



Calculation of Fuel Consumption and Exhaust Emissions from Ship in Ice Conditions

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Szczecin, January 2013



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ABSTRACT

During the past few decades, we have seen a dramatic decline of the Arctic sea ice level; this decline has raised high interest in efforts to establish new trade passages, and in raising the possibility of economically viable trans-Arctic shipping. Although increased Arctic shipping may provide commercial and social development opportunities, the associated increased environmental impacts are also of concern.

To better understand the impact of shipping in Arctic area, this thesis focus on the calculation of fuel consumption and related exhaust emissions for various ship types in different ice conditions along the Northern Sea Route in the Arctic Ocean.

The topic subject is a part of the project ACCESS (Arctic Climate Change Economy and Society). ACCESS is a European Project supported within the Ocean of Tomorrow call of the European Commission Seventh Framework Programme. Its main objective is to assess climatic change impacts on marine transportation (including tourism), fisheries, marine mammals and the extraction of oil and gas in the Arctic Ocean.

As a result of ice, a ship operating in ice conditions experiences an increase in the resistance due to extra work or energy required to break and remove the ice. The increase in resistance associated with ice navigation leads to higher fuel consumption rate for the vessel. In addition, delays due to ice may lead to the longer duration of the voyage which in turn also leads to more fuel consumption. Related emissions are therefore expected to be higher in open water conditions.

By developing a computer program using FORTRAN language, the calculation was carried out for three different ship types, namely, bulk carrier, oil tanker and LNG carrier, which are very common seen in Arctic area. The fuel consumption of these ships is calculated in four different periods, varied from September 2000 to November 2007. Related exhaust gases are estimated for these following pollutants: carbon dioxide (CO₂), methane (CH₄), nitrogen oxides (NO_x), sulphur oxides (SO_x), carbon monoxide (CO), and various species of particulate matter (PM) including organic carbon (OC) and black carbon (BC).

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ACRONYMS

ACCESS	Arctic Climate Change Economy and Society
BSFC	Brake Specific Fuel Consumption
ECA	Emission Control Areas
EPA	Environmental Protection Agency
HFO	Heavy Fuel Oil
HSVA	Hamburg Ship Model Basin
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
MARPOL	Marine Pollution
MARPOL 73/78	The International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978
MDO	Marine Diesel Oil
MFO	Marine Fuel Oil
MGO	Marine Gas Oil
NEP	Northeast Passage
NSR	Northern Sea Route
NWP	Northwest Passage
NSIDC	National Sea Ice Data Center
NWP	North-West Passage
SFOC	Specific Fuel Oil Consumption

ABBREVIATIONS

α	Waterline entrance angle
δ_p	Density different between water and ice
σ_b	Bending strength of ice
ϕ	Stem angle
ψ	Angle between the normal of the surface and a vertical vector
μ	Friction coefficient
ω	Speed of the engine
g	Gravitational acceleration
l_c	Characteristic length of the ice sheet
r	Fuel consumption rate
A_f	Area of the bow
A_u	Area of the flat bottom
B	Breath of the vessel
H_{ice}	Ice thickness
L	Length of the vessel
L_{oa}	Length overall of the vessel
L_{pp}	Length between perpendiculars of the vessel
L_{wl}	Length of the water line of the vessel
P	Power
P_D	Delivered power
P_E	Effective power
P_{MCR}	Engine power at maximum continuous rating
R	Ship resistance
T	Draft of the vessel
V	Speed of the vessel

1. INTRODUCTION

1.1. BACKGROUND

During the past few decades, we have seen a dramatic decline of the Arctic sea ice level, culminating in a record minimum sea ice extent of 3.41 million km² in 2011 (in compare with approximately 10 million in 1970). This decline in Arctic sea ice has re-ignited interest in efforts to establish new trade passages, raising the possibility of economically viable trans-Arctic shipping as well as increasing access to regional resources and spurring growth in localized shipping supporting natural resource extraction and tourism. Although increased Arctic shipping may provide commercial and social development opportunities, the associated increased environmental impacts are also of concern.

Many studies have assessed the potential impacts of international shipping on climate and air pollution and have demonstrated that ships contribute significantly to global climate change and health impacts through emission of many pollutants such as carbon dioxide (CO₂), methane (CH₄), nitrogen oxides (NO_x), sulphur oxides (SO_x), carbon monoxide (CO), and various species of particulate matter (PM) including organic carbon (OC) and black carbon (BC). Although at present the shipping in Arctic Ocean makes up a relatively small proportion of global shipping emissions, there are region-specific effects from substances such as BC and ozone (O₃) which are becoming increasingly important to quantify and understand.

To better understand the impact of shipping in Arctic area, this study focus on the fuel consumption of different ship types and estimate the exhaust emissions in according with the fuel consumption data.

1.2. OBJECTIVES

Based on the existing program ICEROUTE developed at HSVA Ice & Offshore and with new improved modules to the program, the fuel consumption of different types of ship with different propulsion arrangements is to be determined for operation in different ice conditions along the Northern Sea Route. The determined values for fuel consumption will then be used to predict exhaust emissions depending on consumed power per nautical mile.

The advance code shall then be used to carry out calculations for different arctic routes.

The calculation is based on data for ice conditions of the year 2000 and 2007, within two periods of September and November, in total four calculation point:

- September 2000

- November 2000
- September 2007

Four different transit routes along the Northern Sea Route are considered. All route starts from Murmansk and leads to Bering Strait via different alternatives:

- Murmansk to Bering Strait via Kara gate and south of Novosiberian Island
- Murmansk to Bering Strait via Kara gate and north of Novosiberian Island
- Murmansk to Bering Strait via north of Novaya Zemlya and south of Novosiberian Island
- Murmansk to Bering Strait via north of Novaya Zemlya and north of Novosiberian Island

While the directions of all these four routes are from West to East, it is obvious that the similar calculation can be easily carried out for the reversed direction from East to West.

Three different ship types are calculated:

- Bulk carrier
- Oil tanker
- LNG carrier

The topic subject is a part of the project ACCESS (Arctic Climate Change Economy and Society). ACCESS is a European Project supported within the Ocean of Tomorrow call of the European Commission Seventh Framework Programme. The project is coordinated by the University Pierre et Marie Curie (Paris, France), with the participation of 27 institutions from 9 European countries and the Russian Federation, including more than 80 researchers. Its main objective is to assess climatic change impacts on marine transportation (including tourism), fisheries, marine mammals and the extraction of oil and gas in the Arctic Ocean. ACCESS is also focusing on Arctic governance and strategic policy options. ACCESS is composed of 5 working groups, in which the second group will study the opening to marine transportation of the northern passages, north of Europe and Siberia (North-East Passage) and through the Canadian Archipelago (North-West Passage) as well as the impact of these transportation activities on marine ecosystems and society.

1.3. ORGANIZATION OF THE THESIS

The thesis is organized as follows:

Chapter 1 is the introduction to the thesis. In chapter 2, the methodology is presented, along with general information about the Northern Sea Route and the characterization of vessels. Chapter 3 is devoted to explain about the resistance and the corresponding power of

ship navigation in ice conditions, this knowledge will be then applied to calculate the fuel consumption. Chapter 4 and chapter 5 are details about the calculation of fuel consumption and exhaust emissions. Chapter 6 is used to summarize all the calculated results and then in chapter 7, some conclusions are presented.

2. METHODOLOGY

2.1. OVERVIEW

Figure 2.1 shows the initially defined flow chart of the calculation process. First of all, the ice routes need to be determined according to the ice condition data that is available at HSVA. The second task will be specification of different types of ship operating in Arctic area. From all kind of ships, we just choose three of them for the calculation, due to the available data and the strictness of time, but the calculation is obviously applicable to others kind of vessels. The data of ship will be then used to calculate the resistance in ice conditions. The method of calculation the ice resistance of a ship is briefly presented in Section 3. The effective power in ice can be calculated by multiplying the value of ice resistance by ship speed. By comparing the required power with the installed power of the vessel, one can determine the actual speed of the vessel in certain condition, and then the travel time can be estimated by dividing the distance of the journey to the ship speed. Following the calculation of ship power and the travel time, with a correction of the specific fuel consumption corresponded to the actual power, it is possible to calculate the fuel consumption. The exhaust emissions can be calculated after we have the fuel consumption rates, with regard to the portion of each pollutant distributed in the exhaust gas. The fuel consumption and exhaust emission calculation processes will be then implemented into a program for more convenient in calculating later on.

A separated illustration is used to show the procedure of calculating the fuel consumption and exhaust emissions as seen in Figure 2.2.

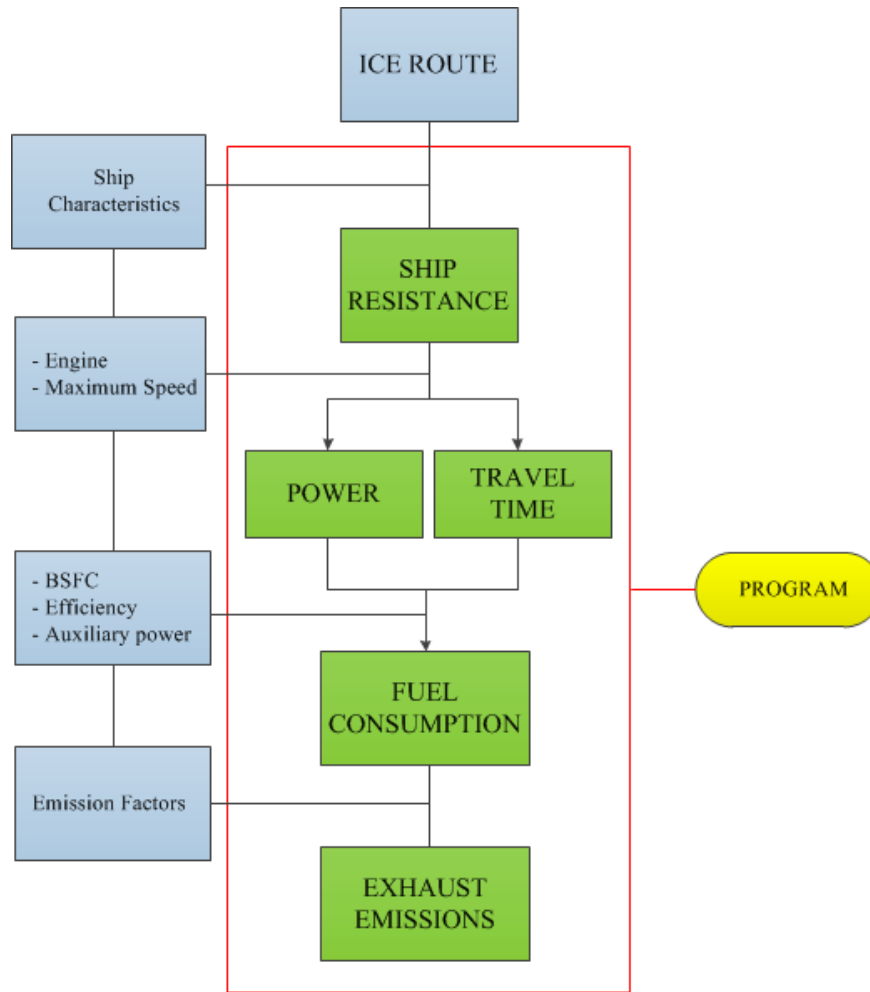


Figure 2.1: Flow chart of the calculation process

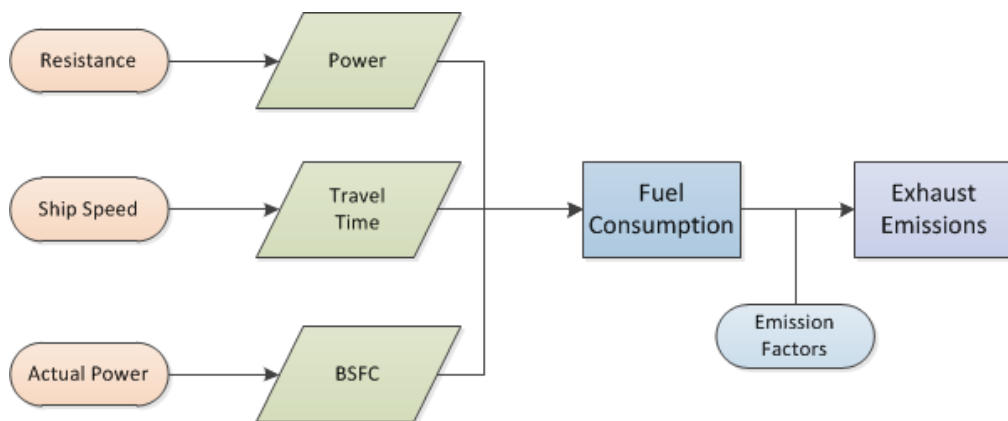


Figure 2.2: Calculation of fuel consumption and exhaust emissions

As we already chose three kinds of ship to calculate, i.e. bulk carrier, oil tanker and LNG carrier, for each ship type many available configurations can be considered. For example with regard to the propeller type, a ship can be equipped with either a controllable pitch propeller, a fixed pitch propeller or with a more advanced podded azipod propeller. Or considering the engine type, the most common type would be a diesel engine fuelled with

heavy fuel oil, but nowadays to fulfil the more and more strict regulation on exhaust gases in sensible areas, vessels can be seen with some new kinds of engine such as dual fuel. And it is also need to mention that for the LNG carrier, steam engine is still a very common type of engine that can be seen in many vessels even for some new building ships of our time.

In this thesis, of course we cannot consider all the available alternatives which a ship owner can choose to use with a vessel. We can only carry out the study with some configurations as show in Figure 2.3.

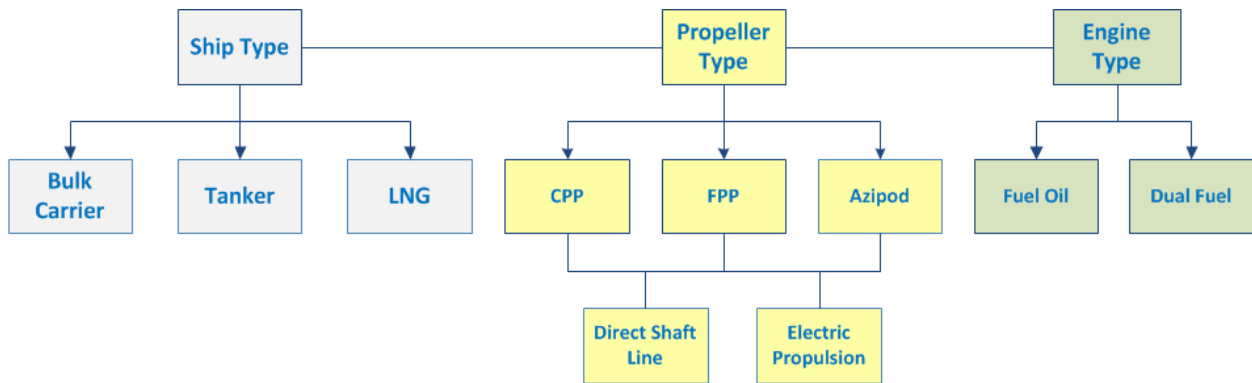


Figure 2.3: Different considerations

Finally, the thesis has been done with different calculated cases as summarized in the following table:

Table 2.1: Calculated cases

No.	Ship type	Engine type	Propulsion type	Propeller type
(1)	Bulk carrier	Fuel oil two-stroke low speed engine	Conventional shaft line	FPP
(2)	Tanker 01	Fuel oil four-stroke medium speed engine	Electric propulsion (x2)	FPP
(3)	Tanker 02	Fuel oil two-stroke low speed engine	Conventional shaft line	CPP (01)
(4)	Tanker 02	Fuel oil two-stroke low speed engine	Conventional shaft line	CPP (02)
(5)	Tanker 02	Fuel oil two-stroke low speed engine	Conventional shaft line	CPP (03)
(6)	LNG	Fuel oil four-stroke medium speed engine	Azipod propulsion (x3)	FPP

2.2. THE NORTHERN SEA ROUTE

2.2.1. Introduction

The Northern Sea Route (Russian: Сѣверный морскѳй путь, Severnyy morskoy put, shortened to Севморпуть, Sevmorput) is a shipping lane officially defined by Russian legislation from the Atlantic Ocean to the Pacific Ocean specifically running along the Russian Arctic coast from Murmansk on the Barents Sea, along Siberia, to the Bering Strait and Far East. The entire route lies in Arctic waters and parts are free of ice for only two months per year. Before the beginning of the 20th century it was called the Northeast Passage, and is still sometimes referred to by that name.¹

At the western end of the NSR, services from Murmansk across the Barents Sea and Kara Sea, and up the Yenisey River to Dudinka have been operation regularly since about 1980, but it was not used by commercial vessel to transit from Europe to Asia and vice versa until 2009.

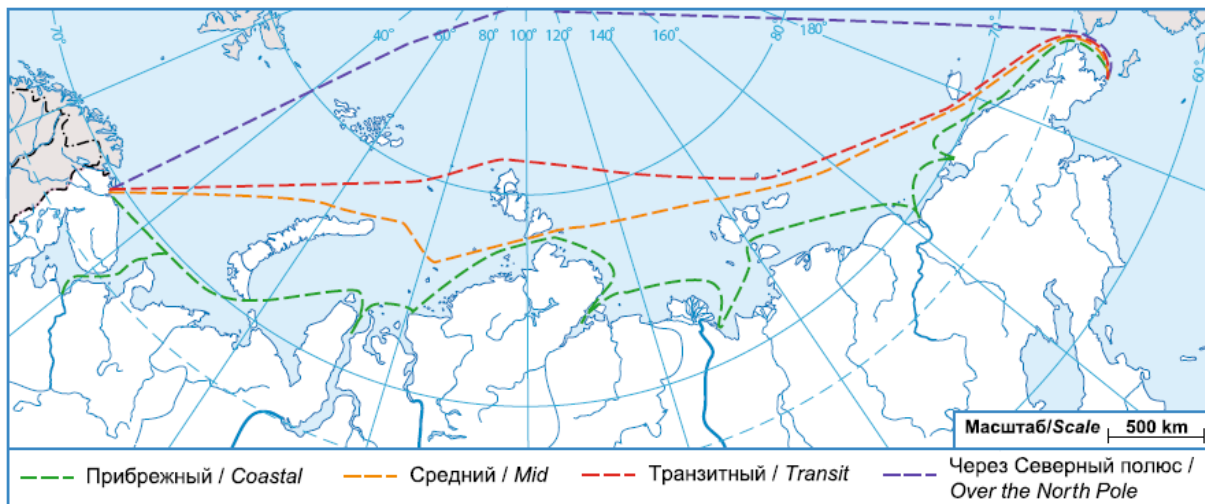


Figure 2.4: Navigation corridors on the Northern Sea Route [15]

2.2.2. Recommended Routes

The seaway of NSR is running through Kara, Laptev, East Siberian, and Chukchi seas. The NSR can be entered from West through the Straits Yugorskiy Shar and Karskiye Vorota, or by passing North of Ostrova Novaya Zemlya around Cape Zhelaniya, and from East through the Bering Strait.

¹ http://en.wikipedia.org/wiki/Northern_Sea_Route

The NSR extends for about 3000 miles. The factual length of the route in each particular case depends on ice conditions and on the choice of particular variants of passage of different stretches of the route.

The main factor influencing navigation through the NSR is presence of ice. The navigation season for transit passages on the NSR starts approximately at the beginning of July and lasts through to the second half of November. There are no specific dates for commencement and completion of navigation; it all depends on particular ice conditions. In 2011 the navigation season on the NSR seaways for large vessels constituted 141 days in total, i.e. more than 4.5 months. In recent years quite easy ice conditions have been observed and that offers more considerable opportunities for operation at the NSR seaways. All NSR seaways are currently located in the area of one-year ice. In the Arctic conditions first-year ice grows approximately up to 1.6 metres. In early July, at the beginning of the navigation season ice is not pressurized. The ice is broken and can be easily moved through. In September and October the NSR seaways can be completely ice-free. Therefore, the vessel may have the same speed as in open water condition. A voyage from Cape Zhelaniya in Novaya Zemlya to the Bering Strait can be travelled at the speed of 14 knots within 8 days. In November the Laptev Sea and the East Siberian Sea are covered with new ice up to 30 centimetres and that allows for safe pilotage of a vessel supported by an icebreaker.

In 2011, there were 41 vessels which had their transit voyages through the NSR: 26 vessels with cargo and 15 – in ballast. Among them 15 tankers, 3 bulk cargo vessels, 4 refrigerator vessels and 4 general cargo vessels. In all 834 931 tons of cargo were transported which was a record amount over the history of transit transportations on the NSR seaways. By comparison, in 2010 only four vessels used the route for transit to another country, and the total amount of cargo was 111 000 tons.

During the navigation season in 2011, a new route north of the New Siberian Islands was established, where the water is deep enough to accommodate tankers with draughts of over 12 meters, and for the first time in history, the route was navigated by the tanker “Vladimir Tikhonov”, a Suezmax class vessel with deadweight of over 160 000 tons.



Figure 2.5: New route via north of the New Siberian Islands opened in 2011

The new route is a shorter transit route and it reduces the travel time.

Table 2.2: Recently finished transits

Vessel name	Type	Size	Ice class	Transit time	Sailing time (days)	Ave. speed
MT Uikku ²	Tanker	Handysize	1AS	Sep 1997	12	
Beluga Fraternity and Beluga Foresight	Cargo ship	Handysize	GL E3 (1A)	Aug 2009		
SCF Baltica	Tanker	Aframax	1A	Aug 2010	8.3	
Nordic Barents ³	Bulk carrier	Handymax	1A	Sep 2010	11	12 knots
Perseverance ⁴	Tanker	Panamax	1A	June 2011	15	7.6 knots
STI Heritage	Tanker	Panamax	1A	July 2011	8	14 knots
Marilee	Tanker			Aug 2011	9.7	
Vladimir Tikhonov ⁵	Tanker	Suezmax	1A	Aug 2011	7.5	14 knots
Stena Poseidon	Tanker	Panamax	1A	Sep 2011	6.9	
Perseverance (East to West)	Tanker	Panamax	1A	Sep 2011	6.9	
Palva	Tanker	Panamax	1A	Sep 2011	6.5	
Mariann	Tanker	Panamax	1A	Sep 2011	7.1	

² First non-Russian ship to transit the NSR

³ First non-Russian bulk carrier to transit the NSR

⁴ Earliest navigation season

⁵ First super tanker, largest size vessel sailed along NSR

Sanko Odyssey ⁶	Bulk carrier	Panamax	1A	Sep 2011		
Affinity	Tanker	Panamax	1A	Oct 2011	6.9	
Perseverance	Tanker	Panamax	1A	Nov 2011	12	

Table 2.3: Number of ship finished the transit route

Year	Number of finished journey	Cargo transported (tons)
2009	2	
2010	4	111 000
2011	34	820 789
2012	46	1 261 545

November 2012, the vessel Ob River was carrying liquefied natural gas (LNG) and she was the first vessel of its kind to make a trans-Arctic journey from Norway to Japan. The vessel spent nine days on NSR from it passed the Kara Gate on November 9 to in entered Cape Dezhnev on November 18. The journey saved about 20 days when compared to the regular journey time taken via Suez Canal to reach Japan.

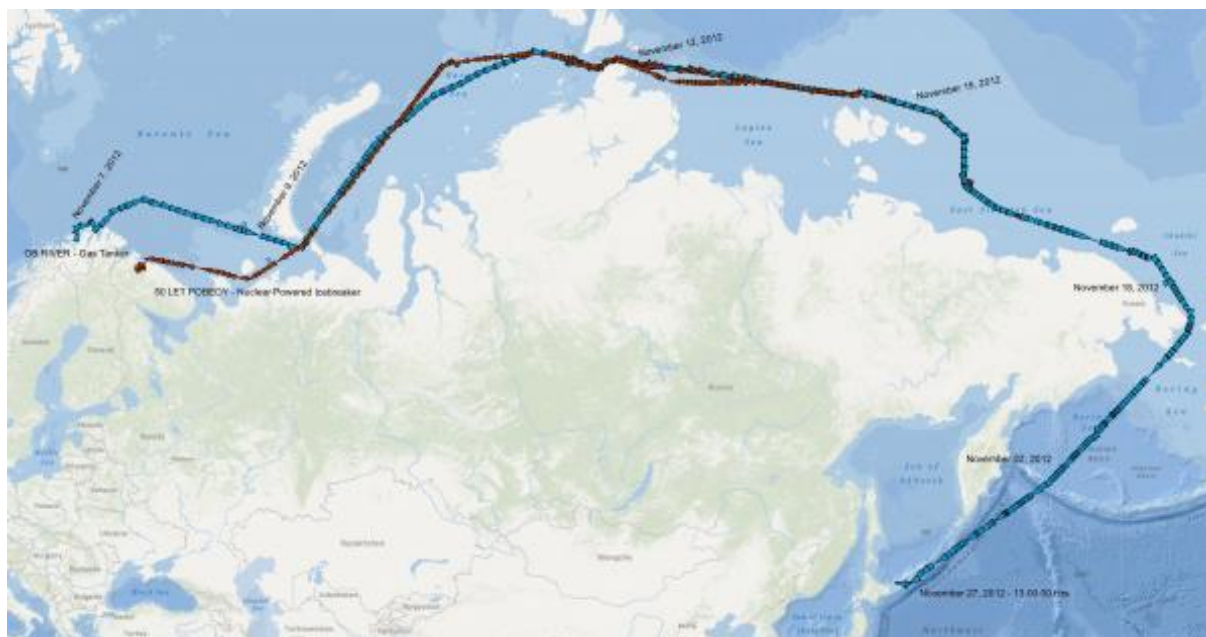


Figure 2.6: Tracking of the Ob River across the Northern Sea Route

2.2.3. Arctic Sea Ice Conditions

Over the last few years, scientists have observed significant changes in sea ice extension, as well as sea ice volume in the Arctic Ocean.

⁶ Largest ever bulk carrier; first Japanese vessel

In 2007, the Northern Sea Route was for the first time opened ice-free during September. It was also at that time the sea ice extension set the record of minimum volume, until last year, 2012, the sea ice volume has even set a new record of a low volume never seen before.

Table 2.4: Minimum Arctic sea ice extents [Source: NSIDC]

Year	Minimum ice extent (km ²)	Date
2007	4.17	September 16
2008	4.55	September 18
2009	5.10	September 12
2010	4.60	September 19
2011	4.33	September 9
2012	3.41	September 13
1979 to 2000 average	6.71	September 10
1979 to 2010 average	6.29	September 12

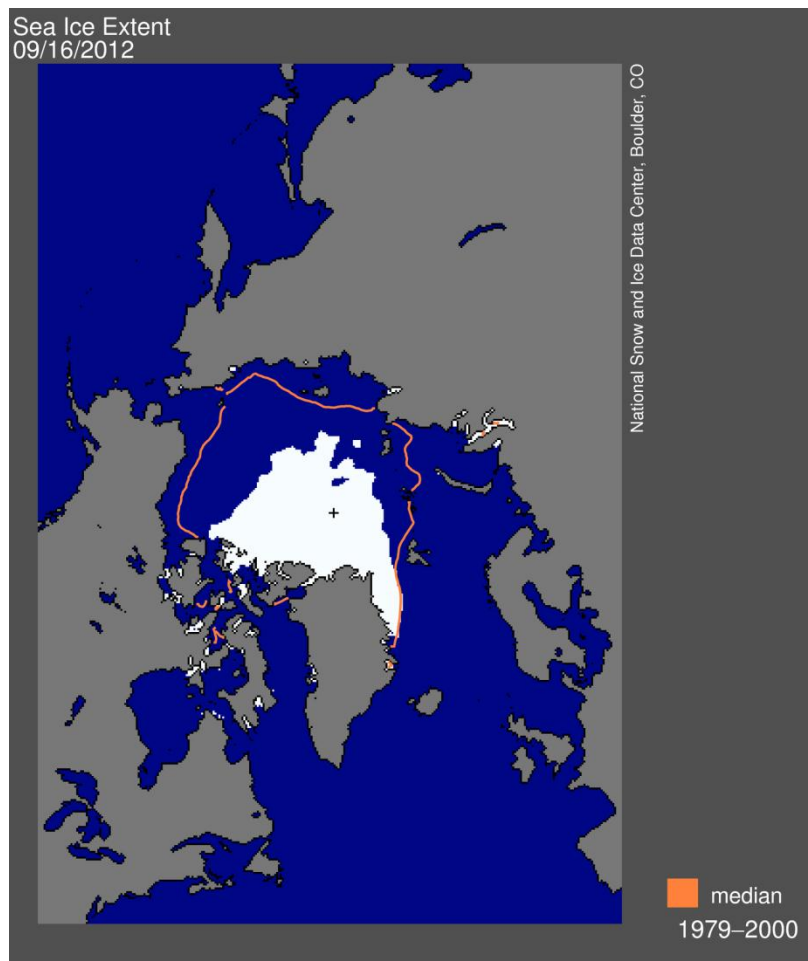


Figure 2.7: Arctic sea ice extent for September 16, 2012 [Source: NSIDC]

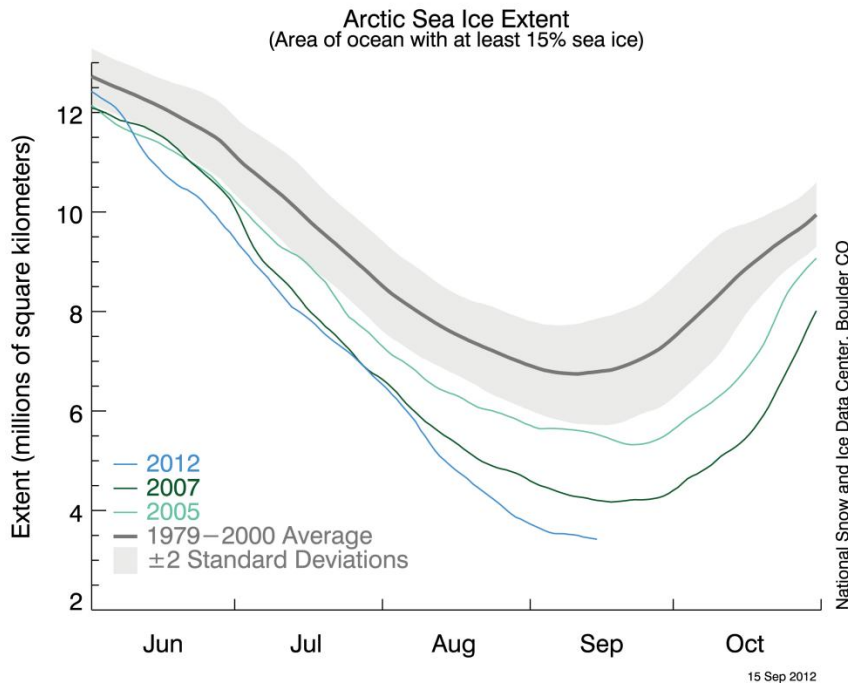


Figure 2.8: Arctic sea ice extent as of September 16, 2012, along with daily ice extent data for the previous five years [Source: NSIDC]

2.3. VESSEL CHARACTERIZATION

In this work we focus on transport vessels, but other ship types such as fishing vessel can also be provided in future work.

Ice-going ships are generally divided into two main groups:

- Ice-strengthened ships
- Icebreaking ships

Ice-strengthened ships are designed for open water operation, but their hulls are strengthened and their machineries often have more power compared to normal open water ships. The ability to move in ice is usually not the main objective of designing these ships, but open water characteristics are generally a very important aspect.

The bulk carrier study is based on the MS Kumpula, belong to ESL Shipping Ltd fleet, completed in 2012 by Hyundai-Vinashin Shipyard Co. Ltd, in Ninh Hoa, Viet Nam. It is a DNV Ice class 1A vessel, 56 372 DWT (Panamax size). The vessel is equipped with a main engine type Hyundai-MAN B&W 7S50MC-C8.1-TII fulfils the Tier II of IMO. The MCR is 11 620 kW at 127 rpm. The engine is connected to a KaMeWa CPP-propeller.

The first oil tanker (tanker 01) is based on the MT Mikhail Ulyanov, a Panamax oil tanker, designed by Aker Arctic (Finland) and is owned by Sovcomflot (Russia). This is a double acting tanker, with ice class LU 6 (equivalent to IA Super). The ship has a deadweight

of 70,000t, and is 257m long and 34m wide. It has a draft of 13.6m and a depth of 21m. The vessel moves through the ice using a pair of 8.5MW Azipod thrusters by the diesel-electric power plant consisting of four main diesels producing a total of 25.2MW. Main engine system consists of four Wartsila 6L 46 C diesel generators (4 x 6,300KW) and one Wartsila 4L 20 (1 x 720KW) as an auxiliary generator.

The second oil tanker (tanker 02) is based on the vessel Palva of Neste Oil (Finland). It is classed by DNV and has an ice class of 1A according to Finnish-Swedish rule, its dead weight tonnage is 74 999 DWT. The vessel was completed in 2007 and is fitted with an engine type MAN B&W 6S60 MC-C7.1-TII, with MCR 13 650 kW at 105 rpm. The engine is coupled with a CPP propeller.

The LNG carrier is based on the vessel Ribera del Duero Knutsen, belong to Knutsen OAS Shipping fleet. Tank capacity of the ship is 173 400 m³. It is an ice class 1A certified by DNV. Main engine system includes three Wärtsilä 12V50 DF and one 9L50 DF running on duel fuel mode, provided a total power of 41000 kW to run two electrical propulsions.

2.4. CONTROLLABLE PITCH PROPELLER AND FIXED PITCH PROPELLER

Ships operating in the Arctic are likely running at highly variable engine loads depending ice conditions and ice breaking requirements.

A controllable pitch propeller (CPP) can adjust its pitch to keep its original hydrodynamic performance at different ship speed. Thus, CPP can approximately maintain its rpm as the MCR engine speed and absorb the MCR engine power at different ship speed. In contrast, for a fixed pitch propeller (FPP), when ship speed becomes slower (operating in ice condition), in order to maintain the rpm as MCR speed, the propeller needs to be supplied with more power from the engine to overcome the higher hydrodynamic torque on the blade compared to the original ship speed condition. This leads to the original propeller demand curve is shifted backward to higher power demand curve, as we can see in Figure 2.9.

Due to the limitation of the engine power limit curve, when the propeller operates off its design condition (design ship speed along with MCR rpm), the engine can only provide the power along the power limit curve, and accordingly the propeller will rotate slower.

Engine power along the limit line can be estimated by the equation:

$$P = P_{MCR} \left(\frac{n}{n_{MCR}} \right)^2 \quad (2.1)$$

For ship with FPP under ice condition, the determined of actual propeller rotation speed n is related to the balance between propulsion thrust and ice resistance. But due to the fact

that CPP can change its pitch by turning the blade to obtain more thrust for propulsion, the propeller rpm can be maintained as the MCR speed even at low ship speed in ice condition. These advantages make CPP more capable and efficient in ice condition.

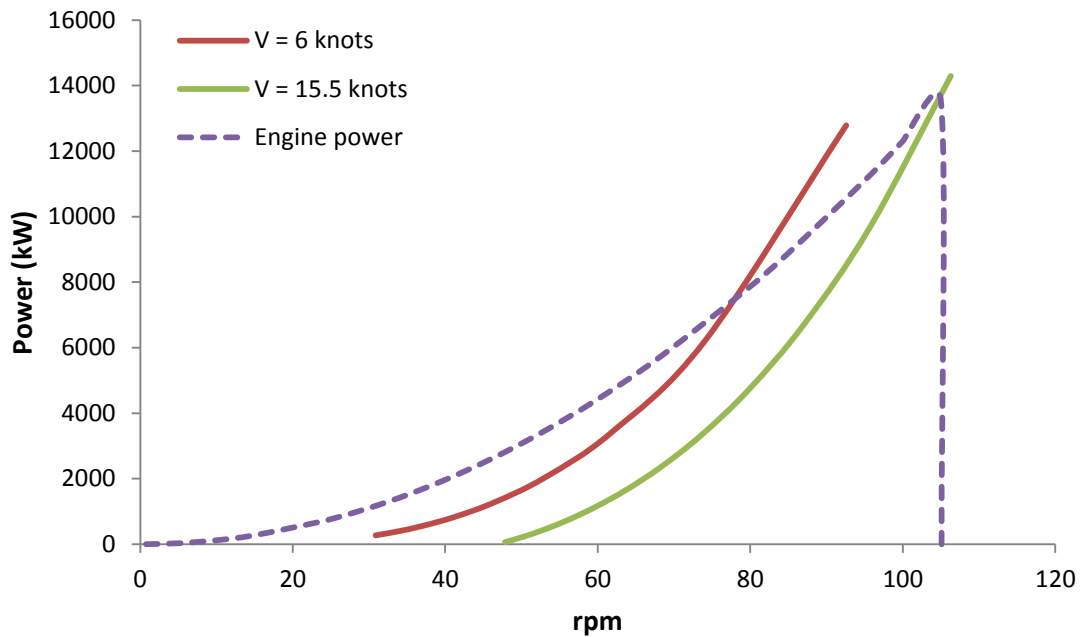


Figure 2.9: Engine and propeller demand curves (pitch ratio $P/D = 0.877$)

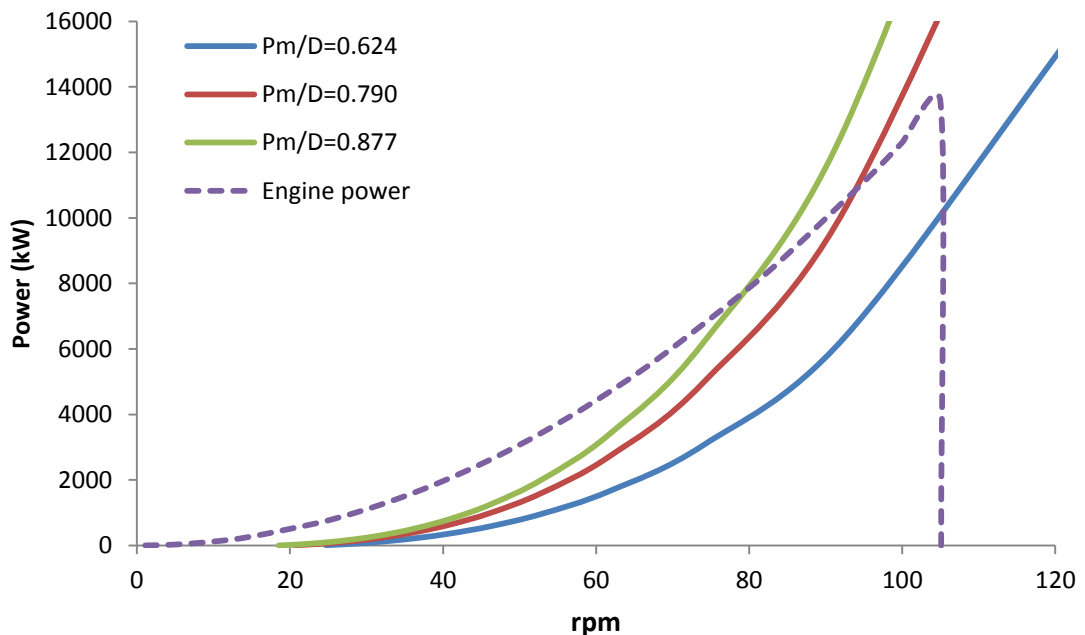


Figure 2.10: Propeller demand curves at ship speed of 6 knots with different pitch ratio

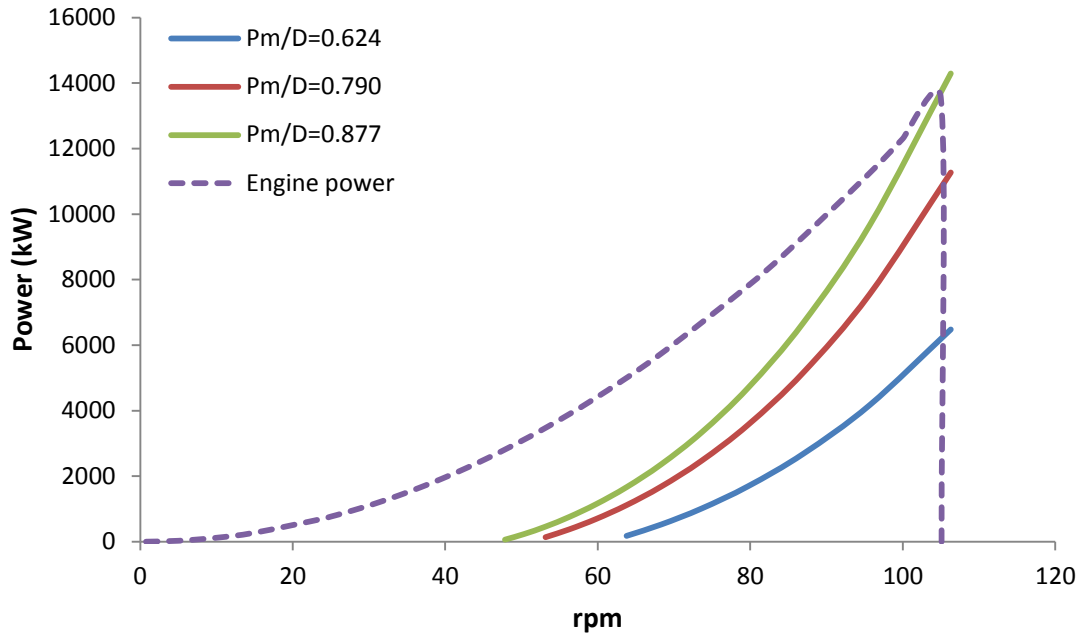


Figure 2.11: Propeller demand curves with different pitch ratio (at ship speed of 15.5 knots)

2.5. MARINE ENGINE OF LNG CARRIER

All large LNG vessels have traditionally been driven by steam turbine propulsion systems. The steam turbine systems have proved extremely reliable however, compared to alternatives, they are inefficient in terms of fuel consumption. But for LNG ships built up to about 20 years ago, it was not necessary to seek more efficient propulsion plants because the natural boil-off gas flow in these ships provided approximately 100% of the fuel requirements, it means that even more efficient plants were available, they could not be used without waiting boil-off gas.

Over the years, many propulsion options have been studied for LNG vessels.

Most modern ships use a reciprocating diesel engine as their prime mover, due to their operating simplicity, robustness and fuel economy compared to most other prime mover mechanisms. The rotating crankshaft can be directly coupled to the propeller with slow speed engines, via a reduction gearbox for medium and high speed engines, or via an alternator and electric motor in diesel-electric vessels.

New LNG carriers continue to be built with steam turbines. The natural gas is stored in a liquid state in cryogenic vessels aboard these ships, and a small amount of 'boil off' gas is needed to maintain the pressure and temperature inside the vessels within operating limits. The 'boil off' gas provides the fuel for the ship's boilers, which provide steam for the turbines, the simplest way to deal with the gas. Technology to operate internal combustion engines

(modified marine two-stroke diesel engines) on this gas has improved, however, so such engines are starting to appear in LNG carriers; with their greater thermal efficiency, less gas is burnt. Developments have also been made in the process of re-liquefying 'boil off' gas, letting it be returned to the cryogenic tanks. The financial returns on LNG are potentially greater than the cost of the marine-grade fuel oil burnt in conventional diesel engines, so the re-liquefaction process is starting to be used on diesel engine propelled LNG carriers.

Dual fuel engines are fuelled by either marine grade diesel, heavy fuel oil, or liquefied natural gas (LNG). Having multiple fuel options will allow vessels to transit without relying on one type of fuel. Studies show that LNG is the most efficient of fuels although limited access to LNG fuelling stations limits the production of such engines. Vessels providing services in the LNG industry have been retrofitted with dual-fuel engines and have been proved to be extremely effective. Benefits of dual-fuel engines include fuel and operational flexibility, high efficiency, low emissions, and operational cost advantages. Liquefied natural gas engines offer the marine transportation industry with an environmentally friendly alternative to provide power to vessels.

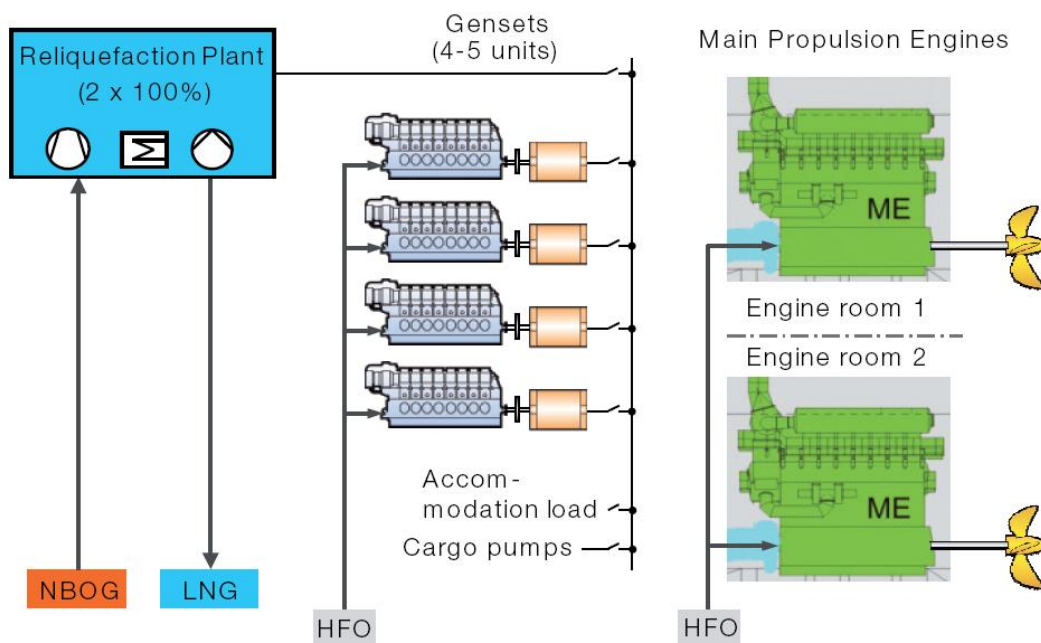


Figure 2.12: Conventional diesel engine system [21]

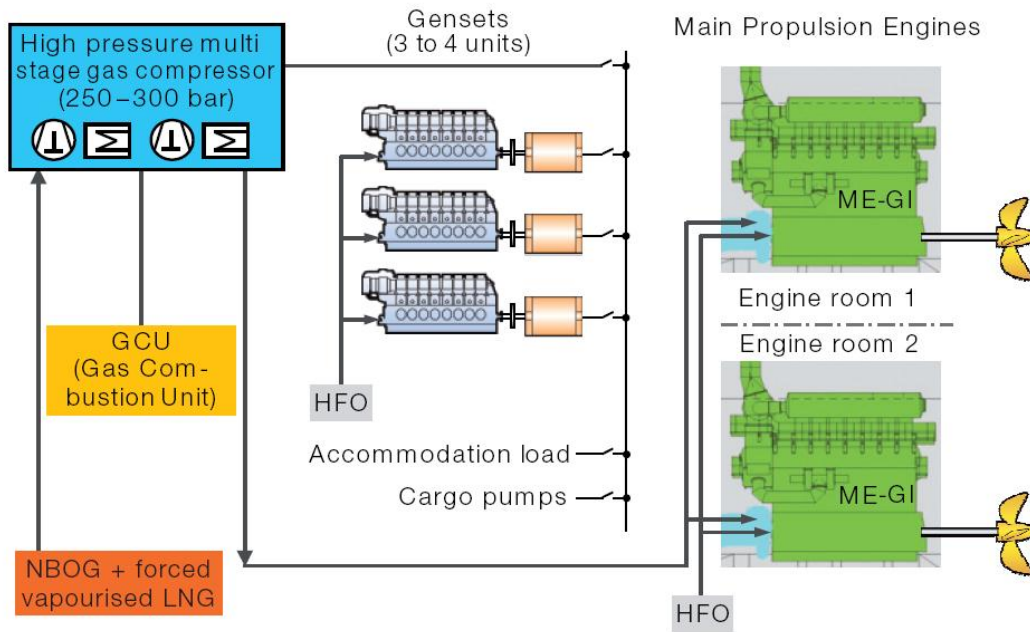


Figure 2.13: Dual fuel diesel – gas engine system [21]

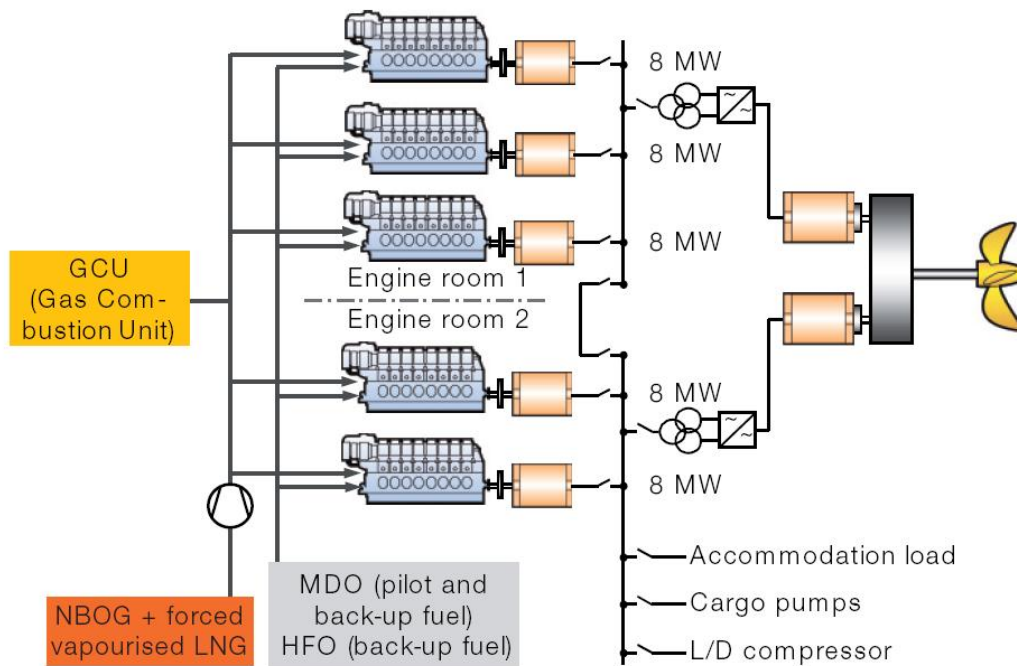


Figure 2.14: Dual fuel diesel – gas engine electric propulsion system [21]

3. SHIP RESISTANCE AND POWER IN ICE CONDITION

3.1. INTRODUCTION

As a result of ice, a ship operating in ice conditions experiences an increase in the resistance due to extra work or energy required to break and remove the ice.

There are three methods to measure the resistance of a ship navigating in ice: experience from ships in service, model-scale testing or analytic calculation. Each of these methods has its own advantages as well as disadvantages. The use of experience is reliable if the new design is close to some existing and tested designs. But it seems unreliable nowadays since new designs always have new innovative solutions. Model-scale testing has become reasonably reliable with the improvement of the model ice and testing techniques. The main drawbacks are the relatively high costs, and the slowness of the testing process. Analytical methods are so far inexpensive, but are not reliable. To achieve better reliability requires an advancement of knowledge of the physics of icebreaking.

3.2. METHOD

The main components of the ice resistance are identified and approximated their contribution with simple but physically sound formulae. The whole ice breaking process is simplified, the goal being not to describe icebreaking with scientific exactitude but to create a tool for evaluation of ice resistance.

The main resistance components used are breaking, submersion and speed dependence. The underwater form of the vessel is approximated as flat surface to make the calculations shorter.

3.2.1. Breaking

a) Crushing at the Stem

Crushing at the stem in a wedge-shaped icebreaker is almost continuous. It seems that the force never grows great enough to break the ice in the bending mode. This is probably due to two reasons. One is that the bending failure force is greater at the stem than further aft, due to the different geometry. The other reason is that the ice is undamaged at the stem, whereas further aft there are clearly many micro cracks due to the interaction at the stem.

We estimate the average vertical force acting on the ice by the formula:

$$F_v = 0.5 \times \sigma_b \times H_{ice} \quad (3.1)$$

where σ_b is the bending strength of the ice, H_{ice} is the ice thickness. Analysis of the force components using cumulative friction and assuming that the friction acts along the verticals shows that the resistance force is:

$$R_c = F_v \frac{\tan \phi \cos \psi + \mu \cos \phi}{\cos \psi - \mu \sin \phi} \quad (3.2)$$

where μ is the friction coefficient, ϕ is the stem angle, ψ is the angle between the normal of the surface and a vertical vector, $\psi = \arctan(\tan \phi / \sin \alpha)$ wherein α is the waterline entrance angle.

b) *Breaking by Bending*

Ice is clearly broken in the bending mode some distance aft of the stem. Although the final failure is in bending mode, this is preceded by crushing and shearing. As the ship comes into contact with the sharp edge of the ice, the edge is crushed until the force is big enough to shear away a small piece of ice. The plane of failure is close to the contact area and the crushing continues in a similar way, but the breadth of the contact area increases. This process continues until the force transmitted through the contact area is big enough to cause a bending failure.

Bending force is estimated by the formula:

$$R_b = kB \frac{H_{ice}^3}{l_c^2} \left(\tan \psi + \frac{\sin \phi}{\sin \alpha \cos \psi} \right) \left(1 + \frac{1}{\cos \psi} \right) \quad (3.3)$$

where k is a constant, B is the breadth of the vessel, l_c is the characteristic length of the ice. The characteristic length, which determines the size of the floes, is proportional to the thickness to the power of 0.75.

3.2.2. Submersion

Model tests and underwater observations from full-scale tests have shown that when the ship is running in level ice the hull is almost completely covered by ice. As ice is lighter in water, it is lifted against the hull and the resistance comes directly through the normal force and indirectly through the friction. In calculating the friction component the bow is assumed to be completely covered by ice and the bottom to be covered for 70% of the length of the ship. This is because the stern region is not completely covered by ice. The ice is assumed to move along the verticals.

The resistance coming from the normal force is not calculated separately for all surfaces. Instead, this component is calculated through the potential energy. In this approach, it is only

necessary to know the distribution of ice at the deepest section to calculate this term. The resistance is the loss of potential energy plus frictional forces.

The final formula is shown in the following equation:

$$R_s = \delta_\rho \times g \times H_{ice} \left(T \times \frac{B+T}{B+2T} + (A_u + \cos \phi \cos \psi A_f) \times \mu \right) \quad (3.4)$$

where, δ_ρ is the density difference between the water and the ice, g is the gravitational acceleration, T is the draft of the ship, A_u is the area of the flat bottom and A_f is the area of the bow.

3.2.3. Speed

Both the breaking and the submersion components are fairly well known, but the speed dependent component is more uncertain. As at normal operating speeds it accounts for about half of the total resistance. The reasons for the uncertainty of this component can be suggested as increased of breaking resistance, increase of submersion resistance, acceleration of ice floes, ventilation of ice flows and viscous drag.

The resistance seems to increase fairly linearly with the speed. Using some empirical assumptions we obtain the total ice resistance:

$$R_{ice} = (R_c + R_b) \times \left(1 + 1.4 \times \frac{V}{\sqrt{gH_{ice}}} \right) + R_s \times \left(1 + 9.4 \times \frac{V}{\sqrt{gL}} \right) \quad (3.5)$$

where L is the length of the ship.

3.3. Program ICEROUTE developed in HSVA Ice & Offshore

The program was written in 1998 by Lars Lübcke (HSVA) as part of the ARCDEV Project. The program is capable to calculate ship resistance and power of ship in ice condition, then estimates the speed through ice and the sailing time along a given route. Input data that is needed to run the program includes ship's parameters such as dimensions, maximum power, maximum ship speed, number of propellers and propeller diagram, also waterline angles and cutting angles at four different sections at the bowlines, as well as parameters c_B , c_{WP} and c_M to define the shape of the vessel.

The route is divided into different segments called legs based on the different properties of sea ice considering its thickness, snow layer, bending strength, the presence of ice ridges, ice floe concentration and ice floe thickness and the thickness of rubble ice will be entered.

The program can estimate the open water resistance by using the method of Holtrop-Mennen or Hollenbach.

The resistance in ice is defined by the equivalent thickness of ice. This is based on an assumption that different levels of sea ice thickness will produce a resistance to the average in time and will be equal to the resistance in flat ice. The procedure uses only empirical balancing functions.

The resistance in level ice is calculated according to the method of Lindquist with some modifications developed by HSVA.

The total resistance is formed by adding the ice resistance to the open water resistance.

The thrust is calculated depending on the ship's speed with the following equation:

$$T_s = \left(F_1 \left(\frac{P_D D}{z} \right)^{\frac{2}{3}} - \left(\frac{P_D}{z} \right)^{\frac{1}{3}} D^{\frac{4}{3}} (F_2 v - F_3 v^2) \right) z \quad (3.6)$$

Where F_1 , F_2 , F_3 are empirical calibration factors.

The total resistance and thrust are calculated at five different velocities. The ship speed is then interpolated by comparing thrust and resistance to be equal. The program then calculates the distance for each leg, sailing on the Great Circle and so the required travel time for each leg.

Finally, the program summarizes the sailing time on all leg to get the total sailing time for a given route.

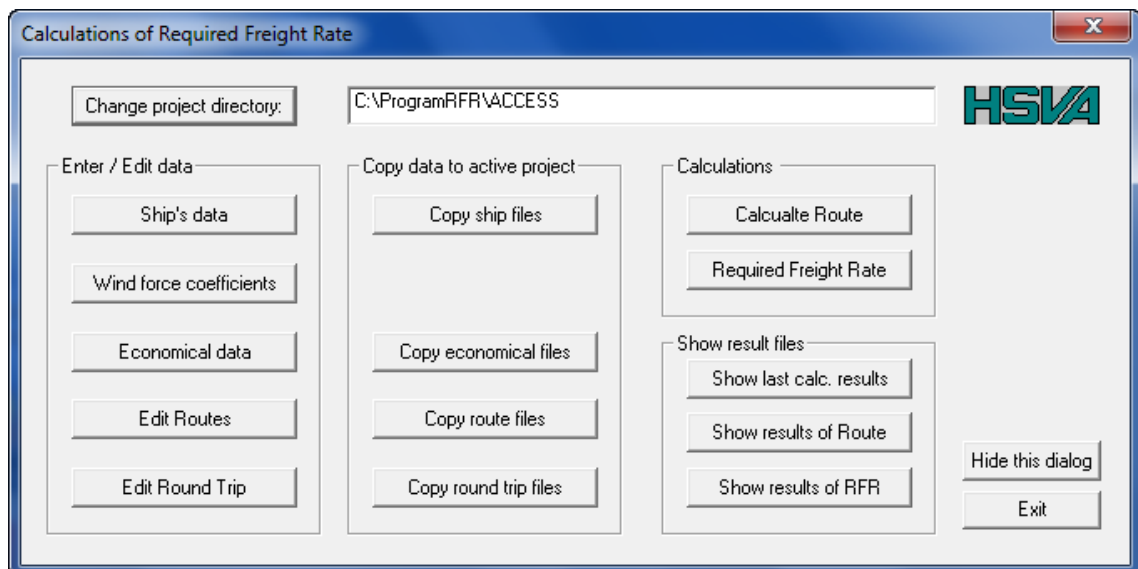


Figure 3.1: Main interface of the program

4. FUEL CONSUMPTION OF SHIP IN ICE CONDITIONS

4.1. INTRODUCTION

The increase in resistance associated with ice navigation leads to higher fuel consumption rate for the vessel. In addition, delays due to ice may lead to the longer duration of the voyage which in turn also leads to more fuel consumption.

Fuel consumption rates of a vessel depends on a variety of factors, such as the vessel itself, the environmental conditions the vessel experiences, and the vessel operating scenarios. Vessels are designed based on estimated resistance values and built with engines which have established specific fuel consumption values. Old vessels have usually less fuel efficiency than new ones due to hull degradation, engine performance deterioration and due to the recent efficiency based technological improvements in vessel and engine design.

The environmental conditions which ships operate in affect vessel overall resistance and consequently the fuel consumption rates. Vessels operating in head seas, strong wind and ice conditions experience more resistance and consequently burn more fuel than vessels operating in calm seas and sheltered waters. A vessel's operating scenario and schedule such as speed, heading, routing, manoeuvres, negotiation of ice, and the use of auxiliary systems, affects the overall fuel consumption.

In order to investigate the fuel consumption profile for a vessel a number of different methods can utilized, such as numerical calculation and prediction of fuel consumption and demand, actual field measurements of fuel consumption rates or simply by keeping track of the money spent on fuel per trip, per person or per year.

4.2. BRAKE SPECIFIC FUEL CONSUMPTION (BSFC)

BSFC is a measure of fuel efficiency within a shaft reciprocating engine. It is the rate of fuel consumption divided by the power produced. It may also be thought as power-specific fuel consumption, for this reason. BSFC allows the fuel efficiency of different reciprocating engines to be directly compared.

$$BSFC = \frac{r}{P} \quad (4.1)$$

Where:

r is the fuel consumption rate in grams per second (g/s) or kilograms per hour (kg/h).

P is the power produced in watts (W) or in kilowatts (kW) where $P = T\omega$, with T is the engine torque in newton meters (N.m) and ω is the engine speed in radians per second (rad/s).

The resulting units of BSFC are grams per joule (g/J) or grams per kilowatts-hour (g/kWh).

The actual efficiency of an engine depends on the fuel being used. The energy densities of different fuels are defined by the fuel's heating values. The lower heating value (LHV) is used for internal combustion engine efficiency calculations because the heat at temperatures below 150°C cannot be put to use.

Table 4.1: BSFC of some marine engines [22]

Engine type	Power	Year	SFC (g/kWh)	Energy efficiency
Wärtsilä 9L38	6.5 MW		176	
MAN Diesel S80ME-C Mk7 two-stroke	23 MW		155	54.4 %
Rolls-Royce Marine Trent turbo shaft	36 MW	2002	210	39.8 %
General Electric LM6000 turbo shaft	43 MW		199	42.0 %
Wärtsilä-Sulzer RTA96-C two-stroke	80 MW	1998	163	51.7 %

Figure 4.1 shows an expected BSFC due to different output power for a 47,000 DWT Tanker at 15.1 knots with different engine set.

In reality, there are many other factors that influent the mass fuel consumption of a vessel. For instance, in Figure 4.2 an average data set analysed from over 600 measured cases of a container ship at sea is presented. This average line can be used to correct the BSFC relates to the actual power of the vessel, as shown in Figure 4.3. Practically, in this thesis, we use this correlation between the BSFC and the actual power when we calculate the fuel consumption. The correlation can be express in term of an equation as follows:

$$\Delta BSFC = 6610.6x^6 - 20524x^5 + 23791x^4 - 11985x^3 + 1803.2x^2 + 340.12x - 36.733 \quad (4.2)$$

Where, $x = P/P_{MCR}$ is the ratio of actual power and the maximum continuous rate power. The variation $\Delta BSFC$ is added to the standard value which is usually available in every technical document from engine manufacturer.

The fuel consumption is then calculated by the equation:

$$FC = BSFC \times P \quad (4.3)$$

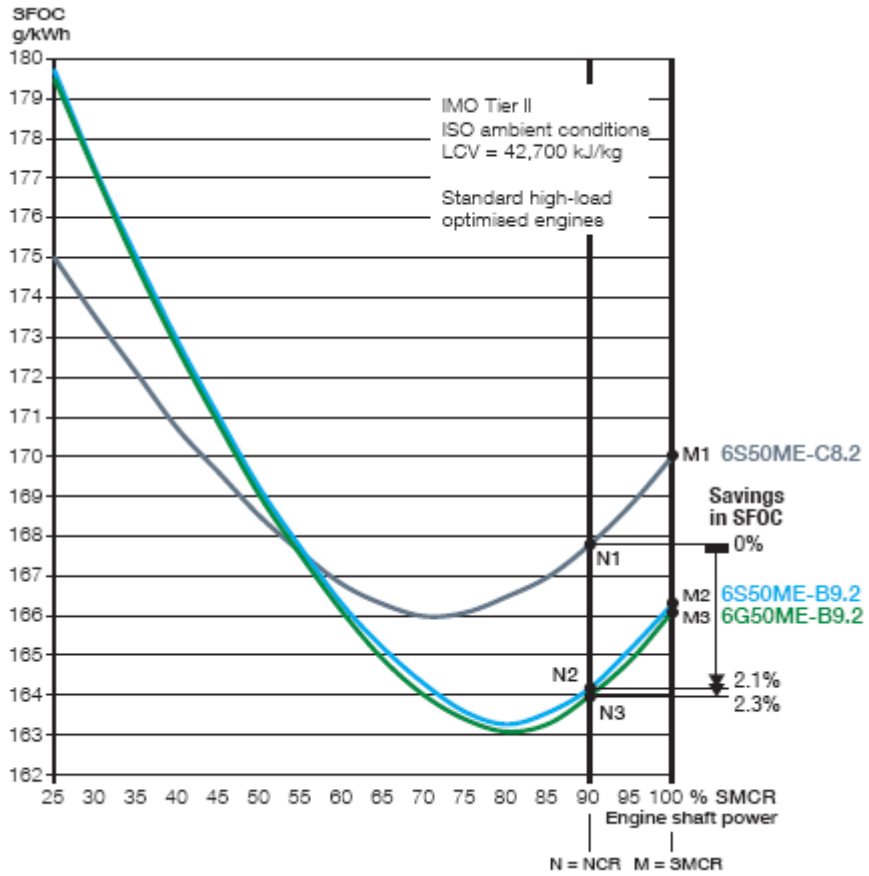


Figure 4.1: Expected BSFC due to different output power for a 47,000 DWT Tanker at 15.1 knots with different engine set [14]

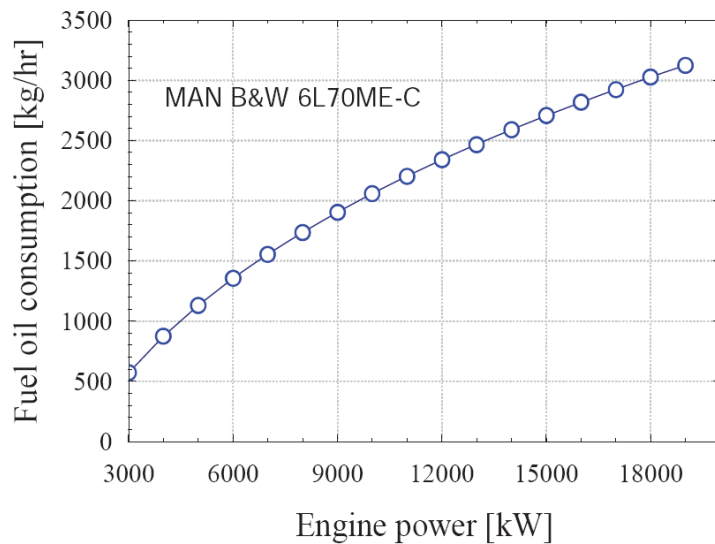


Figure 4.2: Actual fuel consumption measured on board a ship at different power [5]

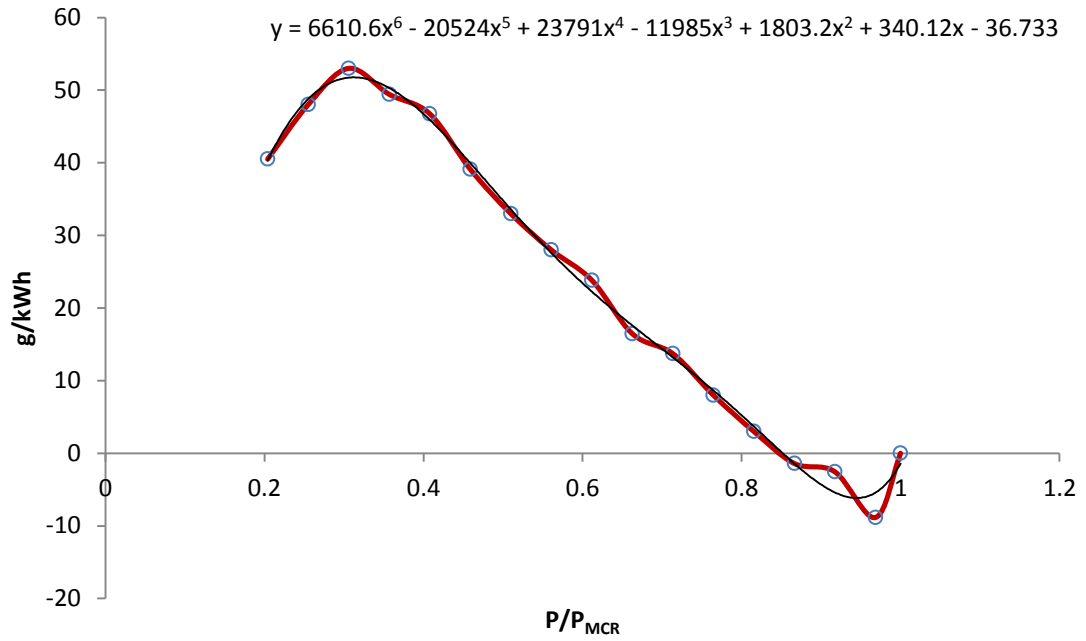


Figure 4.3: Variation of BSFC corrected from actual fuel consumption

5. EXHAUST EMISSIONS FROM SHIP IN ICE CONDITIONS

5.1. INTRODUCTION

A diesel engine has a very high thermal efficiency; moreover, the higher energy density of the diesel fuel compared to gasoline fuel makes it the most efficient internal combustion engine. But in spite of being highly efficient and popular and in spite of all the technological advances, exhaust gas emission of diesel engine has been a concern for a long time. Since 1990s, IMO, EU, and the EPA came up with the Tier I exhaust gas emission norms for the existing engine in order to reduce nitrogen oxides and sulphur oxides. Harsher Tier II and Tier III were later announced for newer engines. Figure 5.1 shows different levels of requirements for the NO_x emission according to three different Tiers.

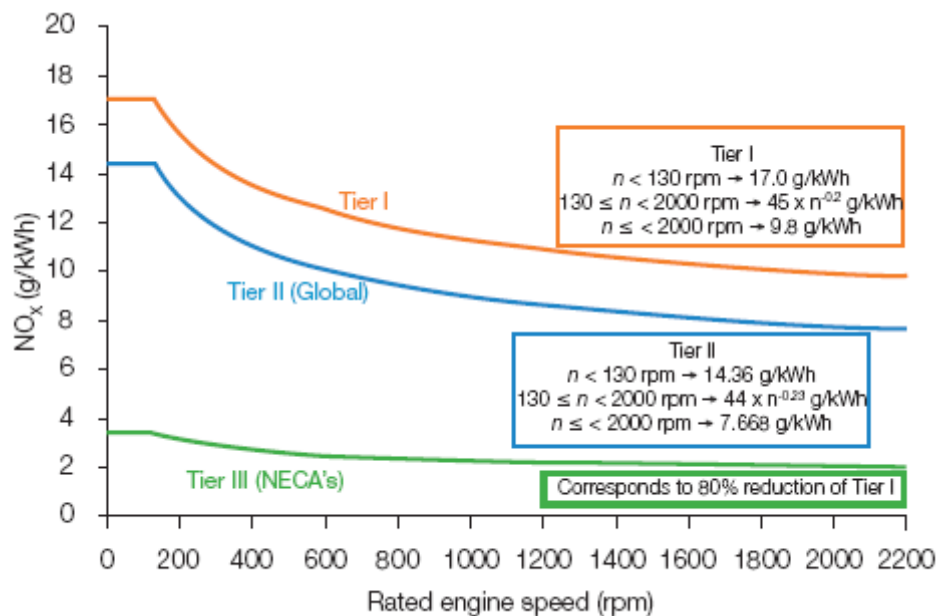


Figure 5.1: IMO NO_x limitations [12]

Diesel fuels commonly used in marine engines are a form of residual fuel, also known as dregs or heavy fuel oil (HFO). They are cheaper than marine distillate fuels but contain higher amount of nitrogen, sulphur and ash content. This greatly increases the NO_x and SO_x in the exhaust gas emission.

The diesel engine combustion process almost always leaves by-products of oxides of nitrogen, unburned hydrocarbons, carbon monoxides, particulate matter.

Nitrogen oxides are a group of toxic gases formed by the reaction of nitrogen and oxygen. At extremely high temperature of combustion, these two gases react to form nitrogen dioxide NO₂, and nitrogen oxide NO. These gases are major source of ground level ozone (smog) and are also a significant source of acid rains and soot formation.

Unburned hydrocarbons come from unburned or partially burned fuel after combustion process. These hydrocarbons are toxic in nature, having adverse effects on our health and in some cases are known to cause cancer.

Carbon monoxide is formed as an intermediate product of hydrocarbons fuel combustion due to the lack of adequate oxygen to form carbon dioxide or due to insufficiently high temperature.

Figure 5.2 shows the typical components from a low-speed diesel engine. Note that 1 ppm = 1/1000000 = 0.0001%.

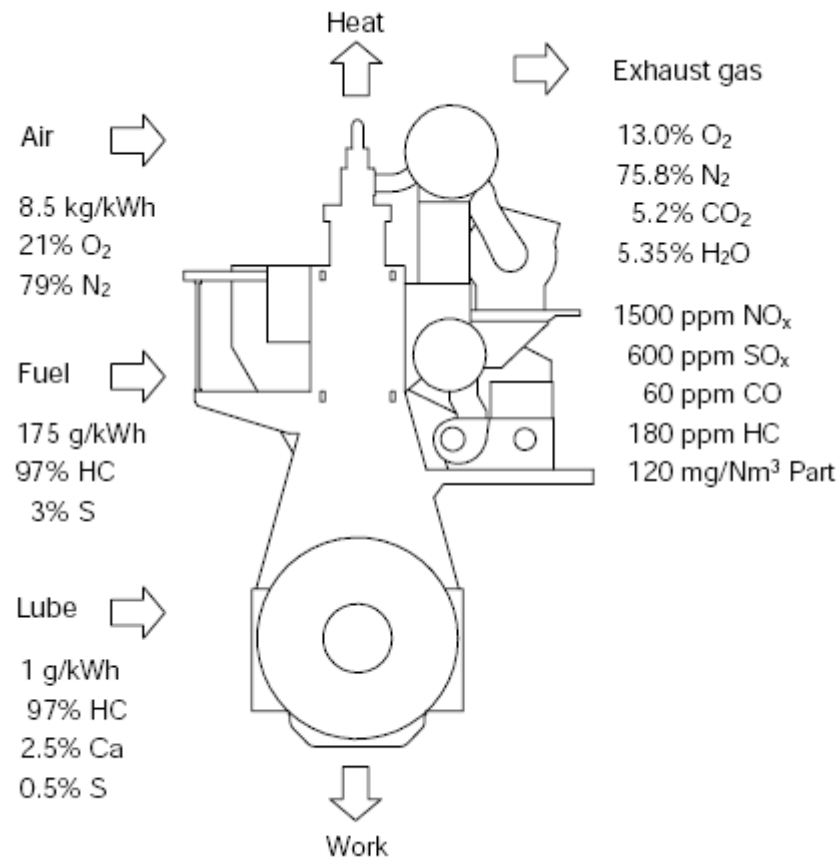


Figure 5.2: Typical emissions components from a low-speed diesel engine [11]

Table 5.1: Comparison of emissions between low and medium speed diesel engines [3]

Pollutant	Medium speed engine (g/kWh)	Low speed engine (g/kWh)
NO _x	12	17
CO	1.6	1.6
HC	0.5	0.5
CO ₂	660	660

SO ₂	4.2x%S	4.2x%S
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5.2. EMISSIONS ESTIMATION

Formula to calculate the emissions from ship:

$$E_{ijk} = EF_{ij} \times LF_{jk} \times \frac{KW_j}{\eta_j} \times T_{jk} \quad (5.1)$$

where, E_{ijk} are emissions of type i from vessel j on route k in grams (g); EF_{ij} is the emissions factor for emissions of type i on vessel j in g/kWh; LF_{jk} is the average engine load factor for vessel j on route k and takes into account periods of manoeuvring, slow cruise, and full cruise operations; KW_j is the rated main engine power in kilowatts (kW) for vessel j ; η_j is the engine efficiency; and T_{jk} is the duration of the trip for vessel j on route k in hour (h). [8] Load factors are similar to those used in many global and regional inventory estimates for shipping.

In Table 5.2 we can find the emission factors that are applied to the emissions from ship in Arctic area at the present and in the future.

Table 5.2: Gas and particular matter emission factors applied to current and future Arctic shipping (g/kg fuel) [8]

Pollutant	Ship type	2004	2020	2030	2050
CO	All	7.4	7.4	7.4	7.4
NO _x	Transport	78	67	56	56
	Fishing vessel	56	56	56	56
PM	Transport	5.3	1.4	1.4	1.4
	Fishing vessel	1.1	1.1	1.1	1.1
SO _x	Transport	54	10	10	10
	Fishing vessel	10	10	10	10
CO ₂	Transport	3206	3206	3206	3206
	Fishing vessel	3114	3114	3114	3114
BC	All	0.35	0.35	0.35	0.35
OC	All	1.07	0.39	0.39	0.39

The emissions very depend on different types of engines, with various speeds of revolutions, range of power and different fuels used. Table 5.3 shows the estimated emissions from some kinds of MAN B&W engine with different injection system.

Table 5.3: Estimated emissions for different MAN B&W engine types [12, 13]

Load 100%	6S70ME-C	6S70ME-GI	6K50MC-C	6S50ME-GI
Pollutant	g/kWh	g/kWh	g/kWh	g/kWh
CO ₂	577	446	556	469
O ₂	1359	1340	1223	1255
CO	0.64	0.79	0.71	0.89
NO _x	11.58	10.12	11.97	10.51
HC	0.19	0.39	0.28	0.57
SO _x	10.96	0.88	10.57	0.85
PM (mg/m ³)	0.54	0.34	0.49	0.31

Figure 5.3 summarizes the available data of emissions from different sources in order to have an overview of the typical values for each type of pollutant.

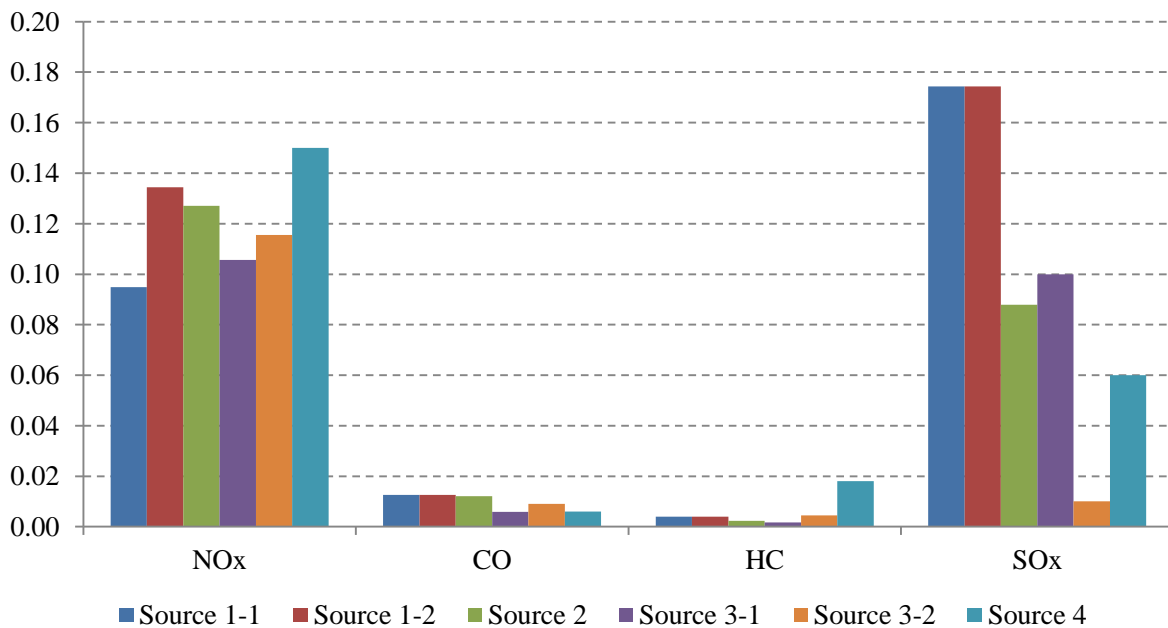


Figure 5.3: Comparison of exhaust gas portions from different sources

Table 5.4: Emissions from propulsion systems (g/kWh) [20]

Type of engine	NO _x	SO _x	CO ₂	PM
2-Stroke diesel (slow speed)	17.0	12.9	550	0.5
4-Stroke diesel (medium speed)	12.0	13.6	612	0.4
Dual fuel diesel electric	1.3	0.05	500	0.05
Steam turbine	1.0	11.0	930	2.5

Gas turbine	2.5	0	590	0.01
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As part of the internship requirements, a new input interface was developed for the calculation of fuel consumption and estimation of the exhaust emissions. Some changes in the form of new subroutines were also implemented into the code of the program for the execution of the newly additional calculations.

Fuel consumption / Exhaust emissions

BSFC at MCR (g/kWh)

Factors to correct BSFC

a0

a1

a2

a3

a4

a5

a6

Emission Factors [g/kg fuel]

CO₂

CO

NO_x

SO_x

BC

OC

PM

Figure 5.4: Newly added interface to the program

6. CALCULATED RESULTS

6.1. Bulk Carrier: Panamax Size, Diesel Engine, Conventional Shaft Line, Ice 1A

The calculated results of bulk carrier are shown as follows:

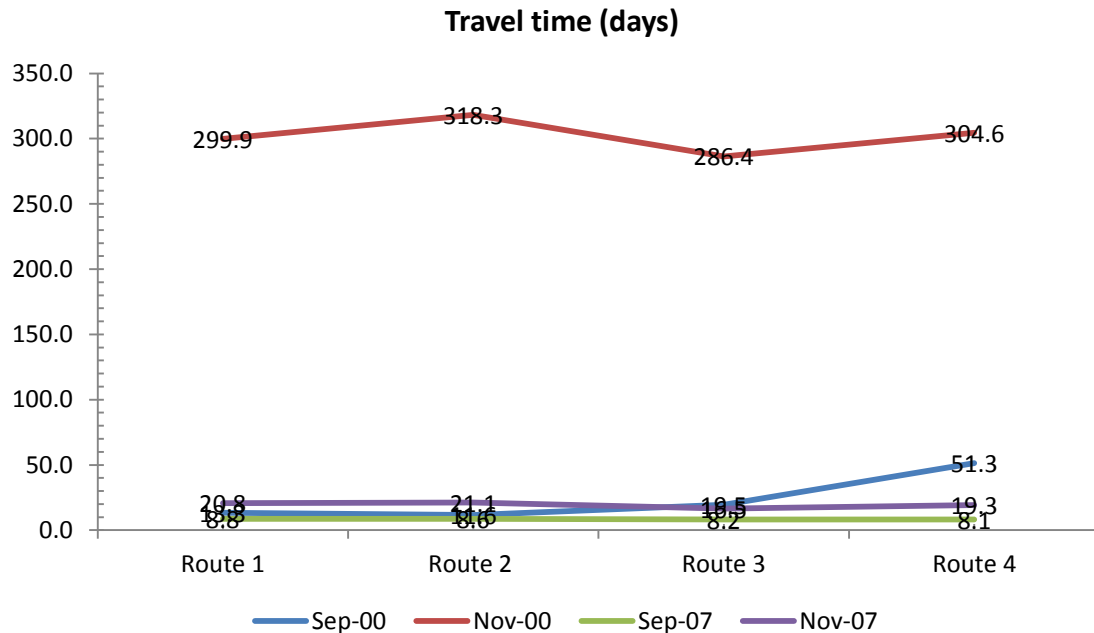


Figure 6.1: Travel time (days) of bulk carrier

It is clear to see that in the condition of November 2000, it was not possible to sail the route since the travel times for all four routes are very high and unlikely to be acceptable.

The calculated values are summarized in the following table:

Table 6.1: Travel time (days) of bulk carrier

Time/Route	Route 1	Route 2	Route 3	Route 4
September 2000	13.3	11.6	19.5	51.3
November 2000	299.9	318.3	286.4	304.6
September 2007	8.8	8.6	8.2	8.1
November 2007	20.8	21.1	16.5	19.3

The travel times on each route are very different. In the condition of September 2000, the second route required least time to complete the voyage, whilst using route 4 may cause the ship to spend more than 51 days on the route.

In September 2007, the sea ice was at the record low of the volume of extension, and in this period, the NSR was ice free. In that condition, a bulk carrier needed just about 8 days to travel from Murmansk to Bering Strait. The travel times on different routes are not the same

but it is less than one day of difference. Also we can see that the route 4 is the shortest way to travel.

The fuel consumptions are presented as follows:

Table 6.2: Fuel consumption (tons) of bulk carrier

Time/Route	Route 1	Route 2	Route 3	Route 4
September 2000	321	328	425	1059
November 2000	7816	10025	7506	9696
September 2007	334	329	314	310
November 2007	461	461	355	453

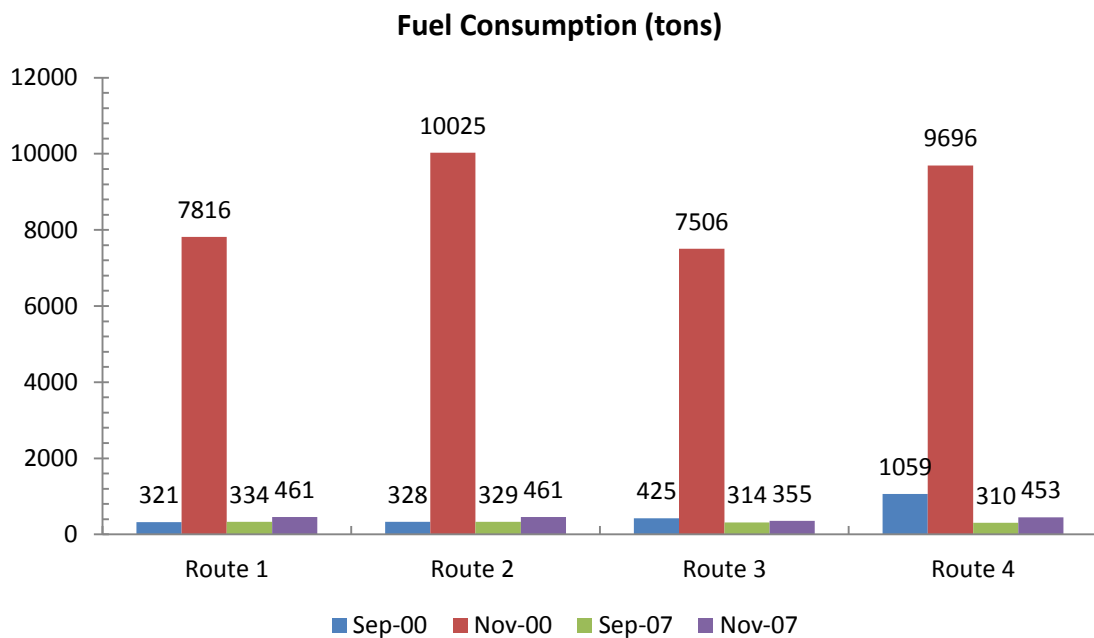


Figure 6.2: Fuel consumption (tons) of bulk carrier

The result for the period of November 2000 was too high and we can easily neglect it, by the mean that it is not reasonable to make a transit in such a condition similar to the condition in November 2000.

In September 2000, even it was possible to navigate through the NSR, but in some part of the route the ice was still very hard to break through. This was shown in the result of the Route 4 since the fuel consumption on this route was three times higher than on the first and the second routes, and was more than two times higher than on the third route.

In the ice free condition similar to what happened in September 2007, we observed that using the fourth route is the most economical option in term of fuel consumption.

And the fuel consumption per day can be deducted from the fuel consumption and the travel time:

Table 6.3: Fuel per day (tons/day) of bulk carrier

Time/Route	Route 1	Route 2	Route 3	Route 4
September 2000	24	28	22	21
November 2000	26	31	26	32
September 2007	38	38	38	38
November 2007	22	22	21	23

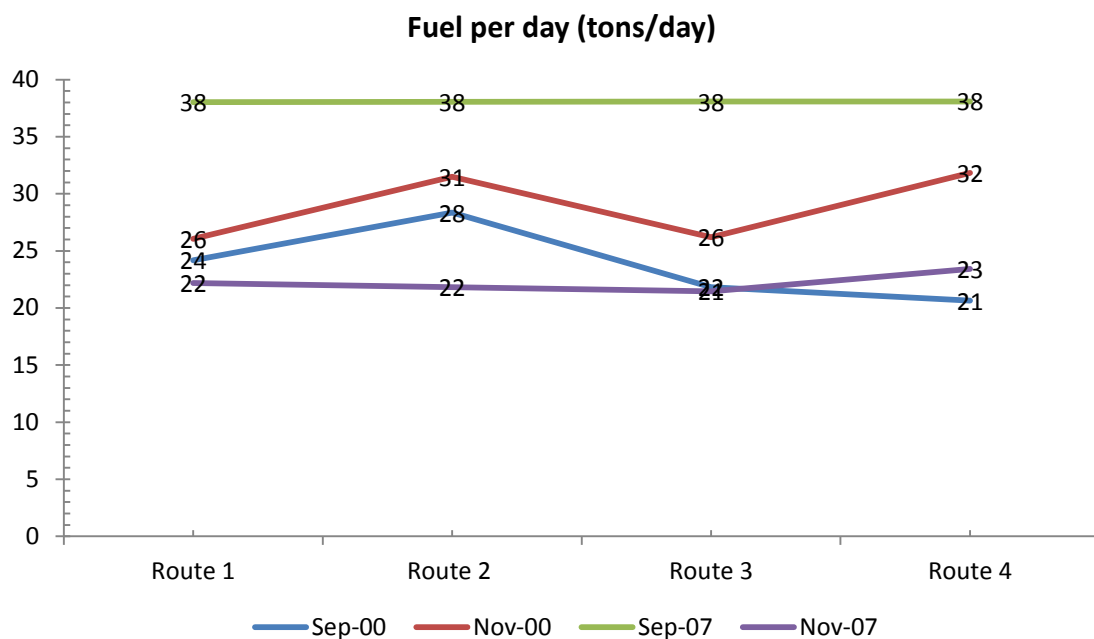


Figure 6.3: Fuel per day (tons/day) of bulk carrier

The result of fuel consumption per day is additional information to help to decide which route should be used in different ice conditions. In some cases, the ship owner may want to choose the route that on it, the vessel can complete the voyage in a shortest time, regardless the fuel consumption. But in other cases, maybe due to some restrictions on the route, the vessel cannot to navigate so fast, and the ship owner may want to choose any route that can save the fuel consumption. For example, in the case of this bulk carrier, taking Route 4 in the ice condition similar to which in September 2000 caused a long travel time, but it led to the lowest fuel consumption per day. In contrast, ice conditions like which in September 2007 reduced a lot of travel time, but in turn, it caused a very high fuel consumption rate in average.

Using the calculated fuel consumption data, with regarding to the emission factor of each component of gases, the exhaust emissions were calculated for some pollutants and were summarized in Table 6.4 as presented below:

Table 6.4: Exhaust emissions of bulk carrier

Bulk Carrier		CO ₂	NO _x	SO _x	CO	BC	OC	PM
		(tons)	(tons)	(tons)	(kg)	(kg)	(kg)	(kg)
Sep-00	Route 1	1029.6	25.00	17.30	2376.40	112.40	343.60	1702.00
	Route 2	1050.7	25.60	17.70	2425.20	114.70	350.70	1736.90
	Route 3	1363.5	33.20	23.00	3147.30	148.90	455.10	2254.10
	Route 4	3396.2	82.60	57.20	7839.00	370.80	1133.50	5614.40
Nov-00	Route 1	25057.7	609.60	422.10	57837.50	2735.60	8363.00	41424.10
	Route 2	32140.9	782.00	541.40	74186.70	3508.80	10727.00	53133.70
	Route 3	24064.6	585.50	405.30	55545.30	2627.10	8031.50	39782.40
	Route 4	31084.3	756.30	523.60	71747.90	3393.50	10374.40	51387.00
Sep-07	Route 1	1069.5	26.00	18.00	2468.50	116.80	356.90	1768.00
	Route 2	1054.6	25.70	17.80	2434.20	115.10	352.00	1743.40
	Route 3	1006.7	24.50	17.00	2323.70	109.90	336.00	1664.30
	Route 4	992.4	24.10	16.70	2290.70	108.30	331.20	1640.60
Nov-07	Route 1	1478.6	36.00	24.90	3412.80	161.40	493.50	2444.30
	Route 2	1478.9	36.00	24.90	3413.60	161.50	493.60	2444.80
	Route 3	1136.7	27.70	19.10	2623.70	124.10	379.40	1879.10
	Route 4	1451.5	35.30	24.40	3350.30	158.50	484.40	2399.50

6.2. Tanker 01: Panamax size, Diesel - Electric Propulsion, Ice class 1AS

Similarly calculated results of a tanker with diesel engines and electric propulsion system are presented in the section that follows.

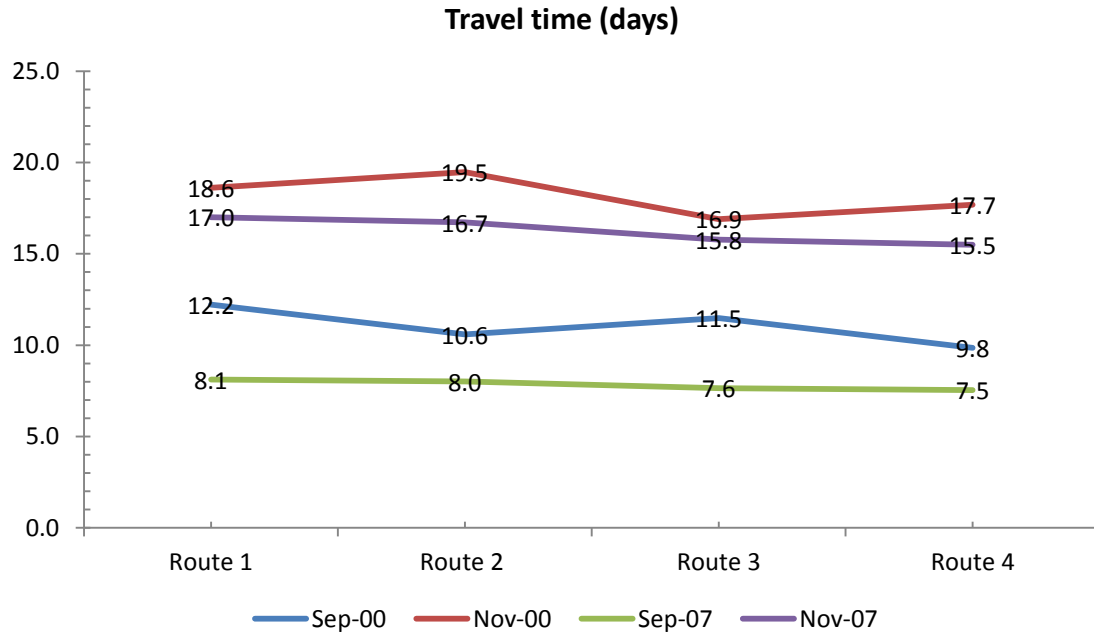


Figure 6.4: Travel time (days) of tanker 01

Table 6.5: Travel time (days) of tanker 01

Time/Route	Route 1	Route 2	Route 3	Route 4
September 2000	12.2	10.6	11.5	9.8
November 2000	18.6	19.5	16.9	17.7
September 2007	8.1	8.0	7.6	7.5
November 2007	17.0	16.7	15.8	15.5

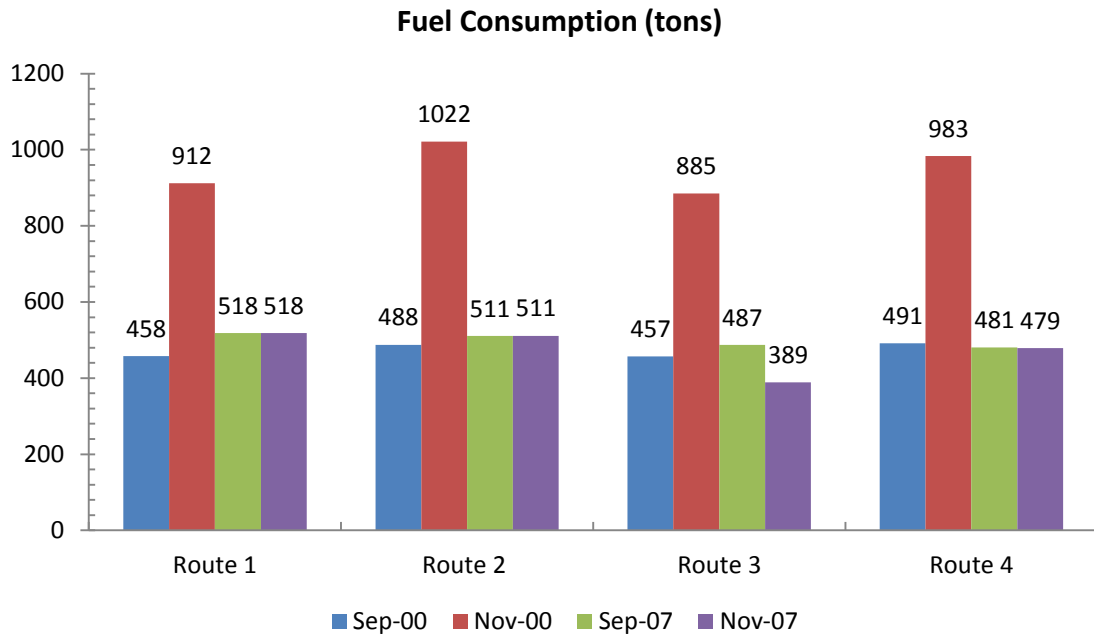


Figure 6.5: Fuel consumption (tons) of tanker 01

Table 6.6: Fuel consumption (tons) of tanker 01

Time/Route	Route 1	Route 2	Route 3	Route 4
September 2000	458	488	457	491
November 2000	912	1022	885	983
September 2007	518	511	487	481
November 2007	518	511	389	479

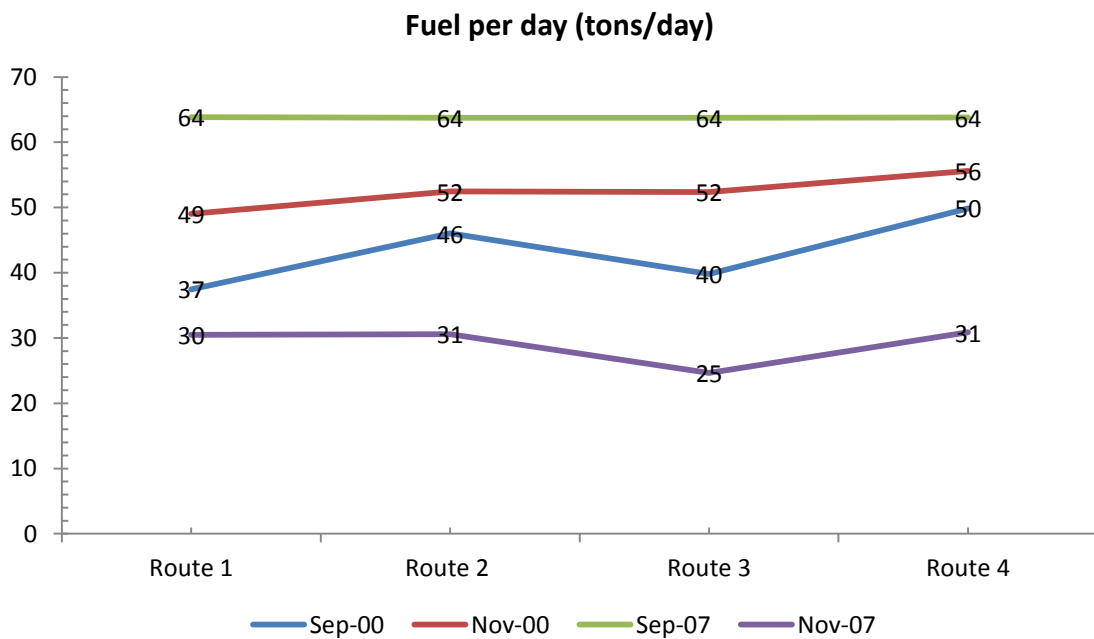


Figure 6.6: Fuel per day (tons/day) of tanker 01

Table 6.7: Fuel per day (tons/day) of tanker 01

Time/Route	Route 1	Route 2	Route 3	Route 4
September 2000	37	46	40	50
November 2000	49	52	52	56
September 2007	64	64	64	64
November 2007	30	31	25	31

Table 6.8: Exhaust emissions of tanker 01

Tanker 01		CO ₂	CO	NO _x	SO _x	BC	OC	PM
		(tons)	(tons)	(tons)	(kg)	(kg)	(kg)	(kg)
Sep-00	Route 1	1468.9	35.70	24.70	3391	160	490	2428
	Route 2	1564.3	38.10	26.30	3611	171	522	2586
	Route 3	1464.7	35.60	24.70	3381	160	489	2421
	Route 4	1575.9	38.30	26.50	3638	172	526	2605
Nov-00	Route 1	2923.4	71.10	49.20	6748	319	976	4833
	Route 2	3274.6	79.70	55.20	7558	358	1093	5413
	Route 3	2837.5	69.00	47.80	6549	310	947	4691
	Route 4	3152.6	76.70	53.10	7277	344	1052	5212
Sep-07	Route 1	1662.8	40.50	28.00	3838	182	555	2749
	Route 2	1638.1	39.90	27.60	3781	179	547	2708
	Route 3	1563.3	38.00	26.30	3609	171	522	2584
	Route 4	1541.8	37.50	26.00	3559	168	515	2549
Nov-07	Route 1	1660.9	40.40	28.00	3834	181	554	2746
	Route 2	1638.6	39.90	27.60	3782	179	547	2709
	Route 3	1245.8	30.30	21.00	2876	136	416	2060
	Route 4	1533.6	37.30	25.80	3540	167	512	2535

6.3. Tanker 02: Panamax Size, Diesel Engine, Direct Shaft Line, Ice Class 1A

6.3.1. Case 01: P/D = 0.624

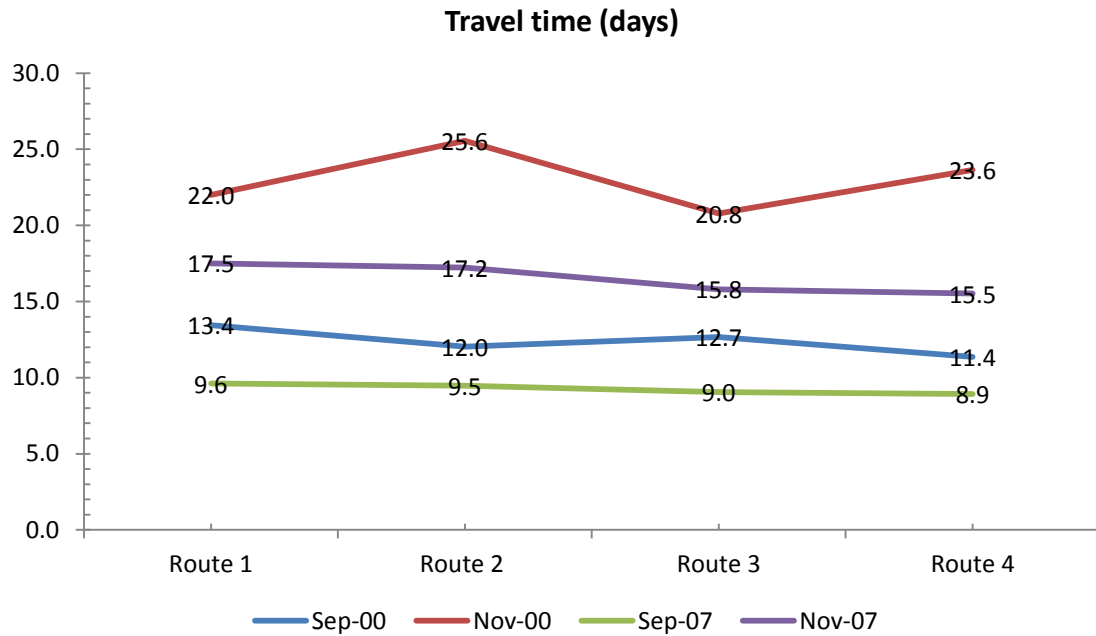


Figure 6.7: Travel time (days) of tanker 02, P/D = 0.624

Table 6.9: Travel time (days) of tanker 02, P/D = 0.624

Time/Route	Route 1	Route 2	Route 3	Route 4
September 2000	13.4	12.0	12.7	11.4
November 2000	22.0	25.6	20.8	23.6
September 2007	9.6	9.5	9.0	8.9
November 2007	17.5	17.2	15.8	15.5

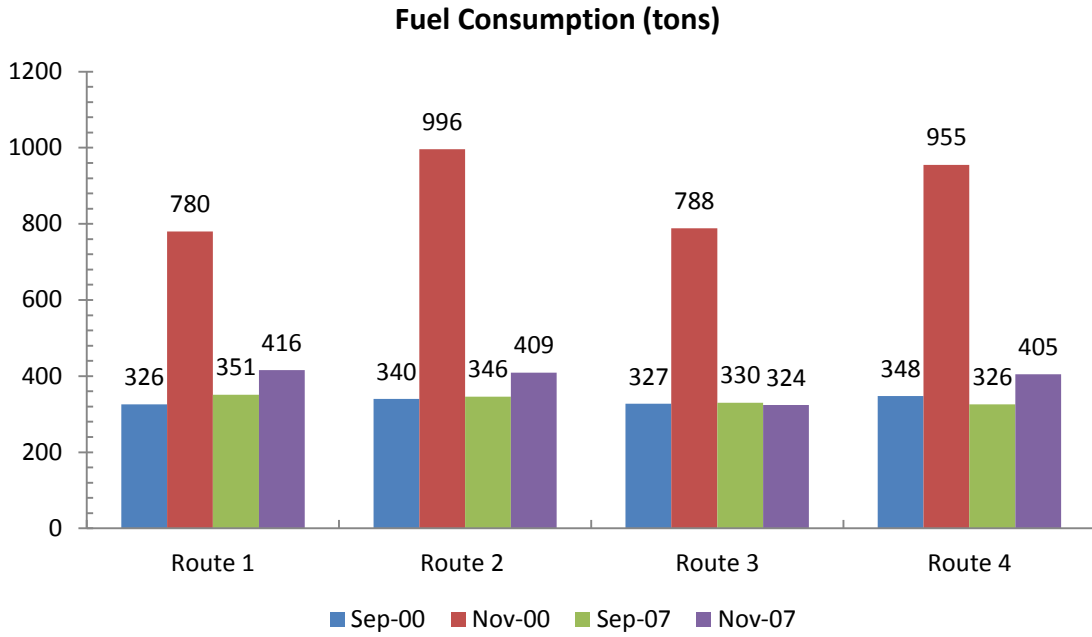


Figure 6.8: Fuel consumption (tons) of tanker 02, P/D = 0.624

Table 6.10: Fuel consumption (tons) of tanker 02, P/D = 0.624

Time/Route	Route 1	Route 2	Route 3	Route 4
September 2000	326	340	327	348
November 2000	780	996	788	955
September 2007	351	346	330	326
November 2007	416	409	324	405

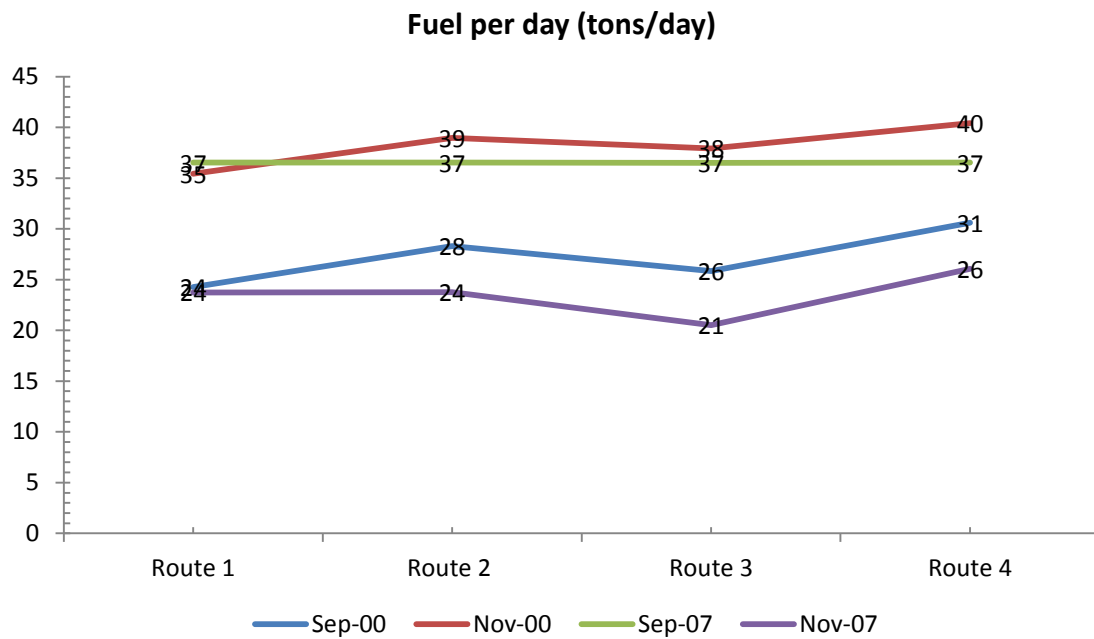


Figure 6.9: Fuel per day (tons/day) of tanker 02, P/D = 0.624

Table 6.11: Fuel per day (tons/day) of tanker 02, P/D = 0.624

Time/Route	Route 1	Route 2	Route 3	Route 4
September 2000	24	28	26	31
November 2000	35	39	38	40
September 2007	37	37	37	37
November 2007	24	24	21	26

Table 6.12: Exhaust emissions of tanker 02, P/D = 0.624

Tanker 01		CO ₂	CO	NO _x	SO _x	BC	OC	PM
		(tons)	(tons)	(tons)	(kg)	(kg)	(kg)	(kg)
Sep-00	Route 1	1045.2	2.4	25.4	17604	114.1	348.8	1727.8
	Route 2	1091.3	2.5	26.6	18381	119.1	364.2	1804.1
	Route 3	1048.9	2.4	25.5	17667.4	114.5	350.1	1734
	Route 4	1115.5	2.6	27.1	18788.5	121.8	372.3	1844.1
Nov-00	Route 1	2500.1	5.8	60.8	42110	272.9	834.4	4133
	Route 2	3192.2	7.4	77.7	53768.1	348.5	1065.4	5277.2
	Route 3	2526.3	5.8	61.5	42551.2	275.8	843.1	4176.3
	Route 4	3062.4	7.1	74.5	51581.7	334.3	1022.1	5062.6
Sep-07	Route 1	1125.3	2.6	27.4	18953.3	122.8	375.6	1860.2
	Route 2	1109.6	2.6	27	18690.2	121.1	370.3	1834.4
	Route 3	1058.8	2.4	25.8	17834	115.6	353.4	1750.4

	Route 4	1044.1	2.4	25.4	17585.4	114	348.5	1726
Nov-07	Route 1	1331.9	3.1	32.4	22434.3	145.4	444.5	2201.9
	Route 2	1312.2	3	31.9	22101.6	143.3	437.9	2169.2
	Route 3	1039.2	2.4	25.3	17502.9	113.4	346.8	1717.9
	Route 4	1297.2	3	31.6	21848.5	141.6	432.9	2144.4

6.3.2. Case 02: P/D = 0.790

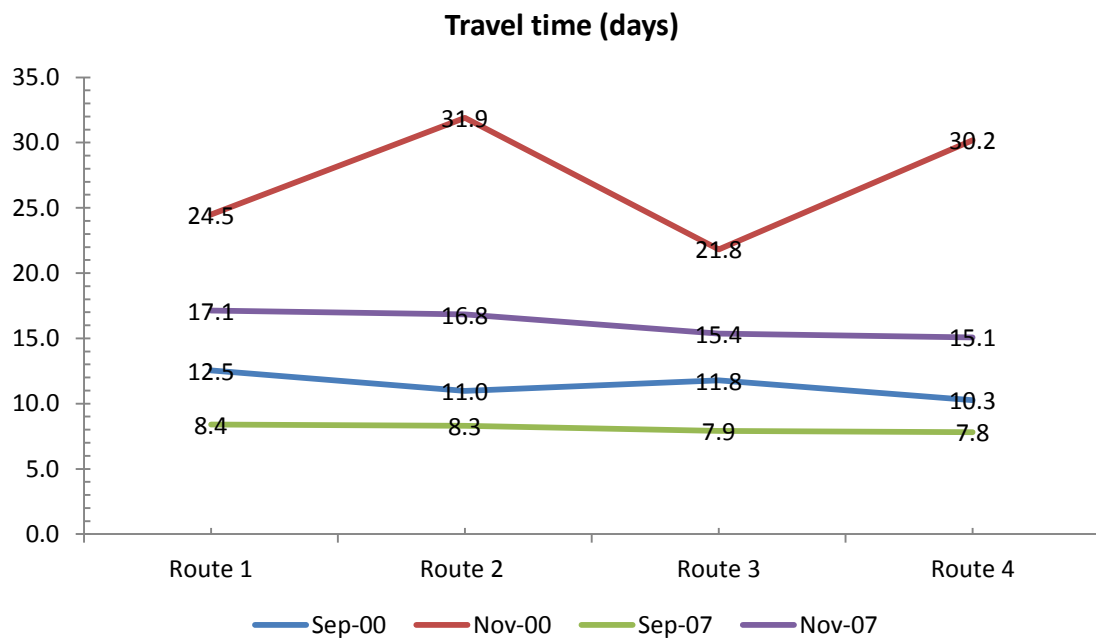


Figure 6.10: Travel time (days) of tanker 02, P/D = 0.790

Table 6.13: Travel time (days) of tanker 02, P/D = 0.790

Time/Route	Route 1	Route 2	Route 3	Route 4
September 2000	12.5	11.0	11.8	10.3
November 2000	24.5	31.9	21.8	30.2
September 2007	8.4	8.3	7.9	7.8
November 2007	17.1	16.8	15.4	15.1

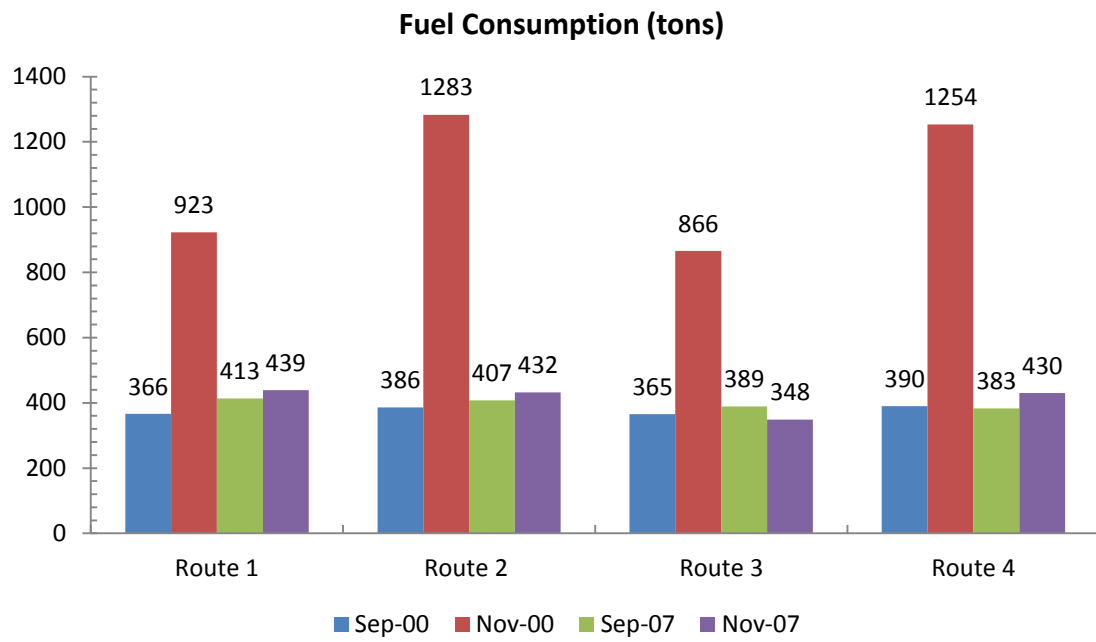


Figure 6.11: Fuel consumption (tons) of tanker 02, P/D = 0. 790

Table 6.14: Fuel consumption (tons) of tanker 02, P/D = 0. 790

Time/Route	Route 1	Route 2	Route 3	Route 4
September 2000	366	386	365	390
November 2000	923	1283	866	1254
September 2007	413	407	389	383
November 2007	439	432	348	430

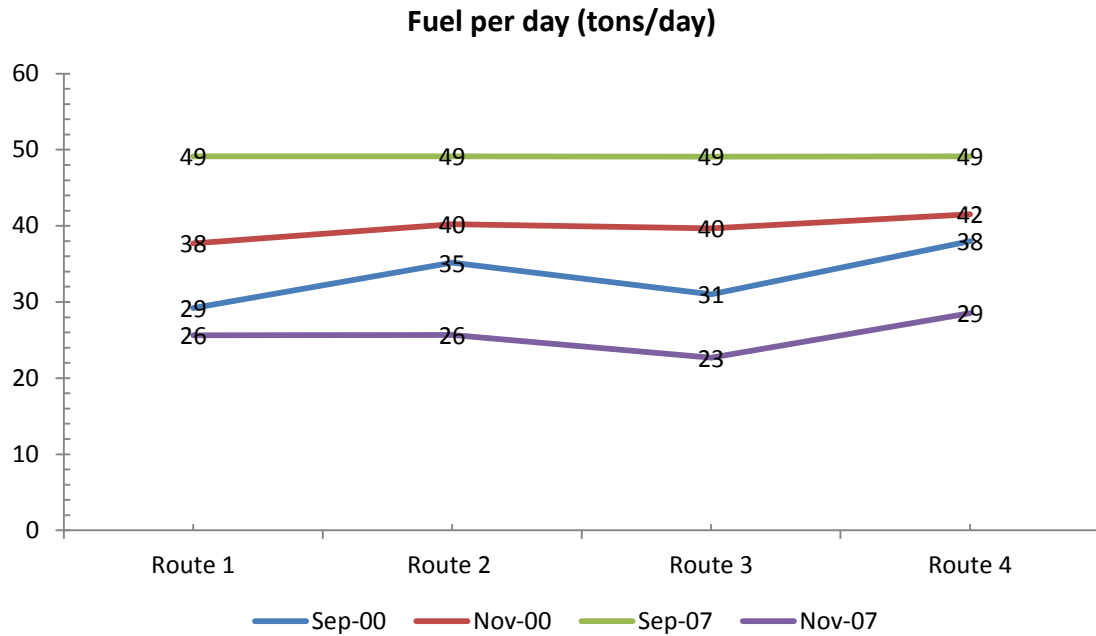


Figure 6.12: Fuel per day (tons/day) of tanker 02, P/D = 0. 790

Table 6.15: Fuel per day (tons/day) of tanker 02, P/D = 0. 790

Time/Route	Route 1	Route 2	Route 3	Route 4
September 2000	29	35	31	38
November 2000	38	40	40	42
September 2007	49	49	49	49
November 2007	26	26	23	29

Table 6.16: Exhaust emissions of tanker 02, P/D = 0. 790

Tanker 01		CO2	CO	NOx	SOx	BC	OC	PM
		(tons)	(tons)	(tons)	(kg)	(kg)	(kg)	(kg)
Sep-00	Route 1	1174.4	2.7	28.6	19780.9	128.2	392	1941.5
	Route 2	1237.7	2.9	30.1	20847.5	135.1	413.1	2046.1
	Route 3	1170.5	2.7	28.5	19714.9	127.8	390.6	1935
	Route 4	1249	2.9	30.4	21037.7	136.4	416.9	2064.8
Nov-00	Route 1	2957.9	6.8	72	49820.7	322.9	987.2	4889.8
	Route 2	4113.9	9.5	100.1	69291.4	449.1	1373	6800.8
	Route 3	2776.7	6.4	67.6	46768.5	303.1	926.7	4590.2
	Route 4	4018.7	9.3	97.8	67689.4	438.7	1341.3	6643.6
Sep-07	Route 1	1324.1	3.1	32.2	22302.8	144.6	441.9	2189
	Route 2	1306	3	31.8	21997.2	142.6	435.9	2159
	Route 3	1246.6	2.9	30.3	20996.6	136.1	416	2060.8

	Route 4	1229.1	2.8	29.9	20701.5	134.2	410.2	2031.8
Nov-07	Route 1	1405.9	3.2	34.2	23679.9	153.5	469.2	2324.1
	Route 2	1385.7	3.2	33.7	23339.3	151.3	462.5	2290.7
	Route 3	1116.8	2.6	27.2	18811.3	121.9	372.7	1846.3
	Route 4	1379.1	3.2	33.6	23228.5	150.6	460.3	2279.8

6.3.3. Case 03: P/D = 0.877

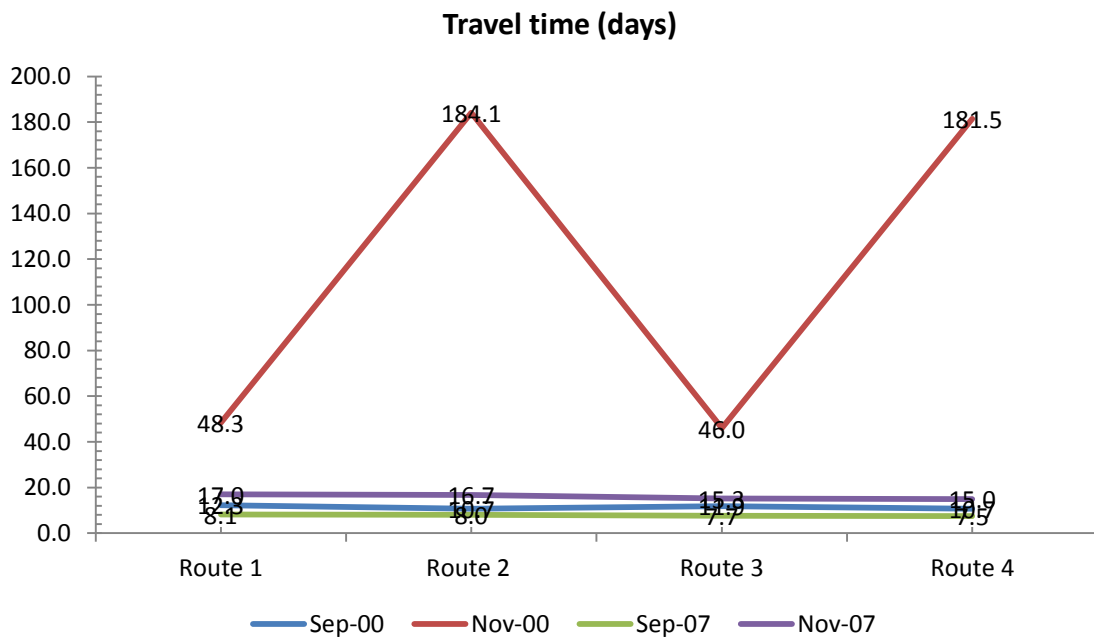


Figure 6.13: Travel time (days) of tanker 02, P/D = 0.877

Table 6.17: Travel time (days) of tanker 02, P/D = 0.877

Time/Route	Route 1	Route 2	Route 3	Route 4
September 2000	12.3	10.7	11.9	10.7
November 2000	48.3	184.1	46.0	181.5
September 2007	8.1	8.0	7.7	7.5
November 2007	17.0	16.7	15.3	15.0

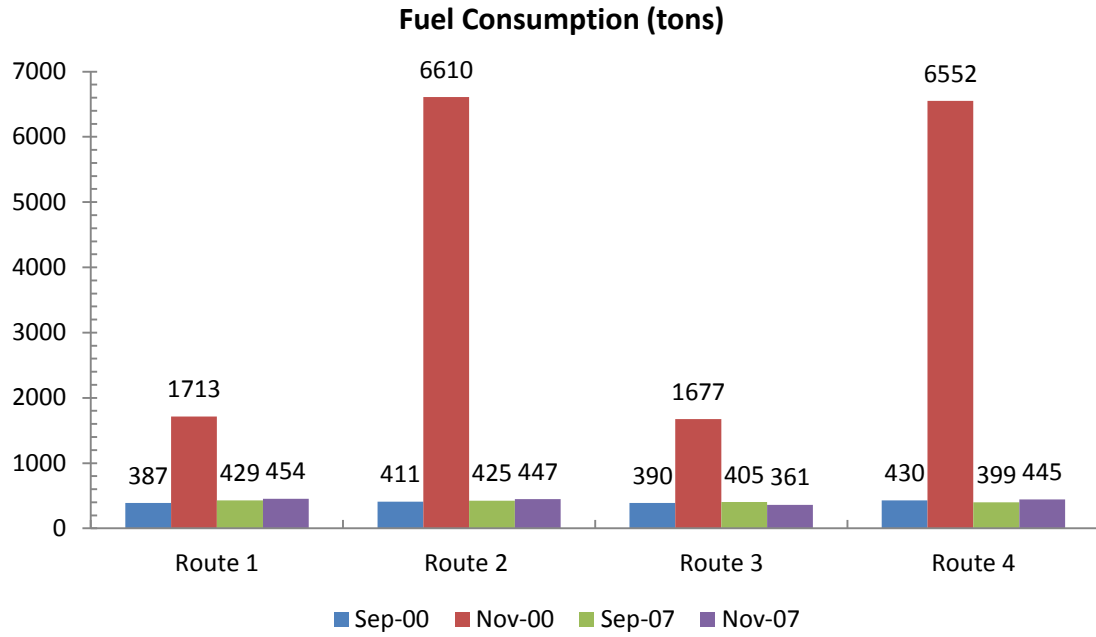


Figure 6.14: Fuel consumption (tons) of tanker 02, P/D = 0. 877

Table 6.18: Fuel consumption (tons) of tanker 02, P/D = 0. 877

Time/Route	Route 1	Route 2	Route 3	Route 4
September 2000	387	411	390	430
November 2000	1713	6610	1677	6552
September 2007	429	425	405	399
November 2007	454	447	361	445

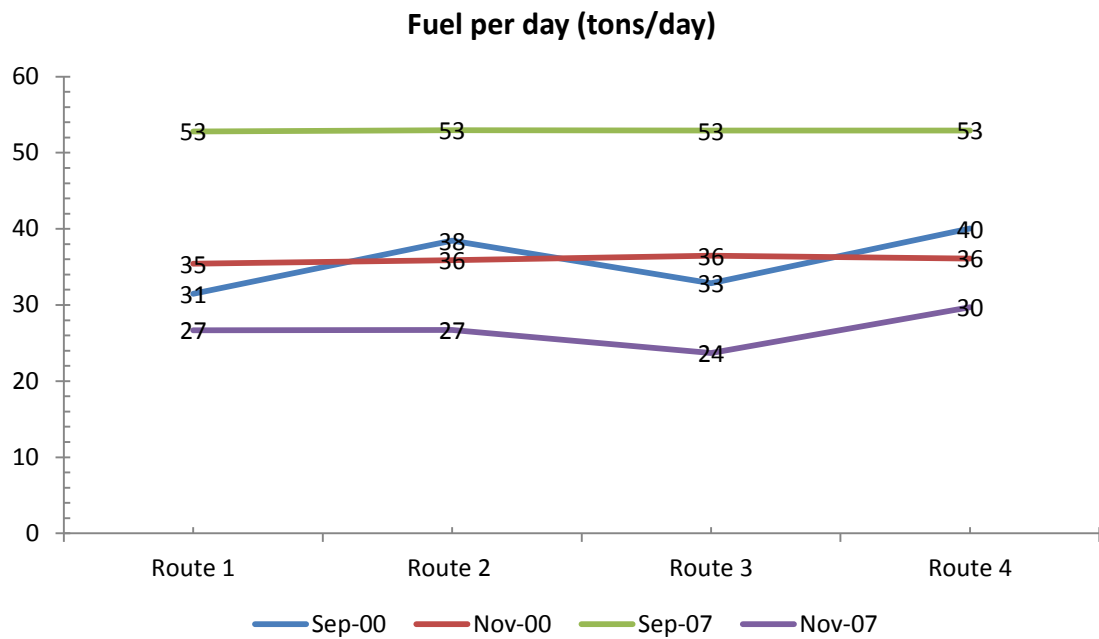


Figure 6.15: Fuel per day (tons/day) of tanker 02, P/D = 0. 877

Table 6.19: Fuel per day (tons/day) of tanker 02, P/D = 0. 877

Time/Route	Route 1	Route 2	Route 3	Route 4
September 2000	31	38	33	40
November 2000	35	36	36	36
September 2007	53	53	53	53
November 2007	27	27	24	30

Table 6.20: Exhaust emissions of tanker 02, P/D = 0. 877

Tanker 01		CO ₂	CO	NO _x	SO _x	BC	OC	PM
		(tons)	(tons)	(tons)	(kg)	(kg)	(kg)	(kg)
Sep-00	Route 1	1240.7	2.9	30.2	20898.4	135.5	414.1	2051.1
	Route 2	1316.4	3	32	22172.2	143.7	439.3	2176.2
	Route 3	1250.4	2.9	30.4	21061.8	136.5	417.3	2067.2
	Route 4	1377	3.2	33.5	23193.1	150.3	459.6	2276.4
Nov-00	Route 1	5490.8	12.7	133.6	92483.3	599.4	1832.5	9077.1
	Route 2	21192.3	48.9	515.6	356950.6	2313.6	7072.9	35034
	Route 3	5377	12.4	130.8	90567.3	587	1794.6	8889
	Route 4	21004.2	48.5	511	353782.6	2293	7010.1	34723.1
Sep-07	Route 1	1376.7	3.2	33.5	23188.5	150.3	459.5	2275.9
	Route 2	1361.1	3.1	33.1	22926	148.6	454.3	2250.1
	Route 3	1298.2	3	31.6	21866.3	141.7	433.3	2146.1

	Route 4	1280.2	3	31.1	21563.3	139.8	427.3	2116.4
Nov-07	Route 1	1454.3	3.4	35.4	24495.9	158.8	485.4	2404.2
	Route 2	1433.5	3.3	34.9	24144.7	156.5	478.4	2369.8
	Route 3	1158.5	2.7	28.2	19512.6	126.5	386.6	1915.1
	Route 4	1426	3.3	34.7	24018.2	155.7	475.9	2357.3

Table 6.21: Travel time (days) of tanker 02

Time/Route	P/D = 0. 624				P/D = 0. 790				P/D = 0. 877			
	Route 1	Route 2	Route 3	Route 4	Route 1	Route 2	Route 3	Route 4	Route 1	Route 2	Route 3	Route 4
September 2000	13.4	12.0	12.7	11.4	12.5	11.0	11.8	10.3	12.3	10.7	11.9	10.7
November 2000	22.0	25.6	20.8	23.6	24.5	31.9	21.8	30.2	48.3	184.1	46.0	181.5
September 2007	9.6	9.5	9.0	8.9	8.4	8.3	7.9	7.8	8.1	8.0	7.7	7.5
November 2007	17.5	17.2	15.8	15.5	17.1	16.8	15.4	15.1	17.0	16.7	15.3	15.0

Table 6.22: Fuel consumption (tons) of tanker 02

Time/Route	P/D = 0. 624				P/D = 0. 790				P/D = 0. 877			
	Route 1	Route 2	Route 3	Route 4	Route 1	Route 2	Route 3	Route 4	Route 1	Route 2	Route 3	Route 4
September 2000	326	340	327	348	366	386	365	390	387	411	390	430
November 2000	780	996	788	955	923	1283	866	1254	1713	6610	1677	6552
September 2007	351	346	330	326	413	407	389	383	429	425	405	399
November 2007	416	409	324	405	439	432	348	430	454	447	361	445

Table 6.23: Fuel per day (tons/day) of tanker 02

Time/Route	P/D = 0. 624				P/D = 0. 790				P/D = 0. 877			
	Route 1	Route 2	Route 3	Route 4	Route 1	Route 2	Route 3	Route 4	Route 1	Route 2	Route 3	Route 4
September 2000	24	28	26	31	29	35	31	38	31	38	33	40
November 2000	35	39	38	40	38	40	40	42	35	36	36	36
September 2007	37	37	37	37	49	49	49	49	53	53	53	53
November 2007	24	24	21	26	26	26	23	29	27	27	24	30

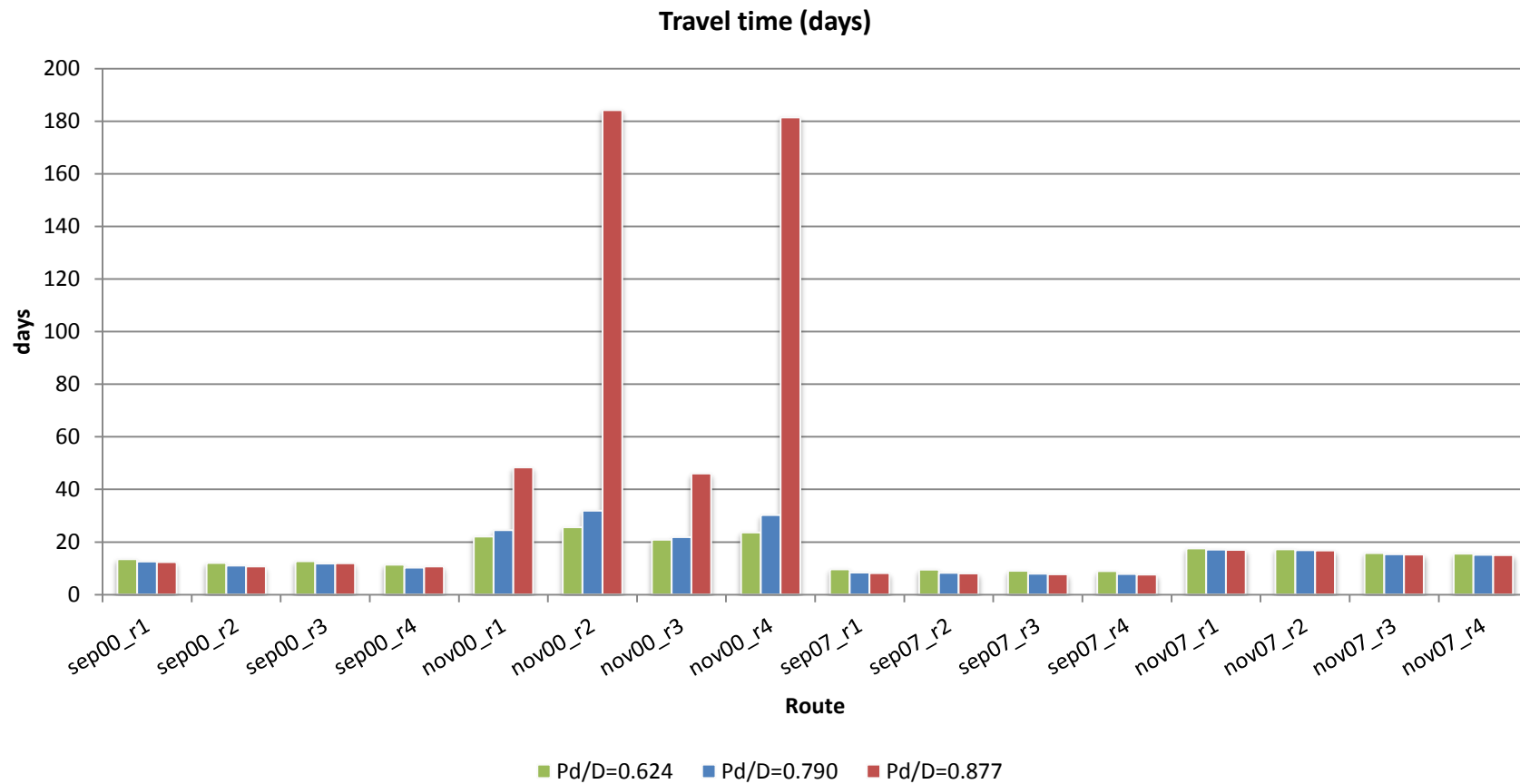


Figure 6.16: Travel time (days) of tanker 02

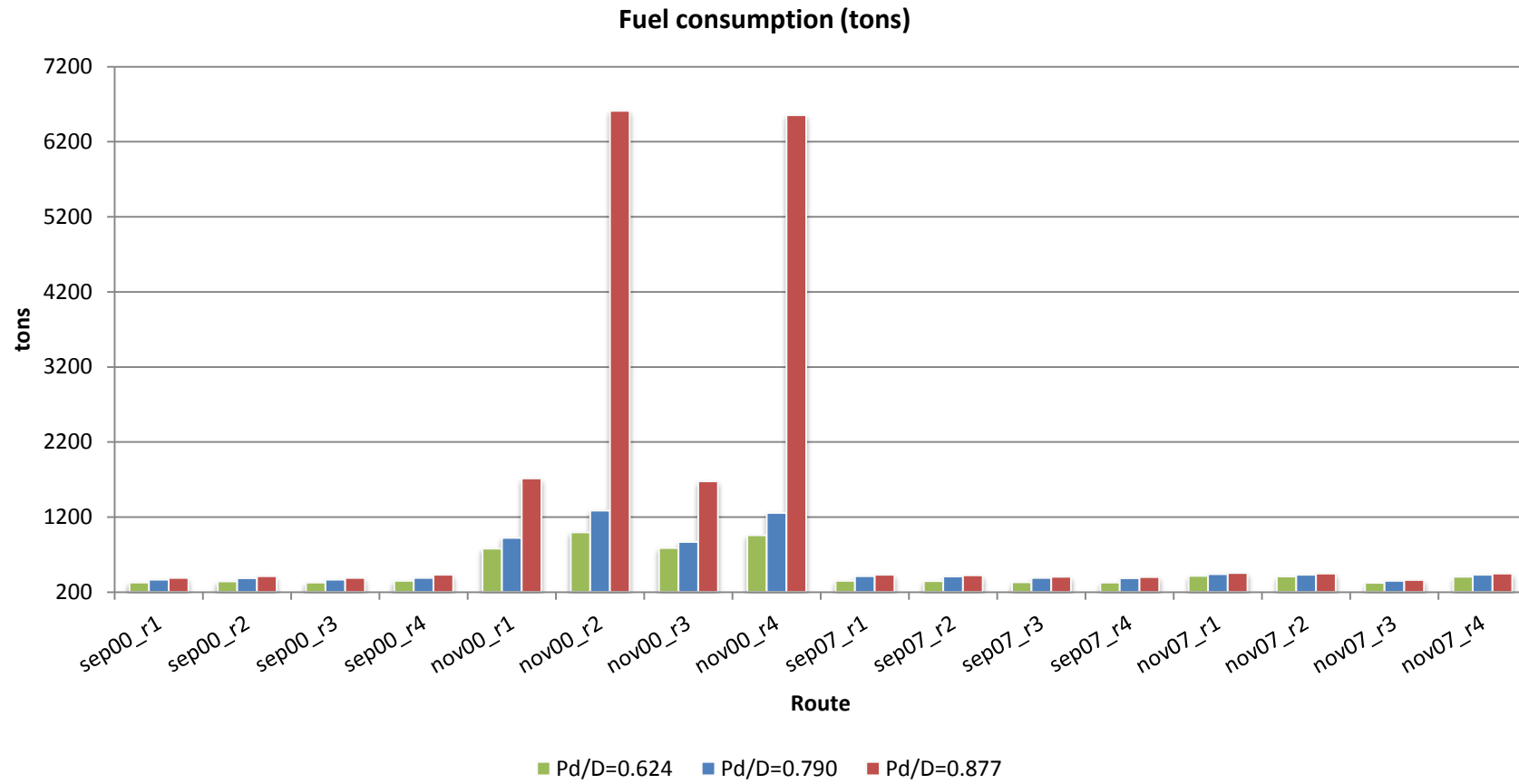


Figure 6.17: Fuel consumption (tons) of tanker 02

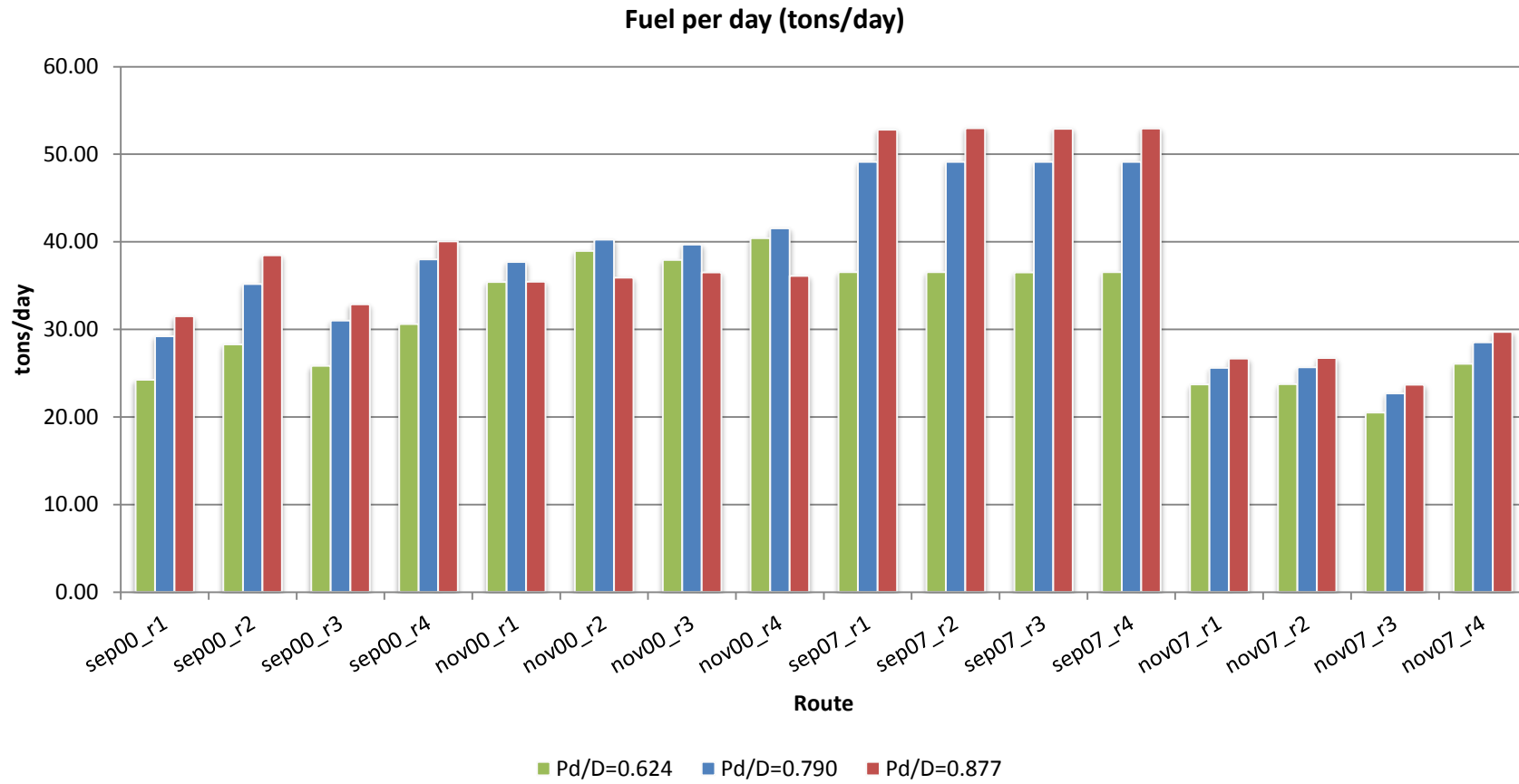


Figure 6.18: Fuel per day (tons/day) of tanker 02

6.4. LNG Carrier: Diesel - Electric Propulsion (Azipod), Ice Class 1A

Due to the fact that the ice breaking capability of this LNG vessel is higher than the bulk carrier and the tankers we considered in the previous chapters, we observed that the travel times in all period are significant lower. And even in difficult conditions, e.g. in November 2000 and in November 2007, the vessel can still finish the voyage in a short time.

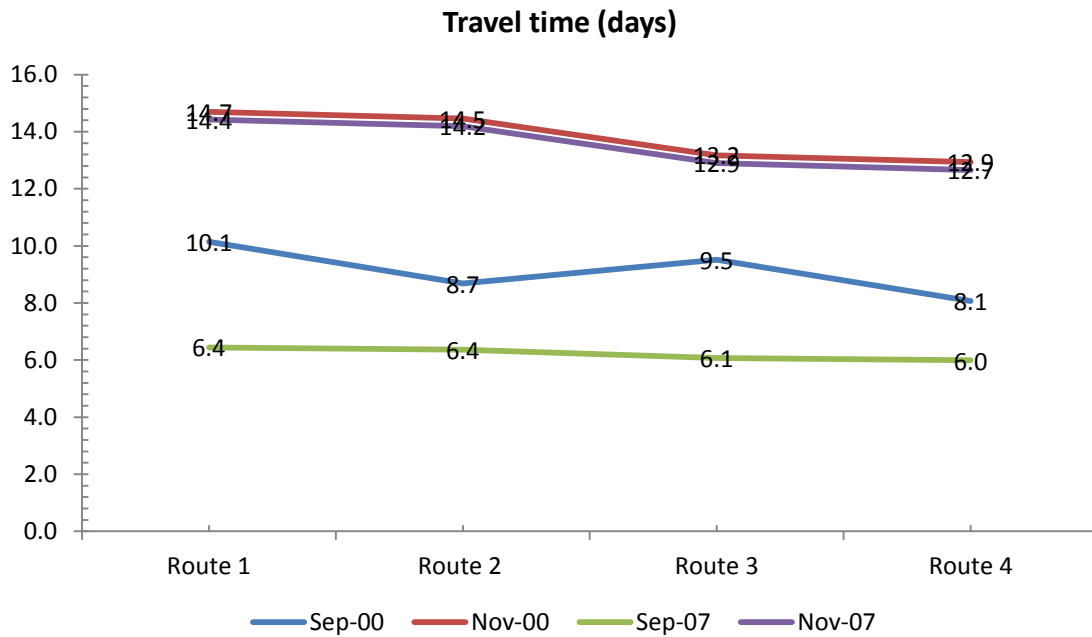


Figure 6.19: Travel time (days) of LNG carrier

Table 6.24: Travel time (days) of LNG carrier

Time/Route	Route 1	Route 2	Route 3	Route 4
September 2000	10.1	8.7	9.5	8.1
November 2000	14.7	14.5	13.2	12.9
September 2007	6.4	6.4	6.1	6.0
November 2007	14.4	14.2	12.9	12.7

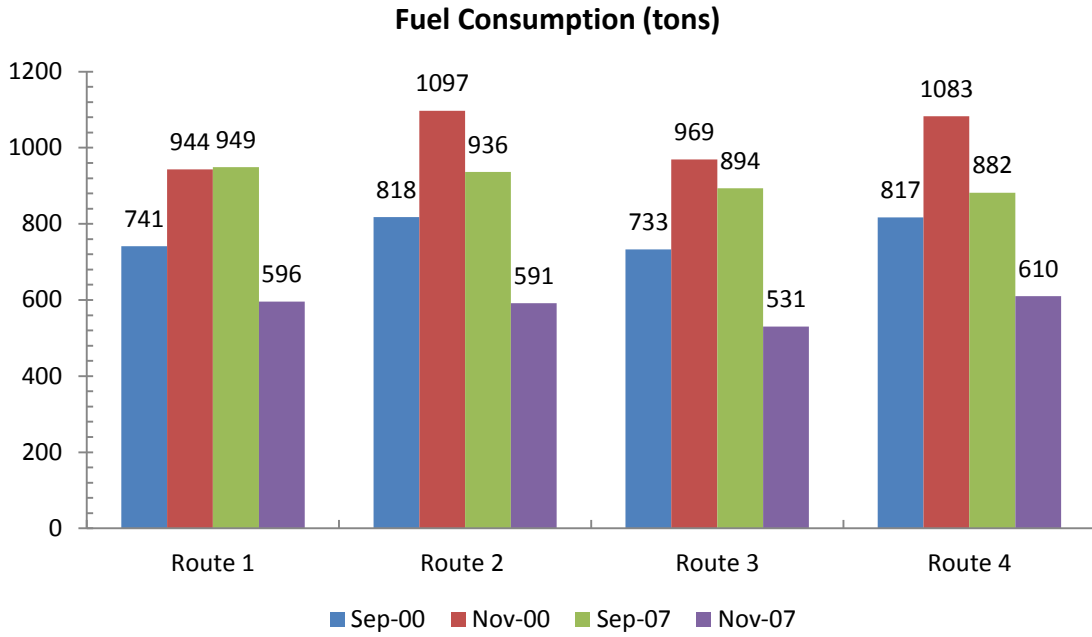


Figure 6.20: Fuel consumption (tons) of LNG carrier

Table 6.25: Fuel consumption (tons) of LNG carrier

Time/Route	Route 1	Route 2	Route 3	Route 4
September 2000	741	818	733	817
November 2000	944	1097	969	1083
September 2007	949	936	894	882
November 2007	596	591	531	610

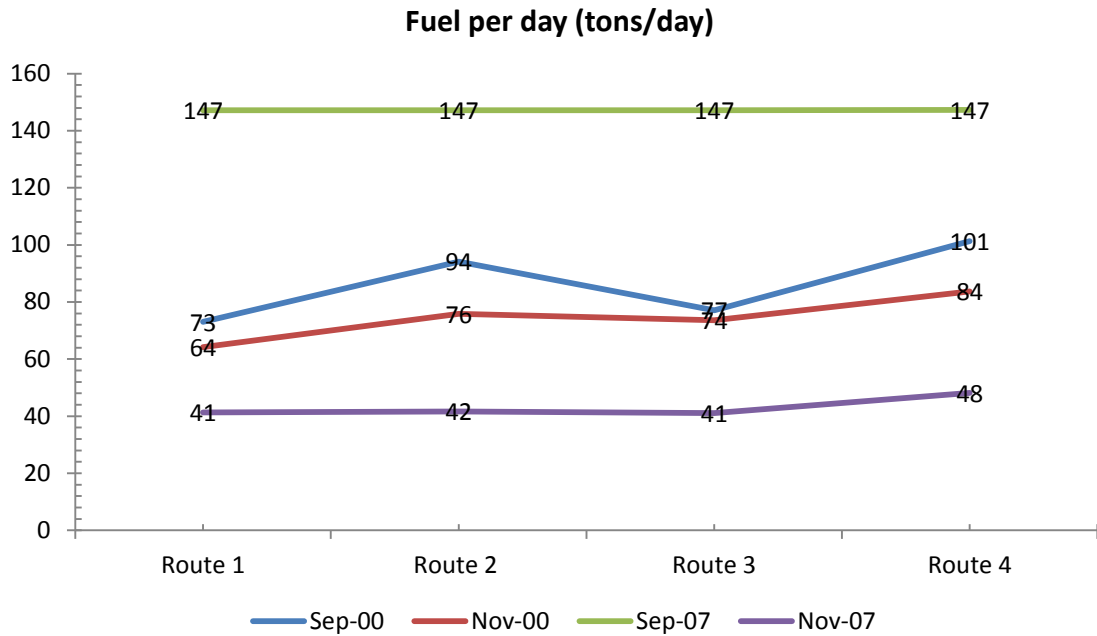


Figure 6.21: Fuel per day (tons/day) of LNG carrier

Table 6.26: Fuel per day (tons/day) of LNG carrier

Time/Route	Route 1	Route 2	Route 3	Route 4
September 2000	73	94	77	101
November 2000	64	76	74	84
September 2007	147	147	147	147
November 2007	41	42	41	48

Table 6.27: Exhaust emissions of LNG carrier

Tanker 01		CO ₂	CO	NO _x	SO _x	BC	OC	PM
		(tons)	(tons)	(tons)	(kg)	(kg)	(kg)	(kg)
Sep-00	Route 1	2375.6	5.50	57.80	40014	259	793	3927
	Route 2	2621.6	6.10	63.80	44158	286	875	4334
	Route 3	2350.4	5.40	57.20	39589	257	784	3886
	Route 4	2620.1	6.00	63.70	44132	286	875	4331
Nov-00	Route 1	3025	7.00	73.60	50951	330	1010	5001
	Route 2	3518.4	8.10	85.60	59261	384	1174	5816
	Route 3	3106.2	7.20	75.60	52319	339	1037	5135
	Route 4	3471.4	8.00	84.50	58471	379	1159	5739
Sep-07	Route 1	3042.1	7.00	74.00	51239	332	1015	5029
	Route 2	3001.7	6.90	73.00	50559	328	1002	4962
	Route 3	2865.8	6.60	69.70	48270	313	957	4738

	Route 4	2826.5	6.50	68.80	47608	309	943	4673
Nov-07	Route 1	1910.3	4.40	46.50	32176	209	638	3158
	Route 2	1895.2	4.40	46.10	31922	207	633	3133
	Route 3	1700.8	3.90	41.40	28647	186	568	2812
	Route 4	1955.1	4.50	47.60	32931	213	653	3232

7. CONCLUSIONS

The thesis is to study about the fuel consumption and exhaust emissions from ship navigating in ice conditions along the Northern Sea Route in Arctic Ocean. The goal is to develop a method for the prediction of exhaust emissions depending on consumed power of various types of ship.

Sea ice has a significant impact on the sailing time and fuel consumption. The presence of sea ice along a route slows down the vessel's speed, increases the required power, and therefore increases the fuel consumption and corresponding exhaust emissions.

The main contribution of the work of the author when performing this thesis was to complete the subroutines and new interfaces to the program to calculate fuel consumption and exhaust emissions.

In this work, we calculated for each ship, but in a higher scale, we can also estimate the total amount of exhaust gases provided that the number and types of vessels are known.

The results obtained from calculating fuel consumption and exhaust emissions of each individual ship are valuable for the ship owner, or shipping company to consider not only the economical aspect but also the environmental requirements when choosing the voyage through the NSR.

BIBLIOGRAPHY

1. Aboulazm, A. F., Alacoque, H. Y., *Fuel consumption analysis for vessels operation in pack ice*, Proceedings Vol. II of the 11th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC'91), pages 746-759, 1991.
2. Athens, T., *Fuel and Horsepower*, 2000. Webpage retrieved 8 July 2012: www.sbmar.com/main/articles/fuel_and_horsepower.
3. BAeSEMA, Land & Sea Systems, *Guide to exhaust emission control options*, Technical report, 1999.
4. Bertram, V., *Practical ship hydrodynamics*, Butterworth-Heinemann, The United Kingdom, 2000.
5. Borkowski, T., Kasyk, L., Kowalak, P., *Assessment of ship's engine effective power fuel consumption and emission using the vessel speed*, Journal of KONES Powertrain and Transport, Vol. 18, No. 2, pages 31-39, 2011.
6. Brussen, P., Vugt, J., Vries, L. B., Stapersma, D., Knoll, H., *CO₂-emissions of various ship typws, simulated in an operational year profile*, report 2006-D-R0262, Netherlands Organization for Applied Scientific Research (TNO), 2006.
7. Carlton, J. S., *Marine propellers and propulsion*, 2nd ed., Butterworth-Heinemann, The United Kingdom, 2007.
8. Corbett, J. J., Lack, D. A., Winebrake, J. J., Harder, S., Silberman, J. A., Gold, M., *Arctic shipping emissions inventories and future scenarios*, Atmospheric Chemistry and Physics, No. 10, pages 9689-9704, 2010.
9. Edga, J., *Brake specific fuel consumption – A really useful concept*, 2008. Webpage retrieved 8 July 2012: www.autospeed.com/A_112611/cms/article.html.
10. Lindqvist, G., *A straightforward method for calculation of ice resistance of ships*, Proceedings of the 10th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC'89), Vol. II, pages 722-735, 1989.
11. MAN Diesel & Turbo, *Emission control two-stroke low-speed diesel engines*, Technical paper, 1996.
12. MAN Diesel & Turbo, *Exhaust gas emission control today and tomorrow – Application on MAN B&W two-stroke marine diesel engines*, Technical paper, 2009.
13. MAN Diesel & Turbo, *ME-GI dual fuel MAN B&W engines. A technical, operation and cost-effective solution for ships fuelled by gas*, Technical paper, 2012.

14. MAN Diesel & Turbo, *Propulsion of 46,000-50,000 DWT Handymax tanker*, Technical paper, 2011.
15. Marchenko, N., *Russian Arctic Seas – Navigational conditions and accidents*, Springer, 2012.
16. McFarland, J., *Brake Specific Fuel Consumption – Enginology*, 2011. Webpage retrieved 8 July 2012:
www.circletrack.com/enginetech/ctrp_1109_brake_specific_fuel_consumption/viewall.html.
17. Herdzik, J., *LNG as a marine fuel – Possibilities and problems*, Journal of KONES Powertrain and Transport, Vol. 18, No. 2, pages 169-176, 2011.
18. International Maritime Organization (IMO), *Annex VI: Regulations for the prevention of air pollution from ships*, The International Convention for the Prevention of Pollution from Ships (MARPOL 73/78), 1997.
19. Kaestner, J., *Effects of ice reduction on Arctic shipping and possible threats to the polar region by the increasing use of new routing – the Northeast Passage (NEP)*, Bachelor Thesis, Hochschule Wismar – University of Applied Sciences, Technology, Business and Design, Germany, 2012.
20. Wayne, W. S., Cooke, J. D., Tooke, R. W., Morley, J., *A natural evolution of the modern LNG carrier – The application of gas turbines for LNG carrier propulsion systems*, The 21st International Conference & Exhibition for the LNG, LPG & Natural Gas Industries (GASTECH 2005), Spain, 2005.
21. Wenninger, M., Tolgos, S., *LNG carrier power. Total flexibility & maintainability with 51/60DF electric propulsion*, MAN Diesel SE, Germany, 2008.
22. Wikipedia, *Brake specific fuel consumption*, webpage retrieved 8 July 2012:
http://en.wikipedia.org/wiki/Brake_specific_fuel_consumption.

Other Internet Websites:

ABB Group	www.abb.com
ACCESS Project	www.access-eu.org
Det Norske Veritas	www.dnv.com
Germanischer Lloyd	www.gl-group.com
Hamburg Ship Model Basin	www.hsva.de
International Maritime Organization	www.imo.org
Lloyd Register	www.lr.org
MAN Diesel & Turbo SE	www.mandieselturbo.com
National Snow and Ice Data Center	www.nsidc.org
Russian Maritime Register of Shipping	www.rs-class.org
The Arctic Institute	www.thearcticinstitute.org
The Arctic Logistics Information Office	www.arctic-lio.com
Wärtsilä Corporation	www.wartsila.com

APPENDIX A: REFERENCE SHIPS

A. 1. Bulk Carrier

Table A-1: Ship characteristics of bulk carrier

Name	MS KUMPULA
Type of Ship	Bulk Carrier
DWT	56 372
Ship size/Class	Panamax
Owner	ESL Shipping
Built	2012
Ice class	DNV ICE-1A
Displacement (tons)	68 416
Gross tonnage	33 958
Net tonnage	18 358
L _{oa} (m)	197.07
L _{pp} (m)	189.00
L _{wl} (m)	194.84
Breadth moulded (m)	32.26
Draft (m)	11.1
Depth moulded (m)	18.5
Speed open water (knots)	15.5
Speed ice (knots)	6.0
Propeller	1
Diameter (m)	6.50
Type	Conventional CPP
Power (kW)	11620
Builder	KaMeWa
Main engine	MAN B&W 7S50MC-C8.1-TII
Builder	MAN B&W/Huyndai
RPM	127
Main engine output (kW)	11620
Fuel grade	IFO380 CST (RMG 380)
SFOC (g/kWh)	175
Air consumption (g/kWh)	8500
Lube consumption (g/kWh)	1
Bow and stern thrusters	(2x) 800 kW
Auxiliary	3
Type	(3x) Huyndai-Himsen 5H21/23
Manufacturer	Huyndai-Himsen
RPM	900

Ouput (kW)	2880
Fuel grade	
Total engine ouput (kW)	14500

Table A-2: Emissions factors of bulk carrier

<i>Gas</i>	<i>g/kg fuel</i>	<i>g/kWh</i>	<i>%</i>
CO ₂	3206	561.05	6.467
CO	7.4	1.30	0.015
NO _x	78	13.65	0.157
SO _x	54	9.45	0.109
BC	0.35	0.06	0.001
OC	1.07	0.19	0.002
PM	5.3	0.93	0.011

A. 2. Tanker

Table A-3: Ship characteristics of tanker

	Tanker 01	Tanker 02
Name	MT MIKHAIL ULYANOV	PALVA
Type of Ship	Oil Tanker	Oil Tanker
DWT	70 000	74 999
Ship size/Class	Panamax	Panamax
Owner	Aker Arctic/Sovcomflot	Neste Oil
Built	2009	2007
Ice class	LU6 (equiv. IA Super)	DNV ICE-1A
Displacement (tons)	102 000	81400
Gross tonnage		
Net tonnage		
L _{oa} (m)	257	228.5
L _{pp} (m)	236	220
L _{wl} (m)	243.30	226.80
Breadth moulded (m)	31	32.24
Draft (m)	14	14.7
Depth moulded (m)	20.8	20.45
Speed open water (knots)	16	16
Speed ice (knots)	3	3
Propeller	2	1
Diameter (m)	6.0	6.5
Type	ABB Azipod V23	Conventional CPP
Power (kW)	17 000	13 560
Builder	ABB	Rolls-Royce

Main engine	(4x) Wärtsilä 9L38 6525kW	MAN 6S60MC-C7.1-TII
Builder	Wartsila	MAN Diesel&Turbo
RPM	600	105
Main engine output (kW)	26 100	13 560
Fuel grade		
SFOC (g/kWh)	177	174
Air consumption (g/kWh)	8500	8500
Lube consumption (g/kWh)	1	1
Bow and stern thrusters	2000 kW	
Auxiliary		3
Type		MAN 6L23/30H 910 kW
Manufacturer		MAN Diesel
RPM		900
Output (kW)		2730
Fuel grade		
Total engine output (kW)	26 100	16 290

Table A-4: Emissions factors of tanker

<i>Gas</i>	g/kg fuel	g/kWh	%
CO ₂	3206	561.05	6.467
CO	7.4	1.30	0.015
NO _x	78	13.65	0.157
SO _x	54	9.45	0.109
BC	0.35	0.06	0.001
OC	1.07	0.19	0.002
PM	5.3	0.93	0.011

A. 3. LNG Carrier

Table A-5: Ship characteristics of LNG carrier

Name	Ribera del Duero Knutsen
Type of Ship	LNG Carrier
DWT	96 740
Tank Capacity (m ³)	173 400
Ship size/Class	
Owner	Knutsen OAS Shipping
Built	2010
Ice class	DNV ICE-1A
Displacement (tons)	115 000
Gross tonnage	111 109
Net tonnage	34 573

L _{oa} (m)	290
L _{pp} (m)	279
L _{wl} (m)	287.63
Breadth moulded (m)	45.8
Draft (m)	11.95
Depth moulded (m)	26.5
Speed open water (knots)	19.5
Speed ice (knots)	7.0
Propeller	3
Diameter (m)	6.0
Type	Electric propulsion
Power (kW)	-
Builder	Mecklenburger
Main engine	(3x) Wärtsilä 12V50 DF + 9L50 DF
Builder	Wärtsilä Italia
RPM	500
Main engine output (kW)	42000
Fuel grade	Dual fuel
Bow and stern thrusters	-
Auxiliary	-
Type	-
Manufacturer	-
RPM	-
Output (kW)	-
Fuel grade	-
Total engine output (kW)	42000

Table A-6: Emissions factors of LNG carrier

Gas	g/kg fuel	g/kWh	%
CO ₂	3206	561.05	6.467
CO	7.4	1.30	0.015
NO _x	78	13.65	0.157
SO _x	54	9.45	0.109
BC	0.35	0.06	0.001
OC	1.07	0.19	0.002
PM	5.3	0.93	0.011

APPENDIX B: ROUTE IDENTIFICATION

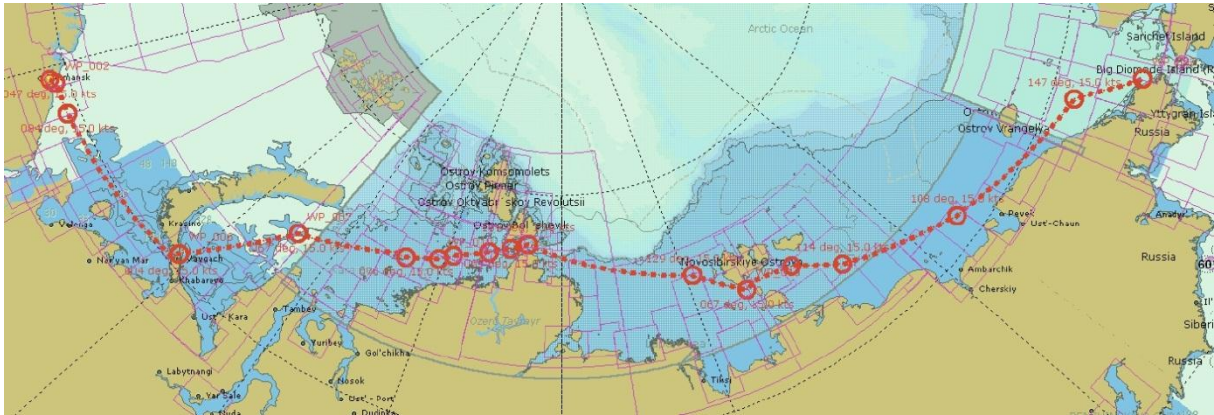


Figure B-1: Route 1: Murmansk to Bering Strait via Kara Gate and passing south of Novosiberian Island (total distance 3017.76 nm)

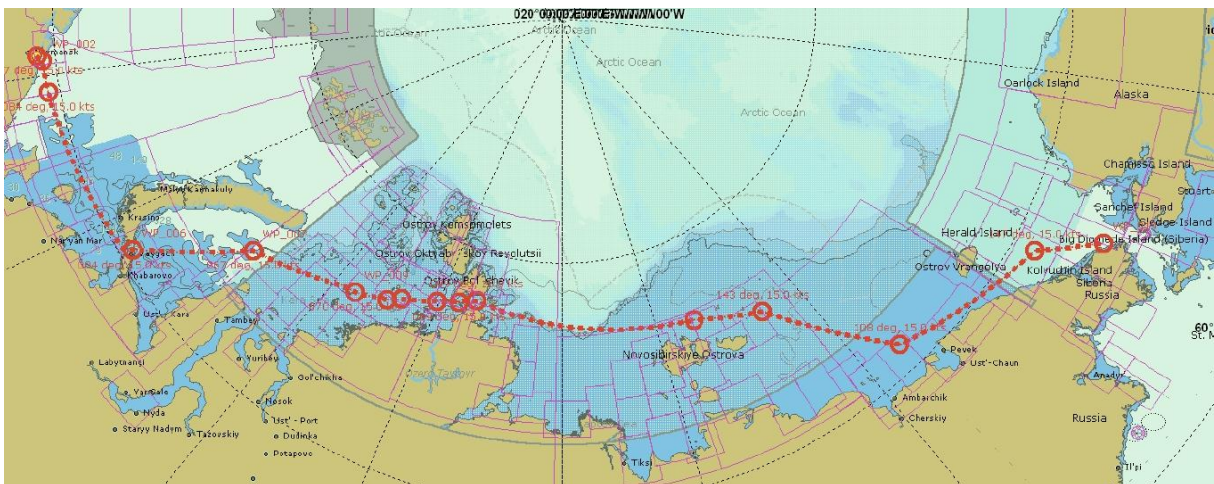


Figure B-2: Route 2: Murmansk to Bering Strait via Kara Gate and passing north of Novosiberian Island (total distance 2976.94 nm)

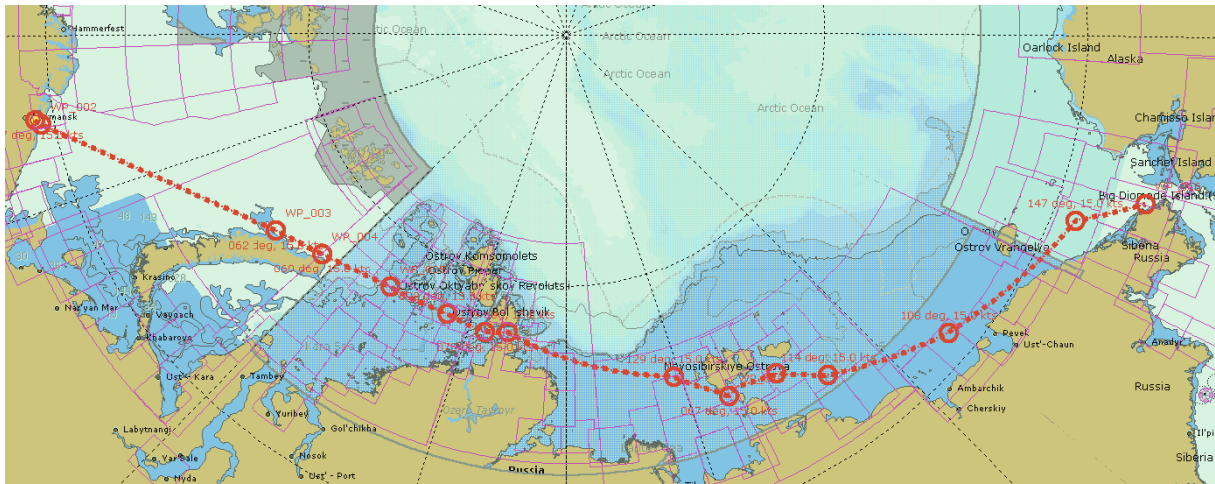


Figure B-3: Route 3: Murmansk to Bering Strait via north of Novaya Zemlya and passing south of Novosiberian Island (total distance 2842.60 nm)

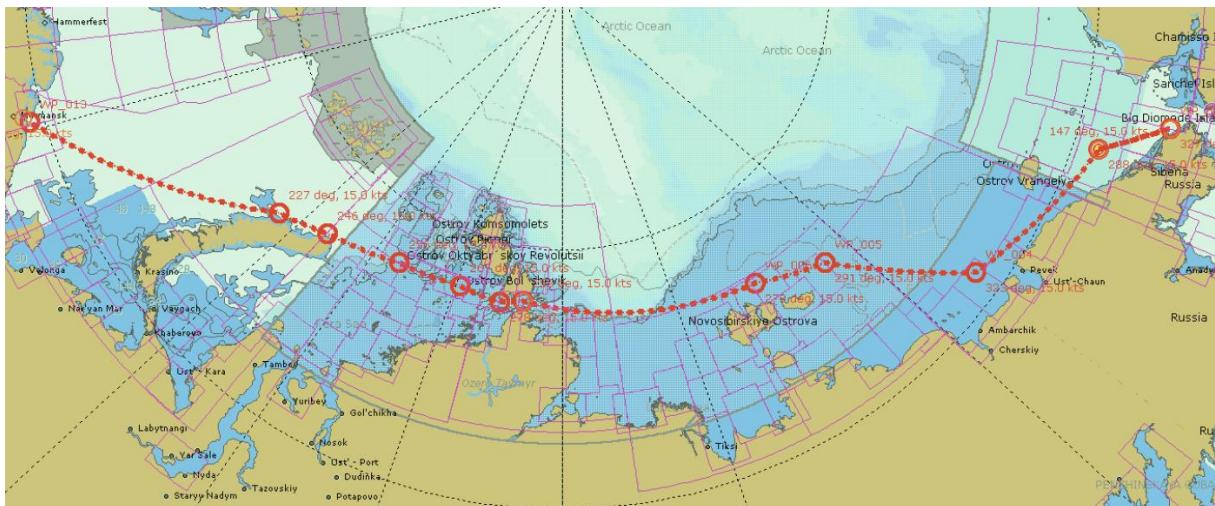


Figure B-4: Route 4: Murmansk to Bering Strait via north of Novaya Zemlya and passing north of Novosiberian Island (total distance 2801.78 nm)