Slow steaming and further emission reductions

A study in collaboration with MAN Energy Solutions

Bachelor thesis for Marine Engineering Program

AXEL JOHANSSON
MATTIAS MÅNSSON

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES

CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2024

Slow steaming and further emission reductions

A study in collaboration with MAN Energy Solutions

Bachelor thesis for Marine Engineering Program

AXEL JOHANSSON
MATTIAS MÅNSSON

Department of Mechanics and Maritime Sciences
Division for Maritime Studies
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2024

Slow steaming and further emission reductions
A study in collaboration with MAN Energy Solutions

AXEL JOHANSSON
MATTIAS MÅNSSON

Department of Mechanics and Maritime Sciences
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
A picture of a merchant vessel under operation. Picture taken from Man Energy Solutions 2023, reprinted with permission.

Department of Mechanics and Maritime Sciences
Chalmers University of Technology
Göteborg, Sweden 2024

PREFACE

This report is crafted as part of the authors undergraduate thesis in Marine Engineering at Chalmers University of Technology Sweden, and in collaboration with MAN Energy Solutions. The authors would like to extend their gratitude to everyone that has contributed to the realization of this thesis. A special appreciation to our supervisor at Chalmers University of Technology Petter Dahlander, and to our supervisor at MAN Energy Solutions Jesper Meldgaard Anthonisen. In addition, we express our appreciation to the librarians at Chalmers University of Technology for their endless support.

Axel Johansson & Mattias Månsson, 2024

Slow steaming and further emission reductions
A study in collaboration with MAN Energy Solutions

AXEL JOHANSSON
MATTIAS MÅNSSON

Department of Mechanics and Maritime Sciences
Chalmers University of Technology

SAMMANDRAG (in Swedish)

Sjöfarten står för en betydande del av de utsläpp som släpps ut i atmosfären, därför är det av stor vikt att minska både bränsleförbrukningen och utsläppen. Slow steaming och andra bränslereduktionsstrategier har potential att bidra till att minska klimatpåverkan från sjöfarten.

Rapporten använder motordriftsdata som samlats in från MAN Energy Solutions testanläggning i Köpenhamn, kombinerat med peer reviewed litteraturstudier och IMO-kommissionens riktlinjer. Driftsdata är från en MAN B&W tvåtakts 7G60ME-C10.5 med SMCR 12100 kW 82 rpm motor. Vid olika drifts områden undersöks utsläppen av NO_x, SO_x, CO och CO_2 för att fastställa vilka utsläpp som ökar och vilka som minskar vid olika belastningar för att välja driftlägen som minskar både bränsleförbrukning och utsläpp. Dessutom vilka bränslen, motormodifikationer (Tier II eller Tier III) som följer de lagar och förordningar som implementerats av IMO. För den undersökta motorn visas det att om motorn körs med 65 % belastning kommer förhållandet mellan bränsle och effekt att vara optimalt, medan om man överväger ytterligare utsläppsreduktion är belastningar kommer under 65 % alltid att ge mindre utsläpp på grund av motorns lägre bränslebehov. Begränsningarna i denna rapport är följande: rapporten undersöker endast motorns avgasutsläpp och implementerar inte system för efterbehandling av avgaser, rapporten tar inte hänsyn till externa faktorer som vind, vågor, vattenströmmar eller andra väderförhållanden; rapporten undersöker inte heller hur slow steaming påverkar motorn i form av slitage.

Nyckelord: Slow steaming, Bränsleförbrukning, Utsläpp, Utsläppsminskning

Slow steaming and further emission reductions
A study in collaboration with MAN Energy Solutions

AXEL JOHANSSON
MATTIAS MÅNSSON

Department of Mechanics and Maritime Sciences
Chalmers University of Technology

ABSTRACT

The shipping industry is responsible for a significant amount of the emission emitted into the atmosphere, therefore there is of high importance to reduce both fuel consumption and the emissions. Slow steaming and other fuel reduction strategies has the potential to help reduce the climate impact from shipping.

The report uses engine operational data collected from MAN Energy Solutions test facility in Copenhagen, combined with peer reviewed literature studies and IMO commission guidelines. The operational data is from a MAN B&W Two-stroke 7G60ME-C10.5 with SMCR 12100 kW 82 rpm engine. At different operating ranges, emissions of NO_x, SO_x, CO, and CO_2 are examined to determine which emissions increase and which decrease at different loads to select operating modes to reduce both fuel consumption and emissions. In addition, which fuels, engine tuning (Tier II or Tier III) that complies with the laws and regulations implemented by IMO. For the examined engine it is shown that operating the engine at 65% load, the fuel to power ratio will be optimal, while considering further emission reduction loads below 65% will always produce less emission due to lower engine fuel demand. The limitations of this report are as follows: the report only examines the engine's exhaust emissions and does not implement exhaust gas aftertreatment systems, the report does not consider external factors such as wind, waves, water currents, or other weather conditions; the report also does not examine how slow steaming affects the engine in terms of wear and tear.

Keywords: Slow steaming, Fuel consumption, Emissions, Emission reduction

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Appendix 1

ACRONYMS AND TERMINOLOGY

IMO	International Maritime Organization
MARPOL	The international Convention for the Prevention of Pollution from Ships
SOLAS	International Convention for the Safety of Life at Sea
CO_2	Carbon dioxide
CO	Carbon monoxide
NO_x	Nitrogen oxides
NO	Nitrogen oxide
NO_2	Nitrogen dioxide
N_2O	Nitrous oxide
SO_x	Sulphur oxides
GHG	Greenhouse gas
RPM	Revolutions Per Minute
MGO	Marine Gas Oil
VLSFO	Very Low Sulphur Fuel Oil
ULSFO	Ultra Low Sulphur Fuel Oil
LNG	Liquified Natural Gas
LPG	Liquid Petroleum Gas
SG	Shaft Generator
TG	Turbo Generator
MEP	Mean Effective Pressure
EEXI	Energy Efficiency Existing Ship Index
SECA	Sulphur Emissions Control Area
ECA	Emissions Control Area
Trp	Tropical
Spe	Specified
ISO	International Organization for Standards
SEEMP	Ship Energy Efficiency Management Plan
CII	Carbon Intensity Indicator
CIIR	Carbon Intensity Indicator Reference Value
ADT	Annual Distance Travelled
AFC	Annual Fuel Consumption
SCR	Selective Catalytic Reduction
EGR	Exhaust Gas Recirculation

1. INTRODUCTION

The shipping industry is going through a transition phase aimed towards reduced environmental impact and sustainability. According to DNV (n.d.) the amount of released greenhouse gases (GHG) needs to be reduced and in July 2023, the International Maritime Organization (IMO) adopted a strategy to reduce greenhouse gas emissions from ships. The strategy focuses on reduction of GHG which states that the ambition is to reach these emission goal by 2030. The primary goal is to reduce Carbon dioxide (CO_2), and by 2030 the IMO strives towards an average reduction of 40% on an international scale of CO_2 emissions, and by 2040 a 70% reduction. In addition, it states incentives of increased focus on near-zero or zero GHG emissions technologies, fuels, and other strategies that would represent a minimum of 5% of the international shipping energy use by 2030.

GHGs are gases that stay in the atmosphere, both re-emitting and absorbing heat leading to an increase in atmospheric temperatures. Emissions such as CO_2 and CO_2 equivalents does have a negative impact on the environment. CO_2 is the most common GHG as a result from human activities, but there are other emissions that have a much higher global warming potential. Methane (CH_4) is a GHG which can be formed when carbon combines with hydrogen, CH_4 has a CO_2 equivalent of 29.8 kg of CO_2 for every kg of CH_4 emitted. CO_2 equivalents describes GHG emissions in common and simplified unit of global warming potential in CO_2 (Matthew Brander, 2023). Furthermore, Carbon monoxide (CO) is a noncolor and odorless gas that is harmful to humans when inhaled in higher quantities, CO is emitted when burning fossil fuels (EPA, n.d.). To add, Sulphur dioxides (SO_x) is an emission produced when using and burning fuels containing sulphur (MAN Energy Solutions, 2023). SO_x emissions may have a detrimental impact on the environment and human health. Studies have shown that people with asthma can worsen their condition and other negative health impacts such as increased chance getting a heart attack (Tokuslu et al., 2020). In addition, Nitrogen oxides (NO_x) includes both Nitrogen dioxide (NO_2) and Nitrogen oxide (NO). NO_x can be formed in different ways as a result of different processes such as during combustion in a diesel cycle. NO_x (thermal NO_x) is formed during this process due to temperature, primary peak temperatures, which determines the level of NO_x formed (MAN Energy Solutions, 2023). The release of NO_x damages the sea because of its negative ecological impact. NO_x can cause eutrophication, the effect of eutrophication is oxygen depletion of our seafloors which is restricting and harmful to the animals living in those sea areas (Gren et al., 2021).

In several publications to the IMO and other forms of documentation, papers, and studies show variation in terminology associated with slow steaming such as speed regulation and speed reduction, which mean the same thing (Psaraftis, 2019). With the implementation of slow steaming, it is indicated that slow steaming will give positive effects on fuel consumption and emissions. At lower speeds drag is reduced consequently leading to less fuel consumed. Also, multiple researchers have examined greenhouse gas emission reduction potential by implementing slow steaming (Farkas et al., 2023).

Slow steaming emphasizes on reducing the speed of the vessel and is simply applied to achieve reduced fuel consumption and emissions. The slow steaming method is achieved by reducing the speed by 15% or potentially more form its normal operational point, the speed reduction is based on the vessels normal operating design speed (Zincir, 2023). Slow steaming effectiveness is dependent on several factors, not only the actual speed of the vessel, but also outside factors such as travel area and size of the vessel. The speed reduction strategy of slow steaming is implemented from the starting point of normal operational speed of the vessel (Peli´c et al., 2023).

The effects of slow steaming are beneficial from an environmental perspective but do have its drawbacks on engine condition. Utilizing the slow steaming strategy for extended periods of time will lead to negative effects on several systems. The long-term effects are built up of carbon on the piston rings resulting in reduced sealing between cylinder rings and cylinder wall. In addition, the turbo charger’s capacity will go down and the injectors will suffer as well, all depending on the prolonged exposure of slow steaming the engine has endured. With the known effects on the engine from slow steaming it is crucial to plan maintenance accordingly and perform the maintenance properly. The sole purpose of slow steaming is to reduce emission and fuel consumption, but with the negative effects of e.g., carbon build up on the piston rings and reduced turbocharger efficiency these parameters will affect the engine negatively (Dere et al., 2022).

Emission depends on what type of fuel is used and other factors such as exhaust gas temperature and surrounding conditions. Fuel class and purity is a determining factor of how clean the exhaust gases will be, consequently the amount of greenhouse gas emissions that will be emitted. For example, looking at a Tier II tuned engine in comparison to Tier III tuned engine it is a noticeable difference in NO_x released (MAN Energy Solutions, 2024a).

1.1 Background

This study has been authored in partnership with MAN Energy Solutions and revolved around load and speed of the main engine when slow steaming and its emissions. Throughout the study, the engine operational data provided by MAN Energy Solutions is the primary focus area and contributing factor to the study’s constructive platform and branching point. The rationale behind the choice of focus is the current global focus on the shipping industry dilemma regarding fuel consumption and emissions.

Slow steaming and emissions reduction has been subjects of focus for a considerable amount of case studies, but relatively few with in depth examination and what the pros and cons may be with the strategy. The primary goal of this speed reduction strategy is to reduce emission, consequently reducing the amount of fuel that is being burned (Supervisor, MAN Energy Solutions, personal communication, 2024). According to Amin Mohammed (2023) the concept of slow steaming is an engine manipulation of speed and load to reach fuel consumption and environmental goals. The biggest challenge is to fulfill the obligated constraints of emissions and cohesively meet location and time schedules.

Historically, speed reduction has been viewed as the easiest and most attainable strategy to produce lower emission levels. The focus on slowing down vessel speed has mainly been centered around reducing CO_2 emissions, which has been incentivized through environmental and political standpoints (Berthelsen & Nielsen, 2021). The recommendations of speed reduction “slow steaming” is a policy established by the International Maritime Organization to limit CO_2. The policy assumes that emissions from the main engine are proportional to the engine speed and therefore assumed to be less at lower speeds. However, the speed to emissions assumption may not be true and therefore not supported by all members of the IMO (IMO, 2020) (Berthelsen & Nielsen, 2021).

During speed reduction the speed of the piston is consequently lower, when the piston speed moves at 6 m/s or less there may be difficulties with cylinder liner lubrication. During these reduced engine speeds piston ring and cylinder wear can increase. However, prediction models are used to predict the maintenance intervals needed to maintain good condition of cylinder and piston rings (Stawowy et al., 2023). In addition, according to Garcia et al. (2014) low engine load for a longer duration may increase the chance of low temperature corrosion and carbonization. To add, engines that are not optimized for slow steaming scavenging air pressure will drop, consequently reducing combustion efficiency. This reduction can cause increased carbon to build up on piston rings grooves, ring lands, and on the fuel injection nozzle which down the line will increase thermal load on the entire piston arrangement.

MAN Energy Solutions is an engine manufacturing company determined to develop and be the frontrunner of 2-stroke engine manufacturing. Environmental and engine sustainability discussions and investigations regarding slow steaming is of their interests. To add, today’s fleet of vessels often operate their engines significantly below the intended operation range to save fuel which may cause engine implications further down line of the engine lifespan. The practice of slow steaming is particularly seen among bulk carriers and tankers while the container segment is still operating at high speeds (Supervisor, MAN Energy Solutions, personal communication, 2024).

1.2 Aim of the study

The aim of the study is to investigate engine operational data for load and speed profiles during slow steaming and evaluate its potential of reducing fuel consumption and emissions. The engine load and speeds for optimal slow steaming are deficient since it varies depending on the engine. This study will shed light on the optimal slow steaming zones for both fuel consumption and emission reductions for a specific bulk carrier with the MAN B&W two-stroke engine 7G60ME-C10.5 with SMCR 12100 kW 82 rpm. The emission aspect of slow steaming will be focused on emission reduction and increase regarding fuel type and consumption. Also, conforming with conventions and regulations regarding load, speed, fuel, and emission which are bound to comply with in the shipping industry. Furthermore, the study will explore other alternative strategies to slow steaming that could potentially reduce fuel consumption and emissions.

The operational data provided of the 7G60ME-C10.5 12100 kW engine will help supply an extensive explanation of what load and speed zones will provide the most effective fuel consumption and emissions. The implementation of slow steaming seems to be a satisfactory solution for fuel consumption reduction, but alternative strategies may be more effective. To gain a wider perspective of the concept of slow steaming, the data will be thoroughly analyzed together with report reviewing. Fundamentally, giving an accurate aim-oriented report with facts supporting the report outcome.

1.3 Research questions

1.3.1 What emissions can be reduced at slow steaming, and what potential emissions increase (CO_2, NO_x, CO, and SO_x)?

    1.3.1.1 Marine Gas Oil (MGO)
    1.3.1.2 Very Low Sulphur Fuel Oil (VLSFO)
    1.3.1.3 Heavy Fuel Oil (HFO)

1.3.2. What load and speed profile are optimal, connected to fuel consumption?

1.4 Delimitations

The report confines its investigation to organizations and companies within Sweden and Denmark. While the literature and theories are collected with no restrictions to different countries, its relevant to note that many of the shipping companies where data is collected operate outside the borders of Denmark and Sweden. However, the report delimitates its scope to analyzing engine operational data provided by MAN Energy Solutions and excludes load and speed data from other sources.

The report will not provide an overly comprehensive explanation of the concept on slow steaming since this terminology is commonly used in the shipping industry. The operational data does not take aftertreatment systems into account or outside factors such as wind, wave, current, hull resistance, or depth. In addition, engine wear and tear correlated to slow steaming will not be of focus in the report. Also, since the study is performed in collaboration with MAN Energy Solutions the questioning and formulations will be within the confines of their research demands.

2. THEORY

To precisely analyze and model the slow steaming fuel consumption and emissions data, it is essential to gather deeper understanding of the subjects to effectively navigate the complex information. The graphs and tables give an overview of all data to enhance the readability of the report, presented with simplicity and accuracy.

Slow steaming is a strategy intended to reduce the speed of vessels, which happens to land outside the engine optimal operational running zone. The approach of slow steaming roots itself from the linear correlation between fuel consumption and emissions. On the other hand, the nonlinear interaction between fuel consumption and speed (Berthelsen & Nielsen, 2021). Implementation of slow steaming may be an arbitrary strategy to fulfill International Maritime Organization requirements, such as Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII). It is stated that slow steaming has beneficial effects not only on emissions, but also economic benefits because of the reduction in engine fuel demand (Vakili et al., 2023).

Looking at the total fuel consumption and CO_2 emissions over a fixed duration, there is shown to be significant reductions when applying engine operational power reduction. When comparing full load to reducing the Main engine operational power to 60 % it proves the benefits of slow steaming/speed reduction, but with a result dependent on implementation of Shaft Generator (SG) and Turbo Generator (TG) are operating. Without SG and TG the total fuel and CO_2 reach a total reduction of 23%, while implemented the total reduction reach 33% (Glujić et al., 2022).

Many articles move towards the same outcome when looking at slow steaming and its benefits on fuel consumption and emissions reduction potential. When changing from a speed of 23 knots and reducing the speed to 12 knots a substantial fuel and CO_2 improvement can be seen. To add, the study was conducted for one tanker vessel, two bulk carriers, and three container ships, showing that at half the speed the CO_2 produced is reduced by four times the amount produced at 23 knots (Pelić et al., 2023).

According to Peli´c et al. (2023), depending on the propulsion system the Break Specific Fuel Consumption (BSFC) may vary. A two-stroke low-speed engine compared to a four-stroke medium-speed engine proves that a low-speed two-stroke has lower fuel consumption than the four-stroke medium-speed engine. In addition, the engine data that is specifically being studied in this report are based on a low-speed two-stroke engine provided by (MAN Energy Solutions, 2024b).

2.1 Two-stroke and Four-stroke Engines

The diesel engine can be categorized into either two-stroke or four-stroke and both these principles of propulsion are utilized in ships. The diesel engine can use direct fuel injection where the fuel is ignited by the high pressure and temperature inside the combustion chamber. The amount of power the engine can produce depends on what torque and rpm it can produce. A marine diesel engine either operates at low speed or medium speed, the low speed refers to two stroke engines while medium speed is for four-stroke. Large four-stroke diesel engine usually runs at medium speed and has greater power density than a two-stroke engine which runs at low speed. The power cycle varies for these two engines, a four-stroke has one power-stroke over its four-stroke. The two-stroke engine, however, performs a power stroke once every two strokes, the fewer the strokes the lower the frictional resistance (MAN Energy Solutions, 2023).

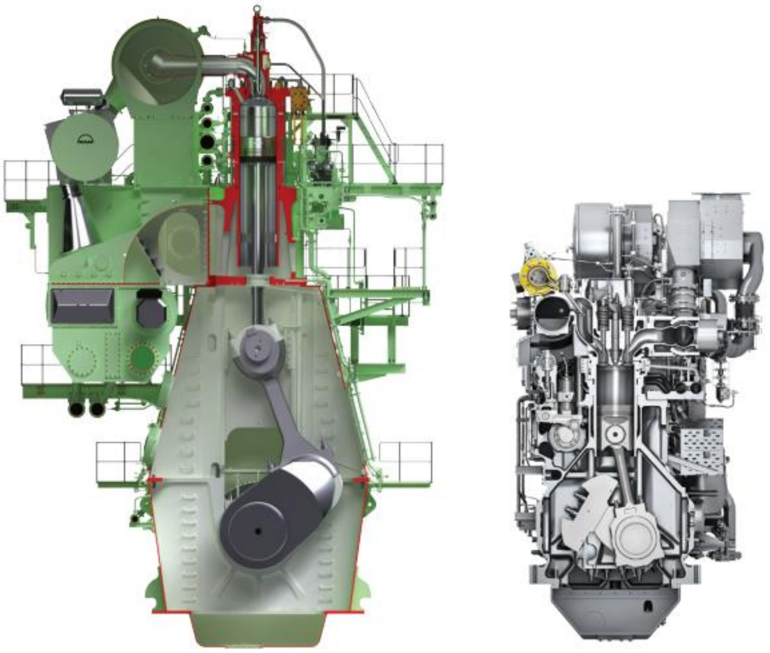


Figure 1 Two-stroke engine & Four-stroke engine (MAN Energy Solutions. 2023) Reprinted with permission

The two-stroke crosshead engine has a larger bore and longer stroke than the four-stroke engine as illustrated in Figure 1. With the longer stroke the engine generates lower speeds and higher efficiency, this enables the engine to be coupled directly to the propeller shaft which reduces complexity and no need for a reduction gear (MAN Energy Solutions, 2023).

2.2 Diesel and Otto cycles

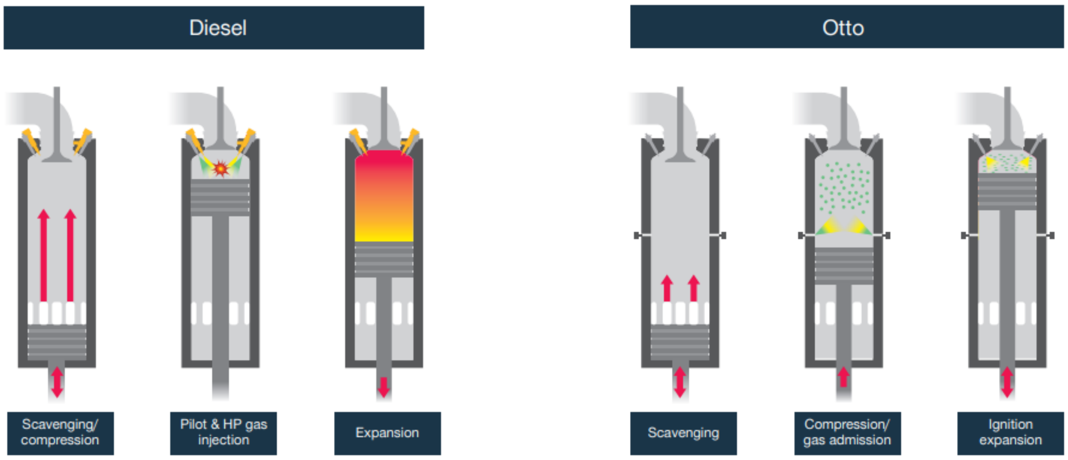


Figure 2 Diesel & Otto cycles for dual fuel uniflow scavenging two-stroke engines (MAN Energy Solutions. 2023) Reprinted with permission

The diesel cycle uses direct fuel injection where the fuel is ignited by the elevated temperature during compression. The diesel engine is also titled a combustion ignition engine and while the Otto engine is titled spark ignition engine. Looking at the Otto cycle in marine applications the fuel and air is premixed inside or outside the engine cylinders. As shown in Figure 2 the air and fuel mixture are ignited by spark plug or pilot fuel (MAN Energy Solutions, 2023).

The combustion ignition two-stroke engine has its benefits compared to the Otto cycled engine. For instance, a diesel engine has extremely low to zero methane slip which applies for Liquified Natural Gas (LNG) powered engines, which is due to the principle of direct fuel injection and diffusion forming burn flame. The methane slip on an Otto cycle engine is higher since the air and fuel mixture rarely reaches total combustion. Furthermore, looking at engine knock, diesel engines are not limited by high compression ratio while an Otto cycled engine is. Since the compression ratio must be lower for an Otto engine, it will not have as high efficiency as a diesel engine (MAN Energy Solutions, 2023).

2.3 Regulations

The IMO is an international organization opting for the sustainability of the maritime trade by implementing regulations to minimize the shipping industry's impact on the environment among other topics. IMO regulations prohibit vessels from releasing emissions such as NO_x and SO_x to more than the regulations allowed limits. These limitations have been in force over many years, but to date Emissions control areas (ECA) and Sulphur emission control areas (SECA) has been rigidly tightened to minimize the release of these emissions even more (IMO, 2023).

The IMO has set requirements on SO_x and other emissions. The regulations are applicable to all fuels, other equipment and machinery that potentially release emissions such as SO_x and particular matter. Fuels that comply are Very low sulphur fuel oil (VLSFO), Ultra-low sulphur fuel oil (ULSFO), VLSFO have a maximum content of 0.5% and ULSFO have a maximum of 0.1% same as Marine gas oil (MGO) (IMO, 2019) (MAN Energy Solutions, 2023). If the fuel has higher amounts of sulphur than the allowed limit of 0.5% or 0.1% depending on geographical placement alternative strategies can be implemented. One common strategy is scrubbers which will lower the sulphur oxides released with the exhaust gases. On the other side of the spectrum, there are fuels containing insignificant amounts of sulphur. LNG is a commonly used fuel within that category, but Liquid Petroleum Gas (LPG) and methanol are currently potential alternatives and in the future ammonia should also be an opportunity once it is fully developed (MAN Energy Solutions, 2023).

The IMO is responsible for publishing the Marpol Conventions, which sets legal limits on emissions. Marpol Annex VI regulation 13 regulates the emission of NO_x, this regulation applies to vessels with a marine diesel engine of more than 130 kW. This regulation does not apply to marine diesel engines used only for emergencies or to power emergency equipment on the vessel. If a major modification is made to the engine that is not certified according to the standards of Tier I, II or III, on or after the 1st of January 2000 the engine must be replaced, or additional systems must be installed to comply with the regulations. The Tier standards do not apply if the engine is installed or constructed between 1st of January 1990 to 1st of January 2000 and has a power output of at least 5000 kW. Engines to date are regulated through the standards of Marpol Annex VI regulation 13 paragraph 7.4 (IMO, n.d.-a).

Marpol Annex VI Regulation 14 regulates the sulphur content allowed in the fuel oil used for the vessel operating outside the ECA. The content of sulphur in the fuel oil is not allowed to exceed 0.5% for regions outside ECA. The ECA was put in place to regulate the emission of SO_x where it can be harmful to these areas which are close to land. The SO_x contents in the fuel are not allowed to exceed 0.1% within the ECA. When entering the ECA the use of fuel oil that meets the regulation must be documented, and if a fuel switchover is performed it must be documented in the oil record book. Every ship must have a fuel oil sapling point where the fuel oil sample can be taken and tested for compliance with the regulation (IMO, n.d.-b).

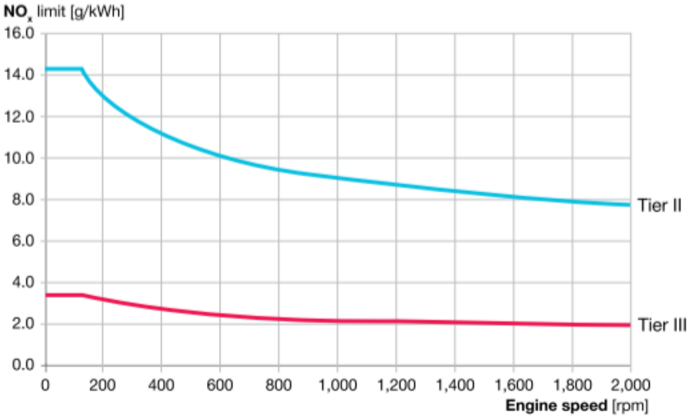


Figure 3 Limit on NO_x *emissions depending on engine speed (MAN Energy Solution. 2023) Reprinted with permission.*

According to Marpol Annex VI Regulation 13, the regulation for controlling emission levels of NO_x in marine engines is classified into two Tiers, Tier II, and Tier III. For Tier II, engines installed after January 1, 2011, must comply with the NO_x emission limit, which is calculated based on the engine's rpm. If the rpm is below 130, the emission should not exceed 14.4 g/kWh. For engines running between 130 to 2000 rpm, the NO_x emission limit is $44 * n^{-0.2}$ g/kWh, where n = rpm. For instance, if the engine runs at 1500 rpm, then the NO_x emission should not exceed $44 * 1500^{-0.2}$ = 10.2 g/kWh. For engines running above 2000 rpm, the legal limit is 7.7 g/kWh. In the same regulation, the legal limit for Tier III can be found, but Tier III has lower limits for NO_x emissions than Tier II, for a Tier III engine running mode with an rpm under 130 the limit is 3.4 g/kWh. If the engine is running between 130 and 2000 rpm the emission limit is calculated $9 * n^{-0.2}$ g/kWh and 2.0 g/kWh if the engine is running at a rpm exceeding 2000. The limits for Tier III only apply to ship that operates in the North American Emission Control Area or the United States Caribbean Sea Emission Control Area and built after 1st of January 2016, and if the ship is operating in the Baltic Sea Emission Control Area or the North Sea Emission Control Area and constructed after 1st of January 2021 (IMO, n.d.-a).

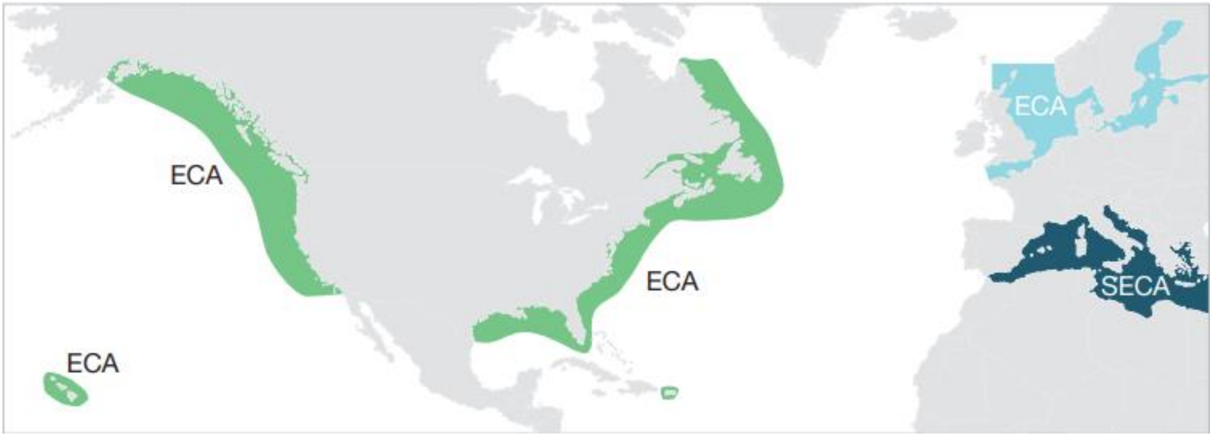


Figure 4 Emission Control Areas (MAN Energy Solution. 2023) Reprinted with permission.

For regulation regarding emissions of SO_x, regulation 14 was put into force. Regulation 14 states the allowed sulphur content in the fuel oil used by any vessel. In areas outside the ECA the maximum limit of sulphur content in the fuel oil 0.5% and within the ECA the limit is 0.1% of sulphur in the fuel oil (IMO, n.d.-b).

There are several ECAs which can be seen in Figure 4. These include the North American Emission Control Area, the United States Caribbean Sea Emission Control Area, the Baltic Sea Emission Control Area, and the North Sea Emission Control Area. In these areas, SO_x and NO_x emissions are limited. Meanwhile, SECA are areas where only SO_x emissions are regulated. In ECAs, NO_x emissions are regulated by running mode Tier III, while SO_x emissions are regulated by the sulphur content of the fuel oil, as shown in the figure below (MAN Energy Solutions, 2023).

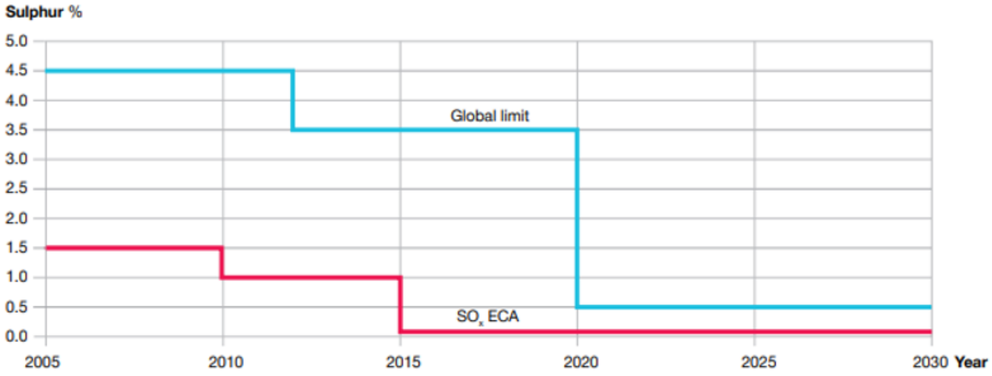


Figure 5 Sulphur limits (MAN Energy Solution, 2023) Reprinted with permission.

As of today, the emission of CH_4 or Nitrous oxide (N_2O) in the marine sector is not regulated. (Kent Salo, personal communication 2024). However, the EU Commission regulates the energy sector for CH_4 emissions and ensures that the energy sector adheres to the rule that the lifecycle CH_4 emission must not exceed 3% of the delivered volume (European Commission, n.d.).

Different greenhouse gases have varying lifetimes in the atmosphere. CO_2 is used as the baseline to measure the impact of other gases. For instance, one kilogram of CH_4 causes 29.8 times more warming than one kilogram of CO_2 over a 100-year period. Similarly, one kilogram of N_2O

causes 273 times more warming than one kilogram of CO_2 over a 100-year period (Matthew Brander, 2023).

After the end of calendar year 2023, Marpol Annex VI regulation 28 - (operational carbon intensity) was implemented by IMO in Marpol to regulate and measure yearly carbon emissions. This is measured by calculating the annual CII of each operating ship with a gross tonnage of 5000 or more and falls into the category according to regulation 2.2.5, 2.2.7, 2.2.9, 2.2.11, 2.2.14 to 2.2.16, 2.2.22, and 2.2.26 to 2.2.29 in Marpol. The resulting rating indicates how carbon-efficient the ship is over the course of a year and whether it meets the required standards (IMO, n.d.-c).

CII is a measurement of a ship's energy efficiency, and it measures the emission of CO_2 per cargo capacity and natural mile. According to Marpol Annex VI regulation 28, at the end of 2023, every ship with a gross tonnage of 5000 or more, which Annex VI regulates, shall calculate the CII over a calendar year. This calculation must be done within three months after the 1st of January every year and reported to the authorities (IMO, n.d.-c). This is calculated as followed.

IMO calculation,

$$CII = \left(1 - \frac{Z}{100}\right) * CIIR$$

DNV calculation,

$$CII = \frac{AFC * CO2\,factor}{ADT * Capacity} * Correction\,factor$$

Z represents the annual reduction factor that guarantees consistent enhancement of a ship's operational carbon intensity within a specific rating level and Carbon Intensity Indicator Reference Value (CIIR) is the reference value. The actual CII shall be compared to the required CII and a rating of A to E will be assigned for the operational carbon intensity. This is a rating of the performance level and C is the required annual operational CII, if a ship gets a rating of D three years in a row or the rating of E they are obligated to undergo corrective actions according to the revised SEEMP (Ship Energy Efficiency Management Plan). (IMO, n.d.-c).

On November 14th, 2020, the European Commission announced a new strategy by the name EU Methane Strategy which focuses on reducing CH_4 emissions. This strategy aims to reach climate neutrality by 2025 by gradually reducing emissions of CH_4. The first milestone is to reduce methane emissions by 29% compared to the levels in 2005 (European Commission, 2020).

2.4 Alternative strategies to slow steaming

The heavy focus on GHG emissions and its connection to fuel consumption brings slow steaming and other potential alternatives into debate. Slow steaming is proven to be overestimated in its potential to reduce fuel consumption when based on speed-power relationship standpoint. The speed-power relationship depends on what type of vessel and draught specifications. Slow steaming is the optimal strategy for fuel consumption reduction during ballast voyages, while speed optimization is better during laden voyages. To add, the choice of strategy is dependent on ship size and category, such as tanker ship, container ship or bulk carrier. The vessels vary in size, operation speed, hull shape and other factors that affect the decision for optimal fuel reduction and emission reduction strategy. The ships studied in this report were tankers which are similar to bulk carriers in shape and operational range. The results mirror strategies applicable for both tankers and bulk carriers (Berthelsen & Nielsen, 2021).

Slow steaming is effective at reducing fuel consumption and emissions, but other costs and time-based profits may suffer. Speed optimization is an alternative strategy that takes outside factors into account which will affect the fuel economy of the vessel. Speed optimization relies on weather forecasting that gives wind, wave, and other indications to added resistance, consequently increasing the fuel consumption. Broadly speaking, under conditions where it is suggested to utilize higher speeds for better fuel efficiency such a speed increase should be executed. On the other hand, according to speed optimization strategy the vessel should lower its speed when those indicators are shown to reduce fuel consumption and emissions (Speed et al., 2023).

Speed optimization is found to be effective for fuel consumption reduction purposes with no need for route changes, but with further benefits when adjusting depending on conditions. In addition, the speed optimization strategy is found to be even more effective in harsh conditions even though there is increased resistance. It is observed that speed optimizing in calm conditions for resistance reduction and avoiding heavy weather will improve the overall fuel consumption for the vessel further (Taskar et al., 2023).

Slow steaming is one engine operational strategy that has been implemented in the shipping industry for a while with intentions to reduce emissions and fuel consumption. The strategy is highly dependent on the route of sailing and location. (Farkas et al., 2023) Trim optimization for ships is one strategy to reduce the total amount of emissions produced by the main engine. This strategy does not require any modifications to the engine or to the ship structure. The method uses different trim conditions to evaluate the optimal trim for reducing the engine load, consequently reducing fuel consumption which correlates to reduced emissions. The trim optimization method implies that adjusting the trim between positive 1.5 meters and negative 1.5 meters depending on speed and design of the vessel gives the highest energy efficiency. To add, trim optimization has been implemented on container ships and bulk carriers, the study suggests positive trim for optimized fuel consumption efficiency (Elkafas, 2022).

3. METHODS

The report will utilize two methodologies: Data collection and literature search. The methods will help with establishing an accurate and credible platform for the report.

3.1 Question structure

This study revolves around two different research questions with a primary focus on the top question and funnels down to the question positioned at the base. **1.3.1** *What load and speed profile are optimal, connected to fuel consumption?* This research question serves as the basis and seed for fundamental knowledge regarding the correlation between load and speed in relationship to fuel consumption. Question **1.3.2** *What emissions can be reduced at slow steaming, and what potential emissions increase* (CO_2, NO_x, *CO, and* SO_x). This research question continues to build on the previous question, but with a focus on emissions. Since emissions are highly cohesive with fuel consumption.

3.2 Literature and Data

The Chalmers library digital repository, also known as the Chalmers database, was the search tool used to collect information from previous written academic peer reviewed journals cohesive with the thesis *Slow steaming and further emission reductions.* These reports were thoroughly read and examined to find the most appropriate and relevant source for valuable information to be used in the report. The data and literature study is focused on evaluating former research with a combination of current engine operational data provided by MAN Energy Solutions to establish a well-rounded and credible report.

The central search engine used was the library search function at Chalmers Technical University digital database. The database provides unlimited diversity in information gathering. It provides studies, books, conference materials and academic journals both peer reviewed, and non-peer reviewed. The Chalmers search engine has been limited to focus on peer-reviewed academic journals for this report. The following variations of search combinations were used to find the sources:

Slow Steaming, Low-load conditions, speed optimization, speed reduction, ship emissions at slow steaming, benefits of slow steaming, slow steaming fuel consumption, slow steaming emissions and low load emissions.

The primary data and research material was provided by MAN Energy Solutions relevant to the thesis of the report. Real running conditions with factual data collected from anonymous engine users were provided. The data provided by MAN Energy Solutions was produced through emissions measurements and by calculation based of the fuel consumption at specific loads with no implementation or activation of aftertreatment systems. The emission calculation methods are classified and not available to the public. To be noted, the engine load to fuel consumption is provided in connection to the power produced, meaning that the data given in g/kWh gives insight into the fuel consumed in relationship to power produced at a specific load.

The source selection was established through evaluation of headlines, summaries, abstract and conclusion to determine which information had potential relevance or usefulness for the report. All data and academic journals underwent a substantial overview determining its credibility and informative significance to the report.

Furthermore, Tier II and Tier III are different engine tuning strategies applied by engine manufactures to reduce NO_x emissions meet the requirements stated in Marpol Annex VI regulation 13, with higher Tier, higher NO_x reduction standard is enforced. Since the NO_x data provided in kg/h the equation below is used to transfer it into g/kWh which is the unit used in Marpol Annex VI regulation 13.

$$\frac{Emissions\ Rate\ (\frac{kg}{h}) * 1000}{Energy\ Output\ (kW)} = Emission\ (\frac{g}{kWh})$$

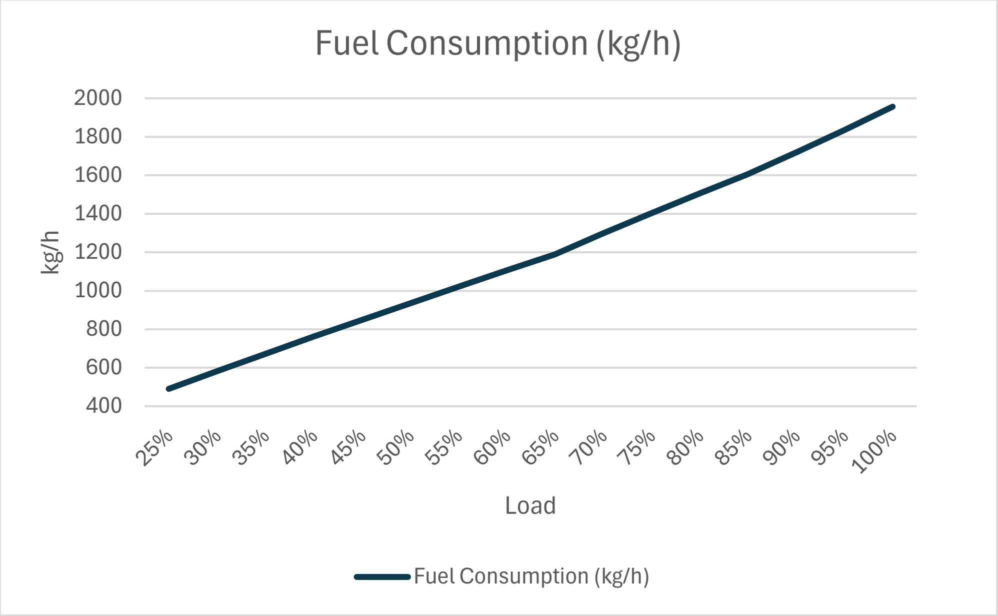


Figure 6 Fuel Consumption to load – ISO conditions Tier II data from (MAN Energy Solutions, 2024a)

The fuel consumption data is provided in g/kWh while all emissions are presented in kg/h, the fuel consumption in g/kWh refers to fuel consumption to power output per hour. This translates to lower loads will give lower fuel consumption than at higher loads, it is because the power output of the engine is higher at higher load therefor requiring more fuel. The equation used simplifies how much emissions that are produced at different loads, consequently giving easier comparability to emission which are presented in kg/h. See Figure 6, Figure 26, and equation 1 below for clarification.

Equation 1:

$$\frac{Fuel\ consumption * Load * Engine\ power}{1000} = Fuel\ consumption\ in\ kg/h$$

Fuel consumption is given in g/kWh, load in percentage and engine power in 12100 kW.

The total fuel consumption and emissions over a set theoretical distance were calculated to exhibit the pros and cons of speed reduction (slow steaming) in terms of load to speed ratio. The units used are g/kWh, hours, kW, kg/h for the following equations, Equation 2: Fuel consumption in grams

$$SFOC * Time * Power = Total\ fuel\ oil\ consumption\ (grams)$$

Specific fuel oil consumption (SFOC) is given in g/kWh, Time in hours and Power in kW.

Equation 3: Fuel consumption grams to tons conversion,

$$\frac{Total\ fuel\ oil\ consumption\ (grams)}{10^6} = Total\ fuel\ consumption\ (tons)$$

Total fuel oil consumption (grams) is given in g/kWh.

Equation 4: Time in hours,

$$\frac{Distance\ travelled}{Speed} = Time$$

Distance travelled is given in nautical miles and speed in knots.

Equation 5: Speed conversion knots to km/h,

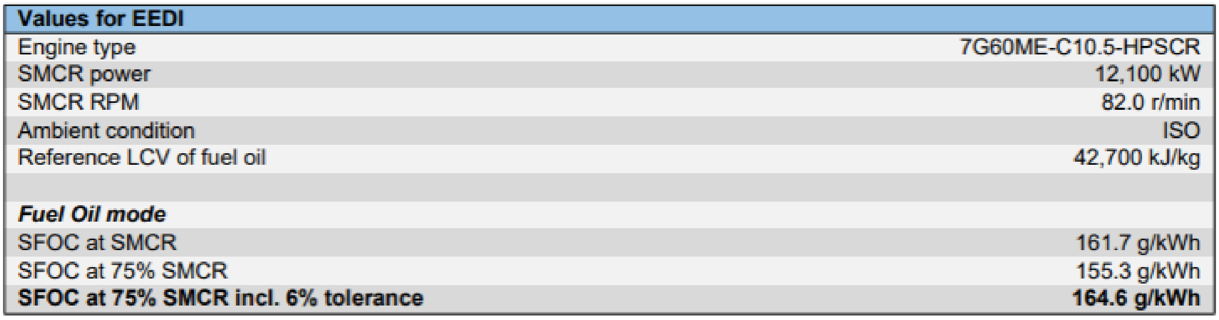
$$Knots * 1.852 = Kilometers\ per\ hour$$

Equation 6: Total emission per distance travelled,

$$Time * Emission = Total\ emissions\ per\ distance\ travelled$$

Time is given in hours and emissions in kg/h.

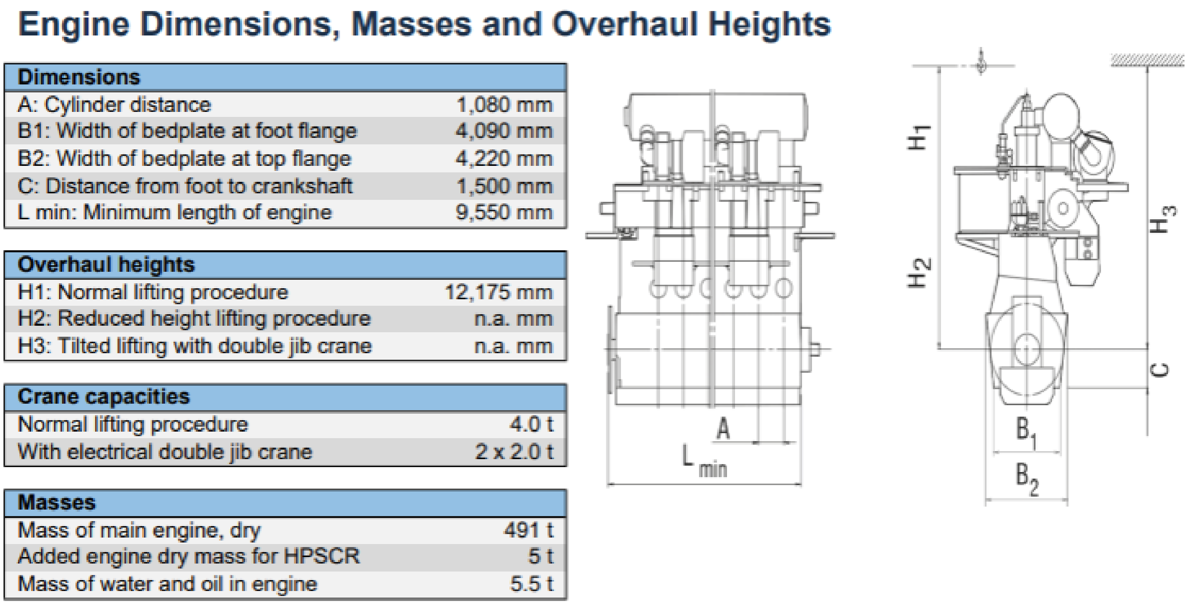
3.3 Engine data & Ship Specifications



Values for EEDI	
Engine type	7G60ME-C10.5-HPSCR
SMCR power	12,100 kW
SMCR RPM	82.0 r/min
Ambient condition	ISO
Reference LCV of fuel oil	42,700 kJ/kg
Fuel Oil mode	
SFOC at SMCR	161.7 g/kWh
SFOC at 75% SMCR	155.3 g/kWh
SFOC at 75% SMCR incl. 6% tolerance	**164.6 g/kWh**

Figure 7 Engine information (Man Energy Solutions, 2024c). Reprinted with permission.

MAN Energy Solutions has provided the data that this report is analyzing. The engine that the data is collected from is a two-stroke engine, a power output of 12,100 kW at 82 rpm as shown in Figure 7. To add, the engine 7G60ME-C10.5-HPSCR has a Mean effective pressure (MEP) of 16 bar (Man Energy Solution, 2024).



Engine Dimensions, Masses and Overhaul Heights

Dimensions	
A: Cylinder distance	1,080 mm
B1: Width of bedplate at foot flange	4,090 mm
B2: Width of bedplate at top flange	4,220 mm
C: Distance from foot to crankshaft	1,500 mm
L min: Minimum length of engine	9,550 mm

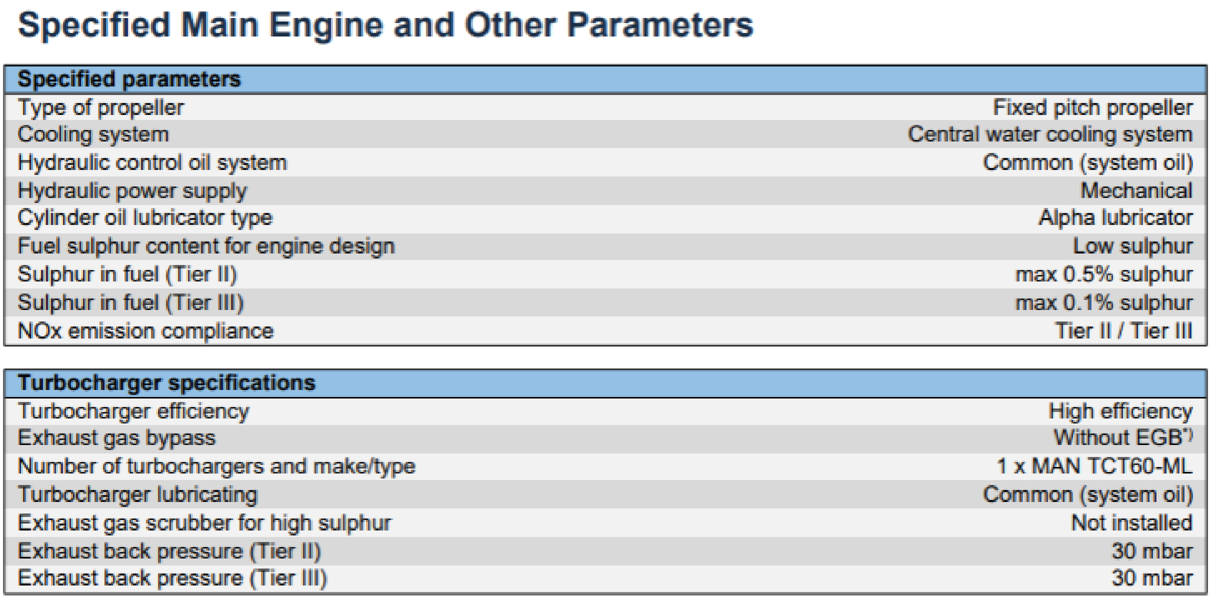
Overhaul heights	
H1: Normal lifting procedure	12,175 mm
H2: Reduced height lifting procedure	n.a. mm
H3: Tilted lifting with double jib crane	n.a. mm

Crane capacities	
Normal lifting procedure	4.0 t
With electrical double jib crane	2 x 2.0 t

Masses	
Mass of main engine, dry	491 t
Added engine dry mass for HPSCR	5 t
Mass of water and oil in engine	5.5 t

Figure 8 Engine Dimensions (Man Energy Solutions, 2024c). Reprinted with permission.

Figure 8 shows the dimensions, masses and overhaul heights of the engine used when performing the tests supplying the data for parts of the report. The specific dimension of each engine is crucial to consider since most engines are different and therefore perform differently, the optimal running conditions and emissions vary depending on the specifics of the engine and ship.



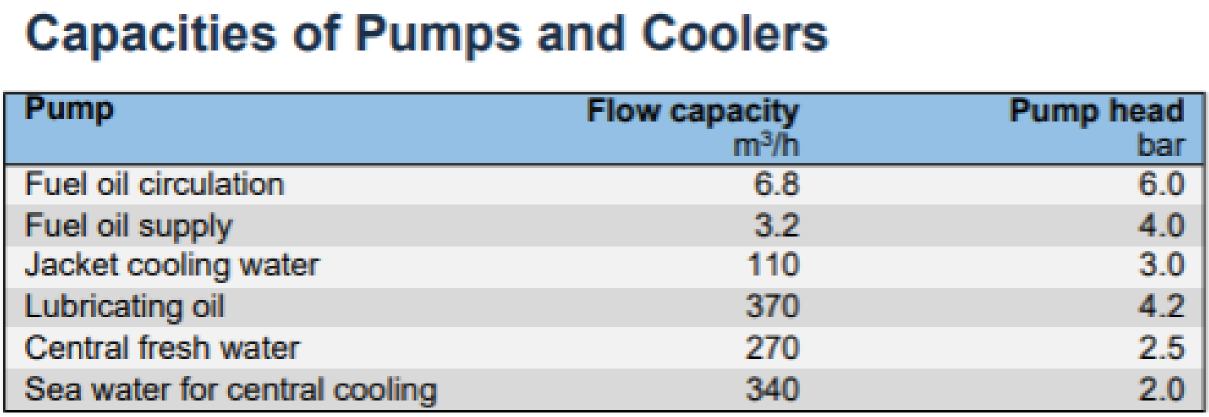
Specified Main Engine and Other Parameters

Specified parameters	
Type of propeller	Fixed pitch propeller
Cooling system	Central water cooling system
Hydraulic control oil system	Common (system oil)
Hydraulic power supply	Mechanical
Cylinder oil lubricator type	Alpha lubricator
Fuel sulphur content for engine design	Low sulphur
Sulphur in fuel (Tier II)	max 0.5% sulphur
Sulphur in fuel (Tier III)	max 0.1% sulphur
NOx emission compliance	Tier II / Tier III

Turbocharger specifications	
Turbocharger efficiency	High efficiency
Exhaust gas bypass	Without EGB*)
Number of turbochargers and make/type	1 x MAN TCT60-ML
Turbocharger lubricating	Common (system oil)
Exhaust gas scrubber for high sulphur	Not installed
Exhaust back pressure (Tier II)	30 mbar
Exhaust back pressure (Tier III)	30 mbar

Figure 9 Other engine parameters (Man Energy Solutions, 2024c). Reprinted with permission.

Figure 9 states parameters including type of propeller, NO_x emission compliance and turbocharger efficiency, and more. The data shown above is great to take into consideration when making conclusions in regards of engine performance, both in the context of fuel consumption and emissions.



Capacities of Pumps and Coolers

Pump	Flow capacity m³/h	Pump head bar
Fuel oil circulation	6.8	6.0
Fuel oil supply	3.2	4.0
Jacket cooling water	110	3.0
Lubricating oil	370	4.2
Central fresh water	270	2.5
Sea water for central cooling	340	2.0

Figure 10 Surrounding system (Man Energy Solutions, 2024c). Reprinted with permission.

The surrounding system's shown in figure 10 provides information about different pump and cooling capacities. These parameters give a foundation for the overall potential of these systems and how it supports engine performance.

The test was carried out in three different conditions, ISO condition, tropical (trp) condition and specific (spe) condition. ISO condition is the standard condition where the temperature is 25℃ for both ambient air and scavenge air coolant. Tropical conditions are when the ambient air is 45°C and scavenge air coolant is 36°C, which refers to sailing areas such as Africa and South America. Lastly, the condition is specified condition the ambient air was 10°C and scavenge air coolant 10°C and could be when sailing the North Sea and during winter in colder climates (MAN Energy Solutions, 2024a).

4. RESULTS

In this section, the result will be presented. The research questions will be answered in written form and with graphs to simplify and clarify the outcome of the engine data.

4.1 VLSFO Tier II Emissions

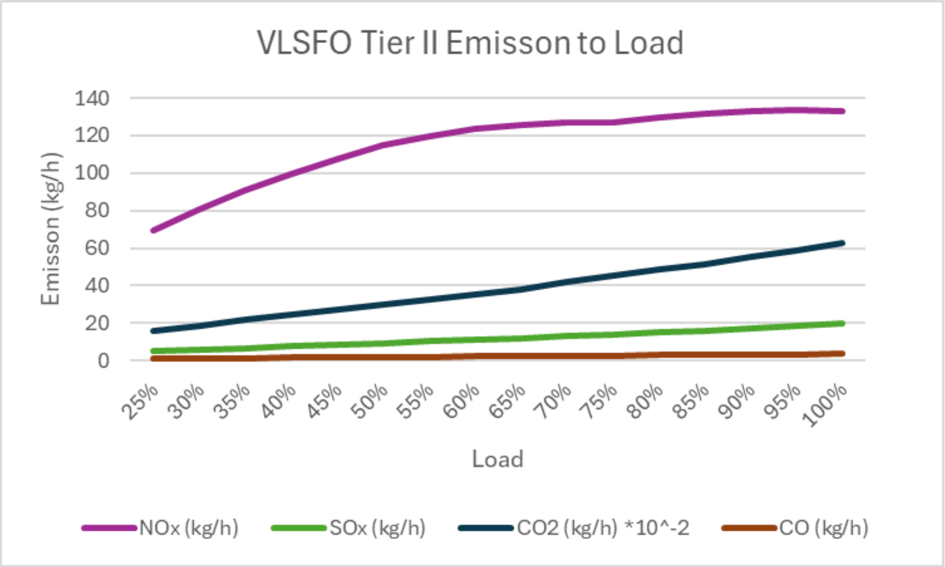


Figure 11 VLSFO Tier II Emission to Load data from (MAN Energy Solutions, 2024a).

The emission of VLSFO Tier II varies depending on the load of the engine. As shown in Figure 11, the emission of CO_2 increases with the engine's load. Similarly, the emission of CO and SO_x also increases with the load of the engine, with slight variations of increase and decrease. Additionally, the emission of NO_x increases rapidly at lower loads, but at higher loads, it levels out. At 75% load on the engine, there is a slight decrease in NO_x emission.

4.2 MGO Tier II Emissions

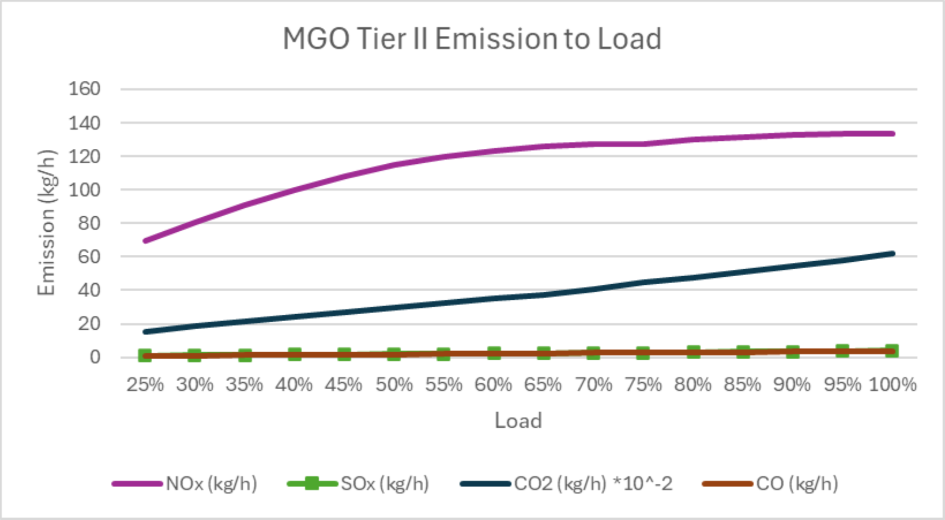


Figure 12 MGO Tier II Emission to Load data from (MAN Energy Solutions, 2024a).

As shown in Figure 12, the emissions of SO_x and CO for MGO Tier II are quite similar to each other. These two emissions increase with the engine load, but only by a few kg/h. On the other hand, NO_x emissions increase rapidly when the engine runs at low loads. In the higher load spectrum, the NO_x emission doesn't change much at different loads, although it has a slight decrease at 75% load. The CO_2 emission increases at the similar rate as the engine load is being increased.

4.3 VLSFO Tier III Emissions

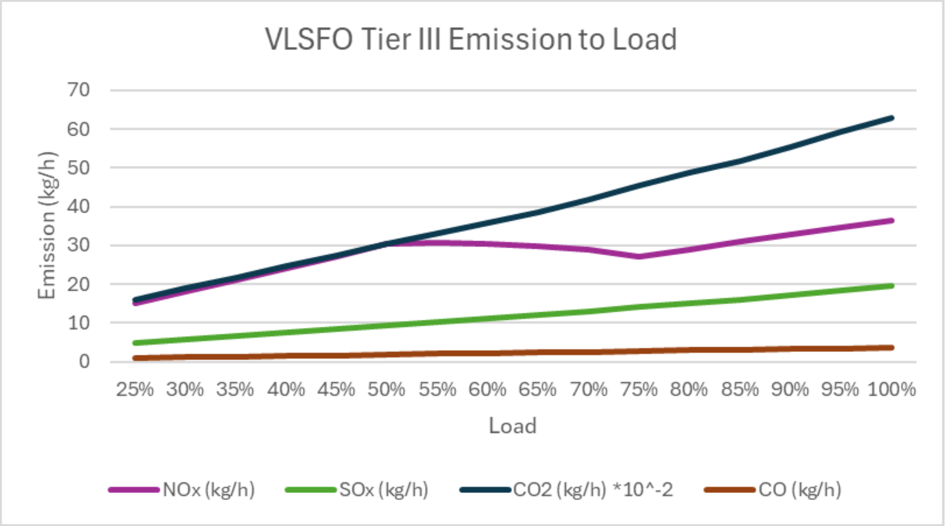


Figure 13 VLSFO Tier III Emission to Load data from (MAN Energy Solutions, 2024a).

The NO_x emissions from VLSFO Tier III, as shown in Figure 13, increase consistently with the engine's load between loads of 25 % to 50 %. After 50%, the NO_x emission starts flattening out and decreasing until 75% load, the emissions have a low point and start increasing again up to full load. The emission of CO_2 continuously increases with the engine's load in the same way as CO and SO_x emissions.

4.4 MGO Tier III Emissions

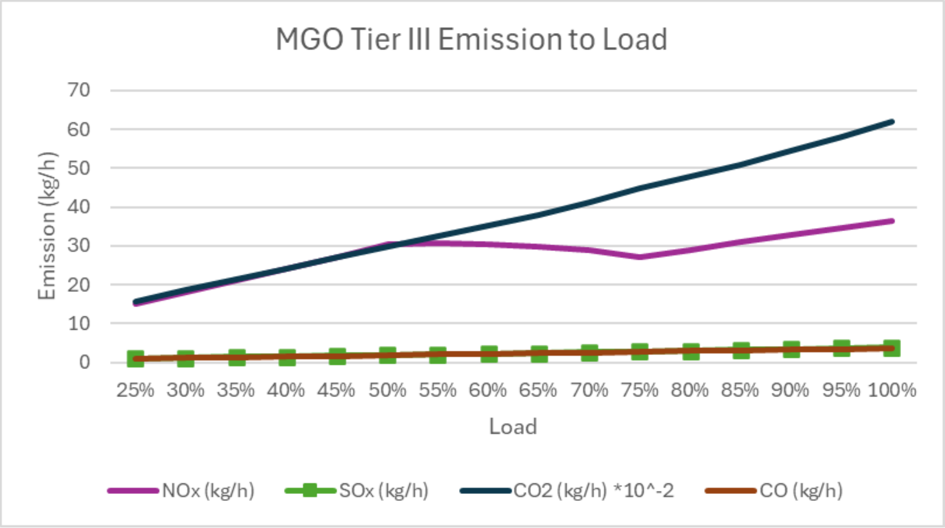


Figure 14 MGO Tier III Emission to Load data from (MAN Energy Solutions, 2024a).

The emission of SO_x and CO increase consistent with the engine load, but not beyond 3.9 kg/h as shown in Table 5. CO_2 emissions increase consistently with the engine load as the load increases, but with larger increments than for CO, SO_x, and NO_x, until it reaches 6,188.8 kg/h at 100% engine load. The emission of NO_x consistently increase between 25% to 50% engine load, and then starts decreasing until it reaches its lowest point at 75% load. Further along the load spectrum, it starts increasing again and reaches its highest point of 36.3 kg/h at 100% load as shown in Figure 14 and Table 5.

4.5 Tier II Fuel consumption

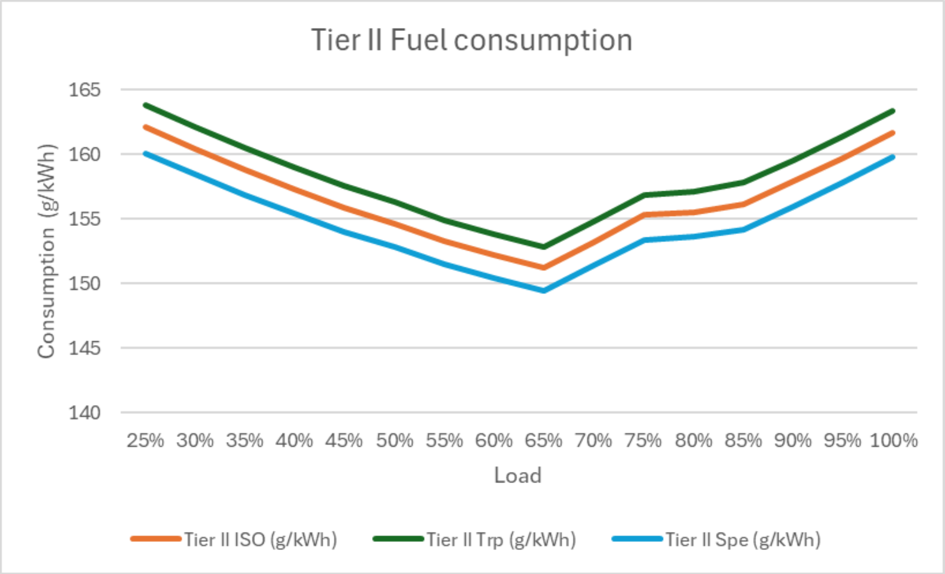


Figure 15 Tier II Fuel consumption data from (MAN Energy Solutions, 2024a).

The Tier II tuned engine fuel consumption is highest when the load is at 25% in relationship to the power produced by the engine at this load. However, as the engine load increases, the fuel consumption to power output starts decreasing and reaches its lowest point at 65% load. After 65%, the fuel consumption starts increasing again, but stabilizes between 75% and 85% before hitting its second highest point at 100% load. The fuel consumption is affected by the engine's running condition, as seen in Figure 15. In colder conditions, the fuel consumption is lower, while in hotter conditions, it is higher. As shown in Table 6 and Figure 15, in tropical conditions, the fuel consumption reaches its peak of 163.8 g/kWh and its lowest point of 152.8 g/kWh. Similarly, in specified conditions, the fuel consumption reaches a peak of 160.1 g/kWh and a low point of 149.4 g/kWh. In ISO conditions, the fuel consumption reaches a high of 162.1 g/kWh and a low point of 151.2 g/kWh.

4.6 Tier III Fuel consumption

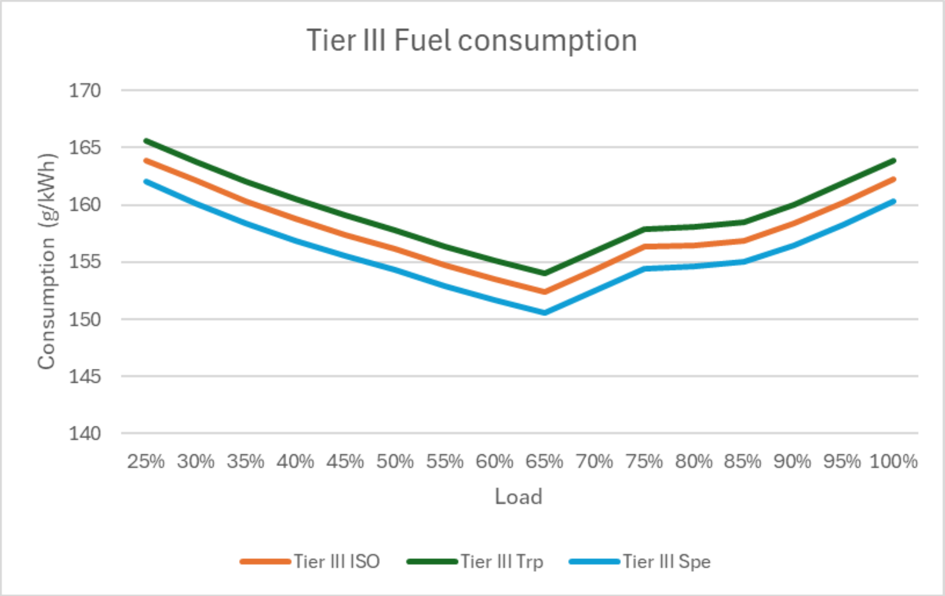


Figure 16 Tier III Fuel consumption data from (MAN Energy Solutions, 2024a).

In Figure 16, it can be observed that the engine's fuel consumption using Tier III tuned engine reaches its highest point of fuel consumption when the load is at 25% in relation to the power produced by the engine. Then gradually decreases until it hits its lowest point at 65% load. Continuously, the fuel consumption increases, but stabilizes between load levels of 75% and 85% before increasing again. As shown in Figure 16 and Table 7, in tropical conditions the fuel consumption reaches a peak of 165.6 g/kWh and a low point of 154 g/kWh. Similarly, in specified conditions, the fuel consumption reaches a high of 162 g/kWh and a low point of 151.7 g/kWh. In ISO conditions, the fuel consumption reaches a peak of 163.9 g/kWh and a low point of 152.4 g/kWh.

4.7 HFO Fuel consumption Tier II and Tier III

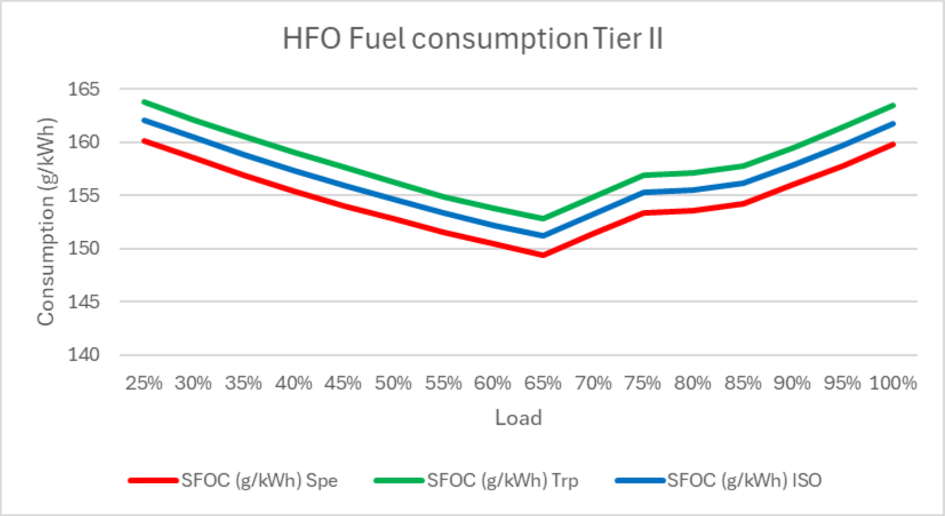


Figure 17 HFO Fuel consumption Tier II data from (MAN Energy Solutions, 2024b)

The fuel consumption for the Tier II tuned engine running on HFO is shown in Figure 17, starts at its highest point at 25% load to power produced and then decreases until it reaches its lowest point at 65% load. After 65% load, the fuel consumption starts to increase again. Between 75% to 85% load, the fuel consumption stabilizes before increasing again. In tropical conditions, the fuel consumption reaches a peak of 163.8 g/kWh and a low of 154.8 g/kWh. Similarly, in specified conditions, the fuel consumption reaches a peak of 160.1 g/kWh and a low of 149.4 g/kWh. In ISO conditions, the engine reaches a fuel consumption peak of 163.8 g/kWh and a low point of 152.8 g/kWh (See Table 8).

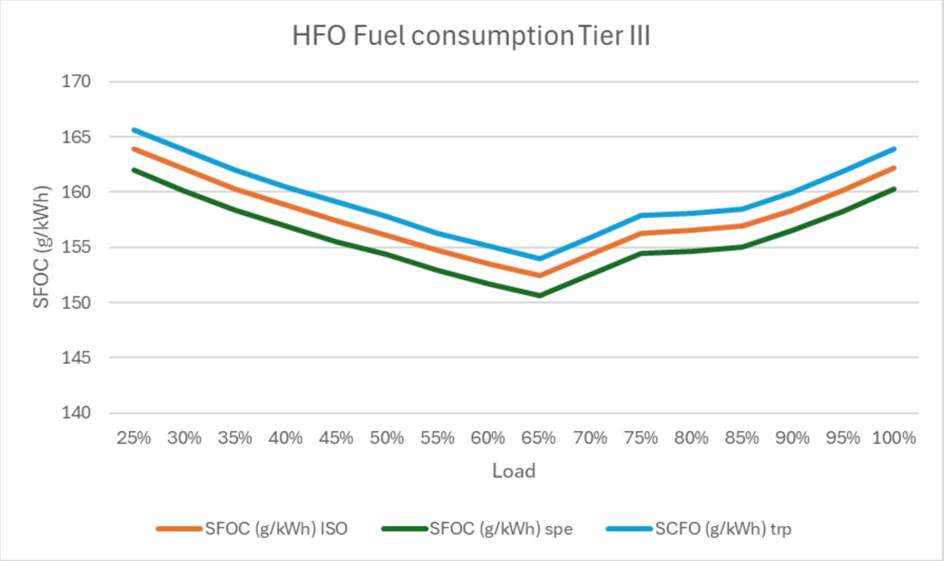


Figure 18 HFO Fuel consumption Tier III data from (MAN Energy Solutions, 2024b)

The fuel consumption for the Tier III tuned engine running on HFO is shown in Figure 18, starts at its highest point at 25% load to power produced and then decreases until it reaches its lowest point at 65% load. After 65% load, the fuel consumption starts to increase again. Between 75% to 85% load, the fuel consumption stabilizes before increasing again. In tropical conditions, the fuel consumption reaches a peak of 165.6 g/kWh and a low of 154 g/kWh. Similarly, in specified conditions, the fuel consumption reaches a peak of 162 g/kWh and a low of 150.6 g/kWh. In ISO conditions, the engine reaches a fuel consumption peak of 163.9 g/kWh and a low point of 152.4 g/kWh (See Table 8)

4.8 Load and speed connected to fuel consumption

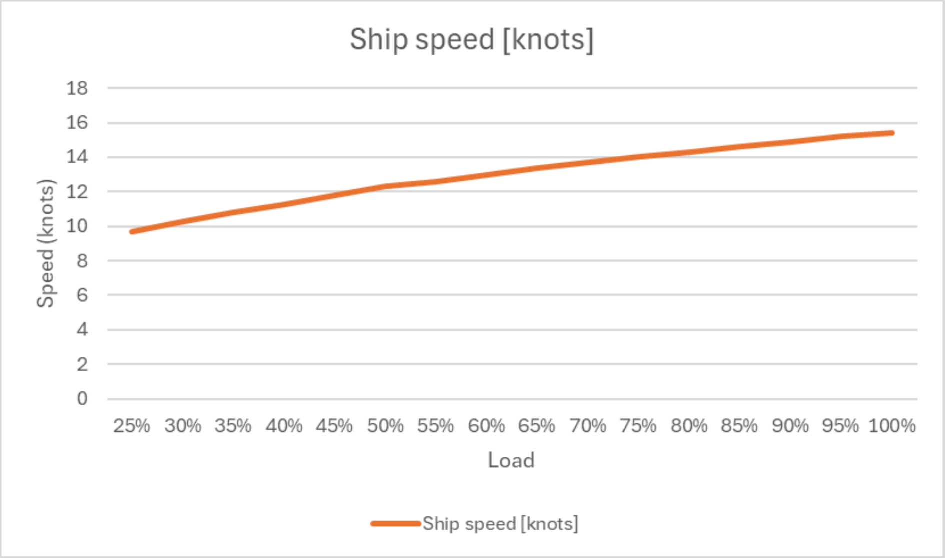


Figure 19 Load to Speed data from (MAN Energy Solutions, 2024c)

When deciding the speed of the vessel an effective speed to load ratio needs to be established, the load and propeller rpm is transferred into the traveling speed of the vessel. In this case, the ship has a fixed pitch propeller and is traveling at a speed of 15.4 knots at 100% load and at 65% the ship is traveling at the speed of 13.4 knots. Figure 19 shows that the speed gradually increases, but the increase intervals in speed between different loads at higher loads are not as pronounced. As stated in MAN Energy Solutions (2023) the speed produced by the engine losses efficiency due to the vessels high depends on the external factors such as, propeller pitch, propeller diameter and hull resistance and weather conditions.

Over a theoretical distance of 10000 km (5400 nautical miles) the fuel consumption saving potential, or increase are dependent of the load and speed of the vessel. For a Tier III tuned engine running on MGO, see Table 1 below.

Table 1 Theoretical travel distance - MGO Tier III (MAN Energy Solutions, 2024a) (MAN Energy Solutions, 2024c)

Load (%)	Power (kW)	Speed (knots)	Time travelled (hours)	Fuel consumed (ton)	NO_x (kg)	SO_x (kg)	CO_2 (ton)	CO (kg)
100%	12,100	15,4	350,62	688,13	12727,51	1367,42	2169,92	1262,23
95%	11,495	15,2	355,23	654,16	12255,44	1314,35	2062,79	1207,78
90%	10,890	14,9	362,39	625,11	11850,15	1232,13	1971,18	1195,89
85%	10,285	14,6	369,83	595,28	11427,75	1183,46	1881,92	1146,47
80%	9,680	14,3	377,59	572,02	10950,11	1132,77	1803,75	1095,01
75%	9,075	14	385,68	547,06	10490.50	1079,90	1725,07	1041,34
70%	8,470	13,7	394,13	515,10	11350,94	1024,74	1624,29	985,33
65%	7,865	13,4	402,95	482,67	12048.21	967,08	1523,03	967,08
60%	7,260	13	415,35	462,87	12668,18	913,77	1459,58	913,77
55%	6,655	12,6	428,54	441,19	13113,32	899,93	1391,21	857,08
50%	6,050	12,3	438,99	414,58	13301,40	834,08	1307,31	790,18
45%	5,445	11,8	457,59	392,17	12446,45	777,90	1236,64	732,14
40%	4,840	11,3	477,84	367,26	11563,73	716,76	1158,09	716,76
35%	4,235	10,8	499,96	399,41	10599,15	699,94	1070,26	649,95
30%	3,630	10,3	524,23	308,47	9540,99	629,08	972,71	576,65
25%	3,025	10	539,96	267,71	8153,40	539,96	844,17	485,96

It is evident that the fuel consumption and emissions increases as load and speed demand is increased, but NO_x has a slight deviation where it drops down between 55% and 75%, to start increase again from 75% and above. In a power to load relationship the optimal zone would be 65%, fuel consumed over 5400 nautical miles at 65% load reaches 482.67 tons with a total travelling time of 402.95 hours. With emissions reduction as a main objective a lower load would always be more beneficial, but with obvious effects on speed and power as shown in Table 1 and Figure 20.

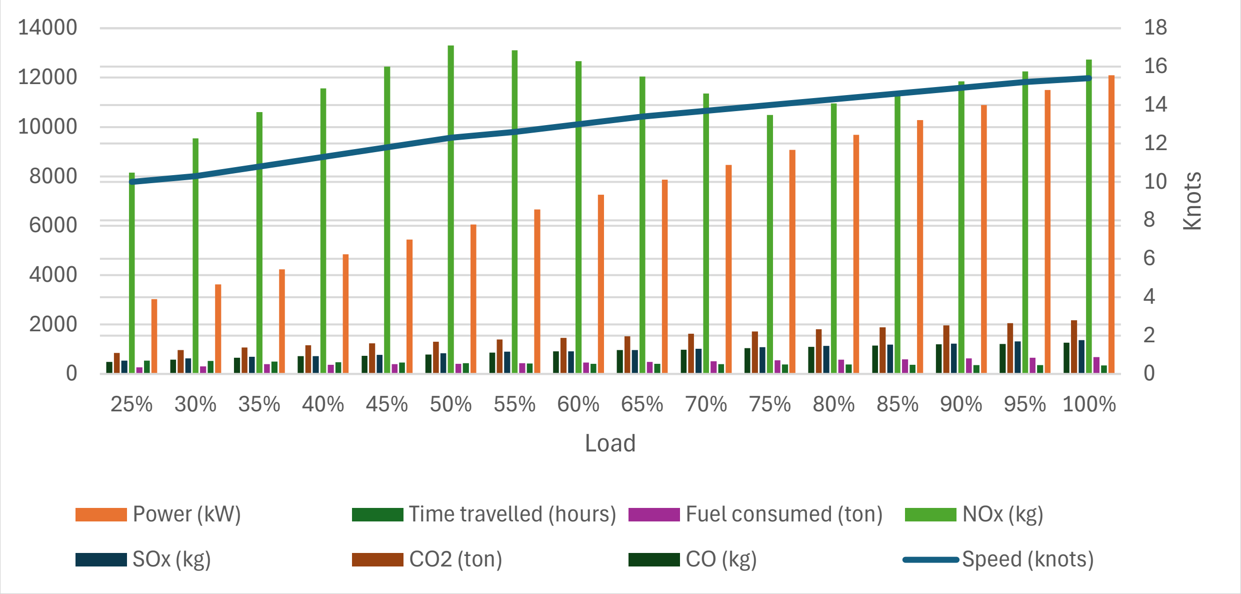


Figure 20 Graph of theoretical travel distance data - MGO Tier III (MAN Energy Solutions, 2024a) (MAN Energy Solutions, 2024c)

Using 65% load as a branching point, the increase or reduction at 100% load is 14.9% time reduction, 42.6% fuel consumption increase, 5.6% NO_x increase, 41.1% SO_x increase, 42.5% CO_2 increase, and a 30.5% CO increase. At 80% load, the time reduced is 6.7%, 18.5% fuel consumption increase, 10.0% NO_x reduction, 17.1% SO_x increase, 18.4% CO_2 increase, and 13.2% CO increase. At 45% load, the travel time is increased by 13.6%, the fuel consumption is decreased by 23.1%, NO_x increases by 3.3%, SO_x are reduced by 24.3%, a CO_2 reduction by 23.2%, and 32.1% CO reduction. At 25% load the travel time is 34.0% higher than at 65% load, an 80.3% fuel consumption reduction, 47.8% NO_x reduction, 79.1% SO_x reduction, 80.4% CO_2 reduction, and 99.0% CO reduction.

5. DISCUSSION

In this part, the method, theory, and result will be discussed along with the reports research questions. The results from the engine running operational data from MAN Energy Solutions provide an opportunity to deliberately highlight factual data with contrast to slow steaming theories. In addition, the IMO regulations are used as a standpoint to elaborate the environmental confines that needs to be obeyed. To add, what alternative strategies may be applicable for fuel consumption and emission reduction purposes compared to slow steaming.

5.1 Fuel consumption and speed to load ratio

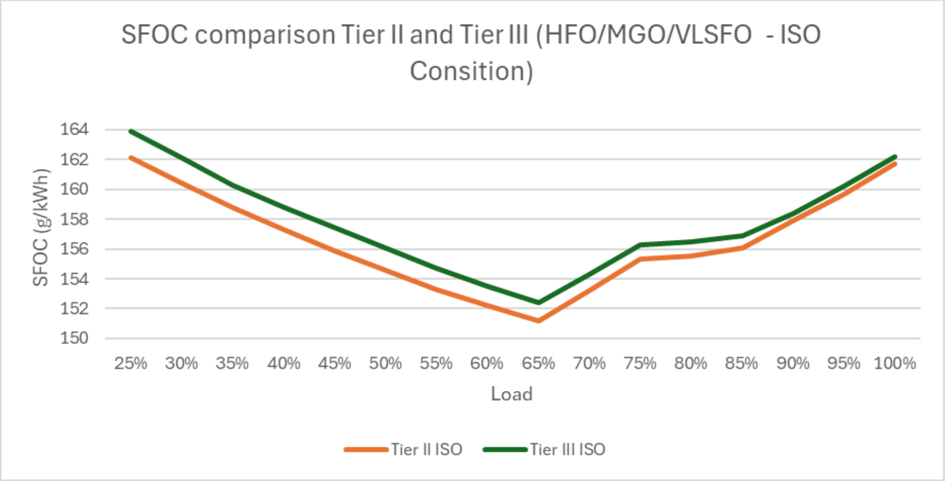


Figure 21 HFO/MGO/VLSFO Fuel consumption Tier II ISO Conditions data from (MAN Energy Solutions, 2024b)

The fuel consumption of an engine varies depending on the load. When the engine is running at a lower load the fuel consumption is at its highest for all fuel types and tiers. To clarify, the fuel consumption to load ratio is higher meaning that less fuel is consumed, but with less power produced by the engine. When the engine is at a higher load, the fuel consumption is higher than at the optimal load of 65%. This is evident in the Figure 21 between 85% and 100% load, where the engine is pushing close to its maximum capacity increasing fuel consumption. To optimize the fuel consumption, the engine should operate at a load of 65%, which is the most optimal point for slow steaming when fuel to power is the desired outcome, potentially during heavy weather and winter conditions. At this point, fuel consumption to power ratio is 7% lower than at 25% load, 6.5% lower than at 100% load, and 3% lower than at 80% load. Furthermore, if a higher speed is required, the second-best interval of operation is at 80%, where the fuel consumption is still relatively low compared to other loads. The design load between 75% and 85% is interval where the fuel consumption stabilizes and does not increase as drastically. However, this is not the most optimal point for slow steaming in regards of minimum fuel consumed. To achieve the most optimal point, the engine load should be lowered to 65% or lower to reduce the fuel consumption.

According to Tables 6, 7, 8, and 9, there is no difference in fuel consumption between HFO, VLSFO, and MGO. The engine still consumes the same amount of fuel regardless of which fuel the engine is running on but may deviate depending on future fuels such as CH_4 or ammonia and scrubber installation. This could be because of the viscosity of the fuel and the volume of injected fuel. The tables also show the fuel consumption for various conditions. As seen in

Figures 15, 16, 17 and 18, different ambient air and scavenging air coolant impact fuel consumption. If the temperature is lower than the ISO condition, the engine consumes less fuel, while if the temperature is higher the engine consumes more fuel than in ISO condition. This may be because the combustion chamber has better operating conditions at lower temperature of the scavenge air. Lower air temperatures lower its density and volume, consequently making it possible to force more air into the engine.

The fuel consumption is also affected by the Tiers of the engine as seen in Figure 21. Tier II engines have a lower fuel consumption than Tier III engines. This is because Tier III is optimized for NO_x emission reduction and not optimized for fuel consumption. NO_x reduction can be done by changing the ignition timing, air/fuel ratio or pressure inside the cylinder.

When deciding operational speed, it is detrimental to factor in speed to load ratio. This entails the relationship between the load of the engine and the outcoming speed of the vessel. As shown in Figure 19, the speed increases gradually with larger increments at low loads and then with smaller increments at higher loads. The speed increase provides reason to think that when getting closer to maximum load capacity there will be diminishing returns concerning the speed of the vessel. In addition, external factors will affect the speed performance and efficiency of the vessel. Weather conditions may assist or hinder the speed to load ratio, down current can help maintain a speed at lower loads while hull resistance will hinder.

By optimizing speed to load ratio, fuel consumption will consecutively be reduced since less fuel burned at lower loads which would transfer over to emission reduction as well. To determine optimal propulsion efficiency a balance between speed and load is required ultimately resulting in higher fuel efficiency and lower emissions.

As of Table 8, our analysis demonstrates the relationship between fuel consumption, load, speed, and emissions demand in a MAN B&W Two-stroke 7G60ME-C10.5 with SMCR 12100 kW 82 rpm engine. As the load and speed increases the fuel consumption and emissions does as well. However, the emissions relationship regarding NO_x exhibits a reduction between 55% and 75% load, and the increases beyond 75%. This interplays the complexity of factors influencing emission at different loads and speeds. While reducing emissions remains the primary objective of slow steaming, it is crucial to acknowledge the trade-offs involved. Lowering the loads and speed will lead to emissions reduction but comes with increases traveling time due to lower speeds as proven in Table 1 and Figure 20. To add, the potential engine wear is a potential outcome when running the engine below its design load. Fundamentally, any strategy to reduce emission must be balanced regarding these competing factors to achieve the most sustainable and efficient outcome.

5.2 Emissions data

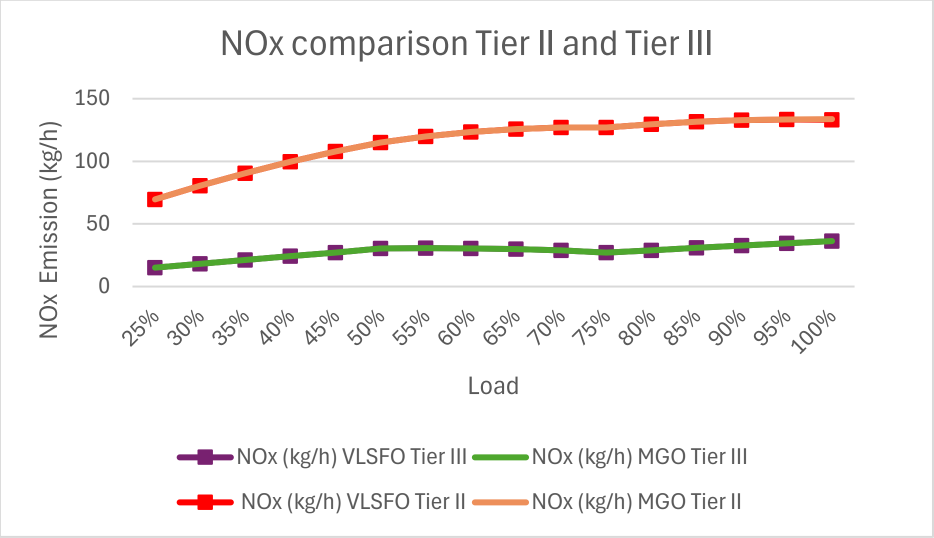


Figure 22 Load to NOx for MGO/VLSFO Tier II and Tier III ISO Conditions data from (MAN Energy Solutions, 2024b)

NO_x emissions tend to increase as engine load increases. With increased engine load the engine requires more fuel which leads to higher temperature inside the combustion chamber. The elevated temperature may cause the oxygen in the air to react with nitrogen, leading to NO_x formation. This increase in temperature and pressure consequently favors NO_x formation. Furthermore, at higher loads more air will be used during the combustion process to support the increased fuel demand of the engine, higher oxygen levels promote the formation of NO_x during the combustion process. Combustion ignition engines operate with a lean air/fuel mixture at higher loads, the leaner the mixture at high temperature will favor the formation of NO_x.

As stated in the theory a Tier II engine does not have the same requirements as a Tier III engine. Tier III is not a fuel consumption reduction strategy, it is aimed to reduce the amount of NO_x released, these restrictions are stated in point 2.3. To add, most NO_x restricted areas do have restrictions on other emissions such as SO_x. Consequently, Tier III is optimized for reducing NO_x and not to be confused with fuel consumption reduction.

Looking at the Figure 22 it is a subtle dip in NO_x at 75-80% load which would indicate optimal slow steaming zone for both Tier II and Tier III in regards of highest possible load at slow steaming keeping NO_x lower. However, the optimal fuel consumption zone for slow steaming is at approximately 65% load according to the result presented in point 4.5 and 4.6 when power to fuel consumption is the goal. This indicates that slightly higher NO_x emissions might be necessary to compensate for better fuel consumption and reduction of other emissions.

At 75% load for Tier II the amount of NO_x released reaches a point of 127.1 kg/h for both MGO and VLSFO, while Tier III only reaches 27.2 kg/h at 75% load. The optimal load for fuel consumption to power ratio and other emissions such as CO, SO_x and CO_2 is 65%. Reducing the load by an additional 10% to 65% would decrease the NO_x emissions for Tier II from 127.1 kg/h to 125.8 kg/h. For Tier III on the other hand, the NO_x emissions will increase from 27.2 kg/h to 29.9 kg/h when reducing the load from 75% to 65%.

The NO_x emissions increase with small increments linearly as the engine load increases for both Tier II and Tier III. As indicated previously, for Tier III the NO_x emission goes down when the load changes from 65% to 75%. In theory the NO_x should increase with the load, but for Tier III that is not the case. The explanation could be a slight change in injection timing, air/fuel ratio or pressure inside the cylinders at this specific load for reasonings of higher load NO_x reduction optimization.

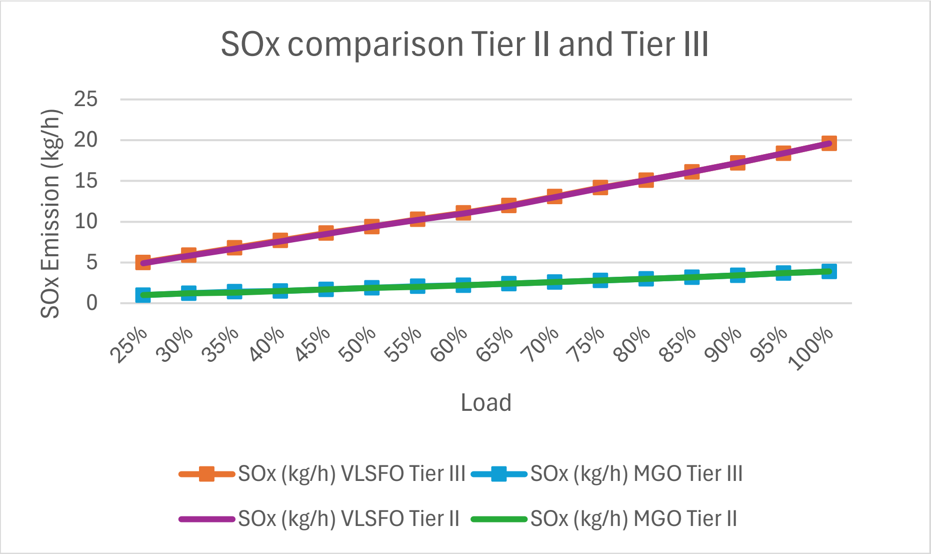


Figure 23 Load to SO_x for MGO/VLSFO Tier II and Tier III ISO Conditions data from (MAN Energy Solutions, 2024b)

SO_x emissions will increase with increased engine load. Both MGO, HFO and VLSFO contains different levels of sulphur which will form SO_x during the combustion process. At higher engine loads more fuel is consumed, consequently leading to more SO_x formation. In addition, other reasons for SO_x emissions may be incomplete combustion which can be correlate to poor air/fuel mixture. As for NO_x the formation of SO_x can increase as higher combustion temperature is reached with increased load. To add, with increased load more air is supplied to the combustion process for compression ignition engines, this can help with the formation of SO_x due to increased oxygen availability.

The noticeable difference in SO_x emissions is shown in Figure 23, the development of SO_x emissions is based on the measurements made during operation. The graph indicates no difference in emission from Tier II or Tier III since Tier does not regulate the emissions of SO_x, However, the fuel type is one determining factor for emissions. The SO_x emissions are dependent on how much sulphur the fuel contains, MGO has lower levels of sulphur than VLSFO as proven Figure 13 and Figure 14.

As stated in the result and proven in Figure 23 the optimal zone for SO_x in relation to fuel consumption to power produced is at 65% load. When the engine runs on MGO regardless of Tier the emissions reach 2.4 kg/h while for VLSFO it reached 11.9 kg/h for Tier II and 12.0 kg/h for Tier III. The slight difference in SO_x emitted from the engine running on VLSFO has an insignificant difference and within tolerant margin of error. An explanation for this could be a variation in volume of fuel injected or completeness of the combustion.

The choice of fuel depends on the geographical sailing area. As stated in theory point 2.3 the allowed sulphur fuel content connects to if the vessel is traversing an ECA, SECA or international waters. Inside these control areas the legal limit is 0.1% sulphur content and outside the legal limit is 0.5% sulphur content. Consequently, the maximum sulphur content of VLSFO is 0.5% while MGO contains a maximum of 0.1%.

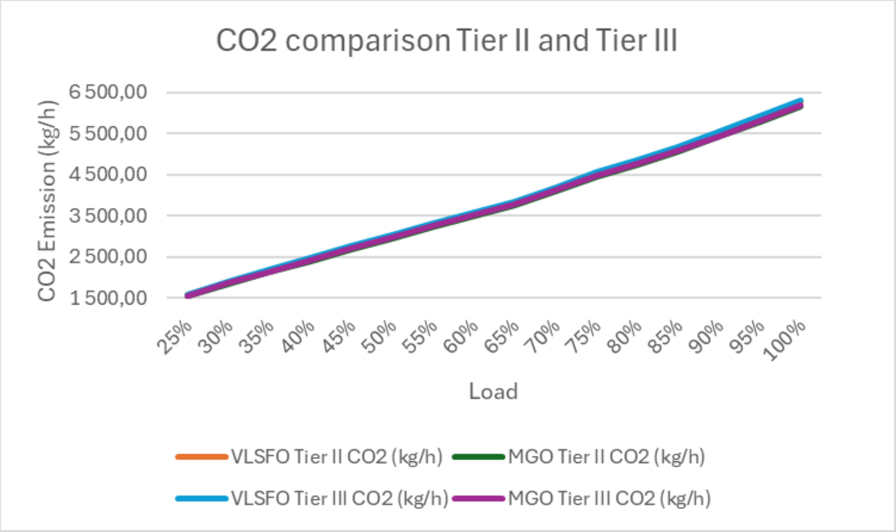


Figure 24 Load to CO_2 for MGO/VLSFO Tier II and Tier III ISO Conditions data from (MAN Energy Solutions, 2024b)

The CO_2 emissions increase linearly as the load increases as shown in Figure 24. As fuel consumption increases, CO_2 emissions will increase, since more fuel burnt leads to more CO_2 emitted. As for both SO_x and NO_x the increase in combustion temperature correlates to load increase which will also result in increased CO_2 emissions due to the fuel consumption increase. To add, higher engine loads reduce efficiency since thermal and mechanical losses increase e.g. higher friction. As stated in the result and shown in Figure 23 there is a slight difference in CO_2 emission between Tier II, Tier III, VLSFO, and MGO.

The emission and fuel to power optimized zone is proven to be at 65% load where an even exchange between emissions to fuel consumption can be found. For Tier III, fuel has a CO_2 increase of about 30 kg/h compared to Tier II. Since engine Tier III is optimized for NO_x reduction it may cause an increase in CO_2 emissions for that specific engine tuning which is the case for this engine.

The Tier is the proven factor that gives either an increase or decrease relative to the load for CO_2 emissions. As shown in Table 2 and Table 3 in appendix, CO_2 increases from 3819.7 kg/h for Tier II to 3850.0 kg/h for Tier III when the engine runs on VLSFO at 65% load. When looking at MGO (65% load) provided in Table 4 and Table 5 the CO_2 increases from 3749.9 kg/h for Tier II to 3779.7 kg/h for Tier III. Since a Tier III engine is optimized for NO_x reduction this will alter other emissions, which consequently leads to reduced NO_x but higher CO_2 emissions in this case.

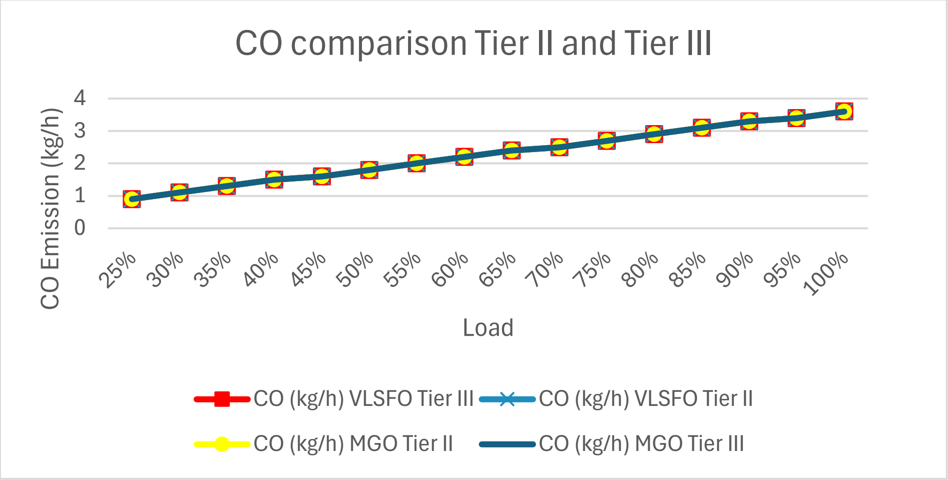


Figure 25 Load to CO for MGO/VLSFO Tier II and Tier III ISO Conditions data from (MAN Energy Solutions, 2024b)

As provided in the result there is no significant difference in CO emission regardless of fuel or Tier. Figure 25 proves how the CO increases linearly, the emissions produced are correlated to the quantity of fuel that is being consumed and the amount of carbon in the fuel. As for all other emissions incomplete combustion is one determining factor of the amount of emission emitted. With increased engine load there may be an insufficient amount of oxygen in the combustion chamber to help oxidize the CO into CO_2. In addition, the combustion process can become less efficient at higher loads leading to increased CO emissions. The reasoning may be poor air/fuel mixture and shorter combustion duration.

Tier III has the same fuel consumption 152.3 g/kWh at 65% load for both MGO and VLSFO, it is obvious that the CO emission will be the same for both fuel types when the fuel consumption is equivalent. Tier II consumes 151.2 g/kWh for both fuel types at an optimal load of 65%. Both Tiers and fuels produce 2.4 kg/h of CO at 65% which is the optimal zone for fuel consumption to power ratio. To add, the CO production is the same which indicates that VLSFO and MGO have the same carbon content and when combusted the CO emission will be similar with slight variation depending on completeness of combustion.

Factors that may affect the CO emission are insufficient air supply which indicates a richer air to fuel mixture, consequently leading to more CO emission formation due to not all fuel being burnt completely. Secondly, bad fuel atomization will affect the formation of CO since diesel engines need to have fine droplets of fuel to fully combust the fuel effectively. To add, the engine operational conditions (load, speed, and temperature) may influence how effectively the engine can combust the fuel.

5.3 Regulations discussion

Marpol Annex VI regulates emissions to air with regards to NO_x, SO_x, and CO_2. For this specific engine running at 82 rpm at 100% load, the NO_x emissions must not exceed 14.4 g/kWh for Tier II and 3.4 g/kWh for Tier III according to (IMO, n.d.-c). This is because the engine's rpm does not exceed 130 rpm, ships that operate with engines fulfilling these requirements are allowed to enter the ECA if the engine is optimized to Tier III, unless additional systems are installed to lower the NO_x emissions.

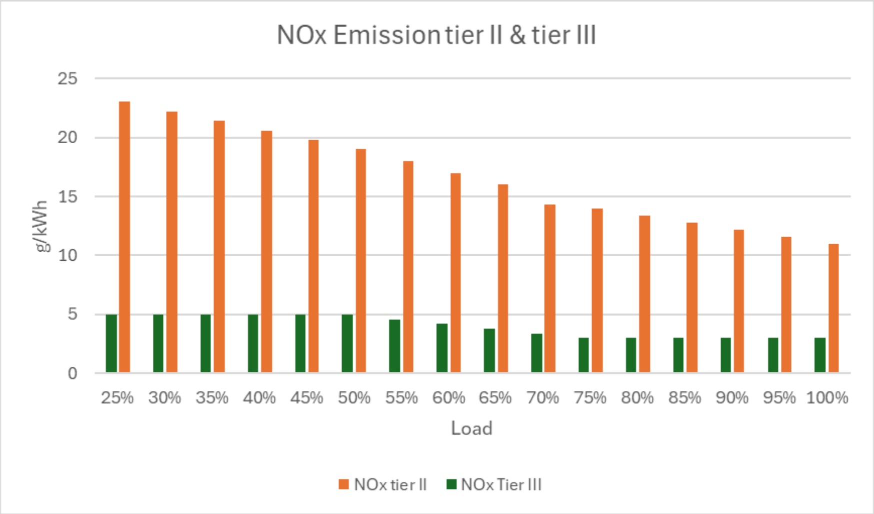


Figure 26 Emissions to load ratio data from (MAN Energy Solutions, 2024c)

In Figure 26 it shows the NO_x produced in both Tier II and Tier III in g/kWh at different loads, the emissions are representable to the units used in Marpol Annex VI Regulation 13 (IMO, n.d.-a). The emissions for the different loads do exceed the legal limit at some of the loads, as stated above, the legal limit for Tier II is 14.4 g/kWh and Tier II 3.4 g/kWh. For both tiers the NO_x emissions requirements are fulfilled at loads between 100% and 70% while at lower loads it exceeds the allowed limit. To reduce NO_x Exhaust Gas Recirculation (EGR) and Selective Catalytic Reduction (SCR) are commonly used, EGR guides exhaust gases back into the combustion chamber to dilute the air/fuel mixture consequently reducing NO_x emissions. SCR is an aftertreatment system which uses urea or ammonia to be spray on the exhaust gases. These two strategies may be used to fulfill the NO_x requirements but are not used when collecting the engine operation emissions data.

SO_x emissions are regulated based on the sulphur content in the fuel. In ECA and SECA, the sulphur content is restricted to 0.1%, while outside these areas, it is limited to 0.5% (MAN Energy Solutions, 2023). The engine does not have a significant impact on SO_x emissions since the sulphur content in the fuel is regulated. However, there are a few low points during running conditions where optimal conditions for SO_x emissions are achieved. These low points occur when fuel consumption is at its lowest.

As stated in the theory, the marine industry currently does not regulate the emissions of CH_4 and N_2O (European Commission, n.d.). However, this is likely to change in the near future as the energy sector has already implemented regulations. Since CH_4 and N_2O are CO_2 equivalents, they may be included in the CII calculation for the efficiency rating. Although CH_4 and N_2O have a greater global warming potential than CO_2, they should be included in the CII instead of being separately regulated. This is because they need to be considered in relation to their CO_2 equivalents to be more strictly regulated.

5.4 Alternative strategies discussion

The discussion on strategies to reduce GHG emission can evidently be approached in different ways, every strategy has disadvantages and advantages to consider. The focus in the shipping industry has been slow steaming, but alternative methods such as trim optimization and speed optimization may be more effective.

Recent research has found overestimation of the effectiveness of slow steaming when taking speed-power relationship and the specifications of the vessel into account. Slow steaming is effective in ballast voyages, but there are further benefits from speed optimization during laden voyages. Consequently, it is important to tailor which strategy to apply depending on size of the vessel, vessel type, voyage, and operation obligations to find the most effective optimization strategy (Berthelsen & Nielsen, 2021).

Looking at speed optimization, the strategy considers outside factors such as weather conditions to adapt the vessel's speed accordingly. This flexible strategy gives fuel saving potential without the need to change course. The strategy is dependent on weather forecasting to reach best optimization, adjusting the speed accordingly will reduce resistance and improve fuel consumption. Fundamentally, speed optimization is effective with accurate weather forecasting and may compete with slow steaming as the most effective strategy (Taskar et al., 2023).

Another promising strategy that does not require any modifications to engine or ship structure is trim optimization. Optimizing the trim based on ship design and speed gives easy applicability with fuel efficiency benefits. Positive trim is indicated to give fuel consumption reduction, to add, trim optimization in combination with other strategies may give further fuel and emissions benefits than only applying one strategy (Elkafas, 2022).

The discussion highlights the complexity of reducing emissions and fuel consumption. The different strategies have promising solutions to the dilemma, each with their own considerations and benefits. The ongoing investigations and technology development are imperative for future improvements with fuel consumption efficiency and environmental sustainability.

5.5 Method discussion

The method used in this study is a comprehensive approach of accumulation of engine operational data and information needed for the report's development. By utilizing the extensive amount of peer-reviewed and scientific reports provided by the Chalmers library digital repository the thesis could be answered effectively. The library search function was used to target peer-reviewed reports to enhance the credibility of the material analyzed, and with expert peer review subject examining. By focusing solely on engine operational data from MAN Energy Solutions and peer-reviewed sources it demonstrates high commitment to academic standard and scholar integrity. However, solely focusing on one engine data source may show deficiencies in the accuracy of the result, due to no comparability with data from other engine manufacturers. Nevertheless, as stated in delimitations the reports only focus on examining data from MAN Energy Solutions.

The information search strategy used a variety of keyword combinations related to slow steaming and further emission reductions. The search method helps with making sure relevant literature is applied and considered for accurate information gathering. To add, it is important to note the limitations of not taking part in the emission data calculation method. Such information gives valuable insight into the report and enhances the credibility and reliability of the report.

The source selection methodology of evaluating headlines, abstracts, summaries, results, and conclusions demonstrates high quality literature relevance. The search method ensured that only the most relevant, credible, and informative sources were used in the literature study. Efforts of incorporating existing research with real operational engine data to address the complexity of slow steaming and emission reduction in the shipping industry was incorporated to giving the report higher validity. To add, supplementing peer-reviewed academic literature with real industry data provided a solid foundation for a credible and well-rounded report.

6. CONCLUSION

The optimal running load and speed for the MAN B&W Two-stroke 7G60ME-C10.5 engine with SMCR 12100 kW at 82 rpm is 65% for achieving the best power to fuel consumption ratio. Running the engine at this load results in a noticeable decrease in fuel consumption by around 4 grams per kWh compared to 80% load, which leads to significant fuel savings over a long journey. However, running the engine at this optimal load or at further reduced load and speed for slow steaming purposes it will increase the journey time, but with high environmental benefits. At 25% load the NO_x emissions are reduced by 47.8%, the SO_x are reduced by 79.1% SO_x, CO_2 by 80.4%, and CO by 99.0% in relationship to 65% load. This in indicates that the lower the load the lower the fuel consumption and emissions. Therefore, the shipping companies and operators evidently needs to choose between lower fuel consumption, environmental impact, and increased travelling time.

Looking at the emissions within the load range of 65% and 75% the emissions it can be observed noticeable difference in NO_x emission. At 65% compared to 75% the NO_x emissions are higher for Tier III tuned engine, while a Tier II tuned engine has a slight dip in NO_x in its increasing curve. However, for other emissions, the level is higher at 75% load than at 65%. As shown in Table 5, at 65% load the engine releases 29.9 kg/h of NO_x while at 75% it releases 27.2 kg/h. In Table 3 it shows that at 65% load the engine releases 125.5 kg/h of NO_x while at 75% it releases 127.1 kg/h.

When it comes to IMO and Marpol regulations, it is not possible to comply with the NO_x emission standards in an ECA using a Tier II engine without additional after-treatment systems. However, with a Tier III engine, it is possible to comply with the regulations in ECA, but only at higher loads because the NO_x emission standards are given in g/kWh, and the emission of NO_x is lower per kWh at higher loads. Running conditions do not affect compliance with SO_x regulations because the emission of SO_x is regulated by the sulphur content in the fuel. Currently, there is no regulation for CH_4 and N_2O in the marine sector, but it is believed that new regulations will be implemented in the near future.

The debate around emissions and fuel consumption in the shipping industry has led to the development of different strategies such as slow steaming, speed optimization, and trim optimization, all having their own dependents on weather conditions and vessel type. Slow steaming effectiveness is dependent on voyage type, vessel specifications, and does is not always the best fuel saving option. However, speed optimization has emerged as a versatile strategy that adjusts to weather conditions and the ships resistance, providing effective fuel reduction without necessarily adjusting the route. To add, trim optimization offers increased fuel efficiency without modifications and with easy applicability for operators and to all vessel types. Fundamentally, these fuel reduction strategies underscore the difficult decision for vessel owners and operators, the need to balance fuel efficiency, emission reduction, operational constraints, and time loss. The effectiveness of these strategies highlights the need for operating the vessels in pursuit of sustainability both environmental and time logistically.

7. RECOMMENDATIONS FOR FURTHER RESEARCH

This report solely focuses on examining the engine's performance and emission variations during different loads to determine the optimal running interval for fuel consumption and emissions. Thus, the aftertreatment system is not investigated. However, it is important to note that the aftertreatment system can significantly reduce emissions, and therefore, the optimal running conditions for both emission and fuel consumption may change. It would be interesting to investigate this aspect since all operating ships have an aftertreatment system.

This report does not consider the impact of slow steaming has on the engine. Therefore, a research study that investigates how the engine is affected in the long run, and whether there will be increased or reduced maintenance required, would be highly relevant. Additionally, an investigation into external factors that affect slow steaming would be interest to research. The report does conclude that slow steaming saves fuel and lower emissions when not considering the weather conditions, hull design, and other external factors.

Further research that would be interesting to investigate would be how much fuel could be saved by combining other fuel reduction strategies with slow steaming. Strategies such as trim optimization may be possible to combined with slow steaming, it would be interesting to see the difference combining strategies would makes. Furthermore, an investigation on how much could be saved in an economical point of view when slow steaming and considering the outside factors, could be interesting for the ship owners and other stakeholders.

Also, as of now engine manufactures are investigating future fuels that will be implemented to the shipping industry. Fuels such as Ammonia has high potential of becoming a future fuel, and a study investigating how such a fuel would affect the environment when implemented into the shipping industry would be of high investigatory purpose.

REFERENCES

Amin Mohammed, H. (2023). *Ship emissions reduction via slow steaming without disrupting the logistical supply chain: A case study of the port of Felixstowe*. https://doi.org/10.1080/25725084.2023.2280416

Berthelsen, F. H., & Nielsen, U. D. (2021). *Prediction of ships' speed-power relationship at speed intervals below the design speed*. https://doi.org/10.1016/j.trd.2021.102996

Dere, C., Zincir, B., Inal, O. B., & Deniz, C. (2022). Investigation of the adverse effects of slow steaming operations for ships. *Https://Doi.Org/10.1177/14750902221074191*, *236*(4), 1069–1081. https://doi.org/10.1177/14750902221074191

DNV. (n.d.). *IMO Regulations*. Retrieved March 25, 2024, from https://www.dnv.com/maritime/hub/decarbonize-shipping/key-drivers/regulations/imo-regulations/?fbclid=IwAR3X3sBM19mzvGiGZnLWD4w3BAHhRAbXUcVAb_v2vnuteMAT1WTf-I4J4-0

Elkafas, A. G. (2022). *Advanced operational measure for reducing fuel consumption onboard ships*. *1,* 3. https://doi.org/10.1007/s11356-022-22116-7

EPA. (n.d.). *Basic Information about Carbon Monoxide (CO) Outdoor Air Pollution | US EPA*. Retrieved March 26, 2024, from https://www.epa.gov/co-pollution/basic-information-about-carbon-monoxide-co-outdoor-air-pollution#Reduce

European Commission. (n.d.). *Methane emissions - European Commission*. European Commission. Retrieved February 16, 2024, from https://energy.ec.europa.eu/topics/oil-gas-and-coal/methane-emissions_en

European Commission. (2020). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS on an EU - strategy to reduce methane emissions. *European Commission*. https://www.eea.europa.eu/media/newsreleases/many-europeans-still-exposed-to-air-pollution-2015/premature-

Farkas, A., Degiuli, N., Martić, I., & Mikulić, A. (2023). Benefits of slow steaming in realistic sailing conditions along different sailing routes. *Ocean Engineering*, *275*, 114143. https://doi.org/10.1016/J.OCEANENG.2023.114143

Garcia, L., Gehle, S., & Schakel, J. (2014). *Impact of Low Load Operation in Modern Low Speed 2-Stroke Diesel Engines on Cylinder Liner Wear Caused by Increased Acid Condensation 101*.

Glujić, D., Kralj, P., & Dujmović, J. (2022). Considerations on the Effect of Slow-Steaming to Reduce Carbon Dioxide Emissions from Ships. *Journal of Marine Science and Engineering*, *10*(9). https://doi.org/10.3390/JMSE10091277

Gren, I. M., Brutemark, A., & Jägerbrand, A. (2021). Air pollutants from shipping: Costs of NOx emissions to the Baltic Sea. *Journal of Environmental Management*, *300*, 113824. https://doi.org/10.1016/J.JENVMAN.2021.113824

IMO. (n.d.-a). *Marpol - Annex VI - Regulation 13 - Nitrogen Oxides (NOx)*. Retrieved February 12, 2024, from http://dmr.regs4ships.com.eu1.proxy.openathens.net/docs/international/imo/marpol/ann_06/013.cfm

IMO. (n.d.-b). *Marpol - Annex VI - Regulation 14 - Sulphur Oxides (SOx) and Particulate Matter*. Retrieved February 12, 2024, from http://dmr.regs4ships.com.eu1.proxy.openathens.net/docs/international/imo/marpol/ann_06/014.cfm

IMO. (n.d.-c). *Marpol - Annex VI - Regulation 28 - Operational Carbon Intensity*. Retrieved February 19, 2024, from http://dmr.regs4ships.com.eu1.proxy.openathens.net/docs/international/imo/marpol/ann_06/028.cfm

IMO. (2019). *RESOLUTION MEPC.320(74) - 2019 GUIDELINES FOR CONSISTENT IMPLEMENTATION OF THE 0.50% SULPHUR LIMIT UNDER MARPOL ANNEX VI.*

IMO. (2020). *Fourth IMO Greenhouse Gas Study*.

IMO. (2023). *Special Areas and Emission Control Areas (ECAs) under MARPOL*.

MAN Energy Solutions. (2023). *Basic principles of ship propulsion*. https://www.man-es.com/docs/default-source/document-sync/basic-principles-of-ship-propulsion-eng.pdf

MAN Energy Solutions. (2024a). *7G60ME-C10.5 HPSCR 12100kW Emission*.

MAN Energy Solutions. (2024b). *CEAS Engine Data report 7G60ME-C10.5-HPSCR*.

MAN Energy Solutions. (2024c). *Speed Power Curve*.

Matthew Brander. (2023). *Greenhouse Gases, CO2, CO2e, and Carbon: What Do All These Terms Mean?*

Peli´c, V. P., Bukovac, O., Radonja, R., & Degiuli, N. (2023). *Marine Science and Engineering The Impact of Slow Steaming on Fuel Consumption and CO 2 Emissions of a Container Ship*. https://doi.org/10.3390/jmse11030675

Pelić, V., Bukovac, O., Radonja, R., & Degiuli, N. (2023). The Impact of Slow Steaming on Fuel Consumption and CO2 Emissions of a Container Ship. *Journal of Marine Science and Engineering*, *11*(3). https://doi.org/10.3390/JMSE11030675

Psaraftis, H. N. (2019). Speed Optimization vs Speed Reduction: the Choice between Speed Limits and a Bunker Levy. *Sustainability 2019, Vol. 11, Page 2249*, *11*(8), 2249. https://doi.org/10.3390/SU11082249

Speed, C., Shih, Y.-C., Tzeng, Y.-A., Cheng, C.-W., & Huang, C.-H. (2023). *Speed Optimization in Bulk Carriers: A Weather-Sensitive Approach for Reducing Fuel Consumption*. https://doi.org/10.3390/jmse11102000

Stawowy, M., Kasprzyk, Z., Kamí Nski, W., & Michalska-Po˙ Zoga, I. (2023). Possibility of Marine Low-Speed Engine Piston Ring Wear Prediction during Real Operational Conditions. *Energies 2023, Vol. 16, Page 1433*, *16*(3), 1433. https://doi.org/10.3390/EN16031433

Taskar, B., Sasmal, K., & Yiew, L. J. (2023). A case study for the assessment of fuel savings using speed optimization. *Ocean Engineering*, *274*. https://doi.org/10.1016/j.oceaneng.2023.113990

Tokuslu, A., Bayirhan, I., & Gaziglu, C. (2020). *Investigation the Effect of SO x Emission Reduction on Transit*. *24*, 149–155. https://doi.org/10.2298/TSCI20S1149T

Vakili, S., Ballini, F., Schönborn, A., Christodoulou, A., Dalaklis, D., & Ölçer, A. I. (2023). Assessing the macroeconomic and social impacts of slow steaming in shipping: a literature review on small island developing states and least developed countries. *Journal of Shipping and Trade*, *8*(1). https://doi.org/10.1186/S41072-023-00131-2

Zincir, B. (2023). *Slow steaming application for short-sea shipping to comply with the CII regulation*. https://doi.org/10.21278/brod74202

APPENDIX 1

Table 2 VLSFO Tier II Emission data from (MAN Energy Solutions, 2024a).

Load (%)	Power (kW)	Speed (rpm)	SFOC (g/kWh)	NO_x (kg/h)	SO_x (kg/h)	CO_2 (kg/h)	CO (kg/h)
100%	12,100	82	161.7	133.1	19.6	6,284.50	3.6
95%	11,495	80.6	159.7	133.3	18.4	5,896.40	3.4
90%	10,890	79.2	157.9	132.9	17.2	5,523.10	3.3
85%	10,285	77.7	156.1	131.6	16.1	5,156.80	3.1
80%	9,680	76.1	155.5	129.7	15.1	4,834.80	2.9
75%	9,075	74.5	155.3	127.1	14.1	4,526.80	2.7
70%	8,470	72.8	153.2	127.1	13	4,167.90	2.5
65%	7,865	71	151.2	125.8	11.9	3,819.70	2.4
60%	7,260	69.2	152.2	123.4	11	3,549.20	2.2
55%	6,655	67.2	153.3	119.8	10.2	3,276.90	2
50%	6,050	65.1	154.6	115	9.4	3,004.30	1.8
45%	5,445	62.8	155.9	107.8	8.5	2,726.60	1.6
40%	4,840	60.4	157.3	99.7	7.6	2,445.40	1.5
35%	4,235	57.8	158.8	90.6	6.7	2,160.10	1.3
30%	3,630	54.9	160.4	80.6	5.8	1,870.20	1.1
25%	3,025	51.7	162.1	69.6	4.9	1,575.00	0.9

Table 3 MGO Tier II Emissions data from (MAN Energy Solutions, 2024a).

Load (%)	Power (kW)	Speed (rpm)	SFOC (g/kWh)	NO_x (kg/h)	SO_x (kg/h)	CO_2 (kg/h)	CO (kg/h)
100%	12,100	82	161.7	133.1	3.9	6,169.70	3.6
95%	11,495	80.6	159.7	133.3	3.7	5,788.70	3.4
90%	10,890	79.2	157.9	132.9	3.4	5,422.30	3.3
85%	10,285	77.7	156.1	131.6	3.2	5,062.60	3.1
80%	9,680	76.1	155.5	129.7	3	4,746.50	2.9
75%	9,075	74.5	155.3	127.1	2.8	4,444.10	2.7
70%	8,470	72.8	153.2	127.1	2.6	4,091.80	2.5
65%	7,865	71	151.2	125.8	2.4	3,749.90	2.4
60%	7,260	69.2	152.2	123.4	2.2	3,484.30	2.2
55%	6,655	67.2	153.3	119.8	2	3,217.10	2
50%	6,050	65.1	154.6	115	1.9	2,949.40	1.8
45%	5,445	62.8	155.9	107.8	1.7	2,676.80	1.6
40%	4,840	60.4	157.3	99.7	1.5	2,400.70	1.5
35%	4,235	57.8	158.8	90.6	1.3	2,120.70	1.3
30%	3,630	54.9	160.4	80.6	1.2	1,836.00	1.1
25%	3,025	51.7	162.1	69.6	1	1,546.20	0.9

Table 4 VLSFO Tier III Emissions data from (MAN Energy Solutions, 2024a).

Load (%)	Power (kW)	Speed (rpm)	SFOC (g/kWh)	NO$_x$ (kg/h)	SO$_x$ (kg/h)	CO$_2$ (kg/h)	CO (kg/h)
100%	12,100	82	162.2	36.3	19.6	6,303.90	3.6
95%	11,495	80.6	160.2	34.5	18.4	5,914.90	3.4
90%	10,890	79.2	158.4	32.7	17.2	5,540.60	3.3
85%	10,285	77.7	156.5	30.9	16.1	5,183.30	3.1
80%	9,680	76.1	156.5	29	15.1	4,865.90	2.9
75%	9,075	74.5	156.3	27.2	14.2	4,556.00	2.7
70%	8,470	72.8	154.3	28.8	13.1	4,197.80	2.5
65%	7,865	71	152.3	29.9	12	3,850.00	2.4
60%	7,260	69.2	153.5	30.5	11.1	3,579.50	2.2
55%	6,655	67.2	154.7	30.6	10.3	3,306.80	2
50%	6,050	65.1	156.1	30.3	9.4	3,033.40	1.8
45%	5,445	62.8	157.4	27.2	8.6	2,752.80	1.6
40%	4,840	60.4	158.8	24.2	7.7	2,468.70	1.5
35%	4,235	57.8	160.3	21.2	6.8	2,180.50	1.3
30%	3,630	54.9	162.1	18.2	5.9	1,890.00	1.1
25%	3,025	51.7	163.9	15.1	5	1,592.50	0.9

Table 5 MGO Tier III Emissions data from (MAN Energy Solutions, 2024a).

Load (%)	Power (kW)	Speed (rpm)	SFOC (g/kWh)	NO$_x$ (kg/h)	SOx (kg/h)	CO$_2$ (kg/h)	CO (kg/h)
100%	12,100	82	162.2	36.3	3.9	6,188.80	3.6
95%	11,495	80.6	160.2	34.5	3.7	5,806.90	3.4
90%	10,890	79.2	158.4	32.7	3.4	5,439.40	3.3
85%	10,285	77.7	156.5	30.9	3.2	5,088.60	3.1
80%	9,680	76.1	156.5	29	3	4,777.00	2.9
75%	9,075	74.5	156.3	27.2	2.8	4,472.80	2.7
70%	8,470	72.8	154.3	28.8	2.6	4,121.20	2.5
65%	7,865	71	152.3	29.9	2.4	3,779.70	2.4
60%	7,260	69.2	153.5	30.5	2.2	3,514.10	2.2
55%	6,655	67.2	154.7	30.6	2.1	3,246.40	2
50%	6,050	65.1	156.1	30.3	1.9	2,978.00	1.8
45%	5,445	62.8	157.4	27.2	1.7	2,702.50	1.6
40%	4,840	60.4	158.8	24.2	1.5	2,423.60	1.5
35%	4,235	57.8	160.3	21.2	1.4	2,140.70	1.3
30%	3,630	54.9	162.1	18.2	1.2	1,855.50	1.1
25%	3,025	51.7	163.9	15.1	1	1,563.40	0.9

Table 6 Tier III Fuel Consumption in different conditions data from (MAN Energy Solutions, 2024a).

Load	SFOC Tier II ISO (g/kWh)	SFOC Tier II Trp (g/kWh)	SFOC Tier II Spe (g/kWh)
100%	161.7	163.4	159.8
95%	159.7	161.4	157.8
90%	157.9	159.5	156
85%	156.1	157.8	154.2
80%	155.5	157.1	153.6
75%	155.3	156.9	153.4
70%	153.2	154.8	151.4
65%	151.2	152.8	149.4
60%	152.2	153.8	150.4
55%	153.3	154.9	151.5
50%	154.6	156.3	152.8
45%	155.9	157.6	154
40%	157.3	159	155.4
35%	158.8	160.5	156.9
30%	160.4	162.1	158.5
25%	162.1	163.8	160.1

Table 7 Tier III Fuel Consumption in different conditions data from (MAN Energy Solutions, 2024a).

Load	SFOC Tier III ISO (g/kWh)	SFOC Tier III Trp (g/kWh)	SFOC Tier III Spe (g/kWh)
100%	162.2	163.9	160.3
95%	160.2	161.9	158.3
90%	158.4	160	156.5
85%	156.9	158.5	155
80%	156.5	158.1	154.6
75%	156.3	157.9	154.4
70%	154.3	155.9	152.5
65%	152.4	154	150.6
60%	153.5	155.1	151.7
55%	154.7	156.3	152.9
50%	156.1	157.8	154.3
45%	157.4	159.1	155.5
40%	158.8	160.5	156.9
35%	160.3	162	158.4
30%	162.1	163.8	160.1
25%	163.9	165.6	162

Table 8 HFO Fuel Consumption Tier II in different conditions data from (MAN Energy Solutions, 2024b).

Load	SFOC HFO (g/kWh) Spe	SFOC HFO (g/kWh) Trp	SFOC HFO (g/kWh) ISO
100%	159.8	163.4	161.7
95%	157.8	161.4	159.7
90%	156	159.5	157.9
85%	154.2	157.8	156.1
80%	153.6	157.1	155.5
75%	153.4	156.9	155.3
70%	151.4	154.8	153.2
65%	149.4	152.8	151.2
60%	150.4	153.8	152.2
55%	151.5	154.9	153.3
50%	152.8	156.3	154.6
45%	154	157.6	155.9
40%	155.4	159	157.3
35%	156.9	160.5	158.8
30%	158.5	162.1	160.4
25%	160.1	163.8	162.1

Table 9 HFO Fuel Consumption Tier III in different conditions data from (MAN Energy Solutions, 2024b).

Load	SFOC (g/kWh) ISO	SFOC (g/kWh) spe	SFOC (g/kWh) trp
100%	162.2	160.3	163.9
95%	160.2	158.3	161.9
90%	158.4	156.5	160
85%	156.9	155	158.5
80%	156.5	154.6	158.1
75%	156.3	154.4	157.9
70%	154.3	152.5	155.9
65%	152.4	150.6	154
60%	153.5	151.7	155.1
55%	154.7	152.9	156.3
50%	156.1	154.3	157.8
45%	157.4	155.5	159.1
40%	158.8	156.9	160.5
35%	160.3	158.4	162
30%	162.1	160.1	163.8
25%	163.9	162	165.6

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2024
www.chalmers.se