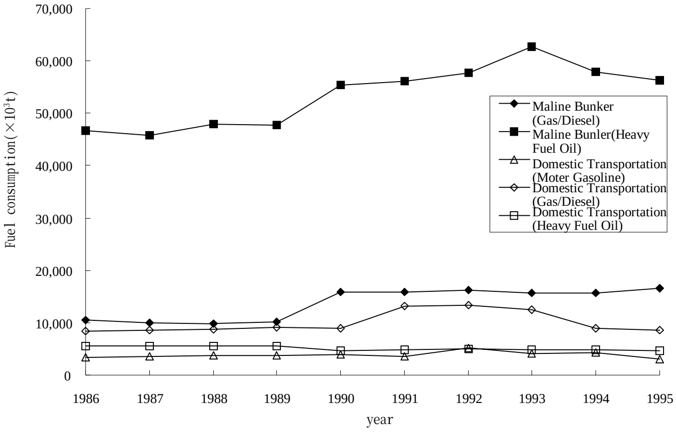
Table 3 Comparison of CO_2 emissions worldwide

		CO_2 emission (10^3 t)	Percentage
World Total		23,503,000	100.0
Vessel Emissions (Including those by fishery, leisure and domestic transportation)		519,407	2.2
of bunker		359,904	1.5
From Major Countries of CO_2 Emissions	USA	5,214,000	22.2
	Japan	1,218,000	5.2
	Sweden	585,000	2.5
	UK	581,000	2.5
	Canada	499,700	2.1
	France	385,000	1.6

Based on the 1999 Ship and Ocean Foundation study, the values shown are from 1995. Nation-specific figures are provided by the IPCC. The total global emission amounts are provided by the Oak Ridge Laboratory CO_2 Information Analysis Center.

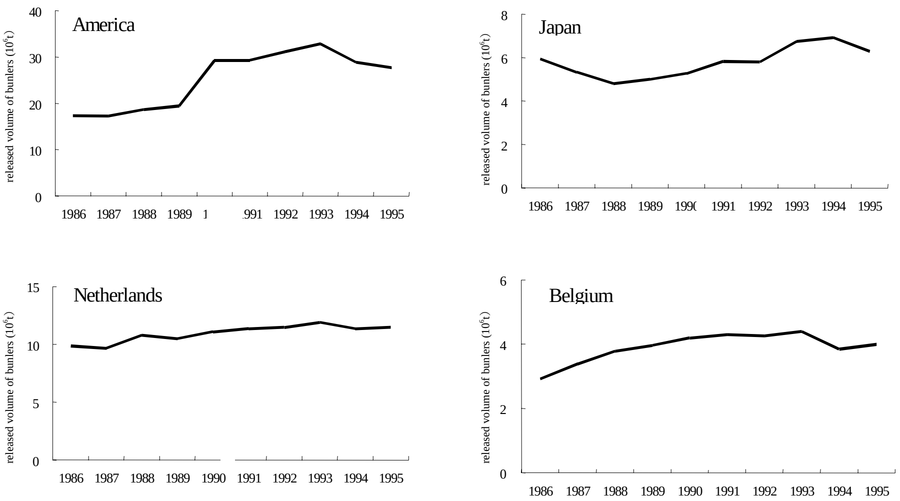
Recent bunker releases are shown in Figure 1, Figure 2 and Figure 3, below.

The total released volume among OECD countries is gradually increasing, as are Japan's release volumes. Moreover, the volume of non-OECD countries shown in Figure 3 indicates that the increases of the main countries (non-UNFCCC members) including Singapore and the United Arab Emirates exceed the overall growth among OECD countries.



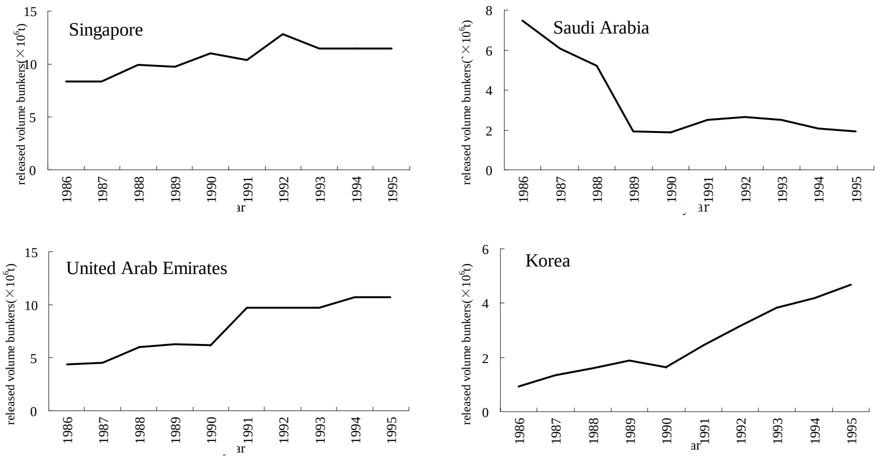
Based on Energy Statistics of OECD Countries (OECD/IEA)

Figure 1 Annual fuel consumption by vessels in OECD countries



The average shipped volume of the top four countries from 1987 to 1995 derived from Energy Statistics of OECD Countries (OECD/IEA, 1997).

Fig. 2 Annual shipped volume of marine bunkers among major OECD countries

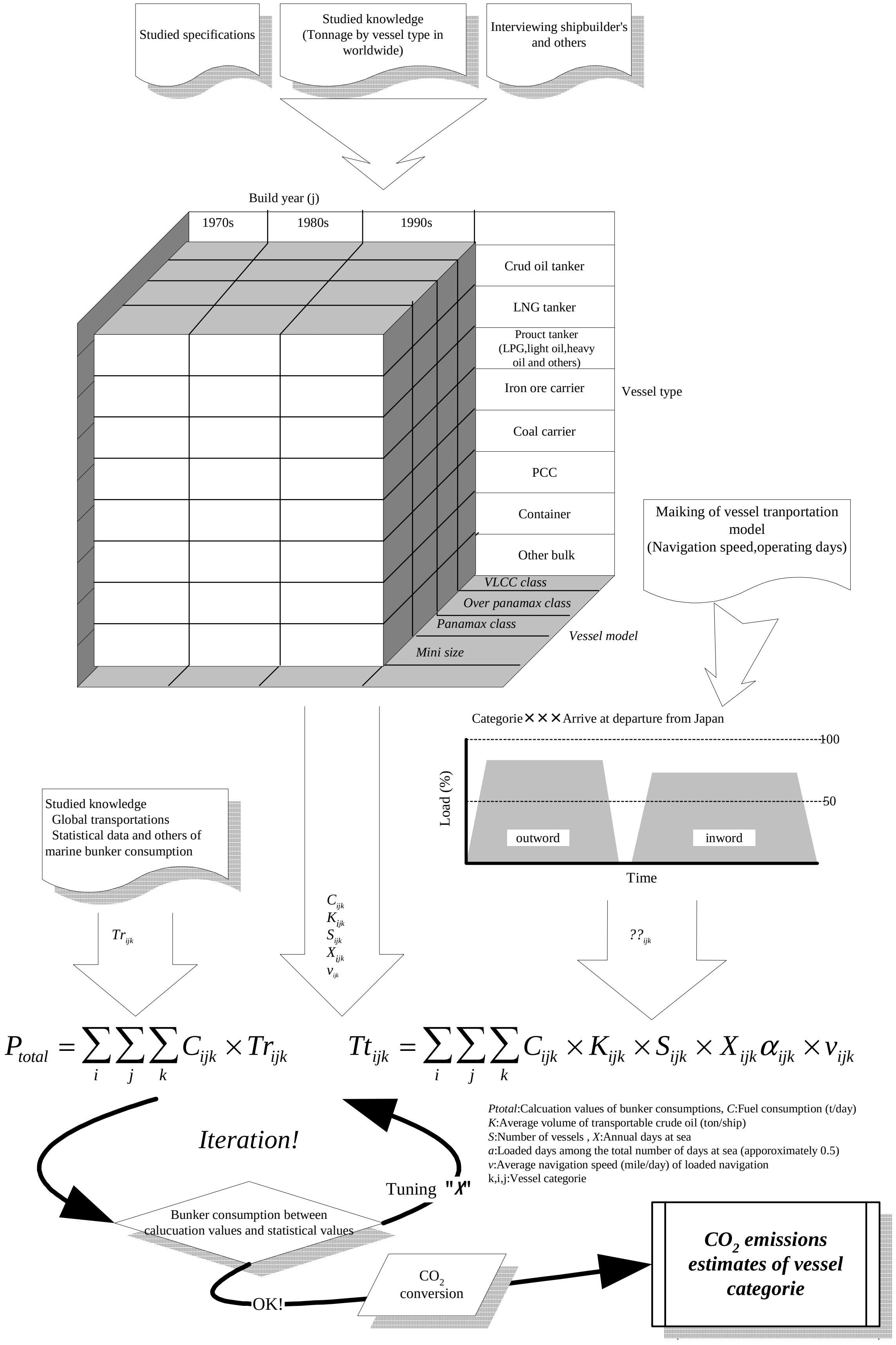


Energy Statistics and Balances of Non-OECD Countries 1994-
The top four countries of average shipped volume from 1987 to 1995 based on 1995 (OECD/IEA, 1997)

Figure 3 Annual released volume of marine bunkers among major non-OECD countries

(2)Calculation method of CO_2 emission

The amount of CO_2 emissions based on fuel consumption is calculated from each country’s marine bunker shipped volume. However, shipping locations and oil consumption routes are not necessarily consistent with the volume of marine bunker shipped. Therefore the amount of CO_2 emissions based on shipped volume may not match regional emission amounts. The emission amount distribution by sea area (navigation route) and vessel type needs to be identified to accurately evaluate and control CO_2 emissions. Presently, statistical data on imported/exported cargo volumes are collected by each country and is relatively easy to maintain accuracy. Therefore, it is best to use transportation tonnage mile emission amounts, based on the actual navigation records, as shown in Figure 4 when calculating fuel consumption amounts by region and vessel type.



$$P_{total} = \sum_{i}\sum_{j}\sum_{k} C_{ijk} \times Tr_{ijk}$$

$$Tt_{ijk} = \sum_{i}\sum_{j}\sum_{k} C_{ijk} \times K_{ijk} \times S_{ijk} \times X_{ijk}\alpha_{ijk} \times v_{ijk}$$

Ptotal:Calcuation values of bunker consumptions, *C*:Fuel consumption (t/day)
K:Average volume of transportable crude oil (ton/ship)
S:Number of vessels , *X*:Annual days at sea
a:Loaded days among the total number of days at sea (apporoximately 0.5)
v:Average navigation speed (mile/day) of loaded navigation
k,i,j:Vessel categorie

Figure 4 Basic overview to estimating CO_2 emissions from ocean vessels

(3)Assessment method of vessel transportation volume by vessel type and size

The volume of global transportation is shown as a comparison of transportation tonnage and transportation tonnage mile by cargo type in Table 4. Transportation TEU is also shown for container vessels. Transportation tonnage comprises 772×10^6 tons with 23t/TEU (loaded container average for the port of Yokohama in 1998) and would account for as much as 30% of total bulk transportation tonnage. Crude oil comprises the majority of both tonnage-based and tonnage mile based groups among bulk transportation. Crude oil is also expected to capture a large share of total fuel consumption. The breakdown of intra-regional crude oil transportation indicates that 20% or less of the total transportation cycle has Japan as its port of destination. Thus, crude oil tankers need to be examined in detail since a corresponding emission amount is certainly expected from shipments traveling to Japan.

Table 4 Global transportation (*TR*) in 1997

	Transportation Quantity (10^6 ton)	Transportation Quantity (10^9ton- mile)	Average Transportation Distance (10^3mile)
Crude Oil	1,534	7,677	5.00
Other Oil Products	410	2,050	5.00
Iron Ore	430	2,444	5.68
Coal	460	2,332	5.07
Grain	203	1,169	5.76
Bauxite and Alumina	54	206	3.81
Phosphate	32	133	4.16
Total Dry Bulk	1,179	6,284	5.33
Total Bulk	2,713	13,961	5.15
Container (original data in TEU)	$33{,}550 \times 10^3$TEU 772 t (When 1TEU 23t)		

Fernley's Global Bulk Transportation Volumes 1998,1999 Ministry of Transportation Report of Marine Transportation in Japan

(a)Estimate of crude oil tanker transportation volumes and average number of days at sea

The oil tankers were studied to design an allocation method for tonnage mile transportation volume by vessel size and age. Typically, crude oil tankers operate filled to capacity on outward voyages and run under unloaded condition(ballasted condition) on backhaul trips in so called ballast status. Thus, model development is considered straightforward due to the relatively simple cargo loading rate and navigation pattern. As shown in Table 4, Fearnley's Marine Transportation Institute has developed source material on annual regional transportation volumes TR (ton-mile/year) by crude oil tankers. However, this material does not offer vessel size breakdowns by class or actual navigation time. Based on the formula shown below, a transportation model was created on the assumption that all tankers operate below a specified average navigation speed.

Annual crude oil transportation volume *TR* (ton-mile/year) by crude oil tankers can be given by following formula where *I* is class of crude oil tanker and *j* is year of manufacture.

Transportation total volume $$TR = \sum_i \sum_j tr_{ij} \quad , \quad tr_{ij} = K_{ij} \times S_{ij} \times X_{ij} \alpha_{ij} \times v_{ij}$$

tr_{ij} : Crude oil transportation quantity (ton-mile/year) for i and j categories

K_{ij} : Average volume of transportable crude oil (ton/ship) for i and j categories
S_{ij} : Number of Vessels for i and j categories
X_{ij} : Annual days at sea (280day/year) for i and j categories
α_{ij} : Loaded days among the total number of days at sea (approximately 0.5) for i and j categories
v_{ij} : Average navigation speed (mile/day) of loaded navigation for i and j categories

TR, K, S have been identified in the statistics described above, while X and v represent the average actual transportation conditions for each category. Originally, these parameters were to be acquired in detail for each vessel size and vessel age because of their close association with operation patterns and capacity operation rate. However, these data are currently not available on a global level. For this reason, X and α are fixed regardless of vessel size or age, and v is set for each average transportation model, created on the navigation speed of brand new vessels with adjustments for sea margin and age deterioration.

Table 5 shows a distribution map of existing tankers worldwide by vessel age and size.

Tankers of $320*10^3$ DWT (ULCC of 160,000 gross total tonnage) or greater have not been built since 1985. Nonetheless, construction of the next smaller size VLCC tankers with total tonnage of 300,000 or less has been on the rise. According to World Oil Tanker Trends by Jacobs & Partners, there were 3,367 commercial tankers (including associated product and gas tankers) of 10,000 tons or more at the end of 1998. The estimated number of oil tankers en route worldwide is approximately 3,000. Table 6 shows the estimated transportable amount of oil for each tanker. In this table, the amount of such non-cargo loads as ballast water and vessel operating fuel, as well as the number of days required for cargo handling, are based on the average DWT in each category. Consequently, the oil tank size (transportable oil amount) is set at 90% for large tankers of 100,000 DWT or more and at 80% for other medium-sized tankers.

Table 5 Tanker size and age distribution
(Distribution of existing tankers worldwide by vessel age and size)

DWT(10^3ton)	-1978	1979-83	1984-88	1989-3	1994-98	Total
10-25	185	82	48	21	34	371
25-50	303	146	145	127	157	878
50-80	61	120	58	40	10	289
80-100	104	89	65	99	53	410
100-120	13	8	17	26	50	114
120-200	117	17	14	83	58	289
200-320	132	9	28	113	91	373
320+	43	9	-	-	-	52
Total	960	479	375	509	453	2,776

Existing vessel counts for each DWT are based on Fearnley’s World Bulk Fleet January 1999. Stockpile tanker counts (21) have been excluded in advance.”-”indicates that a tanker of the given size does not exist.

Table 6 Average amount of oil transportable by tankers (t-crude oil/vessel)

DWT(10^3ton)	-1978	1979-83	1984-88	1989-3	1994-98
10 -25	14,545	14,337	14,167	12,143	12,500
25 -50	27,778	30,068	31,655	32,795	34,650
50 -80	53,468	51,557	54,224	57,375	59,500
80 -100	75,192	73,539	74,538	79,848	80,189
100 -120	97,143	95,625	90,000	88,269	90,100
120 -200	118,292	127,500	115,357	121,867	123,103
200 -320	229,375	226,667	209,464	232,434	247,527
320 +	334,457	340,000	-	-	-

The oil tank size (transportable oil amount) is set at 90 % of DWT for large tankers of more than 100,000 DWT and at 80% for medium-sized tankers. The average DWT of each category is used to determine an average transportable amount. “-”indicates that a tanker of the given size does not exist.

The theoretical transportable tonnage (total tons of oil tank) total for all tankers is approximately 269×10^6 tons. This represents a crude oil transportation total of $1{,}534 \times 10^6$ tons from Table 4 carried on an average of 5.7 voyage/year if transportation distances are ignored. Estimating navigation speed of each category based on the transportation distances shown in Table 7 gives the transportation tonnage mile breakdown as presented in Table 8 on the assumption that all tankers were uniformly involved in crude oil transportation.

It should be noted that older tankers built prior to 1978 and VLCC tankers of 200,000 to 320,000 DWT would have a sizable share of the transportation volume in the age and size classifications, respectively.

Annual total days of both outward and inward voyages are estimated to be 205 days. Specifically, small tankers can be involved primarily in domestic shipping or the transportation of such other petroleum products as heavy oil as described in a following chapter.

Table 7 Average navigation speed of tankers (knot)

DWT(10^3ton)	-1978	1979-83	1984-88	1989-93	1994-98
10 -25	11.0	11.0	12.0	13.0	14.0
25 -50	11.0	11.0	12.0	13.0	14.0
50 -80	11.0	11.0	12.0	13.0	14.0
80 -100	13.5	13.5	14.0	15.0	16.0
100 -120	13.5	13.5	14.0	15.0	16.0
120 -200	13.5	13.5	14.0	15.0	16.0
200 -320	13.5	13.5	14.0	15.0	16.0
320 +	13.5	13.5	-	-	-

Navigation speed of new vessels is estimated based on average navigation speeds from the vessel specifications. Expected speed decline is set at 5%/10 years under a fixed load operation.”-”indicates that a tanker of the given size does not exist.

Table 8 Transportation volume estimates of crude oil tankers by vessel size and age

10^9 Tonmile /year

DWT(10^3ton)	-1978	1979-83	1984-88	1989-93	1994-98	Total
10 -25	70	31	20	8	15	144
25 -50	219	115	133	132	188	787
50 -80	85	163	91	73	21	432
80 -100	250	211	164	289	168	1,081
100 -120	41	24	52	84	178	378
120 -200	440	72	55	370	281	1,218
200 -320	968	64	198	961	888	3,079
320 +	464	93	0	0	0	558
total	2,538	773	712	1,917	1,737	7,677

Total transportation volume is based on Fearnley's World Bulk Fleet, January 1999.
The average number of days at sea is 205. "-"indicates that a tanker of the given size does not exist.

(b) Transportation volume estimate of other petroleum products and the average number of days at sea

Although the transportation record (TR) in Table 8 reflects neither the transportation of petroleum products other than crude oil nor crude oil domestic transportation, Table 9 shows that both of these are expected to have occurred. If large vessels, including VLCC, were engaged in the transportation of other petroleum products, an estimated annual average of 71 days can be derived. This is due to the limited amount of information available on capacity operating rates between small and large tankers, and between old and new tankers. Information is also limited on the distribution between long and short distance transportation routes.

If the average number of 205 days at sea in the previous paragraph is combined with the transportation of other petroleum products and domestic transportation as in the table, and if LPG, LNG large tankers are all included as oil tankers, then the annual average number of days at sea can be calculated as approximately 280. This seems to be a reasonable and suitable value.

Table 9 Fearnley's transportation records of petroleum products not subject to statistical records

		Transportation	
		Ton Mile	Ton
		10^9 ton-mile	10^6 ton
Crude oil	Around North Sea	82	103
	With in Japan	28	26
	With in USA	78	65
	Other Areas	337	96
Total of domestic crude oil transportation		525	290
Other petroleum product transportation		2,050	410
Transportation by Tankers		2,575	700

Area specific transportation volumes are based on import/export volumes, intra-regional transportation volumes and average navigation distances.
Other petroleum products are based on Fearnley's World Bulk Fleet, 1999.

Table 10 Estimated transportation volumes of petroleum products by oil tankers

10^9 Tonmile /year

DWT(10^3ton)	-1978	1979-83	1984-88	1989-93	1994-98	Total
10-25	24	10	7	3	5	48
25-50	73	39	45	45	63	264
50-80	29	55	30	24	7	145
80-100	84	71	55	97	56	362
100-120	14	8	18	28	60	127
120-200	148	24	19	124	94	409
200-320	325	22	66	322	298	1,033
320+	156	31	-	-	-	187
Total	851	259	239	643	583	2,575

(As per domestic transportation of other petroleum products and crude oil)
When liquid tankers uniformly provide all transportation listed in Table 9, the number of days at sea for crude oil tankers increases by 71 days.

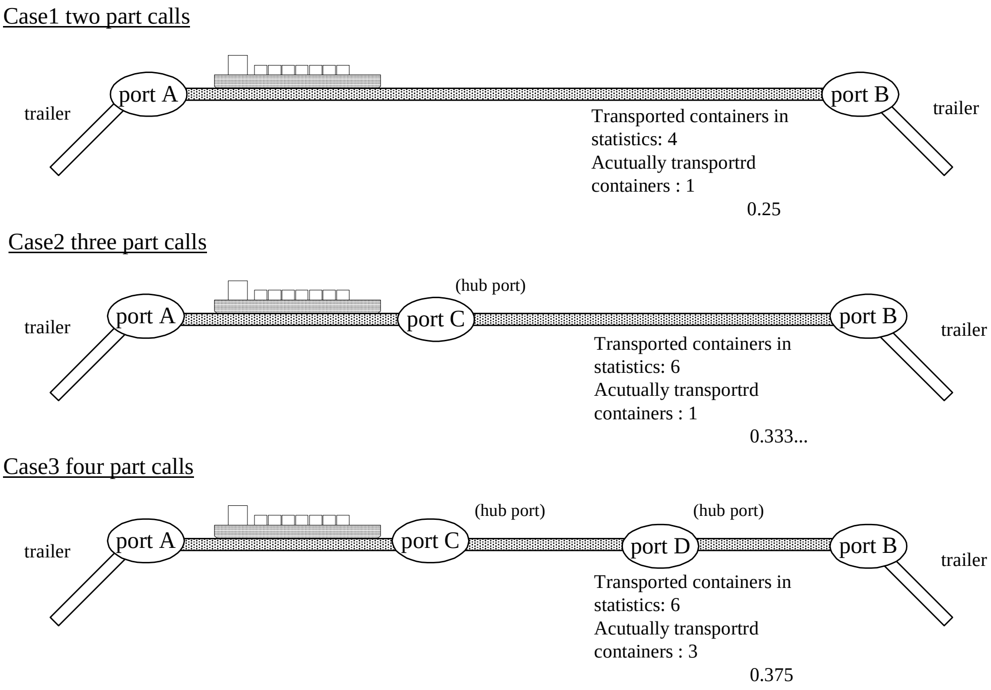
(c) Estimates of container vessel transportation volumes and average days at sea.

Table 11 shows the global transportation record of container vessels.

Annual TEU handling volumes specified in the Containerization International Year Book include transportation container counts of both domestic sea and land-based transportation. Statistical values in this publication are double the recorded counts of containers that passed container yards regardless of their travel route.

It is common for domestic container vessels to use international vessel routes for transpiration, thus these domestic containers are assumed to be outward-bound container vessels running on bunker oil since the expected estimation error is negligible.

For these same reasons, however, vessels may not be primarily used for transportation from consumption, production or other land-based locations. Therefore, the statistical values in Fig. 5 are multiplied by 0.3 ($163{,}744 \times 10^3$ TEU$\times 0.3 = 49{,}123 \times 10^3$ TEU) in further estimations. This is because a growing number of containers are currently re-shipped at hub ports such as Singapore. Based on this formula, intra-regional vessel transportation records of 1997 are shown in TEU in Table 12 and in TEU-mile in Table 14 (the intra-regional coefficient is fixed at 0.3, which is multiplied by intra-regional average miles). Both data tables indicate that cargo transportation cycles are concentrated in Singapore, Hong Kong, Guaxiong or other Asian hub ports. This illustrates a large share of Asian transportation is either intra-regional or departing from / arriving in Asia.



The exact share of each case is unknown → Average statistical value×0.3＝Number of times of navigation

Figure 5 Navigation time calculations for container vessels

Table 11 Annual report of the number of container vessels and container transportation volume

Year	Number of Vessels	Total Capacity for Container Transportation	Average Number of Containers Per Vessel	Total Container Transportation
		(10^3 TEU)	TEU/vessels	10^3 TEU
1988	2008	1881	937	73,810
1989	2082	1997	959	79,816
1990	2172	2132	982	85,597
1991	2271	2296	1,011	93,646
1992	2382	2500	1,050	102,906
1993	2461	2624	1,066	113,212
1994	2703	2940	1,088	128,320
1995	2738	3160	1,154	137,239
1996	2965	3584	1,209	150,753
1997	3189	3972	1,246	163,744

Based on the Containerization International Year Book, 1999

Table 12 Inter-regional container TEU transportation records (1997)

10^3 TEU

Destination	Origin				Total
	North America	Europe	South America	Asia	
North America	0	2,606	1,757	7,321	11,684
Europe	2,196	0	0	4,613	6,809
South America	1,714	0	0	0	1,714
Asia	5,081	3,602	0	0	8,683
Sub total	8,990	6,209	1,757	11,933	28,889
	Unknown Origin				
Asia					8,917
Others					11,318
Total					49,123

Based on the 1999 Japanese domestic marine transportation report and the Containerization International Year Book.

Table 13 Intra-regional container TEU-mile transportation records (1997)

10^6 TEU mile

Destination	Origin				Total
	North America	Europe	South America	Asia	
North America	0	11,816	10,466	45,202	67,484
Europe	9,957	0	0	75,798	85,756
South America	10,204	0	0	0	10,204
Asia	31,370	59,195	0	0	90,565
Sub total	51,532	71,011	10,466	121,000	254,009
	Unknown Origin				
Asia					42,333
Others					55,586
Total					351,927

Based on the 1999 Japanese domestic marine transportation report and the Containerization International Year Book.

In contrast to tankers, the existing number of container vessels by age and size illustrates an active vessel construction history including large-type containers even after 1990 as shown in Table 14. This table also shows the small fluctuations in the number of vessels over the time period categories.

Figure 6 totals the number of container vessels built and their loadable amounts in TEU. This figure shows the increase in vessel construction starting 1990, indicating a growing demand for container transportation.

Table 14 Size and age distribution of existing full containers worldwide as of November 1998

Capacity (TEU/vessel)	-1978	1979-83	1984-88	1989-3	1994-98	Total
- 1000	584	352	266	261	251	1,714
1000-1999	197	153	122	115	202	790
2000-2999	29	56	57	53	171	366
3000-3999	5	29	29	37	78	177
4000-4499	-	-	15	30	41	86
4500 +	-	-	11	32	13	56
Total	815	590	500	528	756	3,189

By Containerisation International YearBook,1999

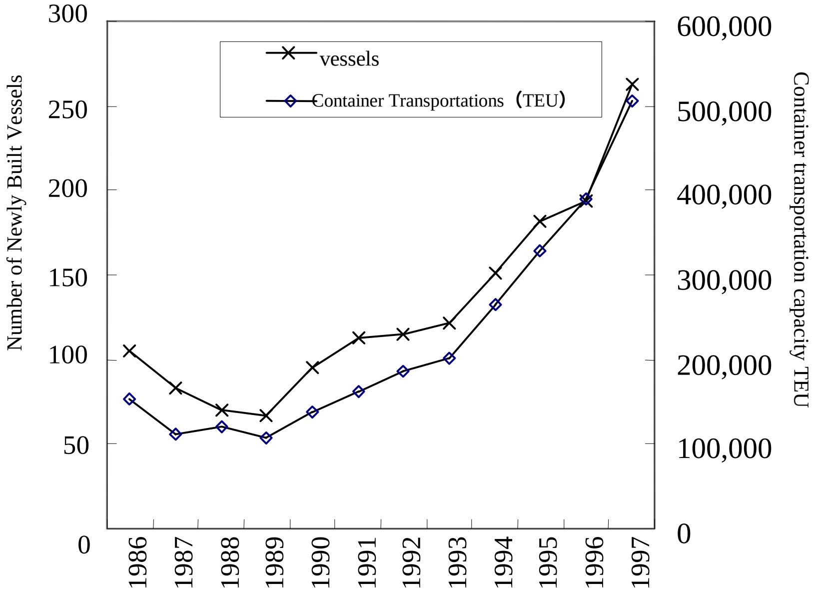


Figure 6 Annual vessel construction and container transportation
(number of vessels built on the left axis; container transportation capacity in TEU on the right axis)

Based on the same formula used for tankers, the total annual transportation volume of container vessels *TR* (TEU-mile/year) can be calculated as shown below, where *I* is the size class and *j* is the construction time period. Unlike the tanker formula, the ballast status at navigation is defined as zero.

Transportation volume total *TR*

$$TR=\sum_{i}\sum_{j} tr_{ij} \qquad \text{Then} \qquad tr_{ij}=K_{ij}\times S_{ij}\times X_{ij}\alpha_{ij}\times v_{ij}$$

However,

tr_{ij} ：Transportation volume (TEU-mile/year) for categories *I* and *j*

K_{ij} ：Average TEU loadable capacity (TEU/ship) for categories *I* and *j*

S_{ij} ：Number of vessels for categories *I* and *j*

X_{ij} ：Annual days at sea (days/year) for categories *I* and *j*

α_{ij} ：Loaded days among the total days at sea (approximately 0.5) for categories *i* and *j*

v_{ij} ：Average navigation speed (mile/day) of loaded navigation for categories *i* and *j*

To calculate the average days at sea of other vessel types, the average load utilization is set at 80% for the three major shipping routes between Asia, North America and Europe, and at 60% for other shorter distances. The average number of days at sea is calculated to be approximately 251 days/year/ship.

According to documents provided by Mitsui O.S.K. Lines, Ltd., the number of container vessels on shipping routes between the Far East and North America and their maximum transportable load are 349 and 1,075,000 TEU, respectively. The number of container vessels necessary and their transportable load necessary to transport the TEU-miles indicated in Table 13 are estimated to be 743 and 865,000 TEU. These figures indicate the estimate is reasonable and proper.

Table 15 Maximum transportable loads per vessel (TEU/vessel)

Capacity(TEU/vessel)	-1978	1979-83	1984-88	1989-3	1994-98
- 1000	432	445	401	414	402
1000-1999	1,276	1,273	1,376	1,443	1,585
2000-2999	2,046	2,022	2,286	2,535	2,503
3000-3999	3,373	3,307	3,253	3,383	3,436
4000-4499	-	-	4,128	4,204	4,229
4500 +	-	-	5,694	5,693	5,881

Maximum loadable TEU is estimated for each category based on DWT averages calculated from Japanese Vessel Specifications.

“-”indicates that a vessel of the given size does not exist.

Table 16 Average navigation speeds of container vessels (knot)

Capacity(TEU/vessel)	-1978	1979-83	1984-88	1989-3	1994-98
- 1000	21	21	21	21	21
1000-1999	21	21	21	21	21
2000-2999	21	21	21	21	21
3000-3999	21	21	21	21	21
4000-4499	-	-	21	21	21
4500 +	-	-	21	21	21

“-”indicates that a vessel of the given size does not exist. Based on navigation speeds under fully loaded conditions as described in vessel specifications.

Table 17 Transportation volume estimates of container vessels by size and age.

10^9 TEU*mile /year

Capacity(TEU/vessel)	-1978	1979-83	1984-88	1989-3	1994-98	total
- 1000	22,347	13,873	9,468	9,563	8,933	64,184
1000-1999	22,284	17,267	14,920	14,769	28,398	97,638
2000-2999	5,259	10,038	11,474	11,889	38,031	76,692
3000-3999	1,495	8,502	8,217	11,079	23,616	52,909
4000-4499	-	-	5,482	11,007	15,545	32,034
4500 +	-	-	5,566	16,262	6,641	28,470
Total	51,385	49,679	55,129	74,570	121,164	351,927

“-”indicates that a vessel of the given size does not exist. Average number of days at sea is 251.

(d) Estimates on bulk carrier transportation volumes and the average number of days at sea.

Transportation volumes of bulk iron ore ships and bulk coal ships are estimated by vessel size and age as shown in Table 18 and Table 19. This is the same as data provided for tankers and container vessels. The exact numbers of bulk iron ore ships and bulk coal ships, as well as the number of general dry bulk carriers engaged in transporting both iron ore and coal are unattainable. Because of this, the numbers of both types of ship are given fixed shares among the total count of dry bulk carriers in Japanese vessel specifications. The average number of days at sea is set at 220 for this calculation.

All cargo carriers other than the two types above are assumed to operate consistently and at a fixed navigation speed of 15 knots (the same as container ships) because, in contrast to data for tankers, the data provided in the vessel specifications are not specific.

Table 18 Estimates of transportation volume of bulk iron ore carriers by size and age

10^9 Tonmile /year

DWT(10^3ton)	-1978	1979-83	1984-88	1989-93	1994-98	Total
10 -25	88	61	51	45	66	311
25 -50	413	284	243	214	309	1,464
50 -80	111	77	65	58	83	392
80 -100	3	2	2	2	2	12
100 -120	10	16	30	32	41	3
120 -200	74	50	44	39	56	262
200 -300	10	13	12	16	10	26
300 +	-	-	-	-	-	0
Total	690	474	407	357	517	2,444

“-”indicates that a vessel of the given size does not exist. Average number of days at sea is 220.

Table 19 Estimates of transportation volume of bulk coal carriers by size and age

10^9 Tonmile /year

DWT(10^3ton)	-1978	1979-83	1984-88	1989-93	1994-98	Total
10 -25	84	58	49	43	63	297
25 -50	394	271	232	204	295	1,397
50 -80	106	73	62	55	79	374
80 -100	3	2	2	2	2	11
100 -120	1	1	0	0	1	3
120 -200	71	48	42	37	53	250
200 -300	-	-	-	-	-	0
300 +	-	-	-	-	-	0
Total	658	452	388	341	493	2,332

“-”indicates that a vessel of the given size does not exist. Average number of days at sea is 220.

Table 20 Estimates of transportation volumes of bulk dry carriers other than iron ore and coal by size and age

10^9 Tonmile /year

DWT(10^3ton)	-1978	1979-83	1984-88	1989-93	1994-98	Total
10 -25	52	37	31	26	42	193
25 -50	256	177	151	130	193	903
50 -80	68	47	42	37	52	240
80 -100	0	0	1	2	2	5
100 -120	0	0	0	0	0	0
120 -200	47	31	26	26	37	162
200 -300	-	-	-	-	-	0
300 +	-	-	-	-	-	0
Total	428	292	250	219	318	1,508

“-”indicates that a vessel of the given size does not exist. Average number of days at sea is 165.

3.1.2 Investigation of fuel consumption rate

By estimating fuel consumption per day (C_{ij}) of each category defined in the previous section, total fuel consumption can be found by multiplying daily consumption by average number of days at sea. It is probable that each category's fuel consumption at a certain speed is influenced by such factors as average shipload, sea margin, and age deterioration of hulls and engines. As a first step, a large-scale study was scheduled to capture the current situation. However, execution of this study proved difficult for various reasons.

It was decided to estimate fuel consumption by adopting the amounts in test navigation records in vessel specifications and to conduct additional research when problems arose with the accuracy of estimates.

(1) fuel consumption factor for tanker

Table 21 shows the number of tankers with fuel consumption records in vessel specifications.

Table 21 Number of Samples with Calculated Fuel Consumption

DWT (10^3ton)	-1978	1979-83	1984-88	1989-93	1994-98	Total
10-25	6	4	0	0	0	10
25-50	14	8	4	1	1	28
50-80	14	26	3	2	1	46
80-100	18	24	2	2	1	47
100-120	4	8	0	0	1	13
120-200	22	3	0	0	0	25
200-320	14	1	17	14	0	46
320+	-	-	-	-	-	-
Total	92	74	26	19	4	215

"-"indicates that a vessel of the given size does not exist.

Theoretical fuel consumption was compared with catalogued specifications to verify the credibility of fuel consumption records in vessel specifications.

ε_H and ε were calculated from admiralty coefficient (C_{adm}), displacement volume (∇), hull length (L), and fluid number (Fn) for each tanker based on vessel specifications.

$$\varepsilon_H = 36.7304 \times (L/\nabla^{1/3})\, Fn^2 \times Cadm^{-1}$$

$$C_{adm} = \nabla^{1/3} \times V^3 / DHP$$

$$\varepsilon = H_0 \times SFC \times \varepsilon_H$$

H_0: calorific value (kcal/kg-Fuel)

SFC : fuel efficiency of the main engine (kg-Fuel/PSh)

ε_H : valid drag lift ratio

A regression formula was determined from SR research material on SFC (the value has decreased from 150 g/PSh in 1970 to 120 g/PSh in 1985 and thereafter).

Total energy consumption in freight transport = ε *valid workload (ton* km)

Energy consumption per day is calculated by multiplying this value by the workload (ton*km) at full load navigation velocity and comparing to the vessel fuel consumption specifications. Results are shown in Figure 7.

The correlation between the theoretical fuel consumption and vessel specifications is valid and consistent in terms of both inclination and correlation coefficient. Thus the fuel consumption from vessel specifications can be regarded as a representative figure for each type at each time.

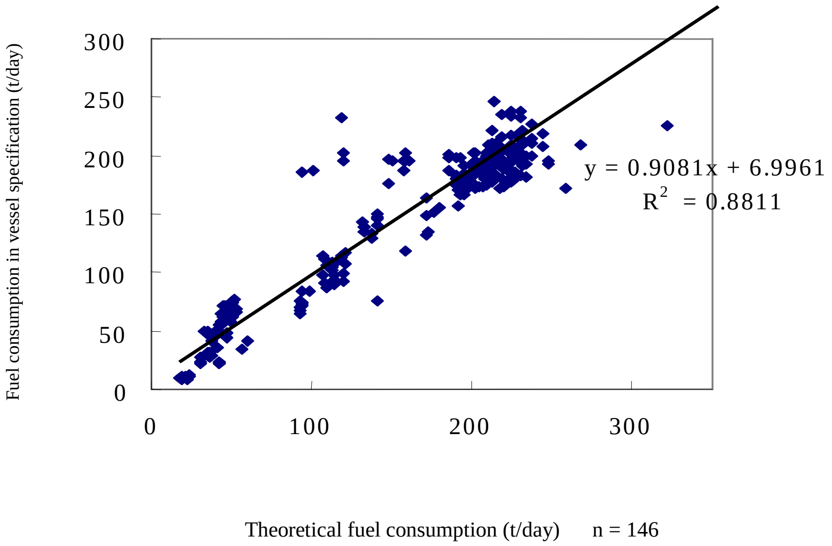


Figure 7 Comparison of crude oil tanker fuel efficiency between theoretical and vessel specification values

Figure 8 shows average fuel consumption from vessel specifications by construction year. The fuel consumption record from vessel specifications is for newly built vessels (in test navigation) at maximum velocity. However, this velocity varies among ships. Thus fuel consumption was fixed at the same speed by using the following formula.

$$FUEL / FUEL_0 = (SPD / SPD_0)^{\beta}$$

Fuel: fuel consumption at the fixed velocity (t/day)
$Fuel_0$: fuel consumption record on vessel specifications (t/day)
SPD: fixed velocity (knot)
SPD_0: full load navigation velocity (knot)
β: coefficient (varies for each type of vessel: 1.87 for tankers, 1.64 for iron ore and coal carriers)

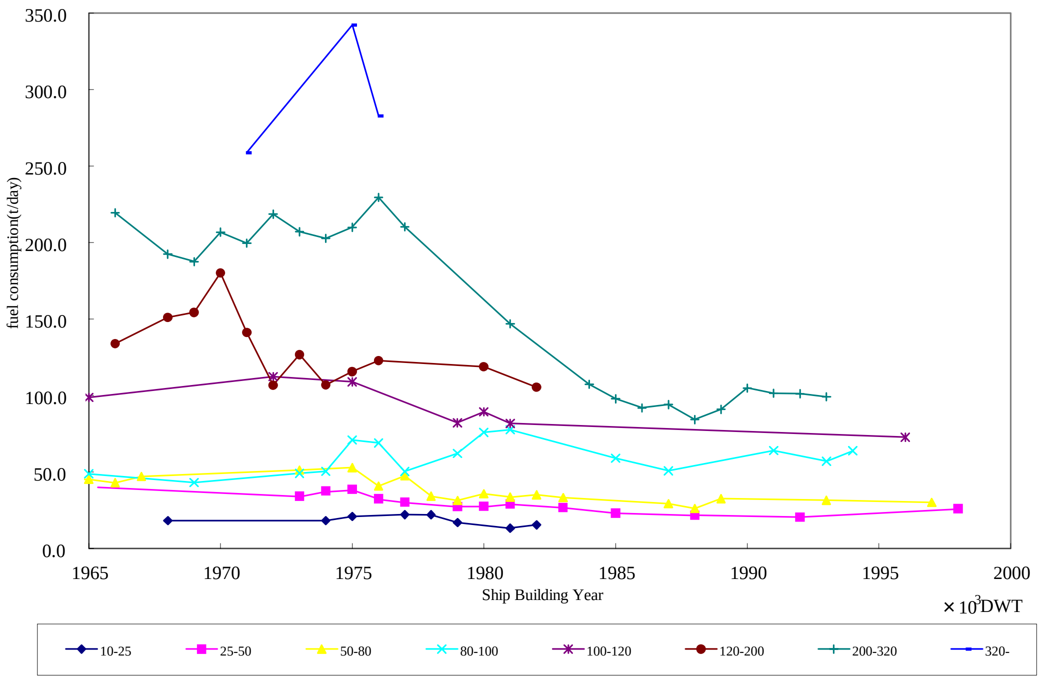


Figure 8 Change in fuel consumption per day crude of oil tankers by built year(when building)

This figure shows the average fuel consumption per day at the adjusted velocity. Consumption is highest among Ultra Large Crude Carriers (ULCC) and becomes smaller with the size of ship. Likewise, fuel consumption decreases in later construction years. The value for Very Large Crude Carrier (VLCC) class vessels (+ in figure) is about half that of the ULCC class.

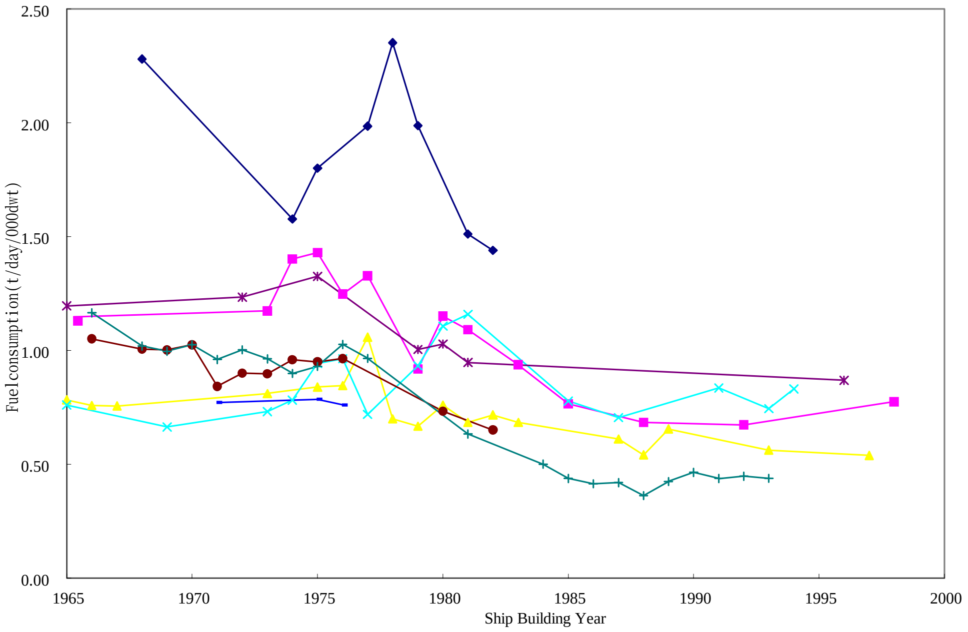


Figure 9: Change in fuel consumption per shipload by newly built crude oil carriers.

Figure 9 shows the fuel consumption values from Figure 5 by vessel size divided by loading capacity. The bigger the ship, the lower consumption becomes. The trend in this figure is slightly different to that of Figure 5 because the average deadweight tons (DWT) each year is different.

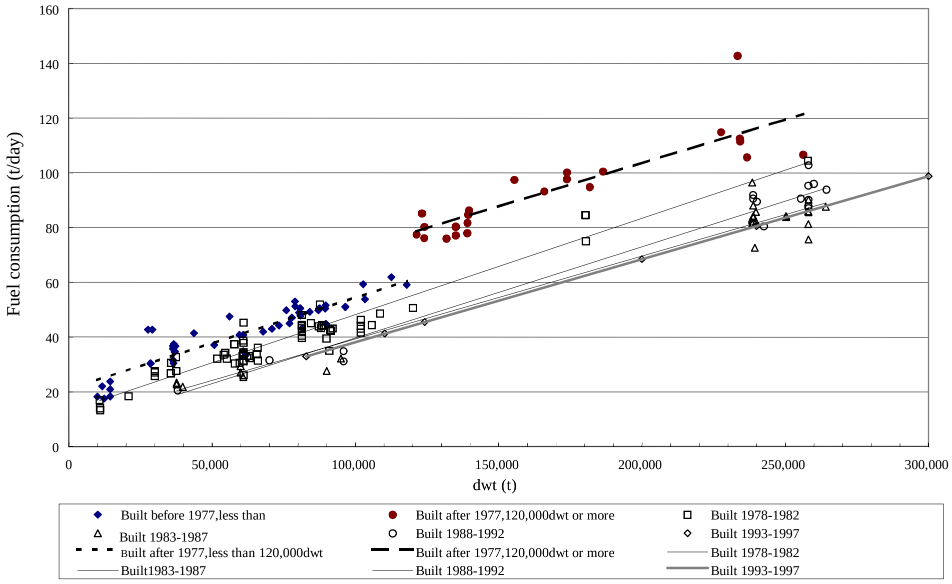
Figure 8 and Figure 9 show older ship fuel consumption data retrieved from old specifications. These include turbine vessels, so the fuel consumption per day of 200,000 DWT tankers is approximately half that of 320,000 DWT tankers, regardless of their age.

To show transport efficiency, Figure 9 also shows a comparison of fuel consumption per day divided by DWT. Figure 9 clearly shows that efficiency has improved. By using the weighted average based on each year's record, tankers built in the 1990s are about 1.2 times more efficient than those made in the 1970s.

Thus the current fuel consumption of each category by ship age and size are calculated based on the above examinations of fuel consumption among newly built ships.

Steam turbine vessels are assumed to have replaced their main engines with diesel engines. Old types of tankers like these are not registered in Japan, so it is difficult to accurately assess replacement timing and details. Therefore, it was assumed that all turbines have been replaced with diesel engines. Figure 10 shows approximate values for each DWT, excluding the data of turbine vessels from specifications. The value of ULCC over 320,000 DWT was approximated using the formula for smaller sized vessels since this could not be precisely determined from vessel specifications.

Table 22 shows fuel consumption values calculated by substituting a fixed velocity and a fixed DWT average for the fuel consumption estimation formula calculated in Figure 9. This table also shows the difference in fuel consumption among newly built tankers with the same DWT over time.



The horizontal axis shows DWT and the vertical axis shows fuel consumption per day (t/day) at a constant speed.

Figure 10: Relationship between tanker DWT and fuel consumption

Table 22: Average fuel consumption of newly built tankers

t-Fuel/day/vessel

DWT(10^3ton)	-1978	1979-83	1984-88	1989-93	1994-98
10-25	28.7	19.1	14.2	12.0	13.1
25-50	34.2	24.5	18.9	17.2	17.8
50-80	44.9	35.1	28.0	27.3	26.9
80-100	53.9	44.1	35.8	35.8	34.7
100-120	63.1	53.2	43.6	44.4	42.5
120-200	84.3	62.0	51.1	52.7	50.0
200-320	125.8	107.9	90.7	96.2	89.6
320+	165.2	151.4	-	-	-

A theoretical value was calculated by substituting the average DWT up to 1978 in the estimation formula of fuel consumption by newly built ships.

Until 1983, the velocity of VLCC between 120,000 and 320,000 DWT was assumed to be 15 knots.

It is assumed that all turbines were replaced with diesel engines.

“-”indicates that a vessel of the given size does not exist.

In fact, adjustments should be made for the slowing and SFC (g/PSh) decline of engines due to age deterioration. Based on inquiries and other sources, it was assumed that heat efficiency deterioration occurs at 5% per every 10 years. The average DWT in the same ship class varies with the year of construction. Adjustments were made to correct for this and to fix the fuel consumption per ship as seen in Table 23.

Table 23: Average Tanker Fuel Consumption

t-Fuel/day/vessel

DWT(10^3ton)	-1978	1979-83	1984-88	1989-93	1994-98
10-25	19	17	16	13	12
25-50	24	23	22	21	20
50-80	34	32	31	31	29
80-100	43	41	39	40	36
100-120	51	50	45	43	40
120-200	70	64	55	56	52
200-320	111	105	92	100	96
320+	151	152	-	-	-

Average fuel consumption has been substituted for fixed velocity by considering age deterioration of the actual DWT and engine. Heat efficiency is assumed to decrease by 5% per 10 years.

“-”indicates that a vessel of the given size does not exist.

(2) fuel consumption factor for container

Figure 11 shows fuel consumption of Full-container ships, arranged by vessel size and year of construction. Like tankers, the velocity (in test navigation) is highest among newly built ships. Velocity depending on vessel specifications varies among ships. Velocity for fuel consumption per day is fixed here as 21 knots.

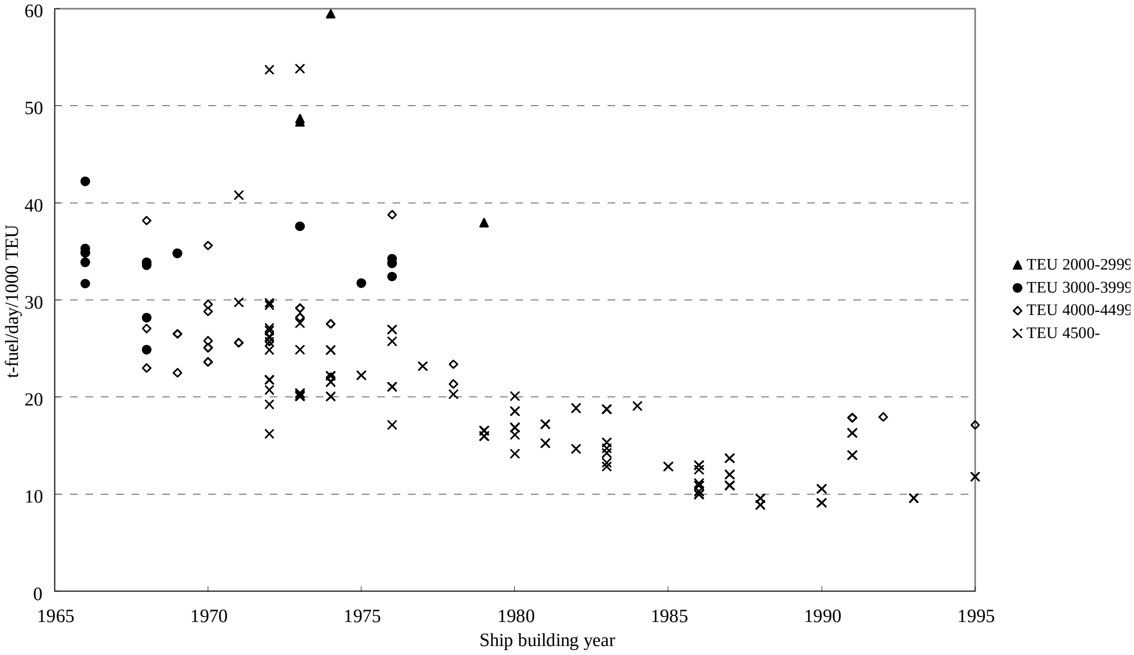


Figure 11: Fuel Consumption per day & TEU, of Full-Container

Table 24: Average Fuel Consumption for Full-Container

t-Fuel/day/vessel

Capacity(TEU/vessel)	-1978	1979-83	1984-88	1989-93	1994-98
-1000	60	55	53	40	40
1000-1999	60	55	53	40	40
2000-2999	74	68	66	53	54
3000-3999	87	81	79	66	67
4000-4499	101	94	91	79	81
4500 +	-	-	104	92	94

Average fuel consumption has been substituted for fixed velocity by considering age deterioration of the actual DWT and engine. The velocity is fixed here at 21 knots. Propulsion efficiency is assumed to decrease by 5% per 10 years.

“-”indicates that a vessel of the given size does not exist.

(3) fuel consumption factor of other vessels

Fuel consumption trends among iron ore carriers and coal carriers are shown in Figure 12 and Figure 13, respectively. There appears to be discontinuities among large iron ore carriers over 200,000 DWT depending on type. Investigating the correlation between DWT and fuel consumption in detail revealed the tendencies shown in Figure 12. This is because 200,000 DWT iron ore carriers built between 1972 and 1988 have lower horsepower engines than smaller ships.

Fuel consumption estimates by size and age are shown in Tables 26 and 27. Age deterioration was taken into consideration in the same way as for tankers and cargo ships. Due to a lack of data, data for other types of vessels were substituted for that of coal carriers.

Table 25: Average fuel consumption by iron ore carriers (t/day/vessel)

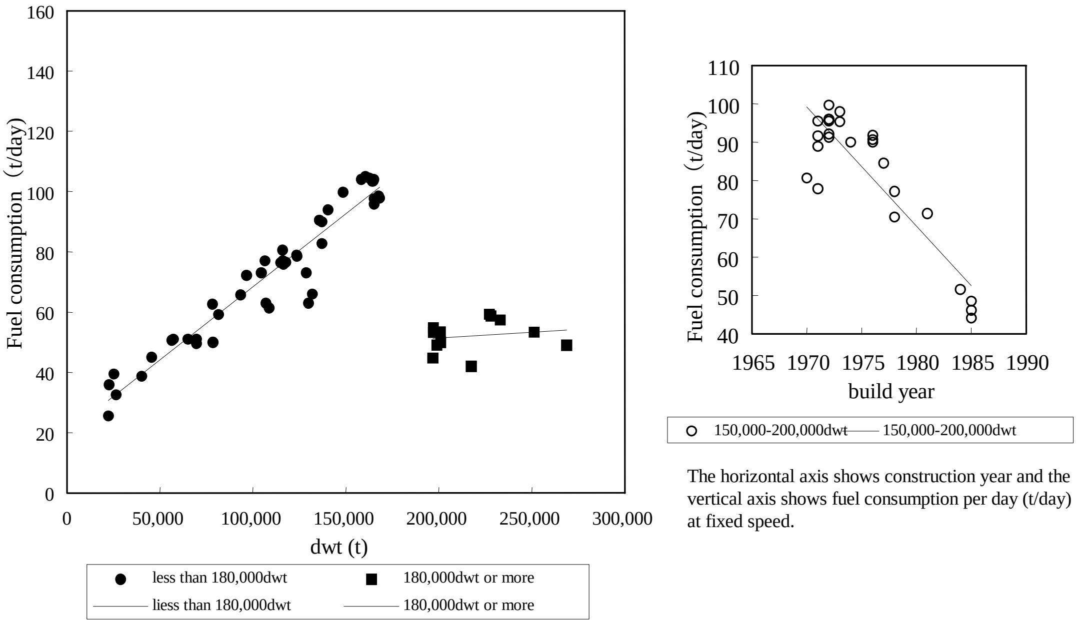
DWT(10^3ton)	-1978	1979-83	1984-88	1989-93	1994-98
10-25	21.9	24.7	21.7	20.6	22.7
25-50	32.2	28.0	20.9	19.8	21.8
50-80	42.5	33.4	26.3	24.9	27.5
80-100	49.8	43.5	30.5	28.9	31.9
100-120	58.4	46.1	45.3	43.0	47.3
120-200	88.9	77.4	58.0	49.9	55.0
200-320	80.0	70.2	50.4	50.4	50.4
320+	-	-	-	-	-

Average fuel consumption has been substituted for fixed velocity by considering age deterioration of the actual DWT and engine. Propulsion efficiency is assumed to decrease by 5% per 10 years. “-”indicates that a vessel of the given size does not exist.

Table 26: Average fuel consumption of coal carriers and other vessels (t/day/vessel)

DWT(10^3ton)	-1978	1979-83	1984-88	1989-93	1994-98
10-25	23.3	24.2	17.4	19.5	19.5
25-50	31.9	27.2	20.5	20.5	21.9
50-80	41.2	35.5	26.1	25.4	25.4
80-100	49.6	35.3	32.0	33.5	36.2
100-120	56.3	46.5	46.0	40.5	42.5
120-200	71.5	62.2	50.4	54.2	52.8
200-320	-	-	-	-	-
320+	-	-	-	-	-

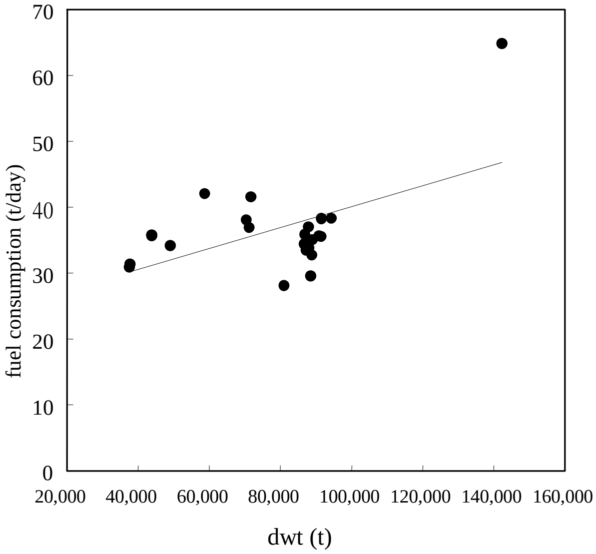
Average fuel consumption has been substituted for fixed velocity by considering age deterioration of the actual DWT and engine. Propulsion efficiency is assumed to decrease by 5% per 10 years. “-”indicates that a vessel of the given size does not exist.



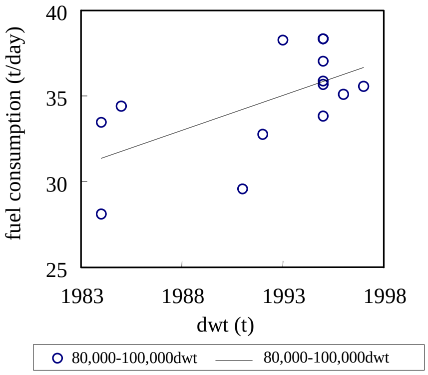
The horizontal axis shows DWT and the vertical axis shows fuel consumption per day (t/day) at fixed speed.

The horizontal axis shows construction year and the vertical axis shows fuel consumption per day (t/day) at fixed speed.

Figure 12: Relationship between DWT and fuel consumption by iron ore carriers



The horizontal axis shows DWT and the vertical axis shows fuel consumption per day (t/day) at fixed speed.



The horizontal axis shows construction year and the vertical axis shows fuel consumption per day (t/day) at fixed speed.

Figure 13: Relationship between DWT and fuel consumption in coal carriers

3.1.3 Investigation of fuel consumption amount by vessel type

(1)Tanker fuel consumption by size and build year

Using the formula below, the fuel consumption (p_{ij}) and the total amount of fuel consumed annually (P) by tankers of each category can be calculated. Table 27 shows the 1997 results.

$$P = \sum_i \sum_j p_{ij} = \sum_i \sum_j C_{ij} \times tr_{ij}$$

p_{ij}: fuel consumption of category i and j (t-fuel/year)

As shown in Table 27, tankers built in 1977 or earlier consume a large share of fuel and make up over 30% of vessels in terms of numbers (see 3.1.1 (3)). It was assumed that these old-type tankers have all replaced their steam turbines with diesel engines. In fact they display low transport efficiency and it is likely they do not navigate at the same operating rate as new tankers. Moreover, the number of old tankers was difficult to verify considering that most foreign and Japanese tankers arriving in Japan are not old. Therefore, inquiries must be made of foreign operators and shipowners to determine the operating rates of old tankers and thereby improve the accuracy of overall estimations.

Table 27: Fuel consumption in 1997 by crude oil tankers by size and age

10^3t/year

DWT(10^3ton)	-1977	1978-82	1983-87	1988-92	1993-97	Total
10 -25	900	375	201	60	79	1,614
25 -50	1,799	850	821	552	642	4,665
50 -80	489	909	440	246	61	2,144
80 -100	1,017	833	605	771	411	3,637
100 -120	154	85	181	219	428	1,066
120 -200	1,741	240	179	902	650	3,712
200 -320	3,105	191	581	2,142	1,931	7,950
320 +	1,372	264	-	-	-	1,636
Total	10,578	3,745	3,007	4,891	4,201	26,423

(2) Full-Container fuel consumption by size and age

Using the formula below, the fuel consumption (pij) and the total amount of fuel consumed annually (*P*) by Full-Container ships of each category can be calculated. Table 28 shows the 1997 results.

$$P = \sum_i \sum_j p_{ij} = \sum_i \sum_j C_{ij} \times tr_{ij}$$

p_{ij}: fuel consumption of category *i* and *j* (t-fuel/year)

Each year’s fuel consumption amounts are almost the same since construction of small tankers dominates while they capture a greater share of fuel consumption. It is likely that the operating rate of container ships smaller than 1000 TEU is fixed higher than the actual rate. However, actual operating conditions are uncertain and the data necessary for more precise estimates are not available.

Table 28: Fuel consumption in 1997 by Full-Container ships by size and age

10^3t/year

Capacity(TEU/ship)	-1978	1979-83	1984-88	1989-93	1994-98	Total
- 1000	8,803	4,864	3,548	2,620	2,520	22,355
1000-1999	2,970	2,114	1,629	1,160	2,032	9,905
2000-2999	535	955	936	705	2,304	5,436
3000-3999	109	589	563	613	1,305	3,179
4000-4499	0	0	344	586	839	1,769
4500 +	0	0	289	745	301	1,335
Total	12,417	8,522	7,309	6,429	9,301	43,979

(3) Fuel consumption factor for other vessels by size and build year

Tables 29, 30, and 31 show the estimated fuel consumption in 1997 of ships carrying iron ore, coal, and other bulk cargo.

Table 29: Fuel consumption in 1997 by iron ore carriers by size and age

10^3t/year

DWT(10^3ton)	-1978	1979-83	1984-88	1989-93	1994-98	Total
10 -25	4,377	1,376	658	209	422	7,042
25 -50	443	178	217	45	110	994
50 -80	1,149	893	506	328	619	3,495
80 -100	13	7	2	2	3	28
100 -120	189	73	6	0	8	276
120 -200	275	400	437	594	853	2,622
200 -320	9	7	10	15	23	0
320 +	0	0	0	0	0	0
Total	6,456	2,935	1,836	1,193	2,037	14,456

Table 30: Fuel consumption in 1997 by coal carriers by size and age

10^3t/year

DWT(10^3ton)	-1978	1979-83	1984-88	1989-93	1994-98	Total
10 -25	1,174	517	341	147	413	2,592
25 -50	1,666	944	1,602	458	1,552	6,224
50 -80	505	551	429	388	1,018	2,892
80 -100	38	29	12	18	35	130
100 -120	54	29	3	0	8	94
120 -200	115	203	287	385	703	1,694
200 -320	0	0	0	0	0	0
320 +	0	0	0	0	0	0
Total	3,552	2,274	2,674	1,396	3,728	13,625

Table 31: Fuel consumption in 1997 by other vessels by size and age

10^3t/year

DWT(10^3ton)	GRAIN	Bouxite	Phosphate	Others
10 -25	0.903	0.132	0.104	0.131
25 -50	4.241	0.413	0.390	0.315
50 -80	1.136	0.351	0.256	0.146
80 -100	0.032	0.016	0.009	0.007
100 -120	0.009	0.000	0.002	0.005
120 -200	0.759	0.348	0.176	0.086
200 -320	0.000	0.000	0.000	0.000
320 +	0.000	0.000	0.000	0.000
Total	7.080	1.260	0.936	0.690

Table 32 serves as a comprehensive collection of average transport efficiencies for all types of vessels, as well as a comparison between total fuel consumption by type and bunker oil consumption as seen in 1.1. Subtracting the unknown amount from bunker oil consumption (131.8×10^6t) gives total fuel consumption (121.8×10^6t). This equates to 92% of all consumption, so this estimate can be said to be appropriate.

According to Table 32, container transport and crude oil transport are almost the same on a ton-mile basis. In terms of fuel consumption, however, the former is 1.7 times larger than the latter. Thus fuel consumption is worse for container transport despite carrying the same amount of cargo. Other bulk carriers such as tankers occasionally operate without cargo. Container transports operating at 40% capacity are regarded as twice as inefficient as fully loaded transport. This seems to significantly influence speed (21 knots), which is fixed markedly higher than that of other freight transport. Considering the overall efficiency of the operation system, a certain amount of the energy and cost required for transport were saved to some degree.

Cargo ships have another merit of simultaneously transporting different types of cargo that is hard to load in bulk. Thus, container transport isn't necessarily as inefficient as a comprehensive system. Table 33 shows the fuel consumption rates of domestic shipping as an example. The merit of scale can is shown, as values are less than half for each type compared to the domestic shipping average.

However, this estimate totally ignores the influences of weather at sea and the seasons. Test navigation data is usually collected under favorable weather conditions, so it is highly probable that these estimates underestimate fuel consumption in actual navigation.

Table 32: Fuel consumption by vessel type in 1997

Type	Transportation ton (10^6t)	Transportation ton-mile (10^9t-maile)	Fuel Consumption (10^6t)	Percentage in Total Emission	Fuel Consumption 10^{-6} t/ton-mile
Crude Oil	1,534	7,677	26	20%	3.4
Oil Products	626	3,500	15	11%	3.5
Iron Ore	430	2,444	14	11%	5.8
Coal	460	2,332	14	11%	6.1
Grain	203	1,169	7	5%	6.3
Aluminium	54	206	1	1%	6.3
Phosphorate	32	133	1	1%	6.3
Others	20	189	1	1%	6.3
Container	933	6,687	43	33%	7.0
Unknown	-	-	10	7%	-
Total			131.8	100%	

Cargo weight per TEU including empty containers is assumed to be 19t.

Table 33: Comparison of fuel consumption per ton in domestic freight transport.

	Cargo	
Transportation A	233,835	10^6ton kg
Fuel consumption per ton -mile	22	10^{-6} t/ton mile
Transportation	528,841	10^3 ton
average transport distance	442	km

This data is drawn from the comprehensive investigation conducted by Environment Agency on greenhouse gases discharged from vessels.

3.2 Investigation of solutions for vessel hardware

There is a tendency among the same types of ship that the larger the vessel, the more efficient transport per ton-mile and the lower fuel consumption per transport ton-mile at the same speed. In terms of age, the newer the ship, the more efficient ship transport becomes. These improvements in transport efficiency are due to a combination of two factors: increased propulsive efficiency through enhanced ship-designs and enhanced heat efficiency of individual engines. Here we investigate these two improvements over the last 10 years and select some potential innovative technologies for transport efficiency.

3.2.1 Technology for heat efficiency of main diesel engine

By examining vessel specifications as in 3.1, it was shown that vessel transport efficiency has improved by about 20% on average from the 1970s to the 1990s. However, efficiency has remained almost constant for the past several years. Thus improvements in main engine heat efficiency seem to have greatly contributed to transport efficiency improvements up to the 1990s.

As shown in Figure 14, the fuel consumption rate (SFC) of 2-stroke low-speed diesel engines made in the 1970s (about 150 g/PSh) is about 20% more than those made in 1990s (about 120 g/PSh). This is likely to become 25% when adjusted by raising the maximum combustion pressure, reducing speed and lengthening the stroke as seen in Figure 15. As well, 4-stroke low-speed engines offer approximately 15% improvement in fuel consumption rate as shown in Figure 16.

At the same time, newer engines are lower in weight, which has led to overall transport efficiency.

Figure 16 also shows that recent heat efficiency improvements have become less in both 2-stroke and 4-stroke engines. This is probably due to the combination of factors below. The appearance of an external factor, such as a sudden rise in fuel prices, will likely trigger development of technology related to fuel consumption rates.

- In the recent years of low fuel prices, emphasis has been placed on engine performance in such areas as improved maintenance, low price and the ability to use low-quality fuel.
- The IMO is scheduled to release NOx-related regulations. NOx emissions reductions and fuel consumption rate improvements are mutually exclusive, so a compromise needs to be reached.
- Speed and output capacity enhancements are demanded of cargo ships.

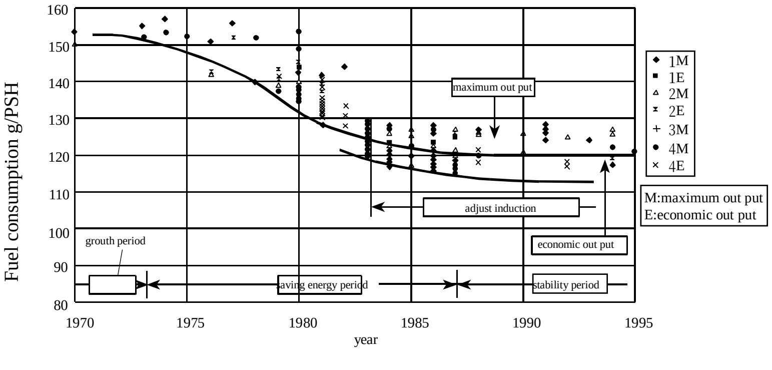


Figure 14: Changes in fuel consumption of low-speed 2-stroke engines by construction year

Investigation of the Utilization of R&D Results on the Enhancement of Diesel Engine Performance, Japan Shipbuilding Research Association (Energy Division), 1998

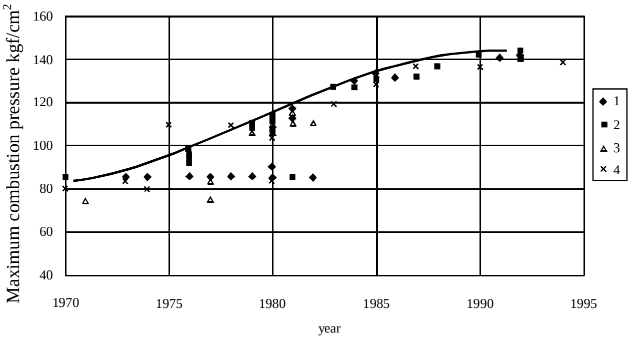
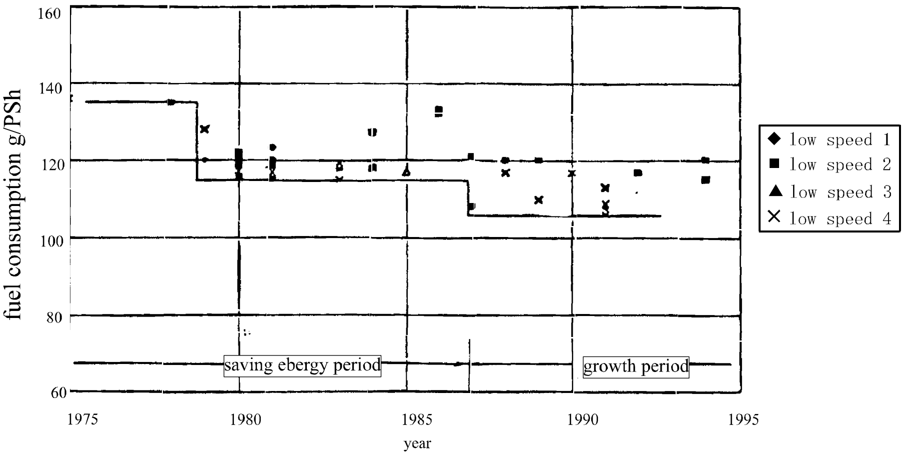


Figure 15: Change in maximum combustion pressure (*Pmax*) of low-speed 2-stroke engines by construction year

Investigation of the Utilization of R&D Results on the Enhancement of Diesel Engine Performance, Japan Shipbuilding Research Association (Energy Division), 1998

Change in fuel consumption



Change in maximum combustion pressure

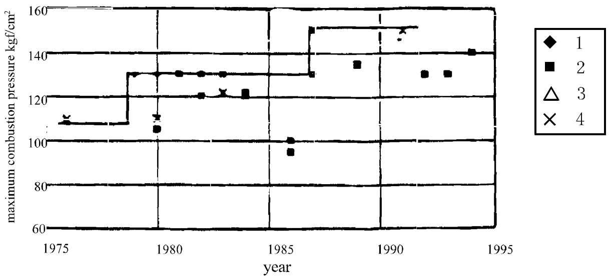


Fig.16: Fuel efficiency enhancement in low-speed 4-stroke diesel engines

Investigation of the Utilization of R&D Results on the Enhancement of Diesel Engine Performance, Japan Shipbuilding Research Association (Energy Division), 1998

3.2.2 Technology for vessel shape (vessel body-shape and propeller)

Transport capacity of a hull ε is defined in formula (1). Here, ε is the unit of energy necessary for navigation at a certain speed. It can also be shown as in formula (2).

ε = total energy consumption (kcal)/ workload (ton*km) (1)

In formula (2), ε_H is an index of hull performance using these energy units. The value gets smaller as fuel consumption decreases and the hull becomes more efficient.

As seen in Figure 17, the value of ε_H of large tankers over 100,000 DWT is smaller than that of small tankers between 20,000 DWT and 100,000 DWT. This indicates large tanker hulls are more efficient. The difference among ships by age is about 15%, although this is not as big a difference as main diesel heat efficiencies. The value of ε_H among other vessels has tended to worsen in recent years. This is probably because freighters recently constructed are wider and faster so as to be able to carry heavy loads.

In the future, if tankers become faster due to future changes in oil supply, it is likely that a high ε_H model will be designed in the long run.

$$\varepsilon = H_0 \times SFC \times \varepsilon_H \qquad (2)$$

H_0: Fuel heat value (kcal/kg-Fuel)
SFC: Main engine fuel consumption (kg-Fuel/PSh)

$$\begin{aligned}\varepsilon_H &= DHP / \Delta \times V \\ &= 6.8587 \times (L / \nabla^{1/3}) \times Fn^2 \times r_T / \eta\end{aligned} \qquad (3)$$

Δ : deadweight displacement tonnage (ton)

V : velocity (knots)

DHP :transmission horsepower (PS)

L: length of the hull

∇ : displacement volume

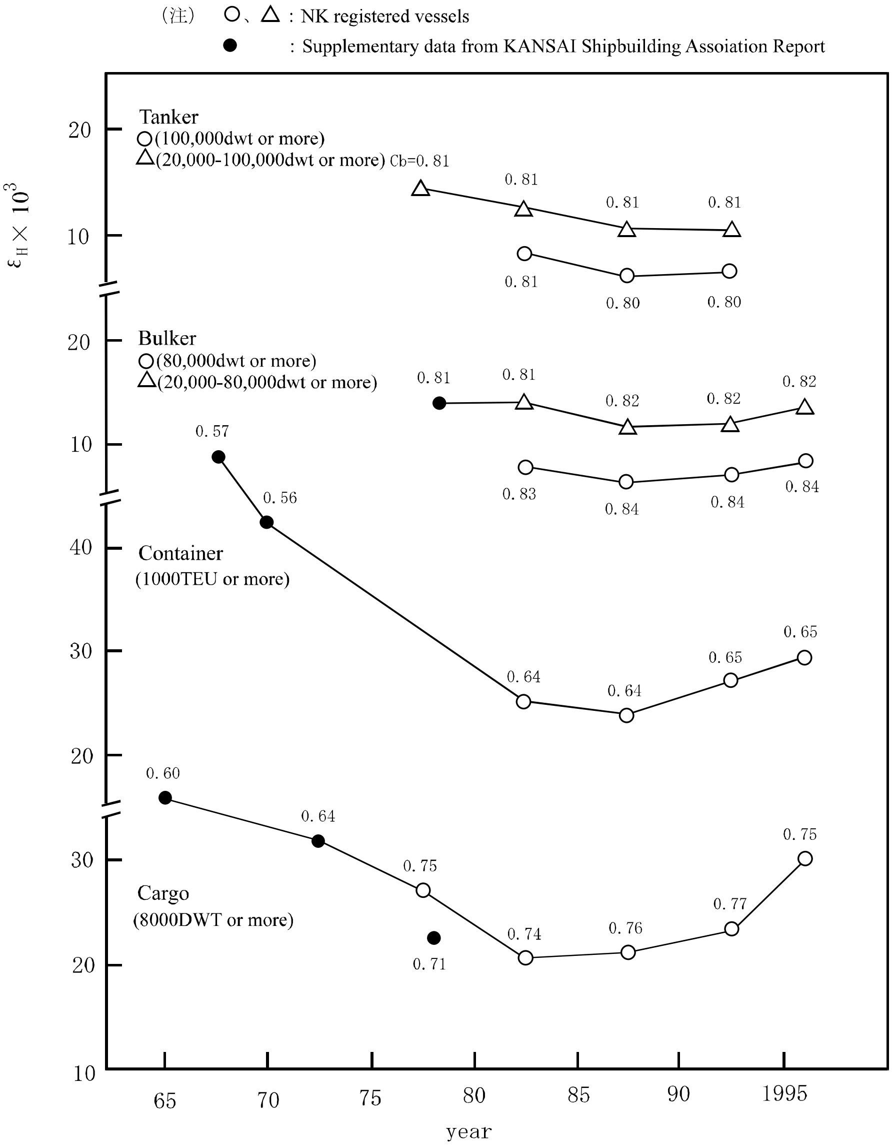
Fn： fluid number

r_T ： total resistance coefficient of the ship (including a coefficient to correct for a margin of error)

η ： propulsive coefficient (η =*EHP DHP* /、 *EHP* shows the valid horsepower)

Cadm： admiralty coefficient

$$\begin{aligned}\varepsilon_H &= 36.7304 \times (L / \nabla^{1/3}) \times Fn^2 \times Cadm^{-1} \\ Cadm &= \Delta^{2/3} \times V^3 / DHP\end{aligned} \qquad (4)$$



Cb in the chart is a fineness coefficient: an index calculated by dividing the full load displacement by the distance between the perpendicular lines at the draft width in full load.

Figure 17: Unit of energy consumption by type

Investigation of the Utilization of R&D Results on the Enhancement of Vessel Diesel Engine Performance, Japan Shipbuilding Research Association (Propeller Division), 1998

3.2.3 Potential technologies to reduce fuel consumption

As described above, the heat efficiency of individual engines has improved about 20%, while enhancements to hulls and propellers have led to energy consumption improvements of about 15%. The fuel consumption per day of ships in the same weight class improved between ships made in 1980-1984 and those made in 1990-1995. VLCC tankers between 200,000 and 300,000 DWT improved by approximately 17% and large cargo ships improved by about 13%.

As will be shown below in 3.4.1, predicted future fuel consumption trends that include increases in transport require further technological developments to maintain CO_2 emissions from ships at 1990 levels. If shipbuilding continues at the current level of technology, CO_2 emissions are likely to increase 3.3% by the 2010s compared to levels in 1990. Thus a qualitative assessment was made of potential technologies related to future transport efficiency improvement by interviewing shipbuilders.

Table 34 shows the results of individual assessments on potential technologies related to future transport efficiency improvements. The distinction between short-term and long-term technologies here is based on the technological feasibility of vessel applications by 2010, the first target year fixed by UNFCCC. The cost for ocean-going vessels already under fierce international competition is difficult to assess. The next qualitative assessment examined the initial cost scale, including R&D costs, to determine if operating cost (roughly equal to fuel consumption) reductions gained by the initial investments would be sufficient.

The results showed that hull additives like PBCF are suitable as a reduction technology because they are easy to attach, adaptable to aged ships, and their initial cost is relatively small. If an immediate measure to reduce CO_2 emission amount were required, slower navigation would be the most effective as this does not require any new equipment additions to conventional ships. In practice, attention must be paid to the fact that slower navigation runs counter to the rapid navigation that is demanded by socioeconomic forces. Moreover, worldwide cooperation would be vital to guarantee effectiveness.

Performance in actual oceans cannot be completely predicted since most current technologies are based on assessments conducted in test tanks and testing beds. Even if an efficiency improvement by a single technology is small, the fact that combining technologies may either multiply or offset its effect must be taken into consideration. Therefore, these technologies should henceforth be assessed by considering actual navigation in heavy seas and other conditions. It is also important to develop methods of collecting, analyzing, and monitoring actual navigation data for comparison to the test data collected on the technologies adapted by conventional vessels.

Table 34: Qualitative evaluation of potential technologies of fuel consumption reduction

section		item		Outline of advantages and disadvantages of technologies	merit	demerit	remark
Short-term technology	Propulsive performance improvements	Enhanced Body-shape	Enhanced body-shape	optimize the ship body-shape. Optimization of valve shape.	An enough finding has been saved by a past research.	The external target of limitation of the loading efficiency and harbors facilities etc. limitation factor is large, and the freedom degree of the design is few.	A resistance improvement is about 5 can be expected.
			Reduce wave resistance	Improvement with hull addition thing such as decrease small size fins.	Retro-Fit is possible	There is a possibility that application is promoted if the fuel expense rises.	A resistance improvement is about 10% can be expected.
			Reduce frictional resistance	Minimization of decrease water line.	An enough finding has been saved by a past research.	It is in the trade-off relation between the both resistance.	There is a calculation example of the decrease by several % by decreasing a water line lower product with almost equal shape.
				The living thing of the stain is prevented from adhering equally to the past or any more by using a new bottom of a ship paint which takes the place of the organic tin system.	Development already underway overall to cope with organotin control.	So far, no paint with cost performance better than organotin developed.	Offset of high cost by mass production expected.
		Enhanced Propeller	Contra-rotating propeller		Effective also for vibration and cavitation prevention.	Initial cost for propeller and gear-box high. Fuel price may facilitate the use.	A propulsive efficiency improvement of about 5-10% can be expected.
			PBCF (propeller boss cap fin)	Attachments such as fins to the boss cap.	Refitting is possible on conventional vessels.	The initial cost is relatively small.	So far there are over 100 examples. A propulsive efficiency improvement of about 4% can be expected.
			Potted propeller	Propeller synchronized with an electric motor attached to the stern of the ship. This serves as a rudder by revolving itself.	This is technologically practical. In fact, it has already adapted to a ferry.	This initial cost is very large. It is more expensive than a dual reversing propeller. The electric motor covers all the propelling energy and the propeller requires a large-scale generator so there is a problem in generation efficiency.	Other improvements are expected such as freedom in stern design since there is no need for a rudder and overall enhancements in transport efficiency by saving space. This can be adapted to newly built ships.
		The utility of mutual interference between the hull form and the propeller		Optimization of propeller position and stern form by considering the flow near the stern.	Suitable methods of performance assessment are prepared based on past research.	Trade-off in terms of hull vibration. Optimization of conventional propellers has already been carried out and few areas remain to be improved.	New types of propeller, such as dual reversal and potted types are likely to improve propulsive efficiency by approximately 10%.

section		Item	Outline of advantages and disadvantages of technologies	merit	demerit	remark
Short-term technology	Engine improvements	Comprehensive main engine heat efficiency improvement	Optimization of the timing, frequency, and electronically controlling the rate of the fuel jet to the burner, and optimizing the form of the burner	Costs are relatively small. Refitting conventional ships is practical.	Trade-offs with NOx emissions. The reliability of long-term jet control systems is insufficient.	By standardizing the temperature in the burner, compatibility is expected between NOx emissions control and engine efficiency improvements. Improved maintenance.
	Enhanced maintenance	Improved maintenance technology and frequency to maintain main engine performance	Periodically remove accumulations on ship bottoms. Pressure match the T/C and clean up scavenger valve.	These are effective for all types of ships and the effects are enormous for the entire ship.	Maintenance should be done at port, so docking periods and costs increase.	It is possible to reduce the age deterioration of propulsive efficiency from current rates by 15% to 10% per 10 years. Maintenance techniques at anchor are lacking. The introduction of bottom-cleaning robots should be considered.
	Reduction of frictional resistance	Speed optimization	Slower navigation	This presents no technological problems.	The number of days at sea increases. The effectiveness of regulating navigating speed can't be guaranteed without worldwide cooperation.	Especially in recent years, consignors have demanded that cargo ships transport loads as quickly as possible. Economic implications are inevitable. See 3.4.1 for the effects of worldwide fuel consumption reductions.
		Optimizing the number of ships	Improve transport efficiency by increasing the size and average loading rate and reducing the number of excess ships, etc.	This presents no technological problems.	The scope available to a single company is quite small. Preparing port facilities and international coordination are also necessary.	Port facilities need to be prepared. See Chapter 3 regarding transport efficiency per ton-mile by size.

section			Item	Outline of advantages and disadvantages of technologies	merit	demerit	remark
Long-term technology	Fuel conversion		Converting to alternative fuels	Convert from crude oil to a fuel with low CO2 emissions per heating value such as methanol, DEM, and LNG.	There are many examples of converting to high-speed diesel engines among land-based transportation.	The heating value per unit of fuel is small and the engine space required is large. Further technological development is necessary to apply this solution to large vessel engines.	Reduce NOx emissions. Separating CO2 from exhaust gases is straightforward when it is withdrawn for recycle. Fuel production and supply systems must also be prepared.
	Reduce friction resistance	Reduce friction resistance	Microbubble	Infuse fine air bubbles into the turbulence border on the surface of the hull.	Technically, it is rather simple to attach air bubble generation equipment near the bow.	To date, the energy needed to generate air bubbles is enormous and thus this is not always an efficient means of saving energy.	Frictional resistance is reduced by about 10% in testing. It is possible to improve fuel consumption efficiency by about 5%. Efficient air bubble generation methods need to be developed.
			Riblets	A line of small grooves, embedded in the surface of the hull under the waterline, parallel to the water flow.	Refitting old ships is possible since the process is carried out on the surface of ships below the waterline.	It's likely that maintenance costs would increase because of barnacles and other things adhering to the hull.	About 8% reductions in frictional resistance have been reported. Optimizing the grooves requires 0.1mm order process.
			Development of the anti-rolling hull	Refitting the hull and bow above the waterline can control resistance to waves.	Navigation routes become freer. This can minimize intentional slowdowns in bad weather.	Requires hull assessment measurements on actual seas.	Examples of systematic research are limited, but there is an extreme example that heavy waves resulted in as much as 30% propulsive performance deterioration. Limiting this deterioration to approximately 15% is required.
	Engine improvements	Development of new engines	Turbo compound engine	Drive the gas turbine in part by exhaust gases and transmit the power to the crankshaft.	There are some examples of this being adapted to land transportation.	Credible improvements to small gas turbines and reduction gears are needed.	This improved high-speed land transportation by 4% compared to constant pressure diesel engine.
			Electrical propeller engine	Generate power by hydrogen battery to drive the motor.	Fuel battery technology has been established and it is relatively simple. There are some examples of this being adapted to land-based transportation.	Weight is a problem when using hydrogen adsorptive alloys as fuel storage. Additional space is also necessary when generating hydrogen from oil and coal on board ship.	After generating hydrogen gas, there are no CO_2 emissions. Large DC (direct-current) motors or large-volume rectifiers are needed.

3.3. Investigation of solutions for vessel operation

3.3.1. Investigation of slow steaming

According to the propeller law, it is generally known that the load factor on the main engine of a vessel is proportional to the cruise velocity cubed. Due to this, when the operating speed is reduced to 90%, the load factor becomes about 80% even after adjusting for the increased operation time. This will lead to the reduction of the direct fuel consumption rates if SFC is constant in this load region.

In practice, it is said that the degree of reduction is set at about 80% to 90% of the theoretical value in many cases by comparing to a propeller or turbocharger.

Under current operation patterns, it is said that this is intended for high-speed applications, focusing on container operation. It is also believed that the trend to limit shipping costs, even through decelerated navigation, has faded since the oil shock. Nonetheless, since for VLCC and other ships this is set at the rate of the basic shipping cost called the contract form WS (World Scale) of transport, it is often more economical to slow down below a mean sea speed 14 knots. This is the reference for the calculation of basic shipping costs when creating a contract with few of the rates.

3.3.2. Investigation of weather routing

(1) WRS overview

A detailed description of WRS is summarized from the Weather Routing Research Group (1992).

From this document, an adjusted overview of WRS is given here. The WRS overview is shown in Figure 18.

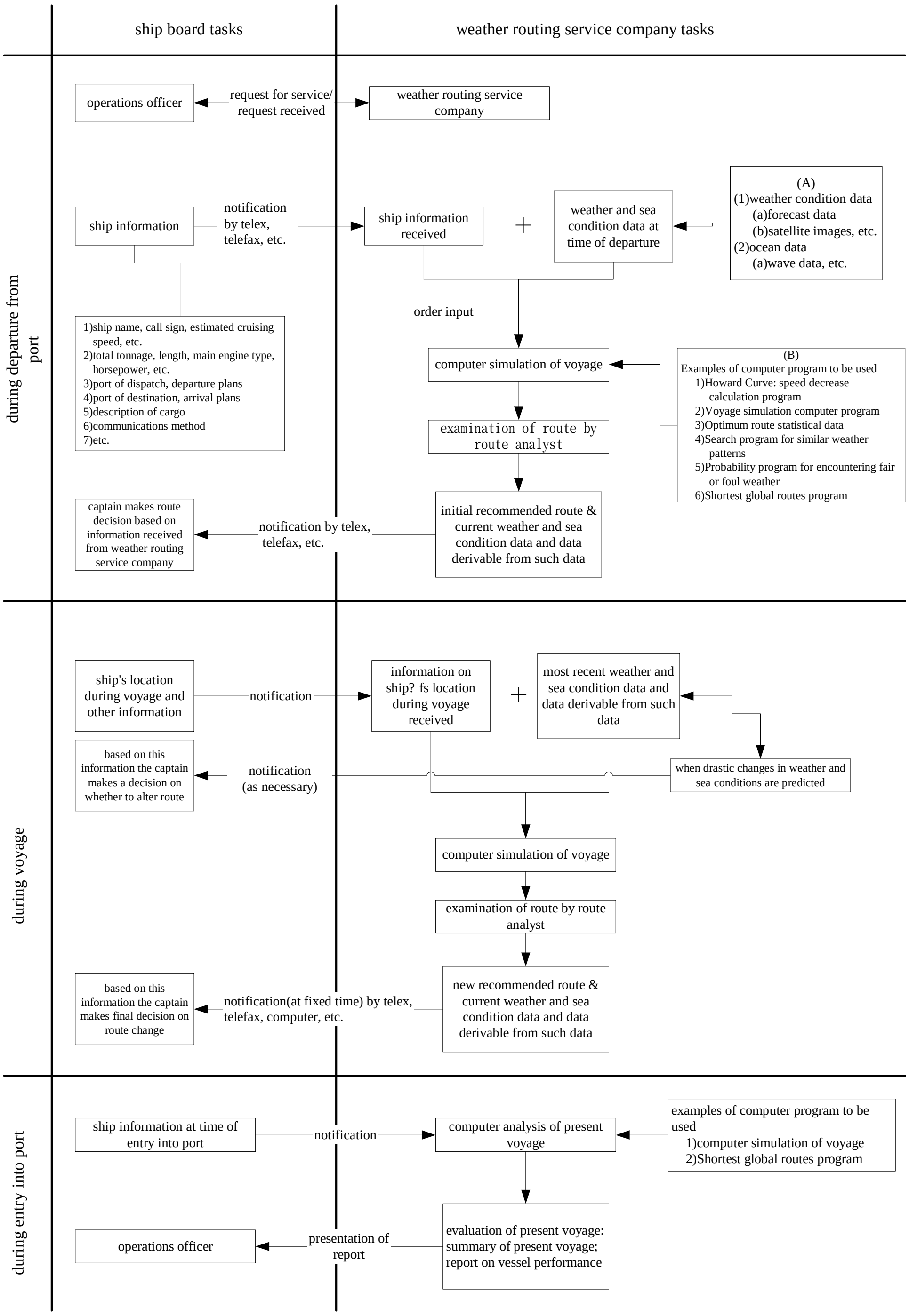


Figure 18 The WRS process

A route analyst who has sufficient knowledge of WR, including knowledge of the vessel and the weather, carries out WRS. Before the vessel subject to WRS puts out to sea, the route analyst collects as much information (the waterline, the cargo conditions, the long-run average water flow velocity, etc.) about the vessel as possible. Next, the analyst approximates a recommended route from existing statistical results and determines the optimum route based on forecast tools (predictive values, iterative values, interactive charts, prognostic charts, etc.) provided by weather association agencies. Next, a computer program based on predicted-value data becomes the center of the optimum route selection process. Presently, the forecastable period for which predicted values retain sufficient accuracy is about 3 to 4 days. For this reason, whenever the forecast product is updated, the route analyst updates the optimum route and informs the target vessels of the newest optimum route.

After completing a voyage, the recommended optimum route (track) based on interactive values and other information is verified and reported to the client. Some computer programs are also used. The general performance evaluation measure is the time difference in hours that the vessel receiving WRS actually cruised and the cruising time over the shortest route under the same hydrographic conditions. The WRS was successful if the actual cruising hours are shorter than the time over the shortest route. However, the cruising hours may also be extended by the time required to bypass bad weather areas, an iceberg on the shipping route, etc.

As mentioned above, although some programs have been developed for WRS, not all programs are used for track selection. Instead, programs are mainly used for post-evaluation. In long-term voyages that exceed 5 days, only trends can be predicted since the present forecastable period is 3 to 4 days. If the forecastable period can be extended, these programs will also be used for track selection.

(2) Recent users of WRS

According to research of civilian WRS organizations, WRS utilization (about 1500 voyages/year) has fallen off by about 60% from its 1991 peak level. This decreasing trend in utilization has been caused by reductions in clients' costs.

Almost all the vessels using WRS are container vessels and PCCs, about 70% are bulk carriers. Tankers hardly ever use WRS. Since hydrographic conditions are more stable in summer, the total rate of utilization drops about 30%. Container vessels use WRS to shorten cruising time. PPCs use it to prevent cargo movement.

(3) Operating days reduction through WRS

Research on the reduction of operating days through WRS was carried out on organizations providing WRS in Japan.

Civilian WRS organizations carried out evaluations on WRS after fiscal year 1995. However, it is difficult to determine trends in the reduction of cruising days due to WRS because there is little data and the detailed conditions at the time of voyage are not known.

Moreover, according to the response of another civilian WRS organization, detailed data from past documents were not collected. Nonetheless, the effectiveness of cruising time reduction due to WRS on the North Pacific shipping route is about one-half day in summer and about a day in winter. (A high-speed vessel takes ten days to make a one-way voyage.) These values have not changed significantly in the last ten years.

(4) Potential forecastable period for high seas

In WR, tracks are selected based on the numerical wave forecasts. The forecastable period affects WR's effectiveness at reducing cruising days.

In present numerical wave forecasts, the forecastable period is about 3 to 4 days. The North Pacific Ocean is described as the most predictable route for the effective cruising days reduction by WR (the Weather Routing Research Group, 1992). However, it takes about ten days for even high-speed vessels traveling at about 20 knots to make the one-way voyage. Taking the North Pacific shipping route as an example, if the forecastable period could be extended to 10 days and predicted values available, the effectiveness of WR at reducing cruising days would improve greatly. This paper describes the transition of wave forecasting to the Meteorological Agency in Japan, the transition of forecast accuracy accompanying this and trends of the future forecastable period.

(a) Wave forecasting trends and forecast accuracy trends

Currently, most developed countries conduct forecasting using numerical weather models.

Improvements to computer numerical abilities have had a large influence on the growth of numerical weather models.

Weather wave forecasting in Japan began in 1972 (Hashima, 1991).

Numerical wave models have been updated several times. When the model is updated, the old and new models are compared and the results are officially announced (Tsuchida et al., 1975; The Meteorological Agency Marine Department, 1986; Ichinari, 1997). Moreover, some results related to the comparative accuracy of the model components that forecast sea winds, important in wave forecasting, are also announced officially (The Meteorological Agency Marine Department, 1989; 1990).

In these documents the correlation coefficient and the root mean square error (RMSE) of the calculated and iterative wave height and cycle values are used to assess models. However, these values cannot, in general, be compared since the measurement points (location, forecast time, etc.) are different. Thus it was difficult to obtain information from existing documentation on trends of the numerical wave model forecastable period.

Although not numerical wave models, data exist that compares the accuracy trends of two numerical weather models: the northern hemisphere spectrum model (NSM) and the global sphere spectrum model (GSM) as shown in Figure 19.

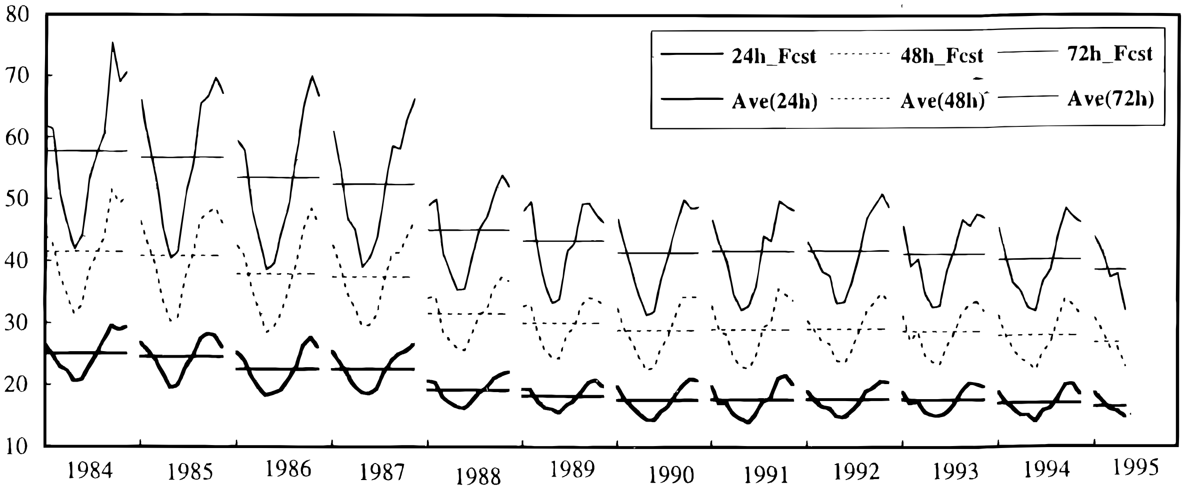


Figure 19 Trend of the root mean square error (RMSE) of the northern hemisphere model and global sphere model (GMS)

The root mean square error (RMSE) of the 500hPa altitude field at 20 °N latitude in the global sphere model (1988. Mar.-) and the northern hemisphere model (1983. Mar.-1988.Feb.), from the Meteorological Agency. The degree of error of each forecast time as an object of analysis is given. The time frame is from March 1984 to April 1995. A thick solid line indicates a 24-hour forecast, a dotted line indicates a 48-hour forecast, and a thin solid line indicates a 72-hour forecast.

A line parallel to the horizontal axis shows the average for one year.

According to this figure, the error in a 72-hour forecast in 1995 is the same magnitude as a 48-hour forecast before 1988. At the same error level, the forecastable period has improved by 1 day over these 10 years.

(b) The future of wave forecast

The accuracy of numerical weather forecast models is improving considerably. The forecastable period is gradually extending by improving the quality of observation data (the Meteorological Agency, 1997). Up to now, most observations of ocean waves have been carried out by visual observation and there has been a large variation in their quality (Ichinari, 1998). Moreover, 75% of observations are collected from common vessels so the data is greatly weighted to ocean areas (Hashima, 1991). In addition, according to recent research results of WRS organizations, crew numbers have been falling as attempts are made to reduce employment costs in vessels of Japanese registry. This tends to reduce the number of observation data reports from vessels.

Advances in earth observation satellites are enabling regular and reliable sea wave observations (including sea wind, wave height and the ocean spectrum). Technical advances to further enhance these data are an important research topic among countries worldwide (Ichinari, 1998).

Moreover, progress continues on the ARGO Plan, in which the Ministry of Transport installs more robotics observation buoys in cooperation with the U.S. FNOC. The information obtained is expected to extend the forecastable period.

(5) WRS as an option to reduce CO_2

Using WRS, a fast vessel takes about 10 days to traverse the North Pacific shipping route one way. If the forecastable period were extended to 10 days, WR’s effectiveness in reducing cruising time would be greatly improved. However, it has been noted that models have not been making progress in improving the forecastable period. In the meantime, as shown in 3.3.2(4)(b) and (4), improvements to the initial condition’s temporal and spatial densities and the base required for real time forecasts may be possible in the near future. This is expected to lengthen the forecastable period and improve the effectiveness of WRS in reducing the number of cruising days.

The following items can be considered when examining the utilization status of WRS.

- Although WRS focuses on minimizing the navigation time of some vessels, policy changes are needed to reduce the fuel consumption rate
- By extending the wave condition forecastable period provided by public agencies, improvements to fuel consumption reductions through WRS are planned. (Under the status quo, a maximum cut of cruising days of about 10% is possible along the North Pacific shipping route.)

---

1) The process to incorporate observation data into models
At the Meteorological Agency, the process of assimilation refers to data quality control, the interpolation processing to each lattice, the initializing procedure that reduces the noise generated by gravity waves, and the generation of the first estimated value.

3.4. Review of solution implementation methods

3.4.1. Review of options to reduce CO_2 emissions

(1) Vessel operation volume forecast

The fuel consumption of crude-oil transport by tanker was calculated as a calculation example of future CO_2 discharge forecasted amounts. As described in the preceding chapter, the discharge amount may grow in the future even if the natural replacement of older vessels occurs while incremental increases in transportation efficiency are balanced by transport performance enhancements. Figure 21 shows the annual changes of crude-oil transport amounts arriving in Japan and the total amount of world transport.

The mean transport distance of DD-oil transport arriving in Japan decreases as the crude-oil source location changes from the Near East to South Asia. Thus DD-oil imports rise 1% per year on a ton base, but only marginally increase when transport performance is measured in ton-miles.

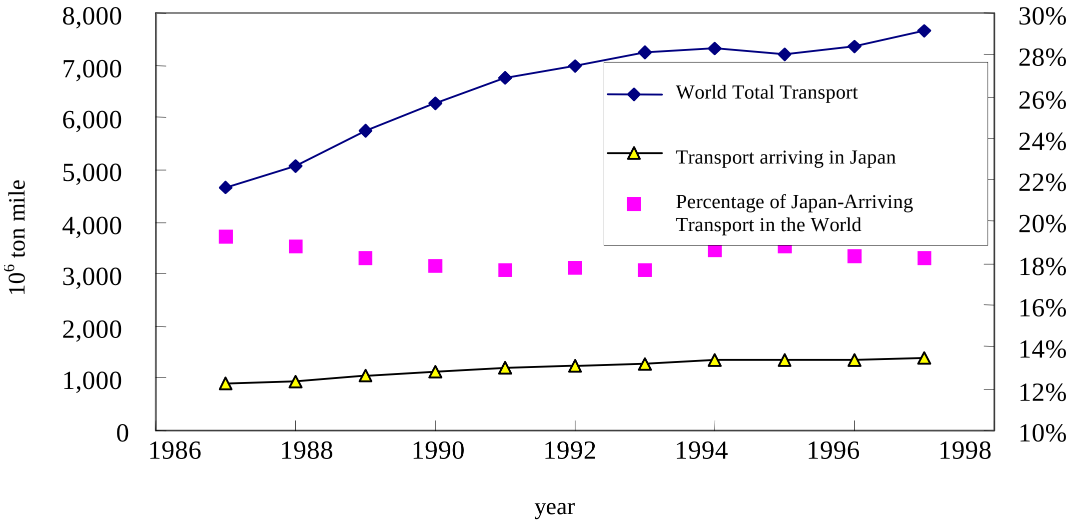
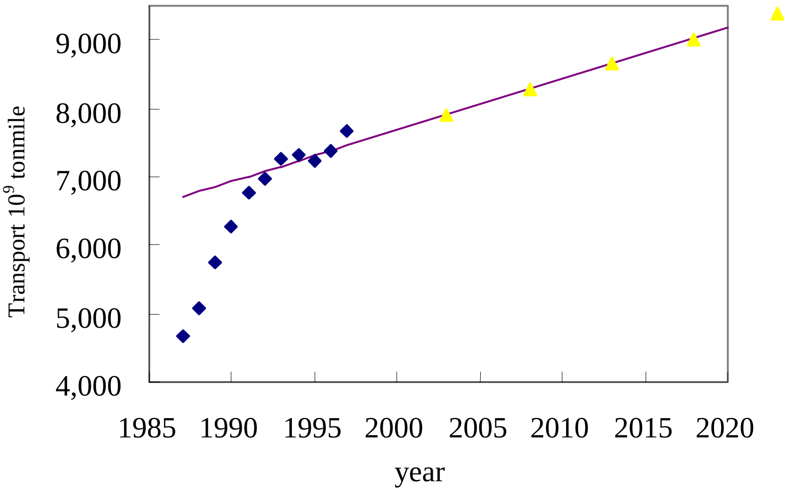


Figure 20 Changes in crude-oil transport amounts worldwide and the transport amounts arriving at Japan

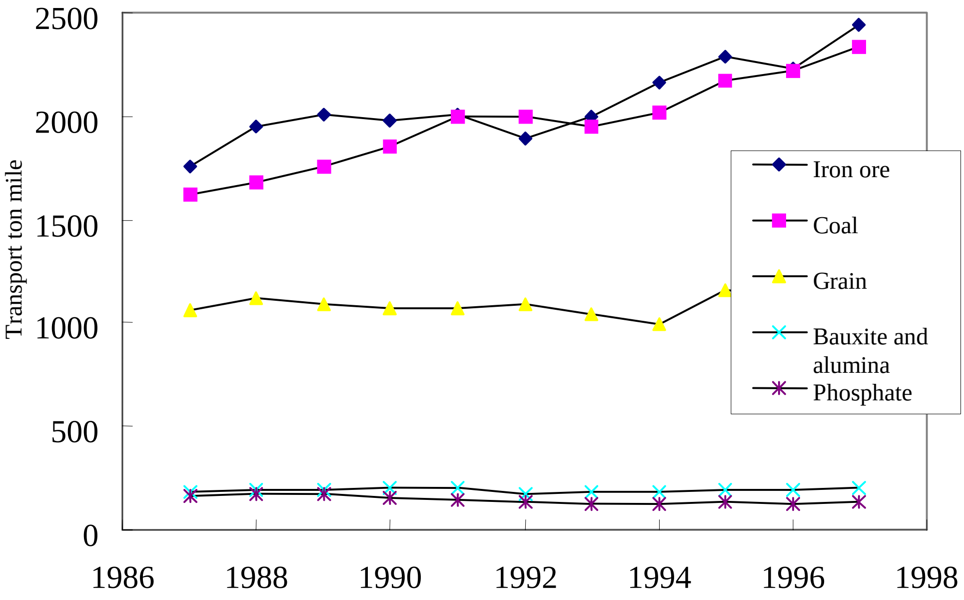
However, global transport amounts show a significant increase. As shown in Figure 21, a linear extrapolation of the past 5 years gives an increase of 75/7677 = 0.97%/year based on 1997 data. Future crude-oil imports to UNFCC affiliate countries are projected to decrease as demands for fuel conservation continue (although shipments of LNG may increase). Thus, given predicted economic growth rates of 2% among OECD countries, a 1% rise in crude-oil shipments seems appropriate.

Figure 22 shows, similar to other cargoes, heavy cargo such as coal and iron ore shipments are expected to grow by 2% to 3% based on 1997 data. Container shipments are predicted to increase by 6%/year as shown in Figure 23.



Based on Fearnley's World Bulk Fleet January 1999

Figure 21 Performance of tanker transport and future forecasts



Iron ore	2.1%
Coal	2.8%
Grain	0.4%
Bauxite and Alumina	0.5%
Phosphate	-3.6%

Figure 22 Performance of other cargo transport and future forecasts

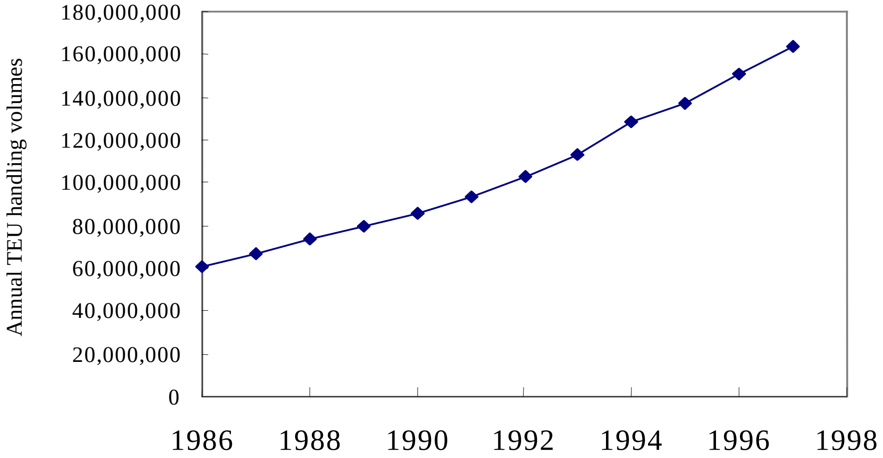


Figure 23 Performance of container handling volume and future forecasts
(An volume handling expansion of 5.68%/year based on 1997data)

Since future fuel consumption forecasts are based on the transport volume assumptions above, Table 35 shows the case of constant transport volumes and Table 36 shows the case of increasing volumes. Figure 24 shows future consumption trends. The dotted line represents the anticipated case of incremental transport. The solid line represents the case of constant transport volume.

It was assumed that the total number of vessels and their DWT composition would not vary in the future. Natural substitution continues for vessels older than 30 years with substitution complete in 35 years. For this reason, a freight space deficiency on tankers and container vessels will arise around 2017 as indicated by the mean operating days shown in Table 35. It was assumed that freight space deficiencies would be mitigated by the largest vessel model of each vessel type.

The effect of natural vessel substitution calculated for each vessel type as ratios of tonnage year and vessel type is different in Case 1, in which transport amounts remain constant. In Case 1, natural substitution has a large effect on tankers. This depends on the significant economizing effect of fuel consumption rates among new-model tankers and a high loading factor of older model vessels compared to other vessel types. Consequently, a fuel consumption decrease of nearly 10% would be realized between 1997 and about 2010.

On the other hand, there would be almost no decrease realized around 2010 in the case of the anticipated transport amount expansion.

To simulate an increasing number of vessels, two pieces of information are necessary: a percentage breakdown by total tonnage by DWT class of the increased number of ships, and when the additional number of ships will come into service based on the increase in ship building capacity.

Future forecasts of the transport matrix, including changes to the place of origin from the Near East to Indonesia (related to a reduction in the number of miles), is required to evaluate the origin of goods delivered to Japan.

Information that is indispensable to future analysis includes economic information such as economic evaluations of tanker operation and future plans for shipbuilding capacity, as well as information on future national energy policies.

Table 35 Forecasted results of fuel consumption (Case 1)

Fuel Consumption Estimation(10^6t)	1997	2002	2007	2012	2017
Tanker	26.1	23.0	22.7	22.7	22.7
Container	43.0	42.1	41.3	40.4	40.4
Other Bulk	62.7	60.7	59.9	59.9	59.4
Total	131.8	125.8	123.9	123.0	122.5
Percentage to 1997 Total	100.0%	95.5%	94.0%	93.3%	93.0%
Average Number of Days Sea for Tanker	289	246	226	217	213
Average Number of Days at Sea for Container Vessel	251	251	251	251	251

The transport amount stays at 1997 levels with only natural substitution

Table 36 Forecasted results of the fuel consumption (Case2)

Fuel Consumption Estimation(10^6t)	1997	2002	2007	2012	2017
Tanker	26.1	23.2	23.1	23.4	23.6
Container	43.0	44.5	46.1	47.7	50.4
Other Bulk	62.7	61.4	61.2	61.9	62.2
Total	131.8	129.1	130.5	133.0	136.2
Percentage to 1997 Total	100.0%	98.0%	99.0%	100.9%	103.3%
Average Number of Days Sea for Tanker	289	292	297	306	318
Average Number of Days at Sea for Container Vessel	251	265	280	296	313

The transport amount increases with only natural substitution.

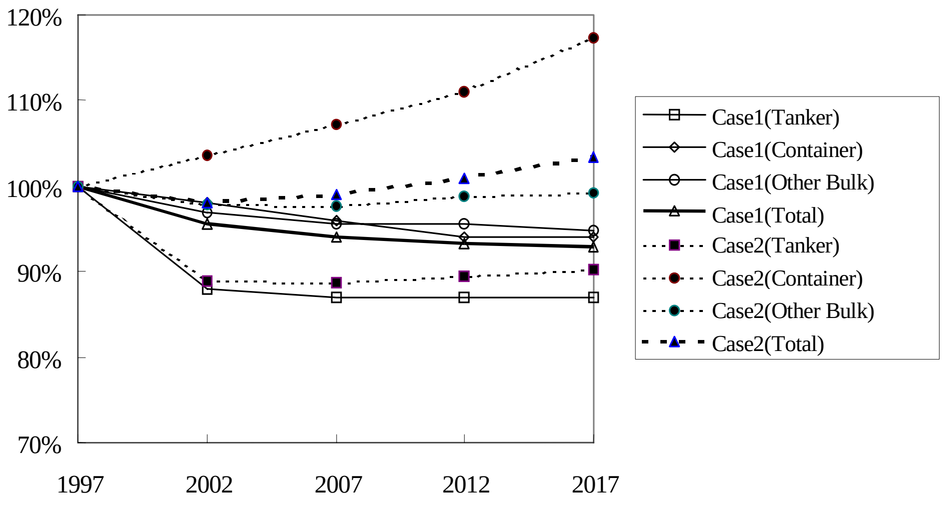


Figure 24 Forecasted results of future fuel consumption rates (besed on 1997 data)

(2) Vessel transportation volume forecast at slow steaming

Future forecasts at slow steaming are shown in Tables 37 to 39.　In Case 3 and Case 4, slow steaming was assumed uniformly at 80% of current conditions for the fastest container vessels, 90% of current conditions for tankers because in many cases they presently apply slow steaming, and 90% of current conditions for other vessels. Extending slow steaming to all vessel size creates a deficiency in the volume of available freight space. When the mean number of cruising days exceeds 310 (85% of the year), the number of the largest vessel types and newest vessel size were increased to make up the shortfall. In case 5, all vessels were assumed to perform slow steaming at 1 knot below cruise velocity as a moderating condition.

In all cases, the effects of slow steaming are larger than that of natural substitution. If an urgent temporary request was made to reduce fuel consumption, universal slow steaming offers a possible means of compliance.

Table 37 Forecasted results of fuel consumption rate (Case 3)

Fuel Consumption Estimation(10^6t)	1997	2002	2007	2012	2017
Tanker	26.1	19.4	19.2	19.2	19.2
Container	43.0	30.2	31.0	30.7	30.7
Other Bulk	62.7	50.2	49.5	49.5	49.2
Total	131.8	99.8	99.7	99.4	99.0
Percentage to 1997 Total		75.7%	75.7%	75.4%	75.1%
Average Number of Days Sea for Tanker	289	273	251	241	237
Average Number of Days at Sea for Container Vessel	251	310	310	310	310

Transport amounts remain at 1997 levels with natural substitution and slow steaming

Table 38 Forecasted results of fuel consumption rate (Case 4)

Fuel Consumption Estimation(10^6t)	1997	2002	2007	2012	2017
Tanker	26.1	19.6	19.6	19.7	19.9
Container	43.0	31.9	32.7	33.5	34.3
Other Bulk	62.7	50.8	50.6	51.2	51.4
Total	131.8	102.3	102.9	104.4	105.6
Percentage to 1997 Total		77.6%	78.0%	79.2%	80.1%
Average Number of Days Sea for Tanker	289	310	310	310	310
Average Number of Days at Sea for Container Vessel	251	310	310	310	310

Increasing transport amount, natural substitution, 80% slow steaming for container vessels and 90% for other vessels

Table 39 Forecasted results of fuel consumption rate (Case 5)

Fuel Consumption Estimation(10^6t)	1997	2002	2007	2012	2017
Tanker	26.1	19.7	19.9	20.6	21.5
Container	43.0	40.1	43.8	44.4	47.4
Other Bulk	62.7	52.8	52.7	55.1	56.6
Total	131.8	112.6	116.4	120.1	125.4
Percentage to 1997 Total	100%	85%	88%	91%	95%
Average Number of Days Sea for Tanker	289	301	310	310	310
Average Number of Days at Sea for Container Vessel	251	279	302	310	310

Increasing transport amount, natural substitution and a uniform slow steaming speed reduction of 1 knot

3.4.2. Implementation framework for options to reduce CO_2 emissions

Options include obtaining information on political incentives such as the CO_2 tax introduced to land-based traffic, fuel consumption quota systems, obligatory official announcements of quantified loads on the global environment, and examining the possibility of introducing an international constitution.

At COP5, no concrete progress was made on the two international cooperative implementation frameworks: AIJ (Activities Implemented Jointly) and CDM (Clean Development Mechanism).

Information has been gathered on emission trading systems that contract between private enterprises, such as power companies or between the Russian and Australian or other governments. Also considered is the application of such systems to vessel operations.

Presently, the only functioning market in emission trading is in Chicago, where contracts are made on U.S. ecological rights. This market controls the total amount of SO_2 ecological rights in the United States. Only administrators of large-scale SO_2 generation facilities that have been assigned emission amounts by federal statutes, such as power companies, can sell ecological rights. However, rights can be purchased by not only generating facilities, but also by local governments and nature conservation organizations. In other words, a local government could use tax dollars to purchase ecological rights within its jurisdiction. This would reduce the locally generated amount of SO_2 below the federally mandated level. This approach may also be applied to CO_2 emissions. In the future it is possible that the sea transport industry or organizations such as the IMO could purchase land-based CO_2 ecological rights.

Within the COP framework, details of such a system are totally undecided despite provisions for a system in Article 17. (However, ratification can proceed without detailed decision since the COP controls its own framework.) As mentioned above and in the latest discussions of COP5, an implementation process does not exist and quantitative evaluation of CO_2 has also been delayed. Thus in the current situation, even if CO_2 ecological rights were purchased, total emission rights have not been determined. Since the present IMO framework is also undecided, it is difficult to envision an emission trading framework.

The United States is opposed to a framework that sets a reduction to the current absolute amount. However, the United States is considering the introduction of a domestic trading system of ecological right credits based on voluntary participation by 2008 (the first commitment year).

In the Chicago and London markets, work continues on establishing an autonomous CO_2 emission trading system for domestic businesses. In the future, it is uncertain whether credits traded on these markets would adapt to a framework created by the COP. The COP will likely monitor any trading mechanism created, track numerical targets and the emission framework, and monitor the progress of ecological rights.

It will likely be difficult to assign ecological rights to cover the traffic emissions of downstream energy consumers. For example, Toyota Motors plans to abide by the ecological rights framework created in Australia. However, this framework would apply to CO_2 generated as part of the automobile manufacturing process. But Toyota would not guarantee the CO_2 generated by the utilization of their automobiles.

Presently, however, ecological rights are not assigned. It is theoretically possible that the sea transport industry or the IMO could independently purchase excess land-based ecological rights.

4 Investigation Review

4.1 Investigation results summary

4.1.1 Calculation of fuel consumption

Yearly consumption of bunker oil can be calculated as $131.8*10^6$ t/y (CO_2 emission equivalent of $3.95*10^8$ t/y) based on statistical values (Energy Statistics of OECD Countries 1994-1995 (OECD/IEA, 1997) and Energy Statistics and Balances of Non-OECD Countries 1994-1995 (OECD/IEA, 1997)).

An understanding of CO_2 emissions from each type of vessel is necessary to study methods of reducing CO_2 emissions originating from vessels navigating between Japan and other countries. Based on statistical documents, annual fuel consumption by tankers, container vessels and bulk carriers was estimated to be 31%, 33% and 29%, respectively. However, the actual operating conditions of container vessels were not clear and the figures presented should be assumed to be less accurate than other vessel types.

The resulting calculated fuel consumption for all the vessels described above was almost the same as the annual fuel consumption statistical value. Since the average number of cruising days in this case is approximately 300 days for oil tankers and 250 days for container vessels, it is believed that current conditions had been reproduced.

4.1.2 Solutions for vessel engines

Although average vessel engine heat efficiency had improved approximately 20% by the 1990s, there has been hardly any noticeable for the past few years. In the future, it should be possible to improve 2-cycle engine heat efficiency by 4% to 6%, and 4-cycle engines by 4% to 8% with electronic fuel injection. However, heat efficiency improvements come at the cost of increased NOx emissions. Depending on gas emission regulation trends, there may be little or no room for improvement.

On the other hand, engine energy consumption has improved approximately 15% in the last 20 years through the improved model development. If the vessel size improvement continues, further gains of up to 5% might be possible in the future. The future development and application of vessel size with reduced resistance coefficients to waves are also expected.

Technically, supplements such as fins and PBCF, double-reverse propellers, vessel bottom coatings (excluding coatings from the organic tin group) have already been partially adopted. However, the issue of cost efficiency remains when considering the widespread use of these coatings.

4.1.3 Solutions through vessel operation

Navigating at reduced speed and Weather Routing Services (WRS) have received significant attention in improving navigation.

When navigating speed is reduced 10%, it is anticipated that fuel consumption would be reduced 10% to 20%, even considering the additional hours of operation needed to travel the same distance.

However, navigating at reduced speed is not compatible to meeting socioeconomic demands for high-speed delivery. The efficiency gained through reduced operating hours through WRS was estimated in one sample study to be 5% to 10% on the navigation of one northern Pacific route (normally requiring 10 days to cross by rapid vessel). However, since the reliable period of sea weather forecasting is 3 to 4 days, WRS has not yet been widely applied.

In the future, improving the amount and quality of usable observation data is anticipated (through developments like ARGOS and satellite data technology). There are also plans to improve and popularize WRS efficiency by appropriate expansion of the weather forecast period.

4.1.4 Review of solution implementation methods

The future volume of vessel traffic was predicted from changes over time for the various types of ship. Then total annual fuel consumption was estimated. Tables 40 to 42 show the estimated results.

Table 40 Estimated fuel consumption (refit vessels, vessel traffic volume stays at the 1997 level)

Fuel Consumption Estimation(10^6t)	1997	2002	2007	2012	2017
Tanker	26.1	23.0	22.7	22.7	22.7
Container	43.0	42.1	41.3	40.4	40.4
Other Bulk	62.7	60.7	59.9	59.9	59.4
Total	131.8	125.8	123.9	123.0	122.5
Percentage to 1997 Total	100.0%	95.5%	94.0%	93.3%	93.0%
Average Number of Days Sea for Tanker	289	246	226	217	213
Average Number of Days at Sea for Container Vessel	251	251	251	251	251

Table 41 Estimated fuel consumption (refit vessels, additional volumes of vessel traffic)

Fuel Consumption Estimation(10^6t)	1997	2002	2007	2012	2017
Tanker	26.1	23.2	23.1	23.4	23.6
Container	43.0	44.5	46.1	47.7	50.4
Other Bulk	62.7	61.4	61.2	61.9	62.2
Total	131.8	129.1	130.5	133.0	136.2
Percentage to 1997 Total	100.0%	98.0%	99.0%	100.9%	103.3%
Average Number of Days Sea for Tanker	289	292	297	306	318
Average Number of Days at Sea for Container Vessel	251	265	280	296	313

Table 42 Estimated fuel consumption (refit vessels, 10% speed reduction by container vessels and 20% by other vessels)

Fuel Consumption Estimation(10^6t)	1997	2002	2007	2012	2017
Tanker	26.1	19.4	19.2	19.2	19.2
Container	43.0	30.2	31.0	30.7	30.7
Other Bulk	62.7	50.2	49.5	49.5	49.2
Total	131.8	99.8	99.7	99.4	99.0
Percentage to 1997 Total	100.0%	75.7%	75.7%	75.4%	75.1%
Average Number of Days Sea for Tanker	289	273	251	241	237
Average Number of Days at Sea for Container Vessel	251	310	310	310	310

When additional volumes of vessel traffic are not considered, it was estimated that slight annual fuel consumption reductions would be achieved by refitting vessels (Table 40).

This tendency is particularly evident when looking at tankers from among the different types of vessels. When considering additional volumes of vessel traffic, it is estimated that annual fuel consumption would remain constant or increase slightly even when relying on refit vessels (Table 36). Considering vessel types, a remarkable tendency to increase can be seen among container vessels. The recent marked volume increase in container vessels and projecting further increases in the volume of vessel traffic justify the estimate that the volume of container vessels will significantly increase in the future. When estimating speed reductions of 10% to 20% combined with vessel refitting, the amount of annual fuel consumption dramatically reduces initially. Thereafter, gradual fuel consumption reductions are estimated (Table 42).

4.1.5. Implementation framework for options to reduce CO_2 emissions

For land-based sources of exhaust gas, political options such as carbon taxes, emission credit trading and others have been studied by COP. CO_2 emission trading systems have been voluntarily established on markets in Chicago and London. However, it is not clear how these trends can be applied globally.

Such a framework also could theoretically be applied to international marine traffic. Considerable attention should be paid to future trends among international organizations regarding the handling of land-based emission sources.

4.2 Future tasks

(1) Calculation of fuel consumption

There is currently insufficient information on navigating speeds, actual fuel consumption and operating conditions of small and older vessels under actual navigating conditions. In particular, there are many uncertainties within the information on container vessels. Therefore, it is necessary to collect detailed information and conduct specific analyses so that future fuel consumption estimates accurately reflect current conditions. Small and older vessels are usually not used for navigation leaving from or arriving in Japan, so information must be collected abroad.

(2) Vessel engine solutions

The IMO is planning to introduce NOx regulations. Technological developments that improve heat efficiency and reduce NOx emissions are required.

To be effective in the future, technology must be quantitatively examined to determine its effectiveness and cost efficiency. Over the long term, radical technological developments, such as substitute fuels and the development of engines capable of using substitute fuels, will be required.

(3) Solutions for vessel operation

・Speed reducing navigation

Navigating at reduced speeds offers drastic reductions in fuel consumption and there are no technological demerit issues. However, the economic loss related to additional operating hours should be considered. An examination is needed that takes into account the entire socioeconomic system to enforce reduced-speed navigation.

・WRS

Improvement in both the quantity and quality of marine observation data related to

WRS is expected in the future. However, the efficiency of WRS is not necessarily derived from a quantitative understanding. Therefore, monitoring WRS efficiency is required as it applies to container vessels that rely heavily on WRS and to areas of large navigation traffic volumes.

(4) Implementation framework for options to reduce CO_2 emissions

Collecting information on developments within COP and other international organizations is necessary to understand political trends in the reduction of CO_2.

(5) Review of solution implementation

Based on the results obtained in sections (2), (3), and (4) above, detailed and practical CO_2 reduction scenarios need to be set and highly accurate future fuel consumption reduction efficiencies need to be estimated. This requires financial efficiency be included in scenario analysis.

(6) Other greenhouse gases

CH_4, N_2O, HFC, PFC, SF_6

While the impact on global warming of these greenhouse gases is larger than CO_2, the actual emission conditions from vessels are unclear. As a first step, the emission conditions need to be understood.

O_3

O_3 is a by-product released when NOx undergoes a photo-chemical reaction. It is difficult to grasp the amount of O_3 in the atmosphere. It is necessary to simulate the photo-chemical reactions occurring over the oceans and examine the relationship to vessel navigation.

5 Appendix

5.1 Greenhouse gases other than the CO_2 discharged from vessels

CO_2 is a widely-recognized greenhouse gas emission. In addition, CH_4, N_2O, HFCs, the PFCs, SF_6, SPM, H_2O and O_3 are also known to contribute to greenhouse gas emissions. Table 43 compares these significant greenhouse gas emissions. When comparing the strength of the greenhouse efficiency per unit density, the effects of CH_4 are approximately 21 times as strong as CO_2, N_2O is 310 times as strong, and chlorofluorocarbons and halons gas are several thousands times stronger than CO_2. Even small amounts of these exhaust emissions can lead to global warming. However, considering the density in the air of these emissions (refer to the table Degree of greenhouse gas emissions), the largest contributor is CO_2. Thus approximately 60% of measurable greenhouse gas emissions are CO_2.

At the COP3 Kyoto Conference held in September 1997, a total of 6 substances: CH_4, N_2O, HFC, PFC, SF_6 were added to CO_2 as targets for reduction. These substances were selected based on their percentage contribution to global warming (absolute volume in the air multiplied by global warming coefficient), other harmful effects, reactive speed, time to decompose, ease of countermeasure enforcement and other factors.

CH_4 is contained in the gas exhausted from vessel engines. It is believed that the emissions released when loading oil tankers cannot be ignored. Moreover, there is a large amount of substitute chlorofluorocarbons used refrigerated container ships. It is likely the control of these ships is not thorough compared to the refrigeration facilities on land. Thus there is believed to be a large amount of leakage.

Table 43 Comparison of greenhouse gases

	CO_2	CH_4	N_2O	HCFC-22 (Typical HFC)	CF_4 (Typical PFC)	SF_6
Concentration in Ambient Air Before Industrial Revolution	280 ppm	700 ppb	275 ppb	0	0	0
Concentration in Ambient Air 1994	358 ppm	1720 ppb	312 ppb	268 ppt	110 ppt	72 ppt
Annual Increase(/year)	0.4 %	0.6 %	0.25 %	0 %	5 %	2 %
Persistence in Air(year)	50-200	12	120	50	12	50,000
Global Warming Factor	1	21	310	1,700	6,300	24,900
Global Warming Instance Wm^{-2}	1.56	0.47	0.14	0.12 (all HFC)	0.10 (all PFC)	0.002

5.2 Amount of CO_2 discharged by domestic vessels

This section explains the need for CO_2 reduction measures by comparing CO_2 emissions originating from vessels calculated from macro fuel consumption to emissions from land-based sources.

Table 44 shows the amount of CO_2 emissions in Japan. The fraction of CO_2 emissions shared among the transportation section reported to the IPCC is approximately 20%. Since 1990, both this fraction and absolute amount have been increasing slightly. Within the transportation section, it is estimated that automobiles account for 90% and vessels only 3.1%.

Specific measures to reduce CO_2 emissions by the transportation vehicles are improving energy efficiency and developing low pollution engines, thereby enhancing the energy efficiency of the entire freight traffic industry.

However, measures to reduce CO_2 emissions originating from vessels operating domestically in Japan have not been thoroughly examined. For example, the Global Warming Technical Plan Committee report compiled by Environment Agency states that domestic vessel emissions per transportation ton is approximately $21.6*10^6$ t/ton miles. Thus a future remedy is not expected soon. In another example, the Committee on CO_2 Emission Control Guidelines for the Vehicle Sector's investigation conducted by the Ministry of Transport stated that the transportation unit of automobiles, currently 585.8 kcal/ton kilo would be reduced to 573.1 kcal/ ton kilo by 2000. The investigation did not include domestic marine transportation unit improvements, currently 146.9 kcal/ton kilo ($27*10^6$ t/ton mile). If modal shift occurs, additional transportation ton kilos for inner marine transportation could be linked to additional CO_2 emissions.

Table 44: The amount of CO_2 emissions in Japan (excluding electric power distribution)

10^3 t-CO_2

Year		1990	1991	1992	1993	1994	1995	1996
1A Fuel Combustion								
1A1 Energy Industry		77,449	78,491	79,608	78,966	83,215	82,695	82,582
1A2 Manufacturing & Construction Industry		455,647	452,381	441,981	435,865	454,921	455,163	461,877
1A3 Transportation		213,780	223,251	228,317	230,127	241,368	248,547	254,815
1A4 Agriculture, Forestry & Domestic fisheries		297,292	306,692	318,989	311,868	332,297	338,462	335,707
1A5 Others		8,792	11,946	16,314	7,570	21,498	13,284	17,183
Total		1,124,532	1,147,845	1,162,314	1,143,794	1,213,940	1,220,218	1,234,904
Percentage in 1A3	Automobiles	90%						91%
	Vessels	3.2%						3.1%
	Air Plains	1.1%						0.9%
	Railways	5.7%						5.1%
(Refernce) Bunker Oil		30,806	33,036	34,095	36,688	37,494	37,328	32,420
Ocean-going vessels (within 200nautical sea mile)								6,022

Reference: Government of Japan, the IPCC Second Report and Third Report