NTNU – Trondheim
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Impacts of Low Load Operation of Modern Four-Stroke Diesel Engines in Generator Configuration

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MSc-ASSIGNMENT
for
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Impacts of low load operation of modern four-stroke diesel engines in generator configuration

Background

IMO regulations of exhaust emissions require stricter control of diesel engine operation. Normally engines are optimized for operation at high and medium load. Damage reports have given indications that prolonged operation at low load, also combined with transient loads, may increase operational problems and increase damage frequency.

Overall Aim and Focus

The project assignment should look into available diesel engine damage reports and other information in order to identify possible operating problems which may be related to low load engine operation. The analysis should be based on data from ships in operation collected in the data bases of DNVGL.

The assignment should be prepared based on following points:

1. Discussion of the concept of low load operation in terms of power and operating time. Also, discuss the influence of low load operation on engine performance, especially related to combustion and lubrication.

2. Impact of NO_x optimization to comply with IMO Tier requirements on damage frequency or severity.

3. Try to identify, and describe, one or more cases where low load operation seems to have caused increased damage frequency on the diesel engines. If possible, supplement your findings with information given by engine operators and engine manufacturers.

4. Using DNVGLs large database, carry out statistical analysis of engine damage in order to identify possible relations between low load operation and increased damage frequency.

This assignment will be in cooperation with DNV , Tormod O Linnerud, Production Manager

The assignment text must be included as a part of the MSc report.

The report should be written like a research report, with an abstract, conclusions, contents list, reference list, etc. During preparation of the report it is important that the candidate emphasize easily understood and well written text. For ease of reading, the report should contain adequate references at appropriate places to related text, tables and figures. On evaluation, a lot of weight is put on thorough preparation of results, their clear presentation in the form of tables and/or graphs, and on comprehensive discussion.
All used sources must be completely documented. For textbooks and periodicals, author, title, year, page number and eventually figure number must be specified.

In accordance with current regulations, NTNU reserves the right to use any results from the project work in connection with teaching, research, publication, or other activities.

The report including computer programs should be delivered in formats according to current regulations at NTNU.

Department of Marine Technology, 2014-01-29

Harald Valland
professor

Preface

This report presents my thesis for the degree of Master of Science in Marine Technology at the Norwegian University of Science and Technology, NTNU. The thesis is an integrated part of my specialization in Marine Machinery. The work is conducted in its entirety by the author and has been carried out during the spring semester of 2014.

The topic of this thesis is the impacts of low load operations of modern four-stroke diesel engines in generator configuration. The topic has been developed in collaboration with DNV GL and builds on the work done in my project thesis during the autumn semester of 2013.

I would like to thank my academic supervisor, Professor Harald Valland, for providing helpful guidance. In addition I would like to thank the employees I've been in contact with at DNV GL for procuring data and relevant information and suggestions concerning the topic. Thanks to Jørgen Christian Kadal, Dag Harald Williksen, Thomas Dirix, Olav Alexander Tage Strøm and Arthur Iversen for their views and inputs. Thank you very much to Chief Engineer Karlsvik for sharing your "real time" experiences with low load operation. A special thanks to my co-supervisor and contact person, Hanne Solum Bentsen at DNV GL, for good help and motivation throughout the semester.

Trondheim, June 2014

Espen Dalsøren Tufte

Summary

Diesel engines in generator configuration are normally optimized for operations at medium to high engine loads. It is suspected that operations at low loads may increase operational problems and thus the damage frequency. It is also suspected that negative effects off low load operations are aggravated by recent exhaust emission regulations issued by IMO. This thesis describes an investigation of the impacts of low load operations on modern four-stroke diesel engines in generator configuration. The problem has been approached by reviewing existing literature, studying damage cases, analysis of existing finding data and by assessing the industry's experiences with low load operations.

Low load operations of diesel engines are defined as engine operations below 40% of maximum continuous rating. Low load operations are typical for, but not limited to, offshore vessels with dynamic positioning systems. Low load operations of diesel engines cause lower cylinder pressure and thus lower temperature. Low temperature can lead to ignition problems and poor combustion which causes increased soot formation and aggregation of unburned fuel in the cylinder. Low cylinder pressure, soot and unburned fuel deteriorate the piston ring sealing efficiency allowing hot combustion gases, soot particles and unburned fuel to leak past the piston rings. This results in increased lubricating oil consumption and fuel dilution. Fuel dilution of the lubricating oil reduces the viscosity which can collapse critical oil film thicknesses. This can cause premature wear of pistons, rings, liners and crank case bearings. The mechanisms of low load lead to a cycle of degradation which means that diesel engines that run at low loads for longer periods of time can become irreversibly damaged. This is illustrated in this paper by an engine damage case. The damage case presents an engine crankcase breakage initially caused by piston scuffing from lubrication oil breakdown after excessive low load operations.

Most modern diesel engines operate at lower cylinder pressure and thus lower temperatures to comply with stringent IMO NO_X emission requirements. The IMO Tier I and II standards are met by primary measures which aim at reducing the amount of NO_X formed during combustion by optimizing certain engine parameters. Modern NO_X optimized engines are more exposed to low load operations than their predecessors due to initially lower cylinder pressures and temperatures. However, recent developments such as common rail, variable injection timing and variable valve control permit engine operations at lower loads than earlier.

Existing finding data from DNV GL's database have been analysed to determine whether one can substantiate the impacts of low load operations quantitatively. The finding data have been analysed by simple frequency measurements. The results show higher finding frequencies for DP-vessels than non-DP vessels, which could indicate that low load operations may have a negative impact on the operational problems and thus the damage frequency. The finding data have also been evaluated with respect to time to determine whether NO_X optimization aggravates the negative impacts of low load operations. The result showed generally higher finding frequencies for engines installed after 2000 than the ones installed prior to 2000. This could indicate that the introduction of Tier I compliant engines have increased operational problems. However, it could not be determined whether NO_X optimized engines have aggravated the negative impacts of low load operations.

Engine manufacturers that have been interviewed agree that low load operations affect the engine operation negatively, but they do not want to confirm that low load operation increases the engine damage frequency. It is consensus among the engine manufacturers that the engines must be loaded to at least 50% of rated power regularly during low load operations to prevent operational problems. The time interval and load requirements can vary from one engine to another and depending on the engine design.

Sammendrag

Dieselmotorer i generatorkonfigurasjon er normalt optimalisert for å kjøre på middels til høy motorbelastning. Det er mistanke om at overdreven lavlastkjøring kan føre til driftsproblemer og dermed økt skadefrekvens. Samtidig er det mistanke om at de negative konsekvensene som følger av lavlastkjøring, forverres av IMOs krav til redusert utslipp av NO_X. Denne masteroppgaven undersøker hvilke mekanismer som inntreffer ved lavlastkjøring og hvilke konsekvenser disse kan ha på motoren. Konsekvenser av lavlastkjøring har blitt undersøkt ved å studere eksiterende litteratur, studere skaderapporter og ved å analysere kvantitativt eksisterende funndata i GLs database. Det har også blitt foretatt en kvalitativ undersøkelse for å kartlegge motorprodusentenes erfaringer med lavlastkjøring.

Lavlastkjøring er definert som lastforbruk under 40 % av motorens maksimale ytelse. Lavlastkjøring er typisk for generatorsett om bord i offshorefartøy med dynamisk posisjonering. Lav motorbelastning medfører lavt sylindertrykk og dermed lave sylindertemperaturer. Lave sylindertemperaturer fører til tenningsvansker og ufullstendig forbrenning og dermed øker mengden sot og uforbrent drivstoff i kammeret. Sot og uforbrent drivstoff kan føre til glasering av stempelringene og dermed reduseres tetningsegenskapene. Stempelringene er også avhengige av høyt sylindertrykk for å fungere optimalt. Lavt trykk og temperatur i sylinderen vil derfor føre til lekkasje av forbrenningsgasser, sot og uforbrent drivstoff forbi stempelet og ned i oljesumpen. Dette medfører økt forbruk og forurensing av smøreoljen. Store mengder drivstoff i smøreoljen vil redusere viskositeten og dermed smøreegenskapene til oljen. Dette vil kunne medføre at kritiske smøreoljefilmer blir for tynne og dermed utsettes stempler, stempelringer, sylinderforinger og veivhuslagre for ekstrem slitasje.

Mekanismene som er beskrevet ovenfor er bekreftet av motorprodusentene og er også illustrert med et skadeeksempel. Skaderapporten som blir presentert tar for seg et veivhusbrudd på en av generatormotorene om bord på et offshorefartøy. Årsaken til skaden var ekstrem slitasje på stempelet som følge av defekte smøreoljeegenskaper på grunn av forurensing av smøreoljen.

Motorer opererer i dag med lavere trykk og temperatur i sylinderen enn tidligere, for å kunne tilfredsstille IMOs stadig strengere krav til utslipp av NO_X. IMOs Tier I krav kan tilfredsstilles ved å benytte såkalte primærtiltak. Primærtiltak innebærer å redusere mengden NO_X som produseres under forbrenning. Dette gjøres ved å optimere motorparametere med hensyn til lavere NO_X produksjon. NO_X optimaliserte motorer opererer med lavere sylindertrykk og temperaturer og er i utgangspunktet dermed mer utsatt for problemer ved lavlastkjøring enn sine forgjengere. Motordesignere har utviklet teknologi, som for eksempel common rail (fellesrør) og variabel injeksjons- og ventilstyring, som skal sørge for at motorene kan kjøre mer optimalt også på lavere laster. Dette har medført at NO_X optimaliserte motorer håndterer lavlastkjøring bedre i dag enn tidlige, men motorprodusentene understreker at lavlast fortsatt bør begrenses til kortere perioder av gangen.

Eksisterende motorfunn fra DNV GLs database har blitt analysert ved hjelp av enkle frekvensberegninger for å kunne vurdere konsekvensene av lavlastkjøring kvantitativt. Analysen viser at lavlastkjøring kan ha en negativ innvirkning på funnfrekvensene og dermed en negativ innvirkning på operasjonelle problemer. Motorfunn har også blitt analysert for å undersøke om innføringen av NO_X optimaliserte motorer forverrer driftsproblemer som oppstår under lavlastkjøring. Analysen viser høyere funnfrekvenser for motorer som er installert om bord på skip etter 2000. Dette kan være en indikasjon på at krav til NO_X optimaliserte motorer har ført til flere driftsproblemer. Ut i fra de analysene som har blitt gjort, er det ikke mulig å avgjøre om NO_X optimaliserte motorer forverrer driftsproblemene som er knyttet til lavlastkjøring.

Motorprodusentene er enige om at lavlastkjøring kan medføre driftsproblemer, men ønsker ikke, av hensyn til sine kunder, å uttale seg om hvorvidt lavlastkjøring fører til høyere skadefrekvens på deres motorer. Det er enighet blant motorprodusentene om at motorbelastingen må økes til minst 50 % av maksimal ytelse med jevne mellomrom under lengre lavlastperioder for å forhindre at problemer oppstår. Et lastpådrag vil øke trykket og dermed temperaturen i forbrenningskammeret. Trykkøkningen vil medføre at stempelringene igjen vil fungere som normalt og dermed kunne skrape av avsetninger som har heftet seg på sylinderforingen. Høyere temperaturer medfører at uforbrent drivstoff og sot kan brennes bort. Krav til lastpådrag og til tidsintervall mellom hvert lastpådrag varier fra en motor til en annen avhengig av motorens design. Retningslinjer for lavlastdrift er uten unntak spesifisert i motorens brukermanual.

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Nomenclature

A/E	Auxiliary engine
AIS	Automatic identification system
AN	Acidity number
BDC	Bottom dead centre
BN	Base number
CAD	Crank angle degrees
CCAI	Calculated carbon aromaticity index
CII	Calculated ignition index
CN	Cetane number
CO	Carbon monoxide
CO_2	Carbon dioxide
DP	Dynamic positioning
DPF	Diesel particulate filter
ECA	Emission Control Area
EGR	Exhaust gas recirculation
EGR	Exhaust gas recirculation
EIAAP	Engine International Air Pollution Prevention
EOI	End of injection
EVC	Exhaust valve closing
EVO	Exhaust valve opening
FIA	Fuel ignition analysers
HC	Hydrocarbons
HCO	Heavy cycle oil
HFO	Heavy fuel oil
HPCR	High pressure common rail (Cummins)
HPCR	High pressure common rail
IMO	International Maritime Organization

IMR	Inspection, maintenance and repair vessel
IVC	Inlet valve closing
IVO	Inlet valve opening
LCO	Light cycle oil
LSFO	Low sulphur fuel oil
M/E	Main engine
MCR	Maximum continuous rating
MCRS	Modular common rail system (Cummins Marine)
MDO	Marine diesel oil
MGO	Marine gas oil
MOU	Mobile offshore unit
NECA	NO_X Emission Control Area
NO_X	Nitric oxides
NPS	Nauticus Production System
OSV	Offshore supply vessel
OSV	Offshore specialised vessel
ROHR	Rate of heat release
RPM	Revolutions per minute
SCR	Selective catalytic reduction
SiO	Ships in operation
SOI	Start of injection
SO_X	Sulphur oxides
TDC	Top dead centre
VIS	Vessel information structure

Chapter 1
Introduction

1.1 Background

The diesel engine has been the workhorse in marine industry for decades and is continuously being developed for higher efficiencies and reduced emissions. Diesel engines have long been the preferred choice for direct-mechanical propulsion systems, but diesel-diesel electric propulsion systems have become increasingly popular over the last decades. Diesel engines in generator configuration are normally optimized for operations at medium to high loads. It is suspected that operations at low loads combined with transient loads may increase operational problems and thus the engine damage frequency. It is also suspected that the negative effects of low load operations are aggravated by the exhaust emission regulations issued by the International Maritime Organisation (IMO). Of particular significance are the emission standards concerning emission of nitrogen oxides and sulphur oxides.

A number of diesel engine damages has been reported over the last years that possibly can be linked to low load operations. This issue concerns relatively new engines from different engine manufacturers of different designs and sizes. The engine types affected are both in-line and V-engines, with power ranging from 500–2200 kW and engine speeds ranging from 1500–1800 rpm. All the damaged engines have been operated as generator drives on ships with diesel-electric propulsion and dynamic positioning systems [1].

1.2 Motivation

A number of diesel engine damages has been reported over the last years that possibly can be linked to low load operations. The motivation for this work is to better understand the mechanisms that may cause operational problems to the diesel engines during low load operations. The purpose of this thesis is to explain these mechanisms and create a comprehensive overview of the engine damages that can be caused by excessive low load operations. This type of documentation is lacking today and thus requested by DNV GL.

1.3 Method

The approach to this problem can be divided into four main parts. Much work has been laid down in advance of this master thesis, where relevant literature has been reviewed to determine what have already been written about low load operations of diesel engines. The pre-work proved that there has not been conducted too many studies on the topic, but that many of the mechanisms that are thought to affect the engine during low load operations are known from common diesel engine theory. To get a better understanding and approach to the problem, is theory that is considered important for the problem reviewed in the first part of this thesis.

The second part of this thesis presents a damage case which intends to illustrate mechanisms and damages that may result from extensive low load operations of diesel engines in generator configuration. Originally, the intention was to present several damage cases to better the understanding of the mechanisms and damages that may occur during low load operations. Unfortunately, it has not been possible to get hold of a sufficient number of damage reports where low load operation is suspected to be the underlying damage cause. The damage case presented can thus not be used to establish any general conclusions, but are very useful for illustration purposes.

The third part of this thesis analyses qualitatively diesel engine finding data, which have been extracted from DNV GL's database. This analysis is based on simple frequency measurements of diesel engine findings. The finding frequency describes the number of findings registered on a component per thousand component year. The intention is to investigate whether low load operations increase the damage frequency of diesel engines in generator configuration and whether the negative effects of low load operations are aggravated by the NO_X emission regulations issued by IMO.

The last part of this thesis examines the industrial experiences with low load operations of diesel engines in generator configuration. Engine manufacturers and engine operators have been interviewed to assess the impacts of low load operations qualitatively. Interesting questions are related to typical mechanisms occurring at low loads, how these affect the engines, recommended corrective actions and how stringent NO_X emission regulations have influenced on the modern four-stroke diesel engine.

1.4 Structure of the Thesis

The approach to the problem is described by four main parts. The structure of this thesis reflects the approach of the problem and includes the flowing seven chapters:

1. Introduction
2. Literature Review
3. Case Study
4. Finding Analysis
5. Industrial Experience
6. Discussion
7. Conclusion

1.5 Low Load Operations

Low load operations of diesel engines are defined by DNV GL [2] as engine operations at loads below 40% of maximum continuous rating. Engine loads below 25% are defined as extreme low loads. Engine loads in the range of 40–80% is defined as regular generator operation load. Definitions of the entire load range are presented in Table 1-1.

Table 1-1: Load levels in percentage of maximum continuous rating [2]

0 – 25%	Extreme low load
25 – 40 %	Low load
40 – 80 %	Regular generator operation load
80 – 90 %	High load
90 – 100 %	Extreme high load

From an engine designer’s point of view, short periods of low load operations are acceptable given that the engine is brought to full load on regular basis. Marine diesel engines in generator configuration may experience long periods of low load operations either because they are left idling as standby power generating units or serving very low power demands during vessel operation.

Low load operations of medium- and high-speed four-stroke diesel engines must not be confused with slow steaming. Slow steaming is a process of deliberately reducing the engine speed of the slow-speed two-stroke engines to cut down fuel consumption and carbon emissions. According to Sanguri [3], slow steaming has been adopted by many shipping companies and ship owners in order to survive in the tough times of rising fuel prices and financial recession

Low load operations of diesel engines in generator configuration are typical for, but not limited to, offshore operating vessels with dynamic positioning (DP) systems. Offshore operating vessels may experience a large variation in load demand as they divide their time between transit and stationkeeping operations. Statiokeeping operations impose stringent demands to the electrical power generation system which are given by the International Maritime Organization (IMO) and thus the classification societies. According to DNV GL [4], the traditional industry practice for redundant DP systems is typically based on an approach where the redundancy is based on running machinery and not utilizing stand-by units or change over mechanisms. These power generation systems have very high reliability due to multiple engine redundancy which means that the power capacity often is much higher than the load demand during operation. A typical operational profile for gensets on board a platform supply vessel (PSV) is shown in the figure below. The abscissa shows the engine power rating in percentage of maximum continuous power and the vertical axis shows vessel operating time in hours. The diagram shows that these gensets are running at extreme low loads for more than 60% of operation time.

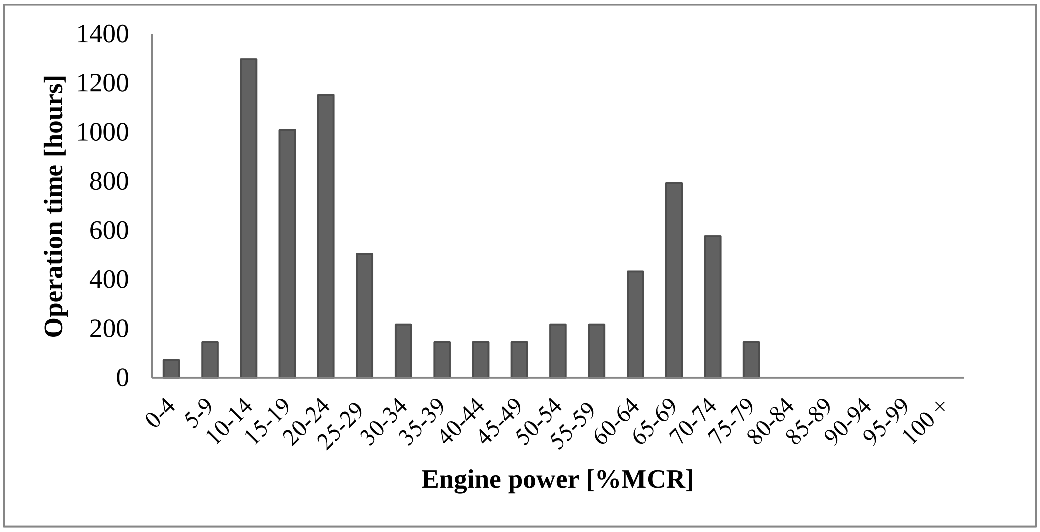


Figure 1-1: Typical operational profile for offshore vessels. Courtesy of [5]

1.6 Transient Load Operations

Transient load operations are together with low load operations suspected to have a negative impact on engine operating conditions. The definition and possible impacts of transient load operations are presented in the following subchapter, but transient load operations will not be emphasised further in this thesis as the main focus are the impact of low load operations of diesel engines.

Diesel engines in general may experience a large variety of operating conditions that can be classified as transient, but for marine diesel engines operating as generator drives are transient load changes regarded as the most important transient condition. Transient load operations of marine diesel engine generator drives are due to sudden changes in power demand from propulsion or deck equipment. Figure 1-2 shows stepwise the load increase in a turbocharged diesel engine used as generator drive. Important stages of the load change are shown in bold letters.

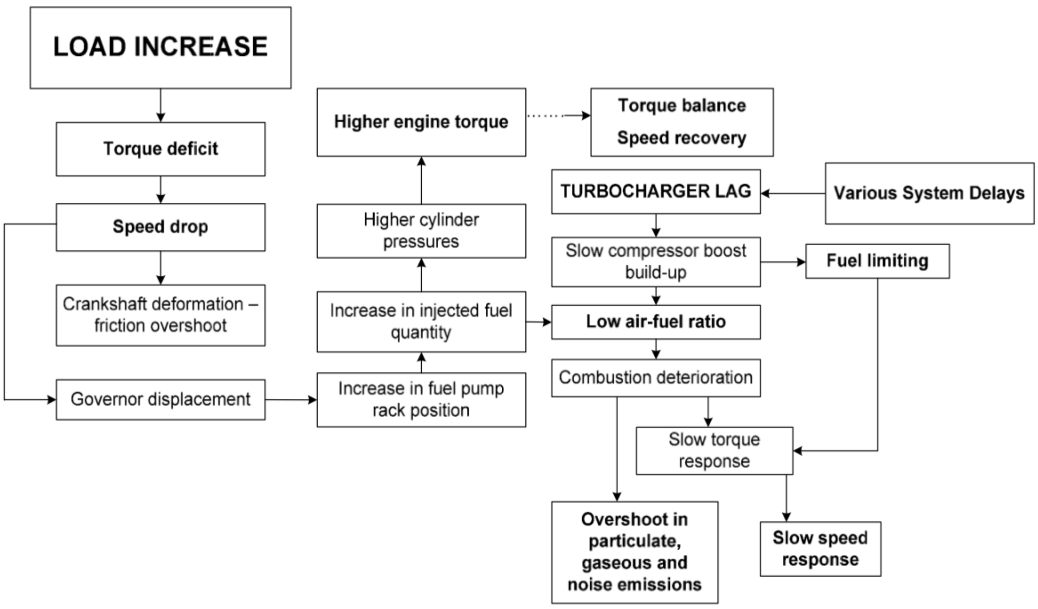


Figure 1-2: Load increase. Courtesy of [6]

The load increase that is illustrated in Figure 1-2 can be described as in the following. Initially the engine and load torque is equal and the air-fuel ratio is relatively high. When the load increases the engine experiences a loss in net torque because the engine torque cannot instantly match the increased load. The torque loss causes the engine speed to drop and thus the governor adjusts to increase the amount of fuel to compensate. Consequently the air-fuel ratio decreases because of insufficient air mass flow rate, which is due to delayed response in the turbocharger. The turbocharger delay can be explained by the fact that the increased exhaust gas power is not capable of increasing the turbine power instantaneously because of the turbocharger inertia. During this short period of delay the engine is running as a naturally aspirated engine and the air-fuel ratio may reach values much lower than stoichiometric. Such low air-fuel values may lead to intolerable smoke emissions and formation of soot. The low air-fuel ratio increases the temperatures in the combustion chamber, which can give a higher rate of NO_X formation depending on the amount of oxygen available. Mechanical stresses in form of deceleration are applied to the crankshaft, as the load torque is larger than the engine torque. The highest value of deceleration is reached in the first cycles where the torque difference between engine and load is at its maximum.

1.7 Diesel Engines in Generator Configuration

The work of this thesis focuses on the impacts of low load operations of diesel engines in generator configuration. Marine diesel engines in generator configurations are commonly referred to as gensets and can be divided into auxiliary gensets or main gensets based on the main propulsion principle of the vessel they are installed on. Diesel-mechanical and diesel-electric propulsions systems dominate the ship propulsion market today and are described as follows:

Diesel-Mechanical Propulsion

Diesel-mechanical propulsion, also referred to as conventional propulsion, is a direct driven or geared propulsion system. The propellers can be directly driven by low-speed two stroke engines or geared driven by four stroke medium-speed engines. The large two-stroke engines remain as the most popular propulsion alternative for deep-sea cargo ships, while medium-speed engines dominate as propulsion alternative for smaller cargo ships as well as larger specialised vessels such as cruise vessels, ferries and RoRo freight carriers [7].

Diesel-Electric Propulsion

Diesel-electric propulsion is in this study defined as a form of indirect drive using electric motors for propulsion and power stations based on multi medium- or high-speed gensets. Diesel-electric propulsion is dominant in cruise ships, new generations of LNG-carriers, short sea and deep sea chemical carriers, North Sea shuttle tankers, offshore vessels and ferries [7].

Genset Configurations

Gensets on vessels with conventional propulsion is in this study referred to as auxiliary gensets. These are primarily used to supply electrical power to electrical consumers on board. Gensets on vessels with diesel-electric propulsion are referred to as main gensets and are used for propulsion in addition to supply the electrical power the consumers on board. In case of DP-vessels, the gensets must supply additional electrical power to DP-thrusters to ensure stationkeeping capabilities. DP-systems are found on vessels with conventional and electric propulsion. Vessels with conventional propulsion utilize their auxiliary engines to supply electric power to DP-thrusters to ensure stationkeeping capabilities. DP operations imposes large variations in load which means that the load profiles for main and auxiliary engines on DP-vessels most likely will not be as uniform as the load profiles for main and auxiliary engines on board non DP-vessels.

Chapter 2
Literature Review

To better understand the mechanisms that can cause operational problems during low load operations, existing literature have been reviewed. Scientific literature on impacts of low load operation on modern diesel engines has proved to be limited. This literature review treats topics concerning marine diesel engines, marine fuels, marine exhaust formation and restrictions, marine lubricants, tribology and maintenance. These are all important topics that can be used to substantiate the discussion of impacts of low load operations on diesel engines.

2.1 Marine Diesel Engines

The diesel engine has been the workhorse in marine industry for decades and is continuously being developed for higher efficiencies and reduced emissions. The following section intends to describe basic diesel engine theory and important features of the modern four-stroke diesel engine to better understand mechanisms that can affect the diesel engine during low loads operations.

2.1.1 Four-Stroke Cycle

The four-stroke diesel engine cycle consist of intake, compression, expansion and exhaust strokes and is completed in two revolutions of the crankshaft. During the intake stroke, fresh air is inducted into the cylinder through intake valves. The fresh air is then compressed by the piston in the compression stroke. Fuel is injected into the cylinder near top dead centre (TDC) and ignites due to the high temperature caused by the high cylinder pressure. Gases expand and push the piston downwards in the expansion stroke. After reaching the bottom dead centre (BDC), the burned gases are pushed through the exhaust valves during the exhaust stroke. The engine cycle is not affected by part loads directly, but the processes taking place during this cycle is affected in many ways.

2.1.2 Engine Speed

Marine diesel engines can be categorized by their rotational speed into three groups named high-, medium- and low-speed engines. High- and medium-speed engines are predominantly four-stroke engines and are both used for propelling smaller commercial vessels as well as generator drives. The crossover point between medium- and high-speed diesel engines is not sharply defined, but for the purpose of this study engines running at 1000 rpm and above are defined as high-speed engines. Valid for both high- and medium speed engines driving generators is that the engine speed has to satisfy the interrelation between the frequency of an alternator (50 Hz or 60 Hz) and the number of pole pairs. The high-speed engine operates at higher piston speeds than the typical medium-speed engine and burns distillate fuels in preference to lower graded heavy fuel oils. High-speed engines have generally higher specific power outputs and higher combustion pressures and exhaust temperatures than the medium-speed engines.

2.1.3 Combustion Process

Fuel ignition in the diesel engine is attained by high temperature resulting from compression of the cylinder charge air. The combustion of the diesel engine spray is a combination of partially premixed and partially diffusive combustion. The combustion process can be described by four stages, including the ignition delay, which are common to all diesel engines and illustrated by Figure 2-1.

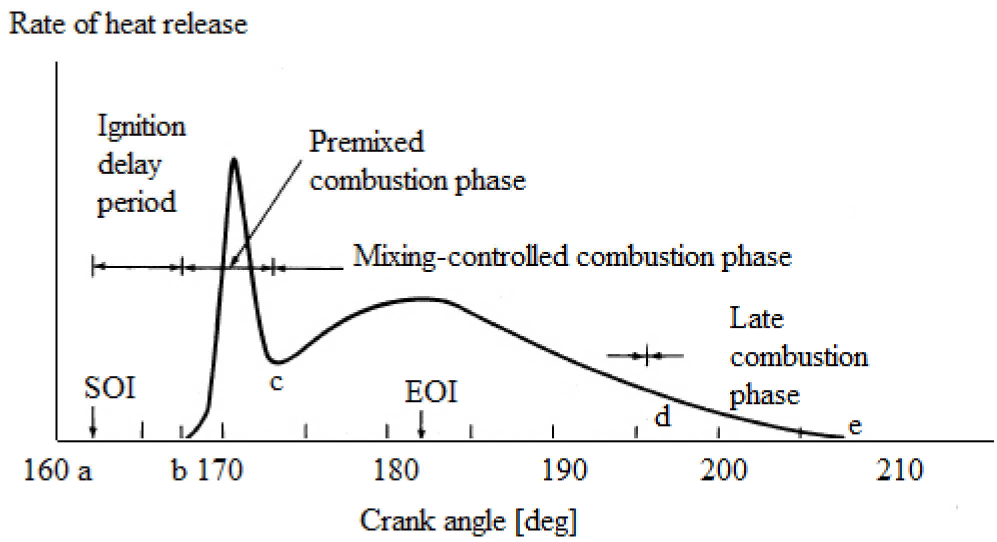


Figure 2-1: Combustion phases and the rate of heat release. Courtesy of [8]

Ignition delay (a-b) is defined as the period from when the fuel injection starts (SOI) to the onset of combustion. Premixed combustion phase (b-c) is the first phase and is the combustion of fuel which has mixed with air to within the flammability limits during the ignition delay period. This phase occurs rapidly in a few crank angle degrees and is characterized by high rates of heat release. The next phase is the mixing controlled combustion (c-d). After the fuel and air which was premixed during the ignition delay is consumed, the burning rate is controlled by the rate at which the mixture becomes available for burning. The injection of fuel ends in this phase (EOI). The last phase is called late combustion (d-e). The burning continues at a lower rate well into the expansion stroke. This is combustion of any unburned liquid fuel and soot when no additional fuel is introduced. The combustion in a diesel engine occurs throughout the chamber over a range of equivalence ratios dictated by the fuel-air mixing before and during the combustion phases. In general most of the combustion occurs under very rich conditions within the head of jet. This produces considerable amounts of solid carbon, commonly referred to as soot.

2.1.4 Combustion Temperature

The temperatures of the diesel flame are very high and a peak temperature of 2700 K has been measured [9]. Heat loss to engine surface metal and excess air causes the gas temperature to be significantly lower than the flame temperature. The gas temperature is also reduced during the piston expansion stroke. The gas temperature is decisive for high combustion efficiency as well as for the removal of engine deposits. At reduced load, the fuel/air-ratio is reduced and thus the gas temperature reduced.

2.1.5 Fuel Injection

Finely atomized fuel is introduced into the compressed air in the cylinder during the compression stroke. The cylinder pressure at this point can be up to 230 bar and the pressure at the atomizer can be between 1300–1800 bar in turbocharged engines [7]. High injection pressures at full load reduces the duration of injection which is favourable in terms of fuel economy, emissions and the ability to accept low grade fuels. In a mechanical fuel injection system, the injection pressure is a function of engine speed and load. During low load operations the injection pressure drops, which result in very large fuel droplets that will not ignite. This can be avoided by using a common rail injection system which ensures that the same high injection pressure is maintained at all engine loads. Most modern four-stroke diesel engines are using this technology. Figure 2-2 shows a comparison of the common rail injection system and a conventional mechanical injection system for different engine loads at constant engine speed. In contrast to conventional systems, common rail systems allow a high injection pressure and small fuel droplets to be maintained down to idling [7]. Electronic fuel injection was first introduced to high-speed engines, but is today successfully applied to medium-speed engines as well. Electronically controlled fuel injection is today essential to meet exhaust emission legislation together with higher injection rates, higher injection pressures, optimized spray patterns, flow-controlled nozzles and low sac volume nozzles. As well as limiting harmful emissions, electronic fuel injection is said to offer enhanced reliability, diagnostic capability, optimized timing and fuel control for all load and speed conditions, including transient operation [7].

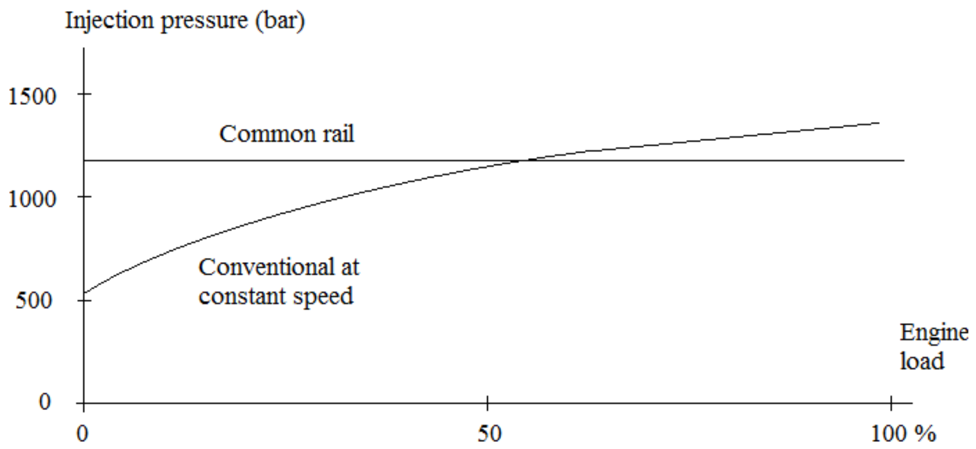


Figure 2-2: Injection pressure and engine load. Courtesy of [7]

2.1.6 Valve Timing

Exhaust valve opening (EVO) generally occur 40–60 crank angle degrees (CAD) before BDC during the expansion stroke. EVO is set to minimize loss of piston expansion work due to EVO before BDC and at the same time minimize piston pumping work which requires EVO before BDC. These two requirements are contradictive which means that EVO timing is a trade-off between lost expansion work and pumping work. Intake valve opening (IVO) normally takes place before TDC during the exhaust stroke and exhaust valve closing (EVC) normally takes place after TDC during the intake stroke. The time when both exhaust and intake valves are open is called the overlap region. The purpose of this overlap is to increase the scavenging of the residual gases in the cylinder so that more fresh air can be trapped inside. The length of the overlap region is in many engines restricted to avoid contact between piston and valve due to geometric limitations. Intake valve closing (IVC) is generally set to

20–60 CAD after BDC during the compression stroke. IVC timing is in most cases set to maximize the volumetric efficiency. A valve timing diagram is shown in Figure 2-3. Volumetric efficiency is used as an overall measure of the effectiveness of a four stroke cycle engine and its intake and exhaust systems as an air pumping device.

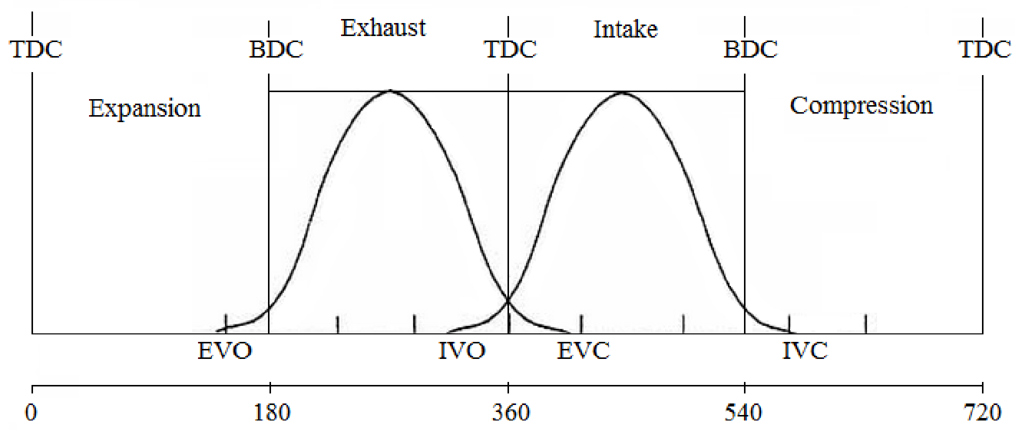


Figure 2-3: Valve timing diagram. Courtesy of [8]

Miller timing is a preferable IVC strategy to improve engine efficiency and reduce NO_X emissions. According to Codan and Vlaskos [10], practically every modern diesel engine is today operated with at least moderate Miller timing. Miller cycle is achieved by closing the intake valve earlier or later than normal i.e. early or late IVC. This type of inlet valve timing reduces the effective compression stroke so it becomes shorter than the expansion stroke. Reducing the effective compression stroke lowers the combustion temperature which is one of the key factors to reduce NO_X emissions. Shorter compression stroke must be compensated by higher charge air pressure i.e. increasing demands is made on the turbocharging system. Thus Miller cycle can give cold start problems, increased smoke emissions and operating problems at part load and especially at low load. Such problems can be avoided by switching to a more beneficial timing by using a variable inlet valve closing system.

2.1.7 Cylinder Arrangement

The upper region of the piston is called the piston crown. The shape of the piston crown is important for how swirl and squish are generated which in turn determines how fuel and air is mixed in the cylinder. The piston bowl can be relatively flat so that the fuel is injected nearly horizontally towards the cylinder wall. Some engines have deeper piston bowls where the fuel is injected at lower angles into the bowl. Piston rings form the seal between the cylinder liner and the piston, preventing leakage of high temperature combustion gases. The lower piston ring is the oil ring, which is designed to collect and distribute oil on the cylinder liner. Removing excess lubricating oil from the cylinder liner prevents an excessive build-up of carbon deposits around the rings and on the piston crown. The piston ring sealing efficiency relies on the cylinder pressure, which can be problematic at low engine loads. The piston pin or wrist pin connects the piston to the connecting rod. Most modern marine medium- and high-speed engines are equipped with a carbon-cutting ring, also termed as anti-polishing ring or fire ring. The ring is inserted in the upper part of the cylinder liner between the top piston ring turning point and the top of the cylinder liner specified to eliminate the phenomenon of cylinder bore polishing caused by carbon deposits. A secondary function is that the carbon-cutting ring helps to reduce the lubrication oil consumption. The ring causes a compressive effect that forces excessive lubrication oil away from the combustion zone [7].

2.2 Marine Fuels

Different types of fuel oil applications and environmental considerations have led to different types of fuel oil specifications. Fuel related operational problems have been introduced with the upgrade of the refinery process from straight run to complex refining in the last decades [11]. This subchapter intends to review relevant marine fuels and fuel properties affecting combustion process and thus engine operation. Most fuel related problems concern heavy fuel oils, but some problems also concern distillate fuels.

2.2.1 Fuel Standards

The literature often refers to Marine Gas Oil (MGO), Marine Diesel Oil (MDO) and Heavy Fuel Oil (HFO) when describing marine fuel types. MGO and MDO are marine distillate fuels, while HFO is a residual fuel. These are not standardised fuel grades, but can be translated into DMA, DMB and RMx which are defined in the International Standard ISO 8217. Both distillates and residual fuels are used to fuel modern four-stroke diesel engines in generator configuration. Most medium-speed diesel engines can run on both residual and distillate fuels while high-speed diesel engines mostly run on distillate fuels.

2.2.2 Low Sulphur Fuels

The sulphur content of marine fuels depends on the crude oil origin and the refining process. During the combustion process, sulphur is converted into sulphur oxides. These oxides are corrosive to engine piston liners and must be neutralized by the cylinder lubricant. If the correct lubricant is used, the sulphur content of marine fuels is technically not important, but sulphur oxides do have environmental implications. Fuels that are within the specification of ISO 8217:2010 are not necessary in compliance with the regulations in force at the vessel's location. IMO MARPOL sets limitations regarding the sulphur content of any fuel oil used on board ships. Low sulphur fuels may have a negative impact on different fuel properties depending on the fuel type. DNV GL [12] suggests a relation between fuel properties and fuel types as shown in Table 2-1.

Table 2-1: Low sulphur fuel properties and fuel types [12]

Low viscosity	MDO
Lubricity	MGO/MDO
Acidity	MGO/MDO/HFO
Flash point	MGO/MDO/HFO
Ignition and combustion quality	HFO
Increased catalytic fines	HFO

2.2.3 Fuel Properties

This subsection reviews marine fuel properties that may have impact on the diesel engine operations. ISO 8217 specifies the required properties for different fuels at the time and place for custody transfer. According to ISO 8217 [13], the general requirement is that the fuel shall conform to the characteristics and limits given in the Standard when tested in accordance with methods specified in the Standard. Fuel properties reviewed in this subsection are given in Table 2-2.

Table 2-2: Fuel requirements according to ISO 8217:2010 [13]

Characteristics	Unit	Limit	MGO/ DMA	MDO/ DMB	HFO/ RMx
Viscosity	mm^2/s	max.	6	11	700
		min.	2	2	N/A
Density	kg/m^3	max.	890	900	1010
Cetane index	-	min.	40	35	N/A
CCAI	-	max.	N/A	N/A	870
Sulphur	mass %	max.	1.5 [1]	2.0 [1]	S/R [2]
Flash point	°C	min.	60	60	60
Acid number	mg KOH/g	max.	0.5	0.5	2.5
Carbon residue	mass %	max.	-	0.3	20.0
Ash	mass %	max.	0.01	0.01	0.15
Water	volume %	max.	-	0.3	0.5
Aluminium + silicon	mg/kg	max.	N/A	N/A	60

[1] Notwithstanding the limits given, the purchaser shall define the maximum sulphur in accordance with relevant statutory limits.

[2] Statutory requirements (S/R). The purchaser shall define the maximum sulphur in accordance with relevant statutory limits.

Viscosity

The viscosity at the moment the fuel leaves the injectors must be within the limits specified by the engine manufacturer to obtain an optimal spray pattern. The spray pattern is important to obtain sufficient fuel atomization in a very short time. Viscosity outside the given limits will lead to poor combustion and thus deposit formations. Excessive formation of deposits may lead to piston scuffing and piston ring failures. The viscosity of the fuel is controlled by the preheating system on board the ship and the fuel viscosity decreases with increased fuel temperature. Too low viscosity affects the lubricating properties of the fuel, which affects all components that depend on the fuel for lubrication. This is mainly a problem to high-pressure fuel pumps where low viscosity can lead to increased wear and even breakage. Low sulphur MDOs has often a lower viscosity than fuels with “normal” sulphur content. Most marine equipment designed for the use of MGO or MDO require a fuel viscosity not lower than about two centistokes at operating temperature. Low sulphur MDO has typically viscosity in the lower allowable range at 40°C [14]. The fuel temperature will normally increase between the storage tank and engine because of pump friction, ambient temperature and recirculation of unused fuel. This will often lead to fuel temperatures higher than 40°C and hence viscosities outside the allowable viscosity range [12].

Density

The fuel density gives an indication of the ignition quality of the fuel within a certain product class. This is in particular applicable to the low viscosity IFOs. High levels of aromatics increase the density and negatively affect the ignition quality of the fuel. The fuel density is important for the on board purification of the fuel. Separation techniques to separate water and fuel are based on the difference in density between the two substances. Diesel engine fuels should ideally be free from dissolved water and salts and extra centrifuging is thus required for high gravity fuels.

Ignition quality

The cetane number (CN) is a measure of the ignition quality of diesel engine fuels. The cetane index is a calculated number based on the density and distillation range of the fuel and is applicable for gasoil and distillate fuels. High cetane numbers denote a shorter ignition delay period, which is a necessity for high-speed diesel engines. Other scales used are used for residual fuels. CCAI is one indicator of the ignition delay which is calculated from the density and the viscosity of the fuel. CCAI limits are given in ISO 8217:2010. Some engine manufacturers even specify CCAI limits for their engines depending on engine type and application [11]. The ignition quality varies substantially for heavy fuel oils. Low sulphur heavy fuel oils in particular have poorer ignition quality than others due to the production process. Low ignition quality may cause trouble at engine start-up and during low loads operations, particularly if the engine is not sufficiently preheated. Poor ignition quality may result in late ignition, poor combustion or prolonged combustion. This can lead to increased soot formation and aggregation of unburned fuel in the cylinders. Sometimes the soot formation is so excessive that the resulting fouling inhibits moving parts such as valves. Modern diesel engines have higher compression ratios and more optimized compression ratios than earlier engine designs and are not that sensitive to the ignition properties of heavy fuel oils as their predecessors.

Flash point

Flash point is the temperature at which the vapours of a fuel ignite when a test flame is applied [13]. The lower limit flash point for all fuels to be used in bulk on board vessels is set at 60°C according to SOLAS. Low sulphur fuel can be manufactured by mixing a normal sulphur grade fuel with very low sulphur graded fuels. These lighter fraction fuels have a much lower flashpoint than “normal” sulphur fuel grades. The flash point of low sulphur fuel grades can be as low as 43°C [14], which will reduce the flash point of the new fuel blends significantly.

Acidity

Fuels with high acid numbers arising from acidic compounds, occasionally cause accelerated damage to diesel engines [13]. Such damage is found primarily within the fuel injection equipment. All fuels have a naturally occurring acid number which is generally less than 0.5 mg/KOH/g for distillate fuels and generally less than 2.5 mg KOH/g for residual fuels [13]. Significantly higher acid number levels may indicate large amounts of acidic compounds and other contaminants. A decrease in the fuel sulphur content decreases the acidity hazard. The cylinder lubrication philosophy is based on the principle that the lubrication oil, which is supplied to the cylinders, contains sufficient alkaline additives to neutralise the corrosive effect of the acidic sulphur products formed during combustion [12]. This means that when the amount of sulphur is decreased in the fuel, the amount of neutralising additives shall be reduced accordingly. Too high amounts of additives in the oil may lead to build-up of deposits that can be harmful to the lubricating film that protects the cylinder liner.

Carbon residues

Carbon rich fuels are more difficult to burn and have a combustion characteristic that can lead to increased formation of soot and carbon deposits. The carbon residue value is used as an indication of the fuel's tendency to deposit carbon [13]. This particular property is independent of combustion conditions, but still an important mechanism related to the formation of carbon deposits in the cylinder.

Ash content

The ash content is a measure of the metals present in the fuel. Residual fuels contain some metallic species, where some are naturally present such as vanadium, sodium, calcium and nickel. Other metallic species are introduced from external sources such as sodium, aluminium, silicon and iron. During combustion, these metals are converted into solid particles of oxides, sulphates or more complex compounds. These particles are collectively known as ash. At certain temperatures, these solid ash particles become partly fluid and adhere to components in the combustion system. Adhering ash deposits can cause damage either by a process called hot corrosion [13]. The temperature, at which the ash particles start to become fluid and to stick to surfaces, is often referred to as the stiction temperature [13]. This temperature is lowest for ashes that are rich in vanadium and/or sodium. For this reason is particular attention paid to these metals in the fuel. Vanadium is a natural component of the fuel and the only practical way to restrict the metal is by limiting its content in the production. Unlike vanadium, sodium is not usually present in the fuel. High levels of sodium are associated with sea water contamination.

Asphaltene content

High asphaltene content indicate that fuel is difficult to ignite and will thus burn slowly. Asphaltenes may also contribute to deposit formation in the combustion chamber and exhaust gas system [13].

Catalytic fines

Heavy cycle oil is used in the complex refining processes as a blending component for residual fuels. Mechanically damaged catalyst particles cannot be removed completely in a cost-effective way, and are thus found in blended residual fuels [11]. Catalytic fines are the main source of potentially abrasive particles in residual marine fuel. These are controlled by the limitation of aluminium plus silicon in the fuel. In order to avoid abrasive wear of fuel pumps, injectors and cylinder liners, it is recommended that the fuel entering the engine contain less than 15 mg/kg after on board fuel treatment [13].

Water

The percentage of water in the fuel can be translated into a corresponding energy loss and cause unstable combustion. Water also gives growth conditions for bacteria, yeast and fungus in the oil-water transition zone commonly referred to as diesel bugs. Such bacteria contamination can cause to clogged fuel filters.

2.2.4 Fuel Quality

Modern refinery processes have become more efficient at producing as much distillate products as possible from a given quantity of fuel. This has resulted in a rapid increase in the number of thermal and catalytic conversion units used in the refinery technology. Conversion or cracking of the residue increases the aromaticity of marine fuels which in turn affects the stability, ignition and combustion quality [11]. Aromatics have high auto ignition temperatures, which increases with increasing aromaticity. The aromaticity of the fuel can be used as a measure of the resistance to ignite or ignition delay.

Two empirical formulas, the calculated carbon aromaticity index (CCAI) and calculated ignition index (CII), can be used as a measure of ignition quality. Both CCAI and CII are calculated from the density and kinematic viscosity of the fuel. Ignition characteristics, determined by the CCAI were added to ISO 8217 in 2010. According to Iversen [15], the problem with these empirical formulas is that they do not consider the effects of modern fuel blending technics. Fuel ignition analysers (FIA) has been developed, but is not yet internationally accepted. The most reliable way to establish factual ignition and combustion properties of fuels is to make use of FIA. This testing method is however considered too expensive by many operators. Therefore, the less costly but highly inaccurate empirical formulas CCAI and CII used instead and accepted as an accurate result.

A CIMAC paper from 2007 [16] reviews the effects of a changing oil industry on the marine fuel quality. The paper concludes that the fuel composition significantly affects the ignition performance of the fuels. It further concludes that it cannot be assumed that generic refinery streams e.g. cycle oils, will have similar ignition performances. The ignition performance of blends cannot be predicted, particularly if the streams come from different sources. Figure 2-4 shows the ignition delay as a function of engine load for different residual blends. High engine load causes high cylinder temperatures and pressures which normally will give shorter ignition delays. Low engine load causes the cylinder temperatures and pressures to decrease which normally will increase the ignition delay. The figure indicates that adding light cycle oil (LCO) to a 500 centistoke fuel will increase the ignition delay because of the high aromaticity and poor ignition quality of the LCO. At low loads, the ignition delay is shorter than for the 500 centistoke fuel. A 60/40 blend of 500 and 380 centistoke gives a significantly shorter ignition delay than any of the other blends. This emphasises the complexity of predicting the ignition quality of new fuel blends.

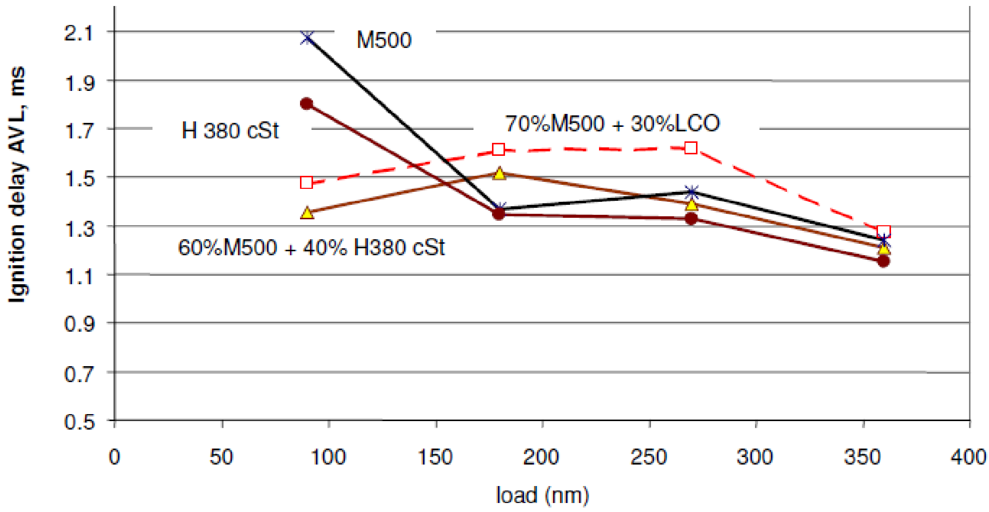


Figure 2-4: Load dependency of marine fuels. Four different fuels blends show different load dependence. Courtesy of [16]

Beside deteriorated ignition qualities, are problems related to the content of catalytic fines and fuel stability an increasing concern to fuels produced from complex refinery processes [17]. Although ISO 8217 have been revised and amended several times since 1987, the standard does not reflect recent advances in process technologies. There are marine fuels in the market today that give problems whilst apparently meeting the ISO 8217 requirements. The requirements of ISO 8217 specify limits on a number of fuel parameters as described in subchapter 2.2.3. These do only define the requirements of fuel and are not necessarily within the requirements of the diesel engine.

The first area of increasing concern is the content of catalytic fines in the fuel, which is the main source of potentially abrasive particles in residual marine fuel. These abrasive particles are limited by the control of aluminium plus silicon in ISO 8217:2010, set at a level of 60 mg/kg. According to Iversen [15], this is equal to the maximum limit of catalytic fines which was accepted by the shipping company Wilh. Wilhelmsen already in the late 1970s. Ideally, the separators should reduce the amount of aluminium plus silicon by 80%, but the separator efficiency highly depends on the effort and the knowledge of the crew on board. A separator must be cleaned frequently and its capacity monitored closely. According to Strøm [18], the reduction grade in separators is typically only around 50-60%. Vessel operators operating their engines on fuels with high catalytic fines content risk component damage such as the cylinder liner scuffing. This is shown in picture (a) in Figure 2-5.

The second area of increasing concern is that today's heavy fuel oils have challenging stability issues. These problems are said to be increased by the introduction of SECAs and thus the production of low sulphur fuel oils (LSFO). This is due to the blending with components that are not fully compatible [18]. The hydroscopic components of these fuels tend to absorb more water and produce greater amounts of sludge [17]. The fuels are also blended with cutter stocks to meet the viscosity and density requirements of ISO 8217. Viscosity reduction of a visbroken fuel with a paraffinic-type cutter stock can make the fuel unstable because of unstable asphaltenes that can start clogging together. This can result in fuel sludge precipitation which is slow at first, but progressively accelerates over time. Stability problems may cause the quality of heavy fuels and distillate fuels to deteriorate during long term storage. Picture (b) in Figure 2-5 shows a sludge plugged fuel filter from a diesel engine in standby generator configuration. Sludge producing fuel incompatibility problems can become quite aggressive just a few days after bunkering [17]. Picture (c) in Figure 2-5 shows that, like heavy fuel oil, marine gas oil can deteriorate in long term storage and loose ignition quality. The sample of MGO to the left in picture (c) has begun to stratify.

(a) (b) (c)

Figure 2-5: Marine fuel quality issues . Picture (a) shows cylinder liner scuffing caused by catalytic fines in the fuel. Picture (b) shows a sludge plugged fuel filter. Picture (c) shows fuel deterioration in long term storage. Courtesy of [17]

Fuels resulting from complex refinery processes, i.e. catalytic cracking or visbraking refinery, have a composition that is very different from fuels resulting from an atmospheric refinery. The complex refining process has introduced new blend components to the distillates, which is called light cycle oils (LCO). According to Vermeire [11], these blends can contain up to 60% aromatics in which increases the density and decreases the ignition quality of the distillates. Distillate marine diesel (MDO) has typically a lower cetane index and higher density than marine gasoil (MGO). Reduced ignition quality due to high aromaticity content in distillates may lead to ignition problems for diesel engines that are not designed to run on heavy fuel. In general, there are according to Strøm [18] significantly less problems when running on distillates than heavy fuel oil. Although, there are some challenges related to sulphur and water content. Distillates has very low particle content, normally less than one mg/kg, but impurities can still cause filtration problems. Too low viscosities and flash points are also more common to distillates resulting from complex refining processes.

2.3 Marine Lubricants

The functions of cylinder lubricants are the same whether the engine is operating on distillates or residual fuel oil. As the piston moves in the cylinder, the lubricant eliminates or minimizes the metal-to-metal contact between piston rings, piston and liner. The oil also assists in providing a gas seal between the piston rings and the cylinder liner. In addition, lubrication oil work as a transportation fluid for the functional alkaline additive system and removes combustion deposits from the piston ring pack. Minimizing deposit build-up on all piston and liner surfaces is another important function of the lubricant [7].

2.3.1 Lubricant Properties

Marine lubricants are valuable indicators of the overall functioning and wear of the engine. The deterioration of a lubricant goes slowly under normal engine operating conditions, but under abnormal conditions and engine malfunctions, the lubricants can degrade much faster.

Viscosity

The most important lubricating property is the viscosity. Increased viscosity of used lubricating oils may be caused by oxidation/nitration or soot contamination. Dilution with high viscosity heavy fuel oil or the use of a higher viscosity grade lubricant is other possible causes. A viscosity decrease of used lubricating oil may be caused by lower viscosity grade lubricants or dilution with low viscosity fuels.

Base number

The Base Number (BN) is an alkaline reserve added to the lubricating oil to neutralise acidic products of combustion derived from sulphur in the fuel, and thus protect the components against corrosion [19]. There are mainly two types of corrosion, namely hot corrosion and cold corrosion. Hot corrosion is caused by vanadium and cold corrosion is caused by sulphur. BN decreases as acids are neutralized and it is common to change oil when the BN level is reduced by 50–

60% [19]. Excessive piston ring blow-by may accelerate the depletion of the base number. This is due to the increased amount of acids from the combustion products entering the oil sump.

2.3.2 Lubricant Contamination

Contamination of the lubricating oil may cause operational problems such as liner lacquering, piston deposits, increased oil consumption, base number depletion, hot corrosion of the piston crown, oil scraper ring clogging and increased piston deposits [11]. Contamination of lubricating oil is a problem that may arise in medium- and high-speed engines. This is mainly due to combustion blow-by gasses and fuel dilution. Modern diesel engines have higher fuel pump pressures which contribute to increased fuel leakage. Heavy fuel oils contain cracked asphaltenes, which do not dissolve in the lubricating oil. The asphaltenes coagulate and form particles that are very sticky and thus form black deposits on all metal surfaces. Lubricant contamination can also be caused by engine operations outside optimum operating point.

According to Fitch [20], any of the contaminants described below is capable of causing premature or even sudden engine failure. The article presents four lethal diesel engine oil contaminants, which the author claims that cause thousands of diesel engines to fail prematurely every year. These contaminates are glycol, fuel, soot and water. Problems are known to be more pronounced when contamination combinations exist, such as high soot content with glycol or high soot content with fuel dilution.

Glycol

Glycol enters the diesel engine lubricating oil as a result of defective seals, blown head gaskets, cracked cylinder heads, corrosion damage and cavitation. Small amounts of coolant containing glycol in the diesel engine oil is enough to coagulate soot and cause sludge and deposits that can lead to oil flow restrictions and filter blockage. According to Fitch [20], glycol contamination can results in wear ten times greater than water contamination alone. Glycol contamination can increase the oil viscosity which impairs lubrication oil properties and the oil cooling process.

Fuel dilution

Frequent engine starts and excessive idling or low load operations can lead to moderate fuel dilution problems. Severe dilution (excess of 2%) is associated with leakage, fuel injection problems and deteriorated combustion efficiency. Fuel dilution can drop the viscosity of the lubricant causing critical oil film thicknesses to collapse. This can result in premature combustion zone wear including piston, rings and liner and crankcase bearing wear. Fuel dilution from defective injectors can cause wash-down of lubricating oil on the cylinder liners. This accelerates ring, piston and cylinder wear. Severe fuel dilution also dilutes the concentration of oil additives and hence reducing their effectiveness.

Soot

The soot formation rate is directly related to the combustion efficiency. Poor ignition timing, low air/fuel ratios and excessive ring clearance can cause soot contamination of the lubricant. The viscosity increases with increased soot contamination. High viscosity corresponds to cold-start problems and risk of oil starvation.

Water

Water is known to be one of the most destructive contaminants in most lubricating oils. It attacks additives, induces base oil oxidation and interferes with oil film production. Excessive idling or low load operations prevent water evaporation and cause water condensation, which can lead to loss of base number and corrosive attack on surfaces and oxidation of the oil. Emulsified water can accumulate dead additives, soot, oxidation products and sludge, which can cause clogged oil filters and consequently restrict the oil flow. Water contamination also increases the corrosive potential of common acids found in the lubricating oil.

2.4 Marine Emission Regulations

Exhaust gas emissions from marine diesel engines are of great concern due to their impact the environment and public health. Emissions from combustion of fossil fuels can be divided into primary and secondary combustion products [21]. Primary combustion products include carbon dioxide (CO_2) and water (H_2O), which affect the environment through greenhouse effects and localized fog. Their emissions can only be reduced through fuel modifications or by exhaust gas treatment. Secondary combustion products include carbon monoxide (CO), unburned hydrocarbons (HC), soot, nitric oxides (NO_X), sulphur oxides (SO_X) and oxides of metals. These pollutants may cause health problems and contribute to acid rain. Marine engine designers have in recent years had to meet the challenges of tightening controls on exhaust gas emissions imposed by national, regional and international authorities. Engine designers are continuously working on optimizing their engines for reduced emissions by tuning engine parameters. Some of these adjustments are suspected to have negative impacts on engine operation at lower engine loads.

2.4.1 Pollution Formation

Temperature and residence time are two important parameters influencing the formation of pollutants in a diesel engine. Temperatures affect the onset of certain chemical reactions and consequently the formation of certain chemical species. Combustion temperature is strongly related to the equivalence ratio, the pollutant formation can thus be influenced by controlling the reactant mixture composition. Residence time is defined as the amount of time reactance reside in the combustion chamber. To complete chemical reactions sufficient time must be provided for the reactants to react. The cylinder temperature is regarded as the most important parameter in the combustion process because of the reaction rate's exponential dependence on temperature. Figure 2-6 shows the trends of emission versus equivalence ratio. NO_X formation is strongly temperature dependant and tends to peak at slightly lean conditions where the temperature is high and there is excess of oxygen. CO and HC levels become large for very rich and very lean mixtures. In very rich mixtures the oxygen level are insufficient which results in incomplete combustion and thus high levels of CO and HC. In very lean mixtures the temperature is too low for oxidation of CO and HC.

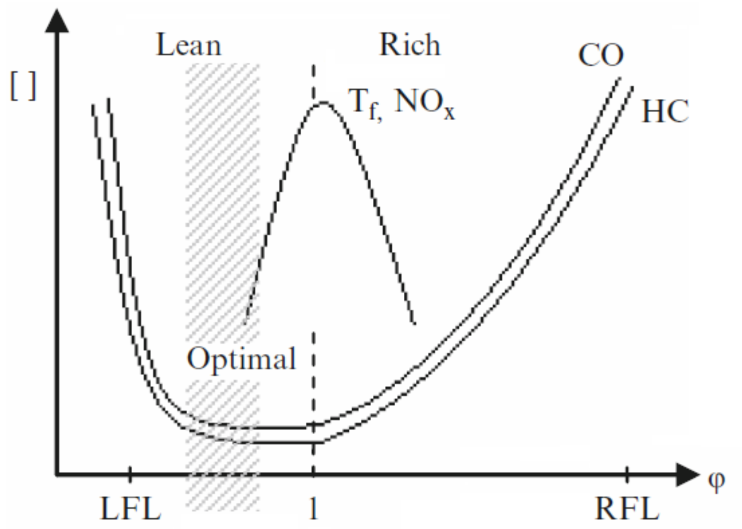


Figure 2-6: Trends of emission in terms of equivalence ratio. Courtesy of [21]

2.4.2 NO_X Emission Control

Nitric oxides (NO_X) refer to the total content of NO and NO_2. NO_X are produced primarily from the nitrogen contained in the air and are the main cause of smog and acid rain. NO_X emissions from ship engines are significant on a global level. The International Maritime Organization (IMO) has adopted a convention for control of NO_X emissions from ships named MARPOL Annex VI. The legislation sets limits for NO_X emissions in standards referred to as Tier I, II and III. Tier I and II limits are global, while Tier III standards will only apply in NO_X emission controlled areas (NECAs). The NO_X control requirements of Annex VI apply marine diesel engines of over 130 kW output of power. Different levels (Tiers) of control apply based on the ship keel layer date or engine installation date and rated engine speed. This is illustrated in Figure 2-7. Tier I (orange) and Tier II (blue) applies to ships constructed on or after 1 January 2000 and 2011. Tier III (green) will apply to ships constructed on or after 1 January 2021. To show compliance an engine has to be certified according to the NO_X technical code and be delivered with an Engine International Air Pollution Prevention (EIAAP) certificate of compliance.

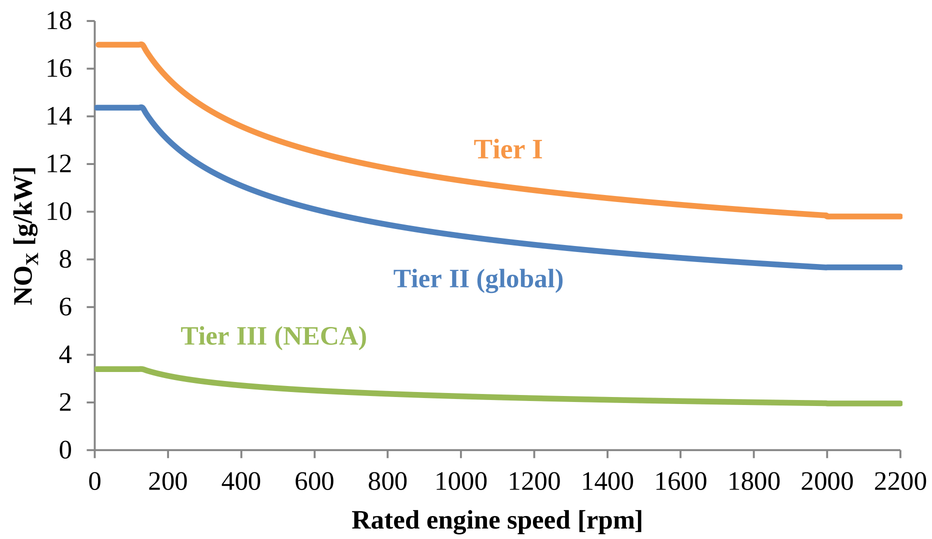


Figure 2-7: MARPOL Annex VI NO_X emission limits

There are two main methods of reducing NO_X emissions in marine diesel engines, namely primary (in-engine) measures and secondary measures. Tier I and II standards are met by primary measures. Engine manufacturers are working with parameters such as fuel injection timing, pressure, rate (rate shaping), fuel nozzle flow area, exhaust valve timing and cylinder compression volume. The focus is to lower the concentration of nitrogen, peak temperatures and the amount of time in which the combustion gases remain at high temperatures. Compliance with Tier III standards require dedicated NO_X emission control technologies, also referred to as secondary measures.

Primary Measures

Primary measures aim at reducing the amount of NO_X formed during combustion by optimizing engine parameters. According to Woodyard [7], NO_X emission levels can be reduced by 30–60% with primary measures.

Water addition

Water can be introduced into the cylinder in three different ways; by fuel-water emulsion, direct water injection or water injection into the intake air. The introduction of water into the combustion increases the specific heat capacity of the cylinder gases and reduces the overall oxygen concentration. The NO_X emissions are reduced due to lower cylinder temperatures and less oxygen available.

Modified fuel injection

Adjustments in injection timing are one of the fundamental means of achieving reduction in NO_X emissions. Late injection leads to lower peak pressures and consequently lower temperatures in the combustion chamber. The retarded injection also reduces the amount of fuel burnt before peak pressure is reached, thus reducing the residence time and degree of after-compression of the first burnt gas. The injection period has also become shorter and more distinct by increasing the fuel injection pressure.

Reducing the fuel spray cone angle decreases the NO_X emissions, but slightly increases the fuel consumption. The reason is that the smaller spray angle reduces the air entrainment into the spray, which in turn results in less prepared mixture for the premixed combustion phase. This causes lower peak temperatures more of the combustion takes place during the mixing-controlled combustion phase. Increasing the nozzle tip protrusion slightly decreases the amount of NO_X because the fuel spray is injected closer to the cylinder wall giving lower cylinder pressure and temperature due to quenching.

Miller cycle

The Miller cycle normally involves early closing of the inlet valve, which means that the inlet valve is closing before the piston reaches BDC during the intake stroke. The charge air expands inside the cylinder as the piston moves downward, which results in reduced charge air temperatures and hence lower peak temperatures in the combustion chamber. Higher emissions of PM at part load are suffered, but can be eliminated by a variable valve timing system with the Miller cycle. To maintain the mean effective pressure, the Miller cycle requires a higher turbocharger pressure than normal to compensate for shorter inlet valve opening.

Exhaust gas recirculation

Exhaust gas recirculation (EGR) system introduces exhaust gas into the charge air which increases the specific heat capacity and reduces the overall oxygen concentration of the cylinder gases. EGR can be attained by either internal or external methods. Internal EGR system utilizes the valve overlap period to regulate how much exhaust gas that shall remain in the cylinder during the combustion process. This method is primarily limited to engines with variable valve timing. External EGR reintroduce cleaned and cooled exhaust in the combustion chamber. This method requires a separate system, but is more efficient than the internal EGR.

Secondary Measures

Secondary measures are designed to remove NO_X from the exhaust gas by downstream cleaning techniques. According to Woodyard [7], emission reductions of over 95% can be achieved by secondary measures.

Selective catalytic reduction

Selective catalytic reduction (SCR) is currently the only secondary measure. In the SCR exhaust gas is mixed with ammonia before it passes a catalyst. The ammonia is usually supplied as a solution of urea in water. This process converts NO_X into water (H_2O) and diatomic nitrogen (N_2).

2.4.3 SO_X Emission Control

Oxides of sulphur from combustion process may consist of SO, SO_2 and SO_3, whereof the two major ones are SO_2 and SO_3. SO_X are highly soluble in water forming acidic sulphurous acid. Annex VI regulations include caps on sulphur content of fuel oil as a measure to control SO_X emissions and thus PM emissions. Special fuel quality requirements exist for SO_X Emission Control Areas, also called SO_X ECAs or SECAs. The sulphur limits are illustrated in Figure 2-8.

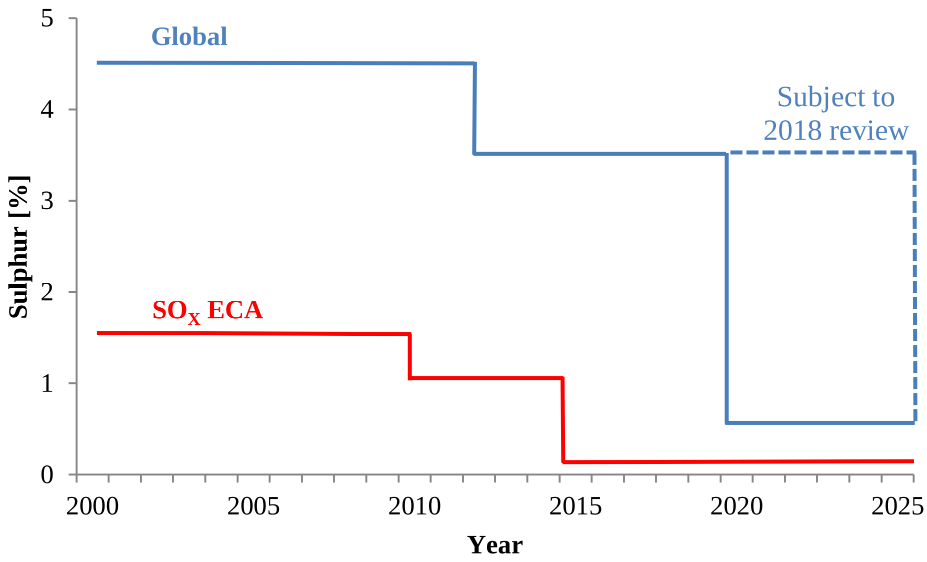


Figure 2-8: MARPOL Annex VI SO_X emission limits

There are currently two methods available to reduce SO_X emissions which are the after-treatment of exhaust gases and the use of fuels with low sulphur content. Two main types of scrubbers can be used to remove SO_X from the exhaust gas and they are known as wet and dry scrubbers. Scrubbers do not affect the combustion process and are not discussed further. Low sulphur fuels can have a negative impact on the fuel properties. This was discussed in subchapter 2.2.2.

2.4.4 Soot Formation

Soot formation in diesel engines results from incomplete fuel combustion. The distribution of soot directly affects the heat radiation and the temperature field of the flame. High pressure fuel injectors on modern diesel engines have been used to decrease the size of the soot particles, but the remaining invisible fine particles are still a toxicological problem. Figure 2-9 shows a desirable pathway of the fuel mixture. The mixture moves from rich towards lean during the three stages of combustion, which include premixed burning, mixing controlled burning and eventually late combustion.

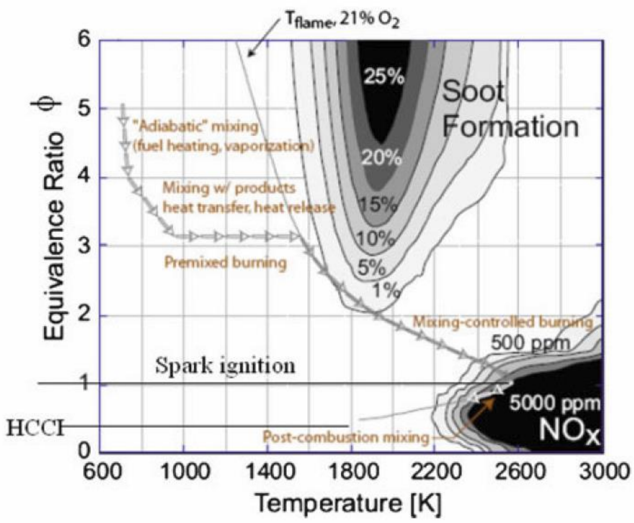


Figure 2-9: Soot and NO_X relationin terms of equivalence ratio and temperature. Courtesy of [21]

The pathway is plotted in an equivalence ratio versus temperature map with contours indicating the locations where soot and NO_X formation occur. The ultimate goal is to modulate the injection timing of fuel to avoid both soot and NO_X formation. Since NO_X and soot are formed in different regions in the (ϕ,T) plot, the injection timing is a trade-off between formation of NO_X and soot necessary. As illustrated in Figure 2-10, a small soot production is at the expense of large NO_X formation and vice versa.

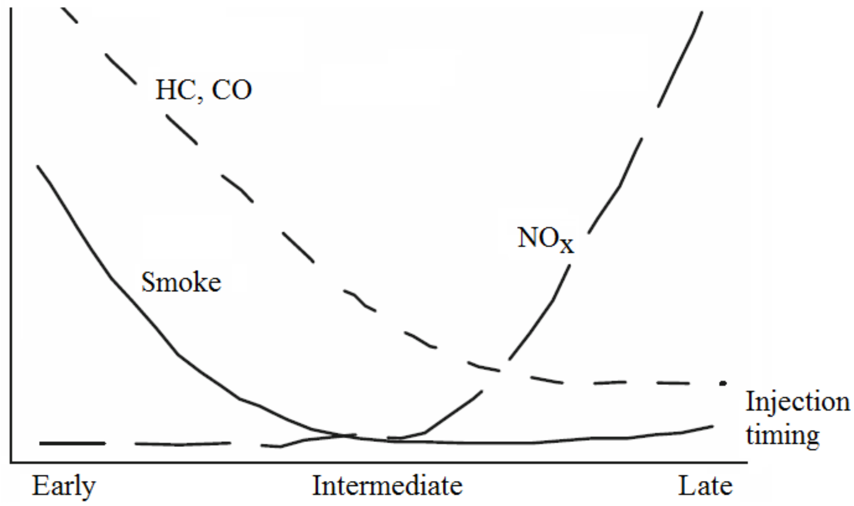


Figure 2-10: Trade-off between NO_X and sootas a function of injection timing. Courtesy of [21]

The majority of soot is transported out of the combustion chamber through the exhaust, but some soot may get past the piston rings and end up in the oil sump. Periods of excessive idling or low load operations, worn piston rings, injectors with poor fuel patterns, rich air-fuel ratios and clogged air filters are common factors that may cause excessive soot levels in the lubricating oil. Individual soot particles are very small and pose no direct risk to engine parts, but soot particles often clump together to form large and damaging soot clumps. Excessive soot levels in the oil can eventually lead to reduced lubrication due higher oil viscosity and thus impeded oil flow through the engine as well as through the oil filter. The performance of anti-wear lubricant additives can also be negatively impacted by soot and lead to increased engine wear. High soot conditions can lead to formation of carbon deposits in the cylinder and in the piston ring grooves. This may cause degradation of the oil seal between the piston rings and cylinder liner, which eventually causes abrasion. As abrasion widens the gap between the piston rings and the cylinder liner, increasing amounts of combustion products are blown into the crankcase.

2.5 Cylinder Liner Deposits

According to Buhaug [9], there is a general agreement that formation and accumulation of deposits depend on the interaction between fuel composition, lubricants, engine design and engine loading. This is illustrated by Allen [22] as shown in Figure 2-11. Cylinder liner deposits are in the literature generally referred to as liner lacquering and shall not be confused with soot deposits.

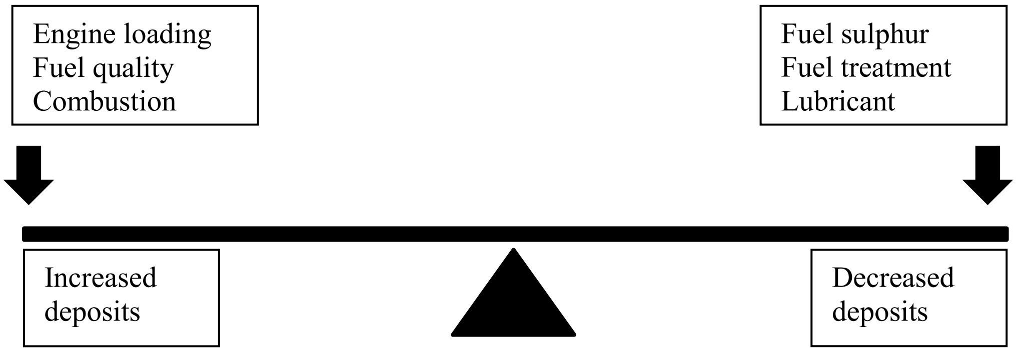


Figure 2-11: Cylinder lacquer balance. Courtesy of [22]

The problem with lacquer formation is mostly found in four-stroke medium-speed diesel engines [7]. Modern and highly rated engines have very high fuel injection pressures and shorter time for injection. During a few crank angle degrees the injection, ignition and combustion have taken place. In this short time period, thermal cracking of fuel components occur. When these reach the relatively cool cylinder liner surface, they will condense and form a resinous lacquer. The build-up of lacquer may result in a smoothed or glazed liner surface, which negatively affect the lubricating oil consumption rate. Together with formation of hard carbon deposits, this phenomenon will lead to scoring or polishing of the liner. According to Woodyard [7] a number of common factors link engines where liner lacquering has been found. These can be summarised as follows. Large variation in load i.e. frequent and long periods of idle followed by full load operations, high mean effective pressure medium-speed designs and low-sulphur distillate fuels. Lacquering has typically been observed on engines on board offshore supply vessels and short sea ships. The fuel composition is also known to be a factor in the lacquer formation. It is suggested by Allen [22] that the formation of liner lacquering is related to high boiling point and or aromatic fuel fractions. According to Buhaug [9], the current understanding of the phenomena is that any fuel may contribute to liner lacquer formation under engine conditions that promote incomplete combustion and thermal breakdown of fuel.

2.6 Tribology

This subsection intends to give a very brief review of some tribology concepts relevant for analysing diesel engine damages. Particle contamination can damage engine components by causing a variety of types of wear. The primary types of wear are shown in Table 2-3. Each of these wear mechanisms result in the generation of excessive particulate contamination capable of causing further damage to the engine components.

Table 2-3: Primary types of wear [23]

Abrasive wear	Particles between adjacent moving surfaces
Erosive wear	Particles and high fluid velocity
Adhesive contact	Surface to surface contact (loss of oil film)
Fatigue wear	Particle damaged surfaces subjected to repeated stress
Corrosive wear	Water or chemicals

Abrasive wear

Abrasive wear is the loss of material by the passage of hard particles over a surface and occurs whenever a solid object is loaded against particles of material that have equal or greater hardness. The particles may remove material by microcutting, microfracture, grain pull-out or fatigue by repeated deformations. In bearings the particle sizes causing the most damage are those equal or slightly larger than the clearance space.

Erosive wear

Erosive wear is caused by particles that impinge on a component surface or edge and remove material from that surface due to momentum effects [23]. This type of wear is typical for components with high velocity flows such as turbine blades.

Adhesive wear

Adhesive wear is a very serious form of wear characterized by high wear rates and a large unstable friction coefficient. Sliding contacts can rapidly be destroyed by adhesive wear and most lubricant failures in sliding metal contacts result in adhesive wear [23].

Fatigue wear

When the contact points between two surfaces are well lubricated adhesion between them can be neglected, but there is still a significant rate of wear. The surfaces are subject to fatigue failures as a result of repeated stressing caused by clearance-sized particles trapped between to moving surfaces. At first, the surfaces are dented and cracking is initiated. The cracks are spread because of repeated stresses and eventually the surface fails producing spalls. Fatigue wear is typical for bearings and baring failures caused by fatigue is usually sudden and highly undesirable [23].

Corrosive wear

Corrosive wear is a general term relating to any form of mechanical wear (adhesive, abrasive, fatigue, fretting etc.) that is combined with chemical or corrosive processes. Corrosive wear occur in both lubricated and unlubricated environments. The fundamental characteristics of these types of wear are a simultaneous reaction between a worn material and a corroding substance, i.e. chemical reagents, reactive lubricants or air [23].

2.7 Marine Engine Maintenance

Overhaul intervals and as well as the lifetime for engine components depend on operating conditions, average loading of the engine, fuel quality used, fuel handling system, performance of maintenance etc. According to MTU [24], the maintenance procedure of marine diesel engines can be divided into nine categories as listed in Table 2-4. Several parameters such as low load operations, transient load operations, NO_X optimization and low sulphur fuels will influence on the stipulated time between overhaul for engine components.

Table 2-4: Engine maintenance categories [24]

Lubrication	Checking levels, changing oil and oil filters, perform oil sampling for trending analysis to optimize oil, change intervals and detect engine wear.
Fuel system	Changing fuel filters and fuel injectors, checking water separators, do fuel and quality analysis to make sure fuel contains proper lubricants and additives.
Cooling system	Fluid level checks, coolant sampling for trending analysis, draining, flushing and refilling the system when required.
Air intake system	Inspecting and changing air filters, inspecting the turbocharger to make sure there is no fouling of the compressor blades from crankcase gases.
Exhaust system	Inspecting for leaks, corrosion and wet stacking.
Emissions system	Inspecting crankcase ventilation systems, selective catalytic reduction (SCR) systems and diesel particulate filters.
Mechanical systems	Inspecting resilient engine mounts and torsional couplings, general inspecting for leaks, wear or deterioration.
Operating systems	System data upgrade.

Chapter 3
Case Study

DNV GL suspects that several diesel engine damages over the past years have been caused by excessive low load operations. These suspicions are mainly based on verbal statements from surveyors and experienced employees in the DNV GL Classification and Support department. Several survey reports and damage investigation reports have been reviewed in order to substantiate the suspicions regarding low load operations.

Diesel engine damages are reported to the classification society and upon request from the customer is an occasional survey conducted by a representative from the Class. A survey report is written by the surveyor after inspection where findings are linked to the NPS product model. The surveyor is not supposed to speculate in the cause of the damage, as his or her role is only to witness the damage and require corrective actions on behalf of the Class. Consequently, survey reports are often very brief and the cause of damage is rarely specified. Surveys are sometimes followed up by more thoroughly investigations upon request from the ship owner or the engine manufacturer. These types of investigations are often conducted by external consultants. Such reports are thus not as easy accessible as DNV GL's own survey reports.

The intention of this chapter was originally to review several damage cases that are suspected to be caused by low load operations, but due to few well documented damage reports available only one damage case has been reviewed.

3.1 Damage Case

This particular damage case is one of very few well documented damage cases that are more or less confirmed to be caused from excessive low load operations. The resulting engine damage is engine crankcase breakage resulting from severe piston scuffing. The details presented in this case study are taken from an investigation report composed by representatives from Mitsubishi Heavy Industries after the incident in 2007. The stricken ship has, according to the damage investigation report [25], a long history of engine troubles and failures. Since the vessel was built in 2003 it has virtually had problems every year. The history of troubles and failures prior to 2007 are presented in Table 3-1.

Table 3-1: History of engine troubles and failures [25]

2003	Replacement of gasket due to exhaust gas leaks
2004	Replacement of nozzle tip and spacer due to damage
2004	Insulator cracks due to exhaust gas leaks
2006	Replacement of piston, liner, connecting rod etc. due to piston scuff
2007	Piston scuff resulting in crankcase breakage

Whether the earlier troubles and failures were caused by low load operations do not appear from the investigation report. The survey reports of the abovementioned damages have also been reviewed to investigate the causes of damage, but without results.

3.1.1 Vessel Characteristics

The stricken vessel is a dedicated IMR, survey and light construction vessel with diesel-electric propulsion and IMO Class 2 dynamic positioning system. An inspection, maintenance and repair vessel (IMR) is a highly technical vessel deployed in the offshore industry. Their primary task comprises the inspection and repair of subsea facilities and installations. These vessels are designed to continue operations in harsh weather conditions, which impose stringent requirements to the power capacity of the propulsion system. The power plant comprises four high-speed turbocharged four-stroke diesel engines in generator configuration. The gensets have been installed after 2000, which means that they are NO_X optimized and comply with the IMO Tier I requirements. Specifications for the troubled diesel engines are presented in Table 3-2.

Table 3-2: Engine specifications

Engine type	Four stroke
Cylinder configuration	V-engine (16 cylinders)
Aspiration	Turbocharged
Engine output	1690 kW / 1800 rpm
Operating hours	15 000 hours

3.1.2 Engine Load Characteristics

The crankcase breakage is suspected to be caused by low load operations. This is based on load patterns from past records of the ship and the result of an oil analysis. The engine breakage is assumed to be caused by a series of mechanisms resulting from longer periods of low load operation. Low load operations are typical for offshore DP vessels with DP class 2 due to redundancy requirements, which is based upon running machinery. It has been attempted to get hold off load data prior to the incident without success.

3.1.3 Observations and Findings

The investigation report is very thoroughly and include more details than presented in this case study. For the purpose of this work, only observations and findings that are considered to be relevant have been reviewed in the following section. This includes observations and findings on the piston and cylinder arrangement as well as findings on bearings.

Piston and piston ring

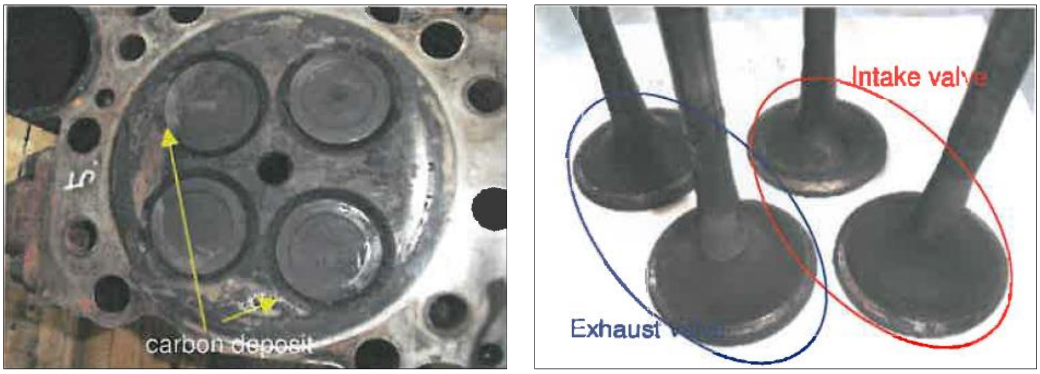
Observations of the pistons show that the entire circumference on the piston of cylinder #5 was scuffed and that the scuffing marks were separated into two parts at the piston boss. This appear from picture (a) in Figure 3-1. Scuffing is known to occur when the lubrication film is lost between two metallic parts that moves relative to each other. The lower part of the piston was found broken into small pieces and had fallen into the oil pan. The upper part of the piston was found stuck at the top of the cylinder. Large amounts of carbon deposits where observed on the top land of other pistons. Figure 3-1 (b) shows top land deposits on piston #4.

(a) (b)

Figure 3-1: Piston scuffing and carbon deposits. Picture (a) shows piston scuffing on piston #5. Picture (b) shows deposits of hard carbon on the top land of piston #4. Courtesy of [25]

Head combustion surface and gasket

Large amounts of carbon deposits were found on the cylinder head surface of cylinder #5 as shown in the picture of Figure 3-2 (a). Carbon deposits were also found on the other cylinder head surfaces. In addition, the combustion surface of cylinder #5 show stamp marks of the piston. No abnormal wear was found on the intake and exhaust valves or valve seats of cylinder #5. The valves are shown in the picture (b) in Figure 3-2.

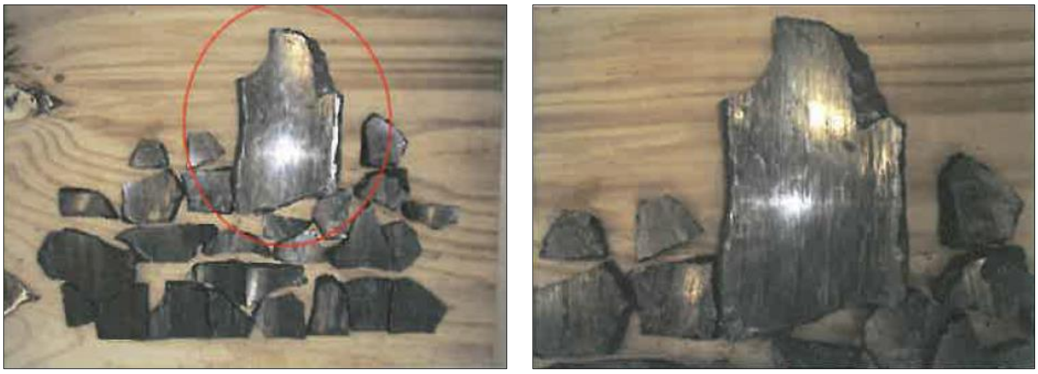


(a) (b)

Figure 3-2: Cylinder head surface, intake and exhaust valves. Picture (a) shows the cylinder head surface of cylinder #5. Picture (b) shows the intake and exhaust valves of cylinder #5. Courtesy of [25]

Cylinder liner

Cylinder liner #5 was found broken into pieces as depicted by Figure 3-3. The inner surface of the broken pieces showed linear scars. Polishing wear due to hard carbon particles was observed on the upper part of inner surface of the cylinder wall. The upper part of all cylinder liners showed vertical streaks of strong contact which is probably caused by carbon polishing. This is exemplified by pictures of cylinder #2 in Figure 3-4.



(a) (b)

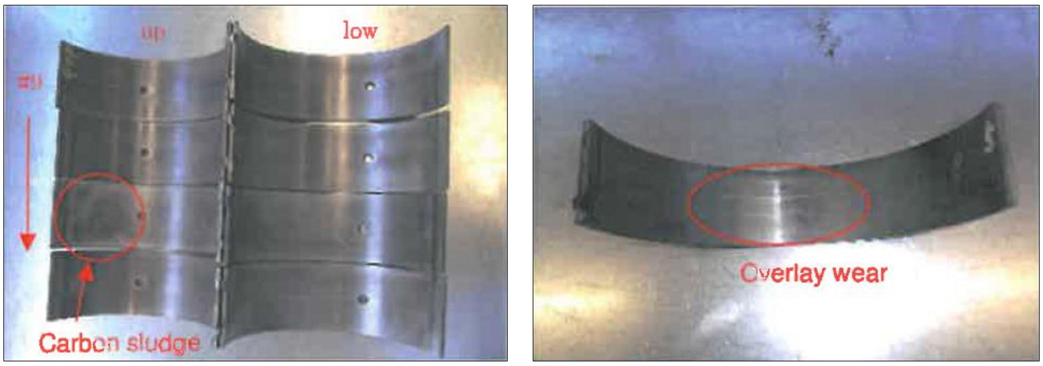
Figure 3-3: Broken cylinder liner. Picture (a) shows inner surface of broken liner and picture (b) is an enlargement of the red circle in (a). Courtesy of [25]

(a) (b)

Figure 3-4: Carbon deposits and polishing wear in cylinder liner. Picture (a) shows carbon deposits in cylinder liner and picture (b) shows an enlargement of the red circle in picture (a). Courtesy of [25]

Bearings

Large amounts of carbon sludge were observed on the plated overlay of the connecting rod bearings. Picture (a) in Figure 3-5 shows carbon sludge on the overlay of the connecting rod bearing of cylinder #11. The main bearing of cylinder #5 was removed and observed as a representative case. A picture of main bearing #5 overlay wear is shown in Figure 3-5 (b).



(a) (b)

Figure 3-5: Carbon sludge on bearing inner surfaces. Picture (a) shows the inner surfaces of the connecting rod bearings of cylinder #9-12. Picture (b) shows the inner surface of the main bearing of cylinder #5. Courtesy of [25]

3.1.4 Possible Mechanisms of Engine Breakage

The resulting damage was breakage of the engine crankcase, which was initially caused by severe scuffing of piston #5. The investigation report suggests that the cause of piston scuffing is extensive engine operations at low loads. This assumption is based on engine load patterns from past records of the ship and the results from an oil analysis. Possible processes and mechanisms that may have caused the engine breakage are shown in Figure 3-6.

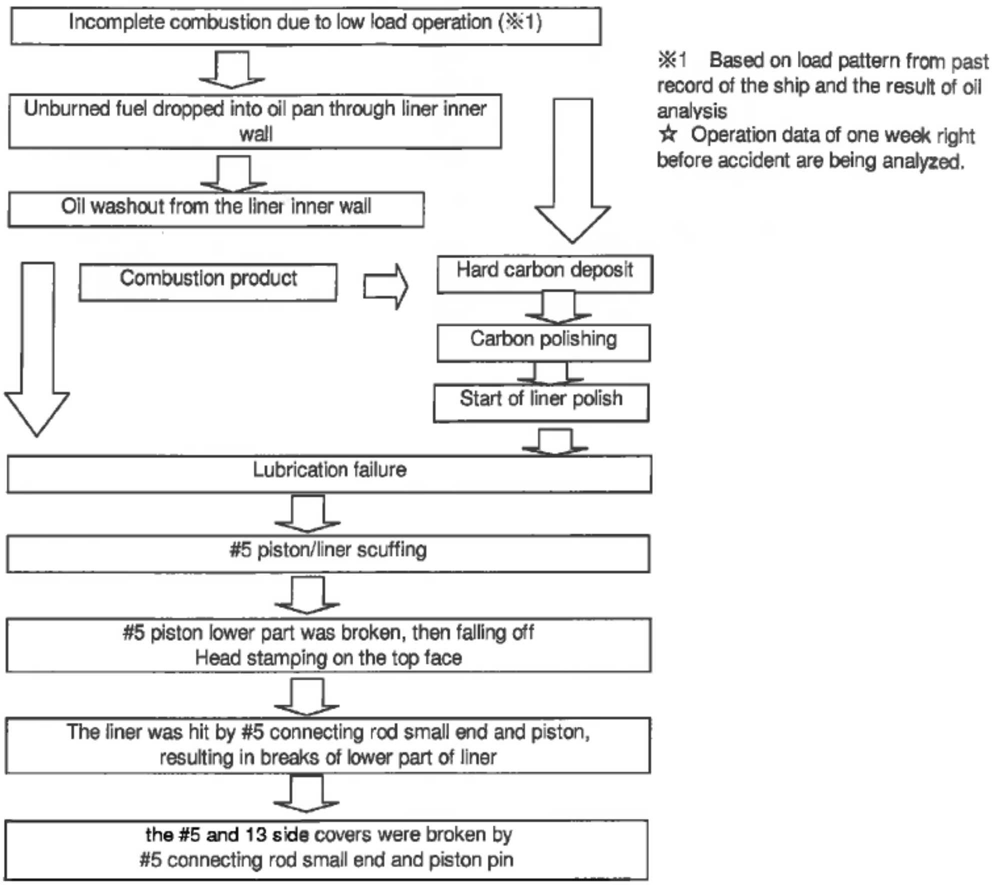


Figure 3-6: Possible processes and mechanisms of the engine breakage. Courtesy of [26]

The possible processes and mechanisms of the engine breakage, which was shown in the flow chart of Figure 3-6, can be described as follows:

Low load operation decreases the cylinder pressure and thus the temperature. Low temperatures lead to ignition problems and poor combustion which increases the soot formation and aggregation of unburned fuel in the cylinder. Low cylinder pressure, soot and unburned fuel deteriorate the piston ring sealing efficiency, which allow hot combustion gases, soot particles and unburned fuel to enter the oil sump. Fuel dilution reduces the viscosity of the lubricating oil significantly which causes critical oil film thicknesses to collapse. This makes the combustion zone (piston, piston rings and cylinder liner) susceptible to polishing from hard carbon particles resulting from the incomplete combustion. This results in premature wear of the combustion zone. Severe fuel dilution causes wash-down of lubrication oil on the cylinder liner inner wall which accelerates the deterioration of the lubricating oil propeties. According to Stachowiak and Batchelor [23], does scuffing result from mechanical contact when there is a breakdown or absence of lubrication. The scuffing of piston and liner #5 are suggested to be caused by the aforementioned mechanisms. Excessive piston scuffing eventually causes the lower part of the piston to break off. The cylinder liner #5 is broken into pieces by the connecting rod small end and the piston. These loose engine components eventually break the side covers of #5 and #13.

3.2 Case Discussion

The damage case presented illustrates possible mechanisms and damages resulting from extensive low load operations. Unfortunately, it has not been possible to find additional damage cases where the resulting damage is suspected to be caused by low load operations. This case study can thus not be used to draw any general conclusions, but can be used to illustrative purposes.

Chapter 4

Finding Analysis

It is suspected that low load operation of diesel engines increases operational problems and thus the engine damage frequency. It is also suspected that operational problems resulting from low load operations are aggravated by IMO's increasingly stringent NO_X emission regulations. The purpose of this analysis is to determine whether it is possible to substantiate these suspicions quantitatively by analysing existing data. The data to be analysed are diesel engine findings stored in the extensive database of DNV GL.

4.1 Nauticus Production System

Diesel engine findings have been extracted from Nauticus Production System (NPS), which is the main production support system of DNV GL Maritime. In NPS, all DNV GL classed vessels are broken down into defined components in what is referred to as vessel product models. These product models can be regarded as virtual reflections of the vessels stored in a computer and should ideally reflect the actual condition of the vessels at any time. The product model is built up as a hierarchy of functions, components and equipment.

NPS contains more than 20 million nodes across about six thousand vessel product models. These are mostly used in the reporting of survey findings during the vessels' operational lives. These findings are important assets as they can be used to improve knowledge about damages and other problems ships may experience throughout their life cycle. The latest version of NPS was launched early in 2005. Since then, all findings from any survey on any DNV GL classed vessel around the world have been stored in this product model. Due to the major restructuring of the production system in 2005, only diesel engine findings from 2005–2014 are available for analysis.

4.1.1 Surveys

Findings used in this quantitative analysis are registered during DNV GL surveys. For the basic class surveys, there is a requirement to undertake five annual surveys, including one intermediate survey (somewhere in the middle of the five year validity period of the certificate) and one renewal survey (at the end of the five year period). The second or third annual surveys shall coincide with the intermediate survey and the last annual survey with the completion of the renewal survey. Surveys shall be carried out within a time window, which is specific to each of the surveys, ranging from ±3 months to ±6 months. Occasional surveys will be conducted upon request from the customer to survey damages and/or repairs following from an incident affecting the class scope. The DNV GL survey regime can be illustrated as in Figure 4-1.

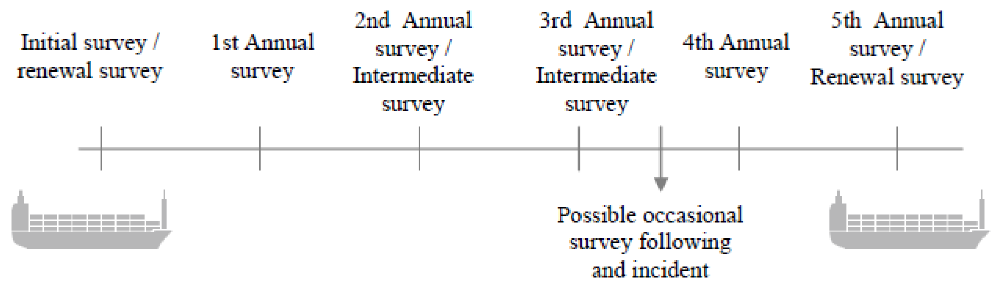


Figure 4-1: DNV GL survey regime. Courtesy of [27]

4.1.2 Findings

Findings will be registered from surveys where there are issues that represent non-conformity with the class or statutory rule requirements. Findings are directly linked to its component in the vessel product model by the surveyor. The number of findings is expected to increase with the age of the vessel and a typical distribution of survey findings at different renewal surveys can be illustrated as in Figure 4-2.

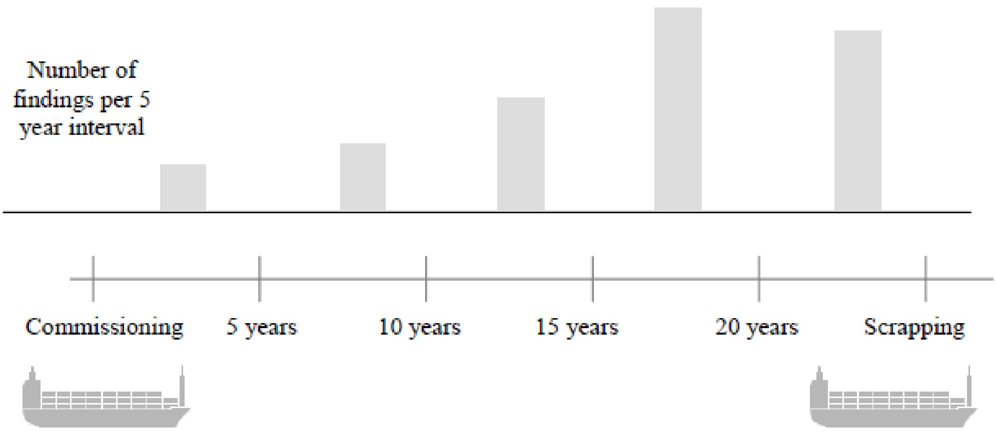


Figure 4-2: DNV GL survey findings. Courtesy of [27]

4.1.3 Entering and leaving class

A large proportion of the DNV GL classed vessels are built to DNV GL class and remain in DNV GL class until they are scrapped. However, there is a good share of turnovers where vessels leave DNV GL class to be classed with other class societies or to be followed up by national authorities. On the other hand, there are also a number of vessels that for various reasons enter into DNV GL class during their service lifetime. There are some vessels that are built into DNV GL class that leave for other societies and then return to DNV GL class again during their service lifetime. This turnover must be taken into account when determining the component age which is used to calculate the component finding frequency.

4.2 Calculations

This quantitative analysis is based on simple frequency measurements of diesel engine findings extracted from NPS. The finding frequency describes number of findings registered on a component per thousand component year.

The finding frequency is calculated as:

$$Finding\ frequency = \frac{Number\ of\ findings}{DNV\ component\ age} \times 1000$$

The number of findings is defined as the number of findings on a component in the time period 2005–2014. DNV GL component age is defined as the number of years the component has been in DNV GL class in the period 2005–2014. Due to class turnover the calculation of number of findings and DNV GL age must reflect the five common scenarios, illustrated in Figure 4-3.

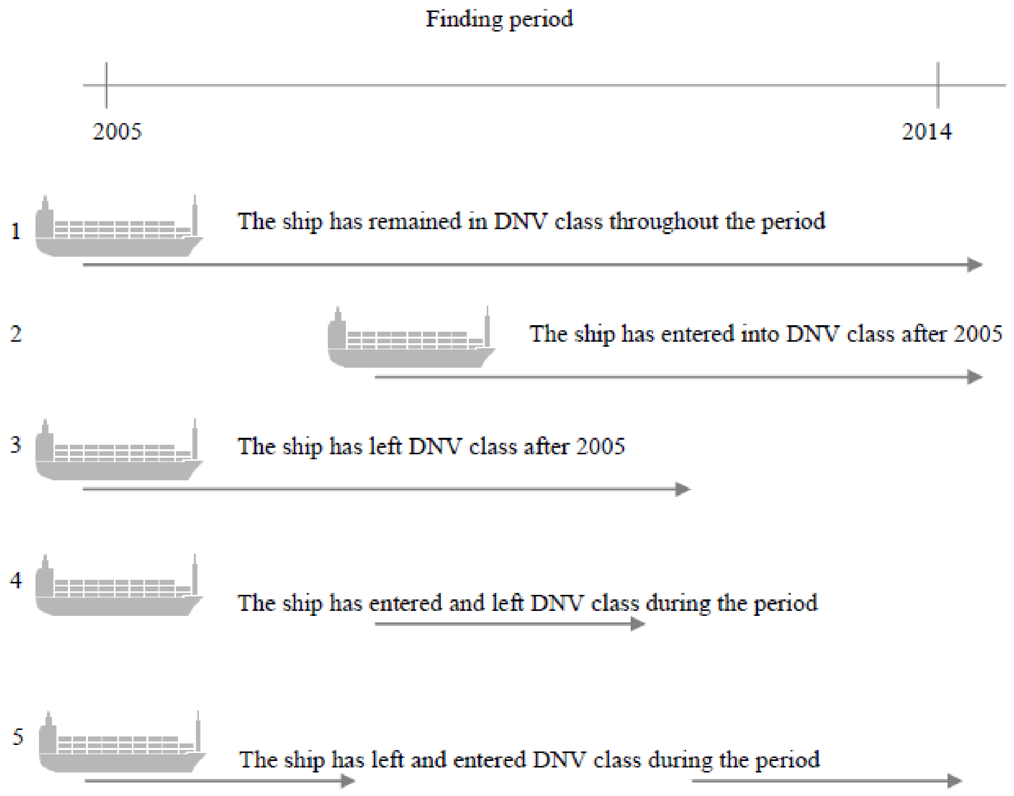


Figure 4-3: DNV GL vessel age

4.3 Data Quality

According to Kadal et. al [27], the data quality that impacts the value of SiO findings for analytical and statistical use can be summarised as follows:

1. Completeness and quality of the vessel product model
2. Quality of SiO reporting
3. Vessel information structure (VIS) changes and subsequently conversion of findings
4. Possible central correction/improvement of quality of findings and their place in the product model.

For the purpose of this study, the main source of inconsistencies is due to variations in the reporting from SiO surveyors and operators. Inconsistent reporting of findings from SiO surveyors makes it difficult to correctly count findings on the individual components. This restricts this analysis to only count findings on the main component. Inconsistent naming of engine parameters such as designer name, model name, engine power, fuel type etc. will also restrict this analysis. Other issues that may affect the data quality are that new engines are covered by a one year warranty and that the practices for reporting to class vary from one vessel operator to another and especially across ship types. Data cleansing in Excel has been an important tool to improve the data quality and has made it possible to present the results graphically.

4.4 Data Filtration

Survey findings have been extracted, re-structured and analysed in a program named Vadis. Vadis is a powerful tool to filter out large amounts of data based on parameters given in the product model. A wide selection of filters has been applied in this analysis, but some fundamental filters have been kept constant throughout this analysis. These are included in Table 4-1. The filter "*New Findings*" filters out findings reported before the restructuring of the product model in 2005. Only survey findings with "*Finding Status: Active or Historic*" have been considered to prevent findings from appearing in the search result more than once. NPS follows the vessel through the entire process from pre-contract to the operation phase, but only survey findings on vessels with "*Current Vessel Operational Status: In Operation*" are considered in this analysis. Some vessels enter and others leave class during their service lifetime, but only findings on vessels with "*Current Vessel Class Status: In class*" are considered.

Table 4-1: Fundamental filters applied in Vadis

New Findings
Findings Status: Active, Historic
Current Vessel Class Status: In Class
Current Vessel Operational Status: In Operation

4.5 Results

NPS contains nearly 30 000 diesel engines that are mainly distributed on conventional propulsion, main electric power generation, and emergency electric power generation. An overview of their product model function codes with corresponding names and distribution is shown in Figure 4-4. All frequency calculations and charts are included in appendix A1 and A2.

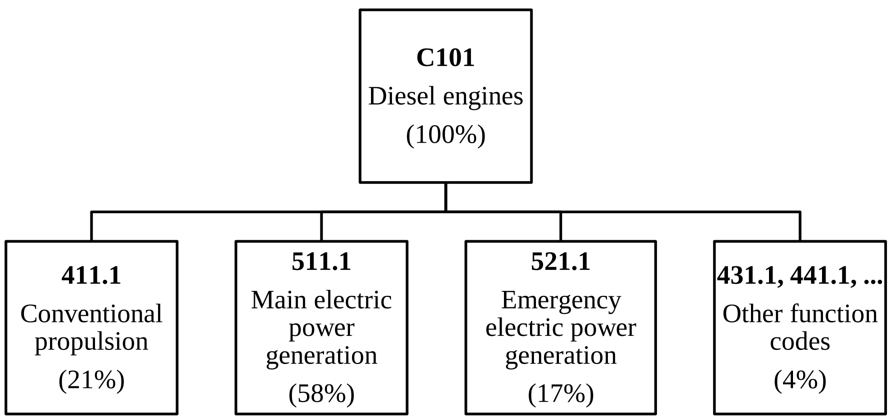


Figure 4-4: Distribution of diesel engines in NPS

In this analysis main engines have been differentiated from auxiliary engines by filtration of the NPS parameters *Main Component Function Code* and *Vessel Propulsion Principle*. Diesel engines with function code 511.1 installed on vessels with diesel electric propulsion are assumed to be main engines (M/E). Likewise, engines with function code 511.1 installed on vessels with conventional propulsion are assumed to be auxiliary engines (A/E).

NPS contains more than 16 500 diesel engines that can be categorised as main or auxiliary gensets. As much as 84% of these engines are auxiliary engines, while the remaining 16% are main engines. Figure 4-5 indicates that main engines have a higher finding frequency than auxiliary engines. Higher frequency for main engines is expected as incidents on propulsion engines are known to be more frequently reported than incidents on auxiliary engines. Higher frequencies on main engines may also be explained by operational conditions. In this analysis are issues related to low load operations of particular interest. To determine if the higher frequency on main engines versus the auxiliary engines result from low load operation, are these engines investigated more closely.

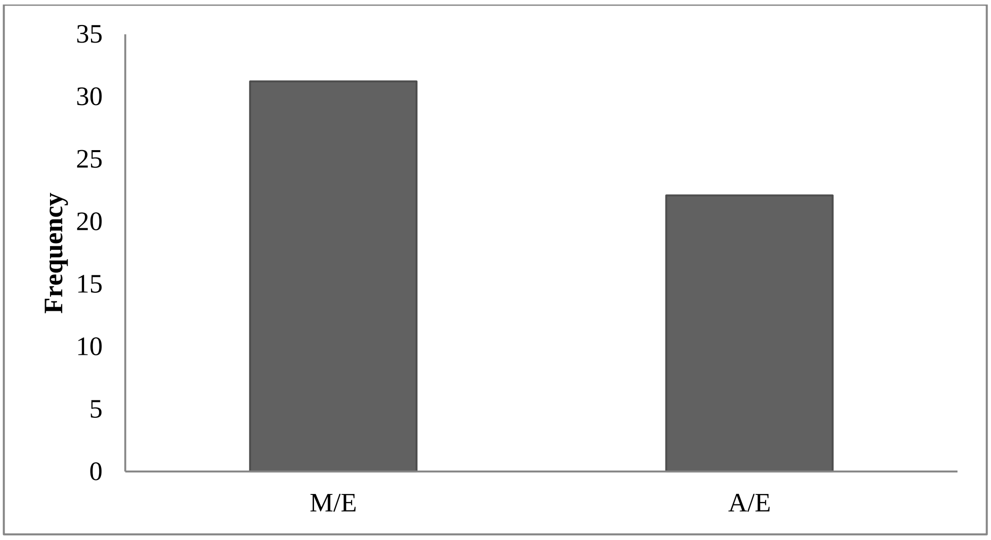


Figure 4-5: Main engines versus auxiliary engines

DP-vessels are generally known to be more exposed to low load operations than non DP-vessels. The finding frequency of generator engines on board DP-vessels is an important asset when investigating whether low load operations have an impact on the finding frequency. The NPS parameter *Vessel Class Notation* is used to differentiate DP-vessels from non DP-vessels. Vessels having DYNPOS in their class notation are categorised as DP-vessels and vessels missing DYNPOS in their class notation are categorised as non-DP-vessels. Figure 4-6 shows the finding frequencies of main and auxiliary engines on DP- and non-DP vessels. The figure indicates higher finding frequencies for main and auxiliary engines installed on board non DP-vessels. This shows that there is not necessarily a correlation between the high finding frequency and DP class notation even though these engines are more exposed to low load operations. On the other hand main engines are still representing the highest finding frequencies for both DP- and non DP-vessels. Main engines are known to be more exposed to larger load variations than auxiliary engines. This can explain the higher finding frequencies on these engines.

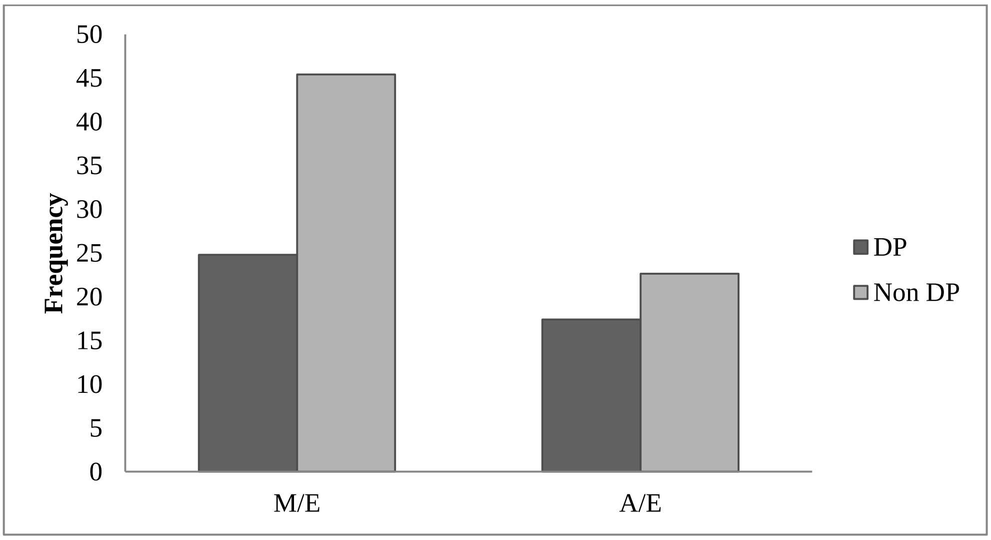


Figure 4-6: Main engines versus auxiliary engineson DP- and non DP-vessels

DP-systems can be divided into different categories according to redundancy and separation requirements. IMO has categorised dynamic positioning systems according to redundancy and separation requirements in three equipment classes. IMO Equipment Class 2 and 3 require redundancy in technical design, which are based upon running machinery. Running machinery means that the capacity of standby gensets is not considered to be a part of the redundant system. Table 4-2 shows the DNV DP class notations that correspond to IMO's Equipment Classes.

Table 4-2: DNV Class DP class notation

Notation Hierarchy	IMO Equipment Class	DNV Class Notation
Notation not requiring redundancy	IMO Equipment Class 1	DYNPOS-AUT
Notation requiring redundancy	IMO Equipment Class 2	DYNPOS-AUTR
Notation requiring redundancy and separation of systems	IMO Equipment Class 3	DYNPOS-AUTRO

Different DP classes and thus redundancy requirements may have different impacts on the finding frequency. It is suspected that the DP redundancy requirements cause generator engines to operate more often at low loads for longer periods of time than vessels without such requirements. This is due to the running machinery requirement, which do not allow for standby gensets.

Figure 4-7 compares finding frequencies with respect to the different DNV DP-notations listed in the table above. The highest frequencies are found for main engines on DP-vessels with redundancy requirements. The figure shows no correlation between the finding frequencies calculated for main and auxiliary engines. The result indicates that the main engine finding frequency increases, while the auxiliary genset finding frequency decreases with higher DP class notation. This could indicate that main and auxiliary engines are operated differently during DP operations.

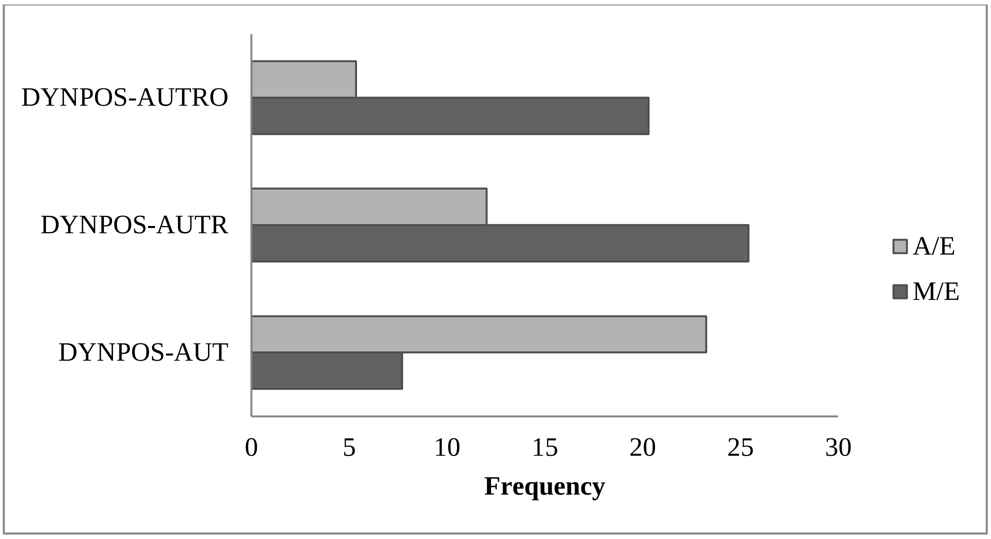


Figure 4-7: DP class notations

Dynamic positioning systems are most common within the offshore industry. According to data from DNV GL, more than 70% of the vessels categorised as offshore vessels are equipped with DP-systems. The offshore vessel category can thus be regarded as a representative sample of DP-vessels. A comparison of the finding frequencies for main and auxiliary engines on DP offshore ships and MOUs are shown in Figure 4-8.

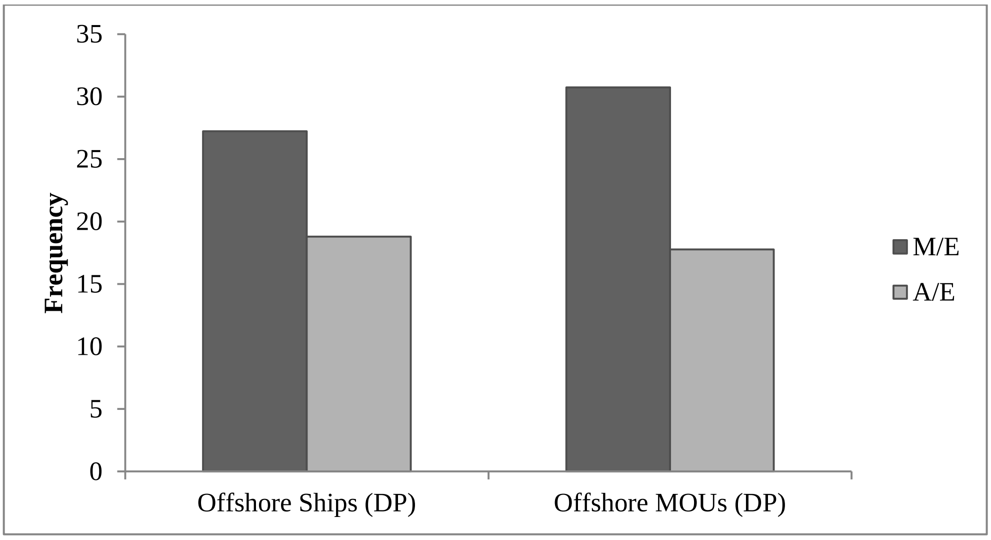


Figure 4-8: Main engines versus auxiliary engines on DP-vessels

Figure 4-8 shows that there is a correlation between finding frequencies within the same vessel category. The result indicates higher finding frequencies for main and auxiliary gensets on DP-vessels than on non DP-vessels. This coincides with the result shown in Figure 4-5, but differs from the result shown in Figure 4-6.

A closer analysis of the engine findings show that certain vessel groups are represented by extreme finding frequencies. This could manipulate the overall finding frequency results. Finding frequencies with respect to vessel types can be seen in appendix A2. Bulk carriers and passenger vessels indicate extreme frequencies for non DP-vessels. Bulk carriers can be discarded based on the low number of generator engines installed, which make them susceptible to extreme frequencies. The passenger category is more interesting as the number of generator engines is significantly larger. This category includes vessel types such as passenger ships and ferries, where passenger ships are represented by very high finding frequencies. The high frequencies may be explained by the quality of reporting. According to Dirix [28] are cruise companies known to be among the more laborious operators. The high frequency may also result from operational conditions. This reasoning leads to that the finding frequencies shown in Figure 4-8 probably gives a more realistic result than the overall finding frequencies shown in Figure 4-6.

DP-vessels and non DP-vessels from different vessel groups are compared in Figure 4-9. This is expected to give a more realistic result than the overall finding frequency calculations given in Figure 4-6 due to the high finding frequencies described above. The two vessel types included for comparison are offshore supply vessels (DP-vessel) and car ferries (non DP-vessels). Offshore supply vessels and car ferries are characterized by different operational conditions. The load profile of a supply vessel is commonly characterized by large load variations during operation with long periods of low load operations. Offshore supply vessels spend a large percentage of time to wait on the weather or the opportunity to serve offshore installations resulting in long periods at low engine loads. Car ferries represent a more uniform and predictable operational profile as they often sail short legs ranging from minutes to hours. During voyage, the engines loaded are to their optimum. When car ferries calls to port the engines are typically kept idling, but only for short periods of time.

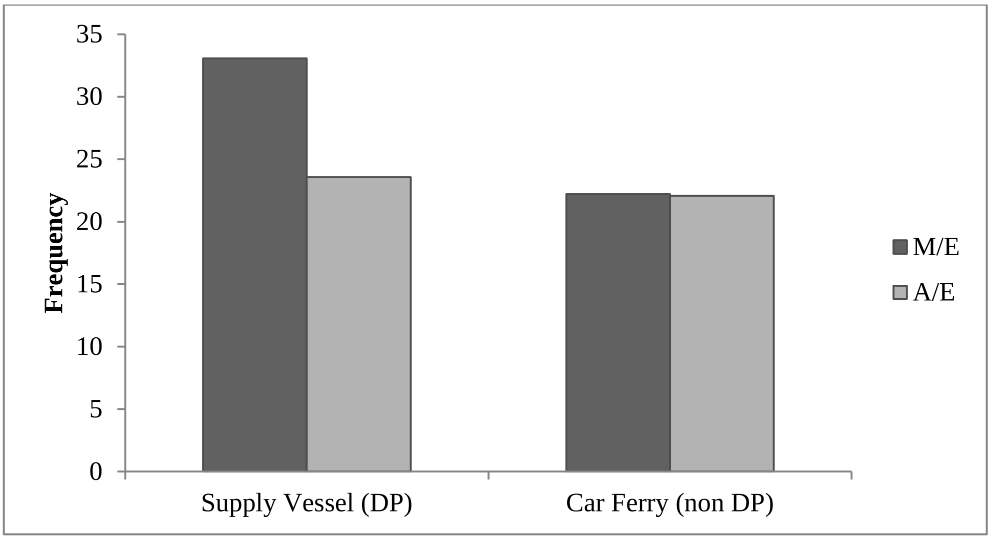


Figure 4-9: Supply vessels (DP) versus car ferries (non DP)

The result is shown in Figure 4-9 and indicates higher finding frequencies for the main and auxiliary engines on board supply vessels than the ones on board car ferries. The frequencies calculated for generator engines on board supply vessels, shows similarities to the finding frequencies calculated for offshore ships. The finding frequencies for generator engines on board car ferries are lower and more equally distributed compared to the ones on board supply vessels. This may reflect the fact that car ferries have a more uniform engine load pattern than offshore supply vessels. Main engines on supply vessels are found to have the highest finding frequency. These engines are also those who are more exposed to low load operations. The difference in finding frequencies of supply vessels and car ferries may indicate that low load operations cause operational problems which result in higher finding frequencies. This can be assumed if other operating conditions and thus other engine problems are more or less similar for the two vessel types.

It is suspected that the negative effects of low load operations are aggravated by NO_X emission regulations issued by IMO. The IMO Tier I compliant engines installed after year 2000 are of particular interest. It is thus interesting to evaluate finding data with respect to time to see whether emission regulations have had any impact on the finding frequencies.

There are some issues associated with the presentation of findings with respect to time. The first issue is due to the restructuring of NPS which prevents the analysis of findings prior to 2005. Consequently it is not possible to see the immediate effect of the introduction of NO_X optimized engines in 2000. The second issue is that all diesel engines are covered by a one year warranty from the engine manufacturer. Typical low load damages are known to occur after relatively few operating hours, but due to this warranty, very few damages are reported to class within the first year after installation. The third issue is that the number of findings is expected to increase with the age of the vessel. The finding frequency should therefore be corrected for normal age development when being evaluated with respect to time. A lot of effort and time has been put down to find a reasonable method to correct the finding frequencies for age development, but without any particular success. It was therefore decided that the best way to evaluate the finding frequencies with respect to time is to compare the finding frequencies of engines installed in specific time intervals. Thus are findings from 2005–2009 on engines installed in 1995–1999 evaluated against findings from 2010–2014 on engines installed in 2000–2004.

The result is shown for main engines on board DP-vessels and non DP-vessels in Figure 4-10. The result indicates higher finding frequencies for engines installed in the period 2000–2014 than for engines installed in the period 1995–1999. The highest finding frequency is represented by the engines installed on or after 2000 on DP-vessels. To evaluate whether NO_X optimized engines aggravate the negative impacts of low load operations, the relative increase in finding frequencies of DP-vessels and non-DP vessel have been calculated. Calculations show that the relative frequency-increase is about 1.3 times higher for main engines on DP-vessels than for main engines on non-DP vessels. This could indicate that the NO_X optimization of diesel engines has increased the operational problems of main engines that operate at low loads.

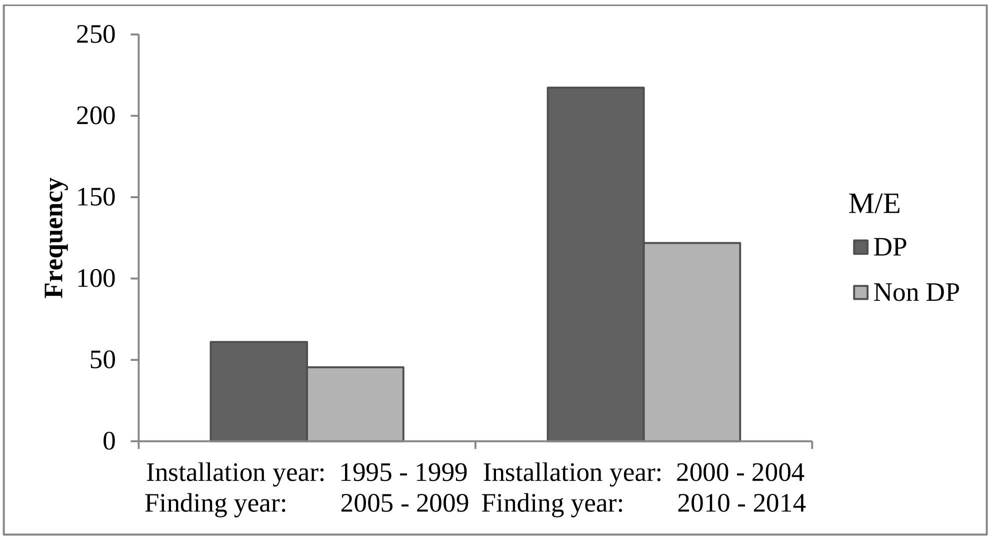


Figure 4-10: Installation year versus finding year for main gensets

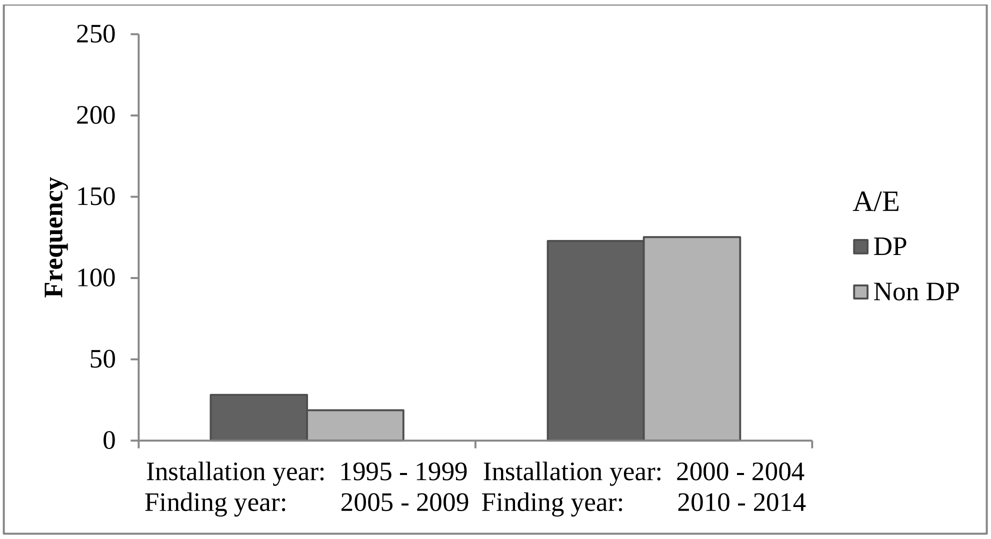


Figure 4-11: Installation year versus finding year for auxiliary gensets

Figure 4-11 shows generally lower finding frequencies for auxiliary engines than for main engines, but similar to main engines are the highest finding frequencies calculated for engines installed on or after 2000. However, the finding frequencies for auxiliary engines are more evenly distributed between DP-vessels and non-DP vessels compared to the main engines. As previously mentioned, this may reflect a more uniform load pattern for auxiliary engines than main engines. In contrast to main engines, the relative frequency increase for auxiliary engines is about 1.5 times higher for non DP-vessels than for DP-vessels. Using the same reasoning as for main engines, this result could indicate that NO_X optimization have not increased operational problems of auxiliary engines that operate at low loads.

The results presented above shows that the highest finding frequencies are found for engines installed on or after 2000. This applies for both main and auxiliary engines on board DP- and non DP vessels. These calculations may indicate that the introduction of NO_X optimized engines in 2000 generally have had negative impacts on operational problems. However, it is difficult to establish any conclusion regarding how NO_X optimized engines impact on operational problems related to low load operations based on these frequency calculations.

4.6 Discussion of Results

The intention of this analysis has been to investigate if one quantitatively can substantiate the suspicion that low load operations of gensets increases operational problems and thus the finding frequency. It has also been attempted to determine whether the introduction NO_X optimized engines have had any negative effect on operational issues related to low load operations.

To analyse the impact of low load operations, it has been assumed that low load operations are most likely to occur to engines on DP-vessels. This appears to be the only way to differentiate vessels that may operate at low loads from vessels that probably not operate at low loads. It is further presumed that other operational problems that could lead to increased finding frequencies are more or less the same for DP- and non DP-vessels. This means that the difference found in the finding frequencies of DP- and non DP-vessels may be a result of low load operations. These assumptions do not necessarily reflect the real world, but this is currently the only known way to analyse these data quantitatively.

Calculations show that main engines generally have higher finding frequencies than auxiliary engines. Overall finding frequency calculations show higher frequencies for non DP-vessels than DP-vessels. The finding frequency of offshore supply vessels with DP was compared to car ferries. The intention was to compare one vessel type that operates at low loads with another vessel type that does not operate at low loads. The result showed higher finding frequencies for main engines installed on board supply vessels than for the ones installed on board car ferries. The results may indicate that low load operations increase operational problems and thus the finding frequency, but this should not be used to establish any general conclusions without further investigation.

Finding frequencies have also been evaluated with respect to time to determine whether NO_X optimized engines have a negative impact on the finding frequency. The result showed much higher finding frequencies for engines installed in the period 2000–2004 than the ones installed in the period 1995–1999. This indicates that stringent NO_X regulations may have increased operational problems and thus the finding frequency. However, it is difficult to say whether NO_X optimized engines have aggravated the negative effects of low load operations. The comparison of DP-vessels against non DP-vessels shows ambiguous results. It is thus difficult to establish any general conclusions regarding low the impacts of low load operations on NO_X optimized engines.

Chapter 5 Industrial Experience

This project was initiated by DNV GL based on a suspicion that low load operations of diesel engines in generator configuration increase the engine damage frequency. This suspicion is based upon engine damages reported to the class over the past years. It is therefore interesting to investigate whether the industry has the same perception. This chapter intends to investigate the engine manufacturers' and their customers' experiences with low load operations on modern diesel engines in generator configuration.

Several major diesel engine manufacturers have been contacted and asked to share their views on low load operations. Those who had the opportunity to contribute were interviewed by phone or in writing by e-mail. The questions asked are included in appendix A3. The quality and level of detail of the responses were very different and thus not directly comparable. For this reason, a general perception of the manufacturers' views on low load operations is presented as a whole, rather than each individual manufacturer´s perception.

A chief engineer working on board a Subsea Support Vessel operating in the North Seas has also been interviewed. The ship operates most of its time on DP at extremely low engine loads. At request from the interviewee, the ships' name, owner and client have been anonymized.

5.1 Manufacturers' Experience

All respondents [29], [30], [31], [32] had experiences with low load operations of their engines and did agree that low load operation of diesel engines is a highly relevant issue of today. One of the manufacturers [31] pointed out that low load operation becomes an issue because gensets too often are over dimensioned for their actual use. Just dimensioning of gensets shall be of primary concern in a design phase, but due to class requirements and demands from ship owners, gensets are frequently oversized. This is particularly relevant for gensets installed on board vessels with dynamic positioning systems.

The respondents did agree that low load operation of their engines for long periods of time could lead to operational problems if precautions are not taken. It is consensus among the engine manufacturers that diesel engines must be brought to higher load (at least 50% of rated power) after a period of low load operation to prevent operational problems. Such recommendations are without exception written in the engine product guides. Two of the manufacturers that were interviewed, have developed and published special recommendations or instructions for low load operations of their engines made for internal use and for their customers.

From the manufacturers´ point of view it was not confirmed that low load diesel engine operations will lead to increased damage frequency, but it was confirmed that longer periods of low load operations will affect the engine operation due to more frequent overhaul intervals. Operational problems that were frequently mentioned were the formation of soot deposits in the cylinders, wet stacking and soot deposits in the turbocharger. Soot formation results from incomplete combustion due to low cylinder pressures and temperatures at lower loads. Most of the soot particles formed during low load operations are burned away when the load and thus the temperature is increased, but over time carbon deposits can build up on the cylinder liner, piston and injection nozzles. Wet stacking is defined as the presence of unburned fuel or carbon in the exhaust system.

Incomplete combustion also results in accumulation of unburned fuel on the cylinder liner and in the crevices around the top land of the piston. When the temperature increases due to higher loads the unburned fuel may ignite and cause local combustion around the piston top land. This can cause small and local damages to the piston. Piston rings prevent leakage of combustion gases past the piston sleeve, but depend on high cylinder pressures to maintain proper sealing efficiency. Low pressures due to low load operations deteriorate the sealing efficiency and allow combustion gases and unburned fuel to leak into the oil pan and cause dilution of the lubricating oil. This may deteriorate the lubricating oil film, which makes the cylinder liner prone to abrasive wear from hard carbon particles from the incomplete combustion. By increasing the load and thus the cylinder temperature, the unburned fuel will evaporate and reduce the possibility of lubricating oil dilution. Low load operation will increase the amount of return fuel, which will impose greater demands to the fuel cooling system. The viscosity of modern distillate fuels is lower than before and can be as low as two centistokes at 40 °C, which is the minimum viscosity limit in most modern diesel engines. Too low fuel viscosity can cause deteriorated fuel injection and cavitation in injection plungers and needles.

One of the manufacturers [29] confirms that they have received feedback on the above-mentioned problems from their customers. One of their customers operates their generator engines at average loads around 30% of rated power. According to the customer, this leads to blackening of engine components such as cylinder tops, liners, injection nozzles etc. This means that they must perform overhauls much earlier than stipulated in the engine maintenance manuals, which is somewhere between eight and ten thousand operating hours. The engine manufactures were asked to provide statistics to support the impacts of low load operations, but none of the respondents would share their engine damage statistics in the interest of their customers.

It is suspected that the negative impacts of low load operations are aggravated by recent IMO regulations due to lower cylinder pressures and temperatures. This includes Tier 1 compliant engines installed on ships on or after January 1 2000. The engine manufacturers were asked if they had experienced an increase in operational problems on their NO_X optimized engines. One of the manufacturers [33] could inform that they had challenges related to their first NO_X optimized engines. The optimum operating point for these engines could be as high as 85% of rated power, which imposed challenges to operations at lower engine loads. However, recent developments have provided engine technologies such as common rail, variable injection timing and variable valve control that allow engine operations at lower loads than earlier. The common rail technology maintains the injection pressure and variable valve controls ensure sufficient time for charge air suction regardless of engine load or speed. It is emphasized from the manufacturer that low load operations, despite technological advancements, still are admissible only for shorter periods of time.

Among other challenges mentioned in relation with NO_X optimized engines was the familiar paradox of NO_X, CO_2 and combustion temperature. High combustion temperature leads to higher combustion efficiency and thus lower CO_2 emissions and soot formation, but also results in higher NO_X formation rates. This paradox is more relevant to other operational aspects such as fuel economy and environmental restrictions. The engine manufacturers must meet increasingly stringent restrictions on NO_X emissions and are today focusing on both primary and secondary measures, which are described in detail in subchapter 2.4.2. Primary measures include EGR, water injection, Miller timing and more efficient cylinder and fuel system designs. Secondary measures include diesel particulate filters (DPF) and selective catalytic reduction (SCR) systems. Since SCR subsequently removes the nitrogen oxide from the exhaust gas, the combustion process can be optimized for low fuel consumption while still remaining within the legal emission limits. The SCR only work efficiently if the exhaust gas temperature is correct. If the temperature is too high, the ammonia burns rather than forming a compound with nitric oxides. If it is too low, it forms ammonium hydrogen sulphate and gradually blocks the catalytic converter. The same also happens if the sulphur content of the exhaust gas is too high. The minimum temperature required depends on the fuel´s sulphur content. Low sulphur fuels can thus be an issue when the engines are operated at low loads.

5.1.1 Specifications for Low Load Operations

Cummins Marine and Mitsubishi Heavy Industries have specified requirements for operations at low loads. They also briefly describe potential problems related to excessive low load operations. These specifications are reviewed more closely in the following subchapter.

Cummins Marine

Cummins Marine has created a document which defines low load limitations for fixed speed engines used in auxiliary and genset applications [34]. The document was issued in a marine application bulletin in 2005 and revised in 2014. The limitations reviewed apply to all Cummins Marine auxiliary and fixed speed diesel engines.

According to Cummins Marine [34], low load operation for extended periods of time is an issue with fixed speed engines used in auxiliary and genset applications. The engine manufacturer encourages that engine power must be properly matched to the load and duty cycle of the intended application, to prevent extended operation at low load. Cummins Marine has developed specific installation requirements to minimize low load operations on their engines. The minimum average load for a fixed speed auxiliary engine or genset must be greater than 30% of prime power. In general, Cummins Marine claims that fixed speed engines and gensets must not run for more than eight hours at a time at less than 30% of prime power, but for the modern four-stroke engines with common rail systems they have less restrictive requirements. Fixed speed auxiliary engines and gensets with common rail, either modular common rail system (MCRS) or High Pressure Common Rail (HPCR), should not run for more than eight hours at the time at less than 10% of prime power or more than 24 hours at the time at less than 30% of prime power. The engine manufacturer claims that when diesel engines run at extreme low loads the cylinder pressure will be much lower than normal and incomplete combustion will occur. Cummins Marine recommend that low load operations (10–30% of prime power) for longer periods of time (maximum 8–24 hours) depending on engine type should, be followed by at least 30 minutes of high load operation (higher than 50% of rated power). The reason for this is to burn off fuel residue and thus reducing the chance of developing long term engine problems. According to Cummins Marine [34], longer periods of low load operations can cause several problems. These are reviewed below.

Wet stacking

When diesel engines run below its designed operating temperature for longer periods, unburned fuel is exhausted and noticed as wetness in the exhaust system. The aggravation of unburned fuel in the exhaust side of the engine results in carbon build-up on exhaust valves and turbocharger. Excessive deposits of carbon can result in loss of engine performance as gases bypass the valve seats and deposits on the turbo blades. Further this can reduce the turbo efficiency.

Carboning

Carboning is the result of carbon particles deposited on top of the piston rings and in the injectors due to incomplete combustion of fuel.

Fuel dilution of lubrication oil

The piston rings are designed for optimized sealing efficiency under elevated combustion pressures. When such pressures are not achieved due to low load operations, the piston rings do not expand sufficiently to adequately seal the space between the pistons and the cylinder walls. This results in unburned fuel and combustion gases escaping into the oil pan and diluting the lubricating properties of the oil, leading to premature engine wear.

Water contamination of lubricating oil

If the lubricating oil does not attain the desirable operating temperature, condensation of water may form in the engine oil pan. Water is known to be one of the most destructive contaminants in the lubricating oil. It attacks additives, induces base oil oxidation and interferes with oil film production. The water may aggregate dead additives, soot, oxidation products and sludge that can clog filters and thus restrict the oil flow to the engine components.

Piston detonation

Excessive engine idling or low load operations can cause aggravation of unburned fuel in the crevices around the top land of the piston. When the temperature is increased due to higher engine, the unburned fuel is ignited. This causes localized burning and uncontrolled detonations above the top ring.

After treatment damage

Engine operations at no load or low loads for extended periods of time can lead to plugging of the after treatment diesel particulate filters (DPF) due to extensive soot formation. Another concern is related to the selective catalytic reduction (SCR) system. The SCR only work efficiently if the exhaust temperature is correct. Too low exhaust temperature due to low load operations, can result in formation of ammonium hydrogen sulphates that gradually blocks the catalytic converter.

Mitsubishi Heavy Industries

Mitsubishi has issued specifications for limited engine operations at no load or low load in an engineering bulletin in 2004 [35]. The bulletin was issued to give information in case of limited engine operations. It also includes corrective actions to avoid engine damage.

The manufacturer advises that minimum allowable load for continuous operation is 25% of maximum power. Maximum allowable operating time at no load with high or low idling is set to one or two hours respectively. After a period of one hour running at 25% of maximum power or below, the engine must be loaded to 60% or more, for a period of at least half an hour. According to manufacturer [35], the following possible problems can occur when running outside the load limits stated above:

Leakage from the exhaust system

Continuous operation on no-load or low load causes unburned fuel and oil mist to condense in the exhaust system, which may result in leakage through the exhaust connections.

Carbon deposits

Unburned fuel, oil mist and soot deposits may pollute the exhaust ports on the cylinder heads and the exhaust manifold, which lower the performance of the engine.

Corrosive damage

Lower exhaust gas temperature may result in condense of sulphuric acids in the exhaust system, causing corrosive damage.

Fuel dilution

Because of decreased combustion efficiency, unburned fuel can dilute the lubricating oil, resulting in decreased lubrication properties and increased wear of rotating parts.

White smoke

Excessive unburned fuel will appear as white smoke from the exhaust stack, it smells and irritates the eye.

5.2 Chief Engineer's Experience

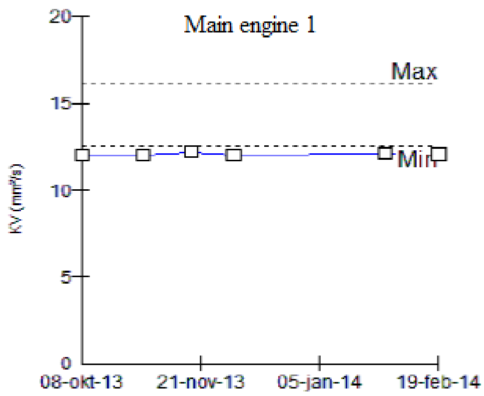
This subsection describes a chief engineer's experiences with low load operations of diesel engines in generator configuration. Karlsvik is working as chief engineer on board a Subsea Support Vessel operating in the North Sea. The ship has IMO DP Class 3 and is configured with four main generators divided into two identical engine rooms. The generator engines are of four-stroke medium-speed type and are rated to about 2600 kW at 720 rpm. At request from the interviewee are the ships' name, owner and client anonymized.

The vessel has operated on the same field in the North Sea on contract from a client since 2003. In 2012 the vessel had some problems with the oil mist detectors which abruptly stopped the main engines without warning during DP operation. Prior to the incident the vessel operated with two or three generators running and, according to Karlsvik [36], the load demand was never a problem no matter how bad the weather was. When the weather is too bad, the ship is ordered to stop its operations at the sea floor and go out of DP. Due to the incident in 2012 the client requires that all four generators shall be running at all times regardless of the weather conditions.

During DP operations, each generator is loaded to 400–500 kW. This corresponds to an average engine load around 15–20% of maximum rated power, which is defined as extreme low load operation. In calm weather the thrusters must be operated with bias, which in practice means that extra load is put on the propellers regardless of the actual load demand from the propellers. This is necessary to ensure that the load distribution is high enough to prevent that the generators abruptly run in reverse power, which means that the generators begin to operate as motors instead of generators. A generator that starts running in reverse power mode is immediately disconnected from the main switchboard. A typical load curve for the generators during DP operation is included in appendix A4.

The ship normally operates continuously on DP in two weeks before it returns to base for crew change. During DP operations, all four generators are running constantly at extreme low loads. Normally, the engines will not run at higher loads until the two week period is over. The only exception is if the ship must leave DP to wait for the weather. The transit time to the base is about ten hours and the crew change is normally done within eight hours in port. Then the ship returns back to the field and continue its DP operation for another two weeks.

A class renewal survey was conducted in 2014, where inspections of the main engines revealed bearing damages caused by high levels of fuel contamination of the lubrication oil. This is typical for engines that operate for longer periods at low load due to the lower cylinder pressure which deteriorate the piston ring sealing efficiency. The crew had performed oil changes frequently from mid-2013 until the stay at the shipyard and were thus not surprised that the engines were damaged. Figure 5-1 and Figure 5-2 show the viscosity measurements from oil samples that were taken before the vessel went in dock for its class renewal survey. The oil analysis showed that the viscosity of the lubricating oil was lower than the minimum requirement for all four main engines. Too low viscosity levels can deteriorate critical lubrication oil films which lead to premature wear of pistons, piston rings, cylinder liners and crankcase bearings. Such damages were confirmed during the renewal survey inspection.



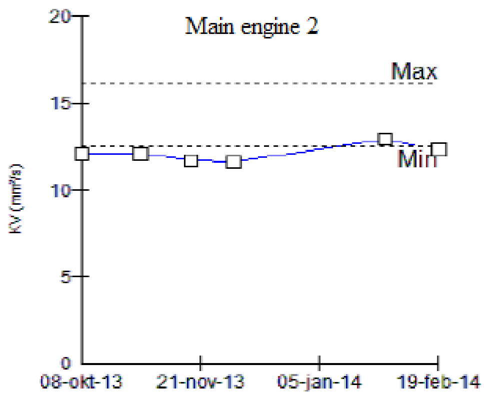


Figure 5-1: Viscosity at 100 °C from oil sample analysis of M/E 1 and M/E 2

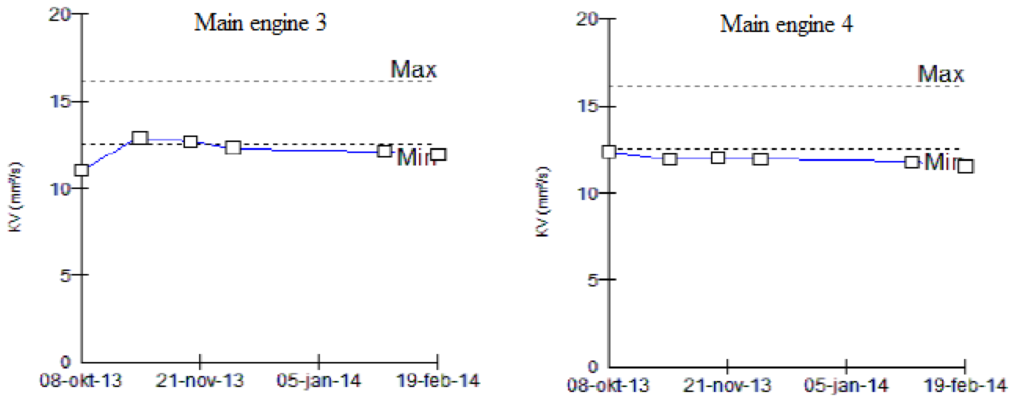


Figure 5-2: Viscosity at 100 °C from oil sample analysis of M/E 3 and M/E 4

According to Karlsvik [36], the soot levels inside the engines have also increased significantly with the new demands of the client. It also appears that soot more easily deposit on fuel valves and nozzles than earlier. This can be explained by the fact that low engine loads lead to lower cylinder temperatures and thus poor combustion efficiency. The rate of soot formation increases with reduced combustion efficiency.

The maintenance intervals for these engines have not been revised after the stay at the yard, despite the damages that were found on the engines. The impression of the crew is that the ship owner does not want to revise the maintenance procedures because the ship is old and will probably be taken out of service at the next renewal service in 2019. A second, and perhaps equally big, challenge is to carry out regular maintenance on the engines as all engines are required to be running at all times during DP operations. The crew do not have sufficient time to go over all the necessary maintenance work when the ship is in transit or in port. In addition, the client has added more stringent restrictions on the technical operation of the engines while the ship operates at the field.

The stringent operational requirements from the client have introduced a number of new operational challenges and problems. According to Karlsvik [36], the operational challenges and problems can be summarised as follows:

- Extremely high wear rates on the engines due to excessive low load operations. Low load operations increase the amount of soot and dilute the lubricating oil, which lead to premature wear of the engine components.
- Higher maintenance costs due to higher numbers of operating hours on the engines. By running all the engines at all times the number of operating hours per engine increases significantly.
- The time available for maintenance work is very limited. Due to the clients' restrictions on the field, maintenance can only be conducted during transit and in port, which is not sufficient.
- The engine operation has negative impacts on the environment. By running twice as many engines as perhaps necessary, the fuel consumption increase and thus the emission levels increase.

The chief engineer's experiences with low load operations is a good example of why offshore vessels with dynamic positioning systems often operate at low engine loads during DP operations. In this case, the client puts demands on the engine operation which is inconsistent with both engine manufacturers' and crew's recommendations. This shows that low load operations is not necessarily a result of over dimensioning of gensets in the initial design phase, nor requirements from the Class , but rather a result of decisions made by the client on-shore.

Chapter 6
Discussion

Relevant literature and a damage case have been reviewed, existing finding data from DNV GL have been analysed quantitatively and experiences from the industry have been assessed qualitatively. The following discussion intends to put these pieces together to form an understanding of the impacts of low load operations of modern diesel engines in generator configuration.

6.1 Low Load Operation

Low load operation of diesel engines is defined as engine operations at load levels below 40% of maximum continuous rating. This study has mainly focused on low load operations of generator engines on board offshore vessels with dynamic positioning systems. The requirement for redundant DP notations, which correlate with IMO DP guidelines, is that the redundancy shall be based upon running machinery [4]. This means that one cannot count on the capacity of standby gensets during DP operations. How this affects the engine operation depends on the division of redundancy groups within the DP system. There are no requirements as to how the redundancy groups shall be divided in terms of capacity, but it is a requirement that the vessel should be able to maintain position and heading after the loss of any of the redundancy groups. The load distribution on the gensets depends on how the redundancy groups are designed, but according to Karlsen [37] it is often the case that gensets runs at low load during DP operations. This is the reason for why it has been focused on DP-vessels to assess the impacts of low load operation of diesel engines in generator configuration.

6.2 Transient Load Operation

Transient load operations of gensets on board ships are mainly due to sudden changes in load demands from propulsion or deck equipment. It is suspected that operations at low loads combined with transient loads increase operational problems. A sudden load increase causes engine torque deficit and thus a speed drop. To obtain torque balance and recover speed is more fuel injected into the combustion chamber. Because of turbocharger lag is the air/fuel-ratio lowered in which causes combustion deterioration and thus excessive soot formation. This topic has not been emphasised in this study, but the impacts of transient load operations may aggravate the negative effects of low load operations due to increasing amounts of soot.

6.3 NO_X Optimization

Most modern diesel engines are operated at lower cylinder pressures and lower temperatures than their predecessors. This is due to the stringent NO_X emission control requirements of IMO Annex VI. The formation of NO_X is strictly temperature dependant and is controlled by primary measures. Primary measures aim to reduce the amount of NO_X formed during combustion by optimizing engine parameters. This is the reason for lowered cylinder pressures and temperatures in most modern diesel engines. Lower temperature reduces the combustion efficiency, which is known to increase the fuel consumption and the formation of CO_2 and soot. Soot is formed when the temperature is "high enough" and the mixture is "rich enough". Soot contaminated lubricants have shown to produce significant amounts of engine wear through abrasion. High concentrations of soot also increase the local acidic levels that may lead to corrosion. Common primary measures to reduce cylinder temperatures are modification of fuel injectors, exhaust gas recirculation (EGR), water addition, and Miller cycle.

Modification of fuel injectors is one way to reduce the temperature level in the cylinder. A smaller spray cone angle reduces the air entrainment into the spray, which results in less prepared mixture during the ignition delay. A reduced premixed combustion phase means that a larger proportion of the combustion takes place in the mixing-controlled combustion phase, which is driven by a diffusion flame. Diffusion flames tend to burn slower and produce more soot than premixed flames. Exhaust gas recirculation (EGR) is another way to reduce the cylinder temperatures. According to Hussein et. al [38], it is observed that EGR reduces the NO_X without deteriorating engine performance end emissions at lower engine loads. However, the exhaust gas which is introduced to the combustion chamber contains several contaminants, which may end up in the engine lubricating oil sump. According to Doyle [39], lubricating oils exposed to the EGR environment show an increase in soot content, acid number and viscosity. The introduction of water has the same effect on NO_X formation as EGR, but injection of water into the combustion chamber is a possible source of water contamination. According to Holtbecker [40], water droplets that reach the cylinder walls can destroy the lubricating oil film, but water droplets only pose a danger when the water is in liquid phase. This may be the case when the engine is running at low loads and with low temperatures. Water cannot affect the oil-film at higher engine loads where it evaporates before it reaches the cylinder wall. Modification of the engine cycle is also a way to reduce the cylinder temperatures. The idea of the Miller cycle is to reduce the effective compression stroke to lower the temperature. Shorter compression stroke must be compensated by higher charge air pressure i.e. increasing demands is made on the turbocharging system. Furthermore, Miller cycle can give cold start problems, increased smoke emissions and operating problems at low load due to low turbocharger efficiency.

According to Selle [33], Wärtsilä experienced operational problems on their earliest NO_X optimized engines. The optimum operating point on the first NO_X optimized engines could be as high as 85% of maximum continuous rating due to the low cylinder pressure and temperature. Selle [33] also mentions that recent developments have provided engine technologies such as common rail, variable injection timing and variable valve control. Common rail fuel injection systems is said to enable precise and flexible control of injection timing and duration helping the engine performance, emissions and fuel consumption to be optimized for the entire load range. Selle emphasises that low load operations, despite the technological advancements, only are admissible for short periods of time.

6.4 Marine Fuel Properties

According to Lewis [17], fuel related operational problems were introduced with the upgrade of the refinery process from straight run to complex refining These problems are mainly related to residual fuels, but are included as most medium-speed gensets can run on both heavy fuel oil and distillate fuels. Related to low load operations, the main concern are the increased level of aromatics in the fuel which originates from the catalytic cracking. Aromatics have high auto ignition temperature which increases with increasing aromaticity. High levels of aromatics affect the stability and ignition quality of the fuel. At low loads, the temperatures are lower than "normal". Fuels that are difficult to ignite in the first place can become even more problematic. This may lead to unstable ignition and combustion characteristics. Higher levels of aromatics are also more common for modern distillate fuels, but for diesel engines that can run on both residual and distillates are the ignition quality normally not a problem. However, high-speed diesel engines are more sensitive to poor ignition qualities than medium-speed engines. In these engines, the ignition characteristics will be of importance. A more common problem with modern distillates is the viscosity. Often low sulphur fuels have lower viscosity than fuels with “normal” sulphur content. The viscosity of some low sulphur fuel can be as low as two centistokes at 40°C, which is the minimum viscosity limit in most modern diesel engines. At low engine loads, the amount of return fuel increases. If the return fuel is not properly cooled, the viscosity can get too low. Too low viscosity may lead to deteriorated fuel injection and can cause cavitation in injection plungers and needles. In addition, it can lead to lubrication problems for engine components that rely on the fuel to be properly lubricated as the lubricating properties depend on the viscosity.

6.5 Lubricating Oil Properties

The deterioration of the lubrication oil goes slowly under normal engine operating conditions, but under abnormal conditions and engine malfunction the lubrication oil will degrade very fast. At low loads, the amount of unburned fuel and soot deposits increase in the cylinder due to incomplete combustion. Low sealing efficiency, due to low cylinder pressure, causes unburned fuel and soot to leak into the oil pan and dilute the lubricating oil. Fuel dilution can reduce the viscosity of the oil, which can collapse critical oil film thicknesses in the engine. This can result in premature wear of pistons, piston rings, cylinder liners and crank case bearing. Severe dilution (excess of two percent), which is often associated fuel injector leakage, injection problems and low combustion efficiency, can cause wash-down of lubricating oil on the cylinder liner. This accelerates the wear of pistons, piston rings and cylinder liners. Severe fuel dilution may also dilute the concentration of oil additives and hence reducing their effectiveness. Liner lacquer formation is also an issue that is known to occur in medium-speed diesel engines running on distillate fuels. Liner lacquering has been found in diesel engines with large variations in load, operating for long periods at idling or extremely low load followed by full load operations. The build-up of lacquer may result in smoothed or glazed liner surfaces, which has a negative effect on the lubrication oil consumption.

6.6 Maintenance

Nominal maintenance intervals and expected component service life time of diesel engines are worked out based on assumptions like regular high load operations, operating on fuels with good ignition qualities, that the vessel is fitted with the engine manufacturer's recommended fuel treatment plant, correct engine specifications according to operations etc. These assumptions do not necessarily reflect the real world, which means that the maintenance intervals must be customized to the individual diesel engine. Long periods of engine operations at low loads contradict any of the above-mentioned assumptions.

6.7 Impacts of Low Load Operations

The literature review, analysis of damage cases and the industry's perceptions, have formed a basis for understanding the impacts of low load operations of modern diesel engines. The mechanisms that are suspected to have negative impact during low load operations are in the following subsection presented as a sequence of events. This presentation is by no means complete or generally applicable, but intends to summarise the mechanisms that are believed to cause operational problems during low load operations.

Low load operations of diesel engines cause lower cylinders pressures and thus lower temperatures, which can result in ignition problems and incomplete combustion. Low cylinder pressure has mainly a negative effect on the cylinder temperature, but also deteriorates the piston ring sealing efficiency as piston rings rely on the gas pressure in the combustion chamber to work properly. Incomplete combustion will lead to increased soot formation and aggregation of unburned fuel in the cylinder. Unburned fuel and soot may glaze the piston rings and cause a further reduction of the sealing efficiency and worsen the initial low pressure in the combustion chamber. Deteriorated piston ring sealing efficiency may cause hot gases and particles to blow past the piston rings and continue down the piston skirt. Hot combustion gases will ignite the lubricating oil film on the liner and result in liner glazing. The glaze smoothes out the honing mark pattern in the liner which is essential to the hold and return lubricating oil to the crankcase via the oil ring. Hard carbons particles resulting from the incomplete combustion have an abrasive effect on the cylinder liner walls. The already glazed honing marks are polished by the hard carbon, which results in a completely smooth liner surface. The lubricating oil consumption increases drastically as more oil is burned instead of being led back to the crankcase. The glazing may also have a negative impact on the cylinder pressure as the oil film trapped in the honing marks are important to maintain the sealing efficiency of the piston rings. As previously mentioned, deterioration of the piston ring sealing efficiency allows for hot combustion gases, soot and unburned fuel to be pushed passed the piston rings into the oil sump. This leads to contamination of the lubricating oil which can change the viscosity of the oil drastically. Soot contamination increases the viscosity of the oil. Too high viscosity may restrict the oil flow and even clog oil filters. Fuel dilution of the lubrication oil reduces the viscosity of the oil. Too low viscosity may collapse the critical oil film thickness.

Excessive fuel dilution seems to be the most problematic oil contaminant resulting from low load operations. Low viscosity lubricating oil can cause premature and rapid wear of pistons, piston rings, cylinder liners and crank case bearings. Severe fuel dilution may also dilute the concentration of oil additives and hence reducing their effectiveness. Acids are formed from condensed water and combustion by-products, which normally would boil of at higher temperatures. During low load operations, cylinder temperatures can be lower than the boiling point, which can cause acidic build-up in the lubricating oil. This causes slow, but damaging wear to bearing surfaces. Individual soot particles are small and pose no direct risk to engine parts, but soot particles may clump together to form larger and more damaging soot clumps. Clogging of fuel injectors may have a negative impact on the fuel spray pattern, the injection pressure and thus the time of injection. Deteriorated fuel injection characteristics, may lead to further degradation of the combustion process.

The mechanisms of low load operations lead to a cycle of degradation, which means that diesel engines running at low loads for longer periods at the time may become irreversibly damaged. Symptoms of the operational issues resulting from low load operations can be seen in the exhaust. White smoke results from unburned fuel, blue smoke from burned lubrication oil and black smoke from damaged fuel injectors.

6.8 Recommendations for Low Load Operation

If precautions are not taken, engine manufacturers agree that low load operations of their engines may have negative impacts on operating conditions. Diesel engines running at low loads for longer periods of time shall be brought up to higher loads on a regular basis to prevent operational problems. A load increase will raise the internal pressures and temperatures, allow the piston rings to scrape glaze off the bores and allow carbon build-up and unburned fuel to be burnt off. However, if glazing is developed to the stage where the piston rings are seized this will not have any effect. Once glazing or carbon build-up has occurred, it can only be removed by re-bore cylinder bores, machining new honing marks and clean combustion chambers, fuel injector nozzles and valves. Regular lubricating oil analysis should also be performed to monitor the contamination levels. Severe fuel contamination of the lubricating oil can be lethal to the diesel engine and should thus be monitored very closely.

It is consensus among the engine manufacturers that diesel engines must be loaded to at least 50% of rated power regularly during low load operation, to mitigate the risk of operational problems. The time interval and the requirements for load increase vary from one engine to another depending on the engine design. Recommendations regarding operations at low loads are, without exception, found in the engine product guides provided by the manufacturers. Cummins Marine has made specifications for low load operations depending on the fuel injection systems of the engines [34]. Engines with conventional injection system shall not be running at less than 30% of maximum rating for more than eight hours at the time. Every low load sequence shall be followed by at least 30 minutes of operation at engine loads higher than 50% of rated power. The low load operation requirements are less restrictive for modern engines with common rail injection systems. The engines shall not be running at less than 10% of maximum rating for more than eight hours at the time, but can run at less than 30% engine load for maximum 24 hours at the time. This shows that modern NO_X optimized diesel engines with common rail are better equipped to handle lower loads than their predecessors.

It shall be emphasised that the recommendations for operations at low load are based on the assumptions of high fuel qualities and correct fuel treatment. In most cases these assumptions do not reflect the actual situation on board. Fuels resulting from complex refining processes may have characteristics that are far from ideal. This means that guidelines for operations at low load should ideally be customized for the individual engine given its operational conditions. The fuel quality and thus the fuel treatment plant is an important factor in this context. Ideally, all new bunker fuels should be tested and evaluated against certain engine parameters such as mean effective pressure, charge air temperature, turbocharger inlet and outlet temperature, exhaust temperature and pump indexes. This should be done for different loads i.e. 25%, 50%, 75% and 100%. Further, the loads should be evaluated against existing results for ideal engine operating conditions.

6.9 Qualitative Analysis

The intention of the qualitative analysis was to investigate whether one quantitatively can substantiate the suspicion that low load operations increases operational problems and thus the damage frequency. The analysis is based on simple frequency measurements of diesel engine survey findings extracted from NPS. Survey findings are not limited to damages, but also include issues that represent non-conformity with the class. For the purpose of this study, it has been assumed that these findings will give a realistic picture of the engines' damage extent. To be able to analyse the impacts of low load operations, it has been assumed that low load operations are most likely to occur on vessels with dynamic positioning systems due to the reasoning discussed in subchapter 6.1. It has also been assumed that other operational problems that could potentially lead to increased finding frequencies are more or less similar for DP- and non-DP vessels. Given the abovementioned assumptions, the difference in finding frequencies for DP- and non DP-vessel could indicate operational problems caused by low load operations. These assumptions do not necessarily give the most accurate result, but it is currently the only way to analyse these finding data quantitatively. The finding frequencies were also evaluated with respect to time to determine whether NO_X optimized engines aggravate the negative impacts of low load operations. There were some issues related to the presentation of finding frequencies with respect to time. One issue was that the only findings from 2005–2014 are available for analyses, which means that the immediate effect of the introduction of NO_X optimized engines in 2000 is not visible. Another issue was related to the one year warranty of new engines, which means that very few findings are reported to class within the first year of operation. The third issue was that the number of findings and thus the finding frequencies are expected to increase with the vessel age. Finding frequencies should therefore ideally be corrected for the normal age development.

The results from the quantitative analysis are discussed in detail in subchapter 4.6. The results show higher finding frequencies for main engines on DP-vessels, which may indicate operational problems caused by excessive low load operations. The result also show higher finding frequencies for engines installed after 2000, which could indicate that stringent NO_X regulations have increased the operational problems. However, from this results it is difficult to say whether NO_X optimization have affected low load operations negatively. Generally, the results from the quantitative analysis are ambiguous and should be read with caution.

Chapter 7
Conclusion

Low load operations of diesel engines are defined as operations at engine loads below 40% of maximum continuous rating. Low load operations are typical for, but not limited to, offshore vessels with dynamic positioning system. This is mainly due to redundancy requirement and conservative safety requirements from ship owners or clients. This work has focused on gensets on board offshore DP-vessels to assess the impacts of low load operations on modern four-stroke diesel engines.

Low load operations of diesel engines causes lower cylinder pressures and thus lower temperatures. Lower temperatures can lead to ignition problems and incomplete combustion which will lead to increased soot formation and aggregation of unburned fuel in the cylinder. The piston ring sealing efficiency relies on the gas pressure in the combustion chamber to work properly. Low cylinder pressure and glazing of piston rings deteriorate the sealing efficiency and worsen the initially low cylinder pressure. Deteriorated piston rings cause hot combustion gases and particles to blow past the piston rings and ignite the lubricating oil film in which will result in liner glazing. Hard carbon particles resulting from incomplete combustion polish the glazed honing marks and smooth out the liner. The lubricating oil consumption increases drastically, as the lubrication oil is burned instead of being led back to the crank case. This will have negative impact on the cylinder pressure as the oil film trapped in the honing marks is important to maintain the piston ring sealing efficiency. Hot combustion gases, soot particles and unburned fuel that are pushed past the piston rings end up in the oil sump and cause dilution of the lubricating oil. Fuel dilution may reduce the viscosity of the oil, which collapses the critical oil film thickness. This results in premature wear of pistons, piston rings, liners and crank case bearings.

Most modern diesel engines operate at lower cylinder pressures and thus lower temperatures than their predecessors. The reason is the stringent NO_X emission control requirements of IMO's MARPOL Annex VI. The engine designers focus on both primary and secondary measures to reduce the amount of NO_X in the exhaust gas. Primary measures aim at reducing the amount of NO_X formed during the combustion by optimizing certain engine parameters. IMO Tier I and II standards are met by primary measures. IMO Tier III standard are met by secondary measures which aim at reducing NO_X from the exhaust gases by downstream cleaning techniques. Primary measures are the reason for lower cylinder temperatures, which can aggravate the negative impacts of low load operations. Earlier designs of NO_X optimized diesel engines are said to have had more problems at low load operations than more recent engine designs. Recent developments have provided engine technology such as common rail, variable injection timing and variable valve control that allow engine operations at lower engine loads than earlier.

The mechanisms presented above show similarities to the damage case that have been examined. The damage case present an engine crankcase breakage initially caused by piston scuffing. Scuffing results from mechanical contact when there is a breakdown or absence of lubrication. Excessive low load operations caused lubrication oil contamination which eventually resulted in oil film breakdown. Unfortunately, it has not been possible to find additional damage cases where the resulting damage is suspected to be caused by low load operations. This case study can thus not be used to establish any general conclusions, but can be used for illustrative purposes.

Existing finding data from DNV GL's database have been analysed to determine whether one can substantiate the impacts of low load operations quantitatively. The finding data have been studied by simple frequency measurements. The results show higher finding frequencies for DP-vessels than non-DP vessels. This could indicate that low load operations may have a negative impact on the operational problems and thus the damage frequency. The finding data have also been evaluated with respect to time, to determine whether NO_X optimization aggravates the negative impacts of low load operations. The result showed generally higher finding frequencies for engines installed after 2000 than the ones installed prior to 2000. This could indicate that the introduction of Tier I compliant engines have increased operational problems. However, it could not be determined whether NO_X optimized engines have aggravated the negative impacts of low load operations.

All the engine manufacturers that were interviewed were familiar with the impacts of low load operations and did agree that low load operation is a highly relevant issue of today. According to the engine manufacturers, the impacts of low load operations are of particular concern if precautions are not taken. Diesel engines running at low loads shall be brought up to high loads (at least 50% of maximum power) regularly to prevent operational problems. Increased engine load increases the pressure and temperature, which allow liner lacquering to be scraped off and soot deposits and unburned fuel to be burned away. Such recommendations are without exception written in the engine product guides.

The bottom line is that the impacts of low load operations are severe and will cause operational problems if precautions are not taken. This is supported in the literature as well as by engine manufacturers and by reviewing engine damage reports. However, it has not been possible to substantiate the impacts of low load operations quantitatively in a satisfying way by frequency measurements. The results from the analysis indicate that low load operations increase operational problems, but the results are ambiguous and should not be used to establish any general conclusions without further analyses.

7.1 Suggestions for Further Work

This thesis has been investigating the impacts of low load operations by reviewing existing literature as well as damage reports and finding data provided by DNV GL.

Further work could focus on the potential that exists in the data base of DNV GL. For more accurate finding frequency results finding data could be linked to the ship's AIS data. AIS data can provide load profiles that can be used to find vessels that operate at low loads. Findings could also be linked to data from DNVPS. DNVPS provide fuel quality testing and bunker quality services, which can be used to link findings to different fuel qualities.

The analysis of the impacts of low load operations could also benefit from a more theoretical analytical approach. An engine model could be developed for engine performance analysis of different engine parameters. The engine simulation software GT-POWER could be used for this purpose.

Further work could also benefit from investigating the impacts of low load operations with a more experimental approach. This could include laboratory engine testing and on board measurements.

References

[1] A. Iversen, “Drift av dieselmotorer på lav belastning/med lav effekt,” Det Norske Veritas, 2012.

[2] H. S. Bentsen, Interviewee, *Senior Engineer, Machinery and Systems, DNV GL.* [Interview]. April 2014.

[3] M. Sanguri, “The Guide to Slow Steaming on Ships,” Marine Insight, 2012.

[4] Det Norske Veritas, “Dynamic Positioning Systems, Pt. 6 Ch. 7 Sec. 2B,” in *Rules for Classification of Ships*, 2014.

[5] V. Æsøy, “"Green Ship Technology" for Arctic Operations,” Høyskolen i Ålesund, 2013.

[6] C. D. Rakopoulos and E. G. Giakoumis, Diesel Engine Transient Operation, Springer, 2009.

[7] D. Woodyard, Pounder's Marine Diesel Engines and Gas Turbines, Butterworth-Heinemann, 2009.

[8] J. B. Heywood, Internal Combustion Engine Fundamentals, McGraw-Hill Book Company, 1988.

[9] Ø. Buhaug, Deposit Formation on Cylinder Liner Surfaces in Medium-Speed Engines, NTNU, 2003.

[10] E. Codan and I. Vlaskos, “Turbocharging medium speed diesel engines with extreme Miller timing,” ABB Turbo Systems Ltd., 2004.

[11] M. B. Vermeire, “Everything You Need to Know About Marine Fuels,” Chevron Global Marine Products, 2007.

[12] Det Norske Veritas, “Low Sulphur Fuels - Properties and Associated Challenges”.

[13] International Organization of Standardization (ISO), “ISO 8217: Petroleum Products - Fuels (class F) - Specifications of Marine Fuels,” 2010.

[14] Det Norske Veritas, “ISO 8217 Fuel Standard, Fouth Edition 2010,” 2013. [Online]. Available: http://www.dnv.com/industry/maritime/servicessolutions/fueltesting/fuelqualitytesting/iso8217fuelstandard.asp.

[15] A. Iversen, Interviewee, *Former Employee, DNV GL.* [Interview]. May 2014.

[16] K. Steernberg and S. Forget, “Paper No.: 198 The effects of a chanigng oil industry on marine fuel quality and how new and old analytical techniques can be used to ensure predictable performance in marine diesel engines,” CIMAC Congress Vienna, 2007.

[17] R. E. Lewis, “Beyond ISO 8217,” *Bunker Spot,* pp. 50-53, 2009.

[18] A. O. T. Strøm, Interviewee, *Senior Aprroval Engineer, Machinery, DNV GL.* [Interview]. May 2014.

[19] “PB Marine,” PB Marine, 2013. [Online]. Available: http://www.bp.com/sectiongenericarticle.do?categoryId=9031132&contentId=7056971.

[20] J. Fitch, “Four Lethal Diesel Engine Oil Contaminants,” *Machinery Lubrication,* no. 5, 2007.

[21] S. McAllister, J.-Y. Chen and A. C. Fernandez-Pello, Fundamentals of Combustion Processes, Springer, 2011.

[22] R. Allen, “The Influence of Marine Fuel Quality on Lubricating Oil Performance,” in *20th CIMAC World Congress*, 1993.

[23] G. W. Stachowiak and A. Batchelor, Engineering Tribology, 4th edition ed., Butterworth-Heinemann Ltd., 2013.

[24] B. Mossey, “MTU - Engines and System Engineering,” 2013. [Online]. Available: http://www.mtu-online.com/fileadmin/fm-dam/mtu-usa/mtuinnorthamerica/white-papers/WhitePaper_PrevMaintenance_Marine.pdf.

[25] Onuki, “Investigation of Engine Breakdown of Electric Propulsion in North European Sea,” Mitsubishi Heavy Industries, Ltd., 2007.

[26] Harada, Fukuzawa and Takimoto, “Investigation Report,” Mitsubishi Heavy Industries, Ltd., 2007.

[27] J. Kadal, M. Rasmussen, K. Ramsrud and J. Melkeraaen, “Basic Principle of the Class Findings Benchmark,” 2014.

[28] T. Dirix, Interviewee, *Principal Engineer, Machinery, DNV GL.* [Interview]. May 2014.

[29] J. Folkedal, Interviewee, *Cummins Marine.* [Interview]. May 2014.

[30] T. Humerfelt, Interviewee, *Rolls-Royce Marine Bergen.* [Interview]. April 2014.

[31] M. Mork, Interviewee, *Yanmar.* [Interview]. May 2014.

[32] Ø. Skår, Interviewee, *Pon Power Scandinavia.* [Interview]. April 2014.

[33] T. Selle, Interviewee, *Wärtsilä Norway.* [Interview]. May 2014.

[34] P. Brooks, “Limitations on low load operation for fixed speed engines,” Cummins Marine, 2014.

[35] E. Kok, “Specification for limited engine operation on no-load or low load,” 2004.

[36] R. Karlsvik, Interviewee, *Chief Engineer.* [Interview]. June 2014.

[37] A. Karlsen, Interviewee, *Principle Specialist - DP Systems, Control Systems, DNV GL.* [Interview]. May 2014.

[38] J. Hussain, K. Palaniradja, N. Alagumrthi and R. Mainimaran, “Effect of exhaust gas recirculation (EGR) on performance and emission characteristics of a three cylinder direct injection compression ignition engine,” *Alexandria Engineering Journal,* no. 51, pp. 241-247, 2012.

[39] D. Doyle, “EGR Systems and Lubricating Oil in Diesel Engines,” *Practicing Oil Analysis,* no. 7, 2002.

[40] G. M. R. Holtbecker, “Exhaust Emissions Reduction Technology for Sulzer Marine Diesel Engines: General Aspects,” Wärtsilä NSD Switzerland Ltd., 1998.

Appendix

A1 NPS Data

	Vessel Type Benchmark Name	Number of Findings	Number of Main Vessel Components	DNV Main Component Age	Main Component Frequency
Main component function code	BLANK	0	3	5,98	0,00
	1099	8	166	1452,53	5,51
	391.123	0	6	18,66	0,00
	411.1	2684	6133	39239,85	68,40
	431.1	249	798	4604,22	54,08
	441.1	10	84	627,64	15,93
	499	2	3	25,59	78,14
	511.1	2359	16924	100511,85	23,47
	521.1	315	4889	28792,57	10,94
	599	0	9	67,83	0,00
	699	0	12	91,45	0,00
	899	0	14	102,57	0,00
	Summary	**5627**	**29041**	**175540,75**	**32,06**
Main propulsion principle	Combustion engine	1829	13481	82971,57	22,04
	Electric motor	396	2660	12719,49	31,13
	Gas turbine	10	78	341,36	29,29
	Hydraulic motor	0	17	54,16	0,00
	None	115	596	3969,80	28,97
	Sails	0	2	1,59	0,00
	Steam turbine	8	66	381,54	20,97
	BLANK	1	0	0,00	0,00
	BLANK	0	24	72,33	0,00
	Summary	**2359**	**16924**	**100511,85**	**23,47**

	Vessel Type Benchmark Name	Number of Findings	Number of Main Vessel Components	DNV Main Component Age	Main Component Frequency
Main engines - DP-vessels	Bulk Carriers	0	14	35,46	0,00
	Dry Cargo	0	3	16,62	0,00
	Gas Carriers	0	8	33,30	0,00
	Offshore MOU	26	205	845,99	30,73
	Offshore Ship	164	1373	6025,98	27,22
	Oil Tankers	1	10	88,99	11,24
	Other	14	177	849,31	16,48
	Other MOU	13	194	872,38	14,90
	Passenger	0	9	30,48	0,00
	Summary	**218**	**1993**	**8798,52**	**24,78**
Main engines - non-DP-vessels	Bulk Carriers	8	36	151,47	52,81
	Dry Cargo	0	3	9,30	0,00
	Fishing	2	21	59,96	33,35
	Gas Carriers	1	60	112,89	8,86
	Offshore MOU	0	2	6,85	0,00
	Offshore Ship	1	26	111,07	9,00
	Oil Tankers	4	25	117,79	33,96
	Oil/Chemical Tankers	6	36	262,17	22,89
	Other	15	171	1059,99	14,15
	Other MOU	2	40	347,35	5,76
	Passenger	139	247	1682,13	82,63
	Summary	**178**	**667**	**3920,98**	**45,40**
Auxiliary engines - DP-vessels	Bulk Carriers	8	8	71,19	112,38
	Dry Cargo	0	4	32,58	0,00
	Fishing	0	7	50,37	0,00
	Offshore MOU	4	66	224,98	17,78
	Offshore Ship	119	1021	6329,79	18,80
	Oil Tankers	16	227	1325,42	12,07
	Oil/Chemical Tankers	0	4	13,75	0,00
	Other	10	122	873,12	11,45
	Other MOU	0	40	111,79	0,00
	Summary	**157**	**1499**	**9032,99**	**17,38**
Auxiliary engines - non-DP-vessels	Bulk Carriers	231	1964	8941,61	25,83
	Container	120	918	4989,09	24,05
	Dry Cargo	312	1563	10032,14	31,10
	Fishing	122	977	7685,87	15,87
	Gas Carriers	43	434	2720,90	15,80
	Offshore MOU	28	35	242,36	115,53
	Offshore Ship	119	558	4179,24	28,47
	Oil Tankers	191	1850	11850,10	16,12
	Oil/Chemical Tankers	246	1906	11498,10	21,39
	Other	149	1051	6636,05	22,45
	Other MOU	0	6	16,54	0,00
	Passenger	111	720	5146,57	21,57
	Summary	**1672**	**11982**	**73938,58**	**22,61**

	Vessel Type Benchmark Name	Number of Findings	Number of Main Vessel Components	DNV Main Component Age	Main Component Frequency
Main engines non-DP-vessels					
Passenger	Car Ferry	10	72	450,41	22,20
	Car-& Train Ferry	1	6	53,39	18,73
	Catamaran	0	2	12,87	0,00
	Passenger Ship	128	167	1165,47	109,83
	Summary	**139**	**247**	**1682,13**	**82,63**
Auxiliary engines non-DP-vessels					
Passenger	Car Ferry	35	224	1585,84	22,07
	Car Ferry/Catamaran	12	133	1009,39	11,89
	Car-& Train Ferry	8	19	169,13	47,30
	Catamaran	7	125	655,88	10,67
	Passenger Ship	39	170	1339,19	29,12
	Passenger Tender	0	11	97,92	0,00
	Passenger/General Cargo	2	11	97,92	20,43
	Passenger/Ro-Ro Carrier	3	21	140,99	21,28
	Surface Effect Ship	5	6	52,30	95,60
	Summary	**111**	**720**	**5148,55**	**21,56**
Main engines DP-vessels					
Offshore Ships	Diving Support Vessel	14	91	448,51	31,21
	Multi Purpose Offshore Vessel	13	287	1266,82	10,26
	Pipe Layer	5	60	378,35	13,22
	Standby Ship	0	10	46,08	0,00
	Supply Vessel	118	875	3568,72	33,07
	Supply Vessel Anchor Hand.Fire Fig	5	5	44,51	112,34
	Supply Vessel/Standby Ship	0	4	35,61	0,00
	Supply Vessel/Tug	6	23	167,34	35,86
	Support Vessel	3	18	73,81	40,65
	Summary	**164**	**1373**	**6029,74**	**27,20**
Auxiliary engines DP-vessels					
Offshore Ships	Anchor Handling Tug	3	13	115,52	25,97
	Core Drilling Vessel	1	7	62,31	16,05
	Diving Support Vessel	13	50	411,91	31,56
	Multi Purpose Offshore Vessel	11	65	391,28	28,11
	Pipe Layer	0	11	96,59	0,00
	Standby Ship	0	4	9,63	0,00
	Supply Vessel	68	452	2885,93	23,56
	Supply Vessel Anchor Hand.Fire Fig	1	23	137,12	7,29
	Supply Vessel Anchor Handling	1	44	302,02	3,31
	Supply Vessel/Standby Ship	0	2	17,80	0,00
	Supply Vessel/Tug	20	347	1877,06	10,65
	Support Vessel	1	3	25,42	39,34
	Summary	**119**	**1021**	**6332,59**	**18,79**

	Job Completion Year	Number of Findings	Number of Main Vessel Components	DNV Main Component Age	Main Component Frequency
Main engines DP-Vessels	2005	7	1997	8814,93	0,79
	2006	12	1997	8814,93	1,36
	2007	21	1997	8814,93	2,38
	2008	9	1997	8814,93	1,02
	2009	19	1997	8814,93	2,16
	2010	35	1997	8814,93	3,97
	2011	35	1997	8814,93	3,97
	2012	32	1997	8814,93	3,63
	2013	47	1997	8814,93	5,33
	2014	1	1997	8814,93	0,11
	Summary	**218**	**1997**	**8814,93**	**24,73**
Main engines non DP-Vessels	2005	3	667	3922,81	0,76
	2006	7	667	3922,81	1,78
	2007	21	667	3922,81	5,35
	2008	14	667	3922,81	3,57
	2009	20	667	3922,81	5,10
	2010	20	667	3922,81	5,10
	2011	21	667	3922,81	5,35
	2012	14	667	3922,81	3,57
	2013	58	667	3922,81	14,79
	2014	0	668	3922,81	0,00
	Summary	**178**	**669**	**3922,81**	**45,38**
Auxiliary engines DP-Vessels	2005	8	1499	9037,10	0,89
	2006	10	1499	9037,10	1,11
	2007	15	1499	9037,10	1,66
	2008	14	1499	9037,10	1,55
	2009	22	1499	9037,10	2,43
	2010	23	1499	9037,10	2,55
	2011	18	1499	9037,10	1,99
	2012	30	1499	9037,10	3,32
	2013	16	1499	9037,10	1,77
	2014	1	1499	9037,10	0,11
	Summary	**157**	**1499**	**9037,10**	**17,37**
Auxiliary engines non DP-Vessels	2005	90	11974	73877,23	1,22
	2006	71	11974	73877,23	0,96
	2007	120	11974	73877,23	1,62
	2008	167	11974	73877,23	2,26
	2009	207	11974	73877,23	2,80
	2010	222	11974	73877,23	3,00
	2011	272	11974	73877,23	3,68
	2012	265	11974	73877,23	3,59
	2013	239	11974	73877,23	3,24
	2014	15	11974	73877,23	0,20
	Summary	**1668**	**11974**	**73877,23**	**22,58**

	Main Component Assigned Year	Number of Findings	Number of Main Vessel Components	DNV Main Component Age	Main Component Frequency
Main engines DP-vessels	1980	2	16	143,30	13,96
	1981	1	8	71,65	13,96
	1982	1	4	35,82	27,91
	1984	0	5	43,01	0,00
	1985	5	5	44,78	111,65
	1987	1	9	80,61	12,41
	1989	2	5	44,78	44,66
	1992	0	2	17,91	0,00
	1993	3	5	44,78	66,99
	1994	1	5	44,78	22,33
	1995	1	10	89,56	11,17
	1996	2	4	35,82	55,83
	1997	1	5	4,16	240,13
	1999	23	27	239,02	96,23
	2000	0	4	35,82	0,00
	2001	2	33	293,40	6,82
	2002	10	33	295,55	33,83
	2003	30	52	465,72	64,42
	2004	21	12	107,47	195,40
	2005	24	101	871,83	27,53
	2006	2	73	575,42	3,48
	2007	8	146	992,81	8,06
	2008	22	169	976,98	22,52
	2009	18	215	1070,24	16,82
	2010	21	188	758,20	27,70
	2011	9	243	660,60	13,62
	2012	8	291	592,55	13,50
	2013	0	286	330,85	0,00
	2014	0	67	20,15	0,00
	Summary	**218**	**2023**	**8987,61**	**24,26**

	Main Component Assigned Year	Number of Findings	Number of Main Vessel Components	DNV Main Component Age	Main Component Frequency
Main engines non DP-vessels	BLANK	0	4	31,33	0,00
	1975	0	4	34,16	0,00
	1976	0	4	35,34	0,00
	1983	0	7	62,69	0,00
	1986	3	9	75,67	0,00
	1988	2	2	14,38	139,05
	1991	0	3	24,44	0,00
	1992	0	3	26,87	0,00
	1995	3	8	71,65	41,87
	1996	8	4	35,82	223,31
	1997	9	12	104,99	85,73
	1998	12	26	225,32	53,26
	1999	12	28	250,77	47,85
	2000	4	20	179,12	0,00
	2001	11	21	188,08	0,00
	2002	16	21	188,08	85,07
	2005	4	33	280,77	14,25
	2006	14	41	329,49	42,49
	2007	6	49	364,51	16,46
	2008	3	48	316,95	9,47
	2009	49	59	301,78	162,37
	2010	13	92	401,22	32,40
	2011	0	32	111,32	0,00
	2012	3	30	123,77	24,24
	2013	0	84	67,48	0,00
	2014	0	23	4,89	0,00
	Summary	**172**	**667**	**3850,92**	**44,66**

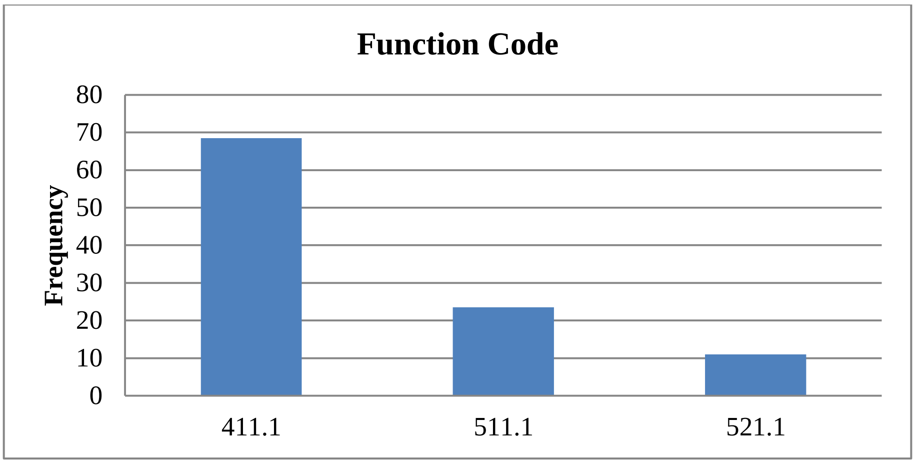
	Main Component Assigned Year	Number of Findings	Number of Main Vessel Components	DNV Main Component Age	Main Component Frequency
Auxiliary engines DP-vessels	1974	1	1	8,96	111,65
	1976	0	2	17,47	0,00
	1977	0	4	35,82	0,00
	1978	2	12	106,96	18,70
	1979	0	6	39,61	0,00
	1981	2	3	26,43	75,67
	1982	1	20	176,93	5,65
	1983	5	17	147,50	33,90
	1984	10	37	323,51	30,91
	1985	14	21	187,21	74,78
	1986	4	15	134,34	29,77
	1987	0	5	43,10	0,00
	1988	1	5	44,78	22,33
	1990	3	7	62,17	48,26
	1991	1	11	96,45	10,37
	1992	1	2	17,80	56,19
	1993	8	13	113,05	70,76
	1994	0	4	35,82	0,00
	1995	0	3	26,87	0,00
	1996	2	17	152,25	13,14
	1997	1	22	194,02	5,15
	1998	10	54	479,61	20,85
	1999	11	85	760,98	14,46
	2000	7	27	224,30	31,21
	2001	6	29	257,22	23,33
	2002	5	43	382,62	13,07
	2003	3	33	294,28	10,19
	2004	0	17	152,25	0,00
	2005	14	114	999,74	14,00
	2006	16	72	570,33	28,05
	2007	6	68	471,35	12,73
	2008	7	70	420,48	16,65
	2009	7	123	628,33	11,14
	2010	7	154	649,55	10,78
	2011	3	149	472,40	6,35
	2012	1	90	186,18	5,37
	2013	0	122	156,91	0,00
	2014	0	24	3,79	0,00
	Summary	**159**	**1501**	**9101,38**	**17,47**

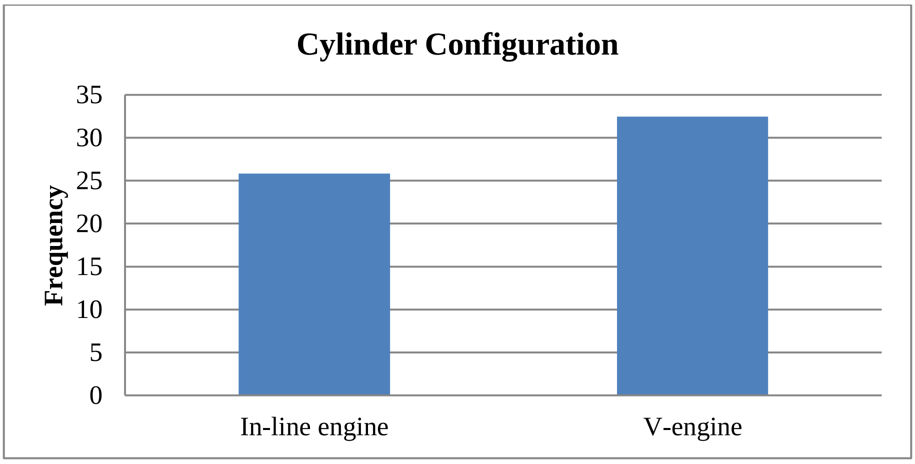
	Main Component Assigned Year	Number of Findings	Number of Main Vessel Components	DNV Main Component Age	Main Component Frequency
Auxiliary engines non DP-vessels	BLANK	28	71	622,35	44,99
	1957	2	2	17,91	111,65
	1958	0	4	32,30	0,00
	1959	0	1	8,96	0,00
	1960	0	1	8,85	0,00
	1963	0	5	44,78	0,00
	1964	0	2	17,91	0,00
	1966	0	3	26,58	0,00
	1967	0	3	26,80	0,00
	1968	4	9	71,06	56,29
	1969	0	1	8,96	0,00
	1970	0	5	44,75	0,00
	1971	0	7	54,12	0,00
	1972	7	34	292,70	23,91
	1973	1	14	123,96	8,07
	1974	8	18	158,82	50,37
	1975	16	45	394,42	40,57
	1976	4	42	347,16	11,52
	1977	2	17	149,52	13,38
	1978	3	33	285,12	10,52
	1979	9	31	261,26	34,45
	1980	14	47	414,64	33,76
	1981	27	67	564,19	47,86
	1982	29	79	684,35	42,38
	1983	24	69	612,99	39,15
	1984	10	59	527,07	18,97
	1985	33	86	734,94	44,90
	1986	52	152	1311,90	39,64
	1987	47	103	910,37	51,63
	1988	15	79	675,09	22,22
	1989	32	111	940,15	34,04
	1990	38	103	855,89	44,40
	1991	46	165	1447,91	31,77
	1992	35	163	1415,97	24,72
	1993	23	89	767,36	29,97
	1994	44	106	922,07	47,72
	1995	51	147	1283,75	39,73
	1996	71	214	1866,47	38,04
	1997	66	295	2566,46	25,72
	1998	53	245	2133,81	24,84
	1999	70	326	2884,60	24,27

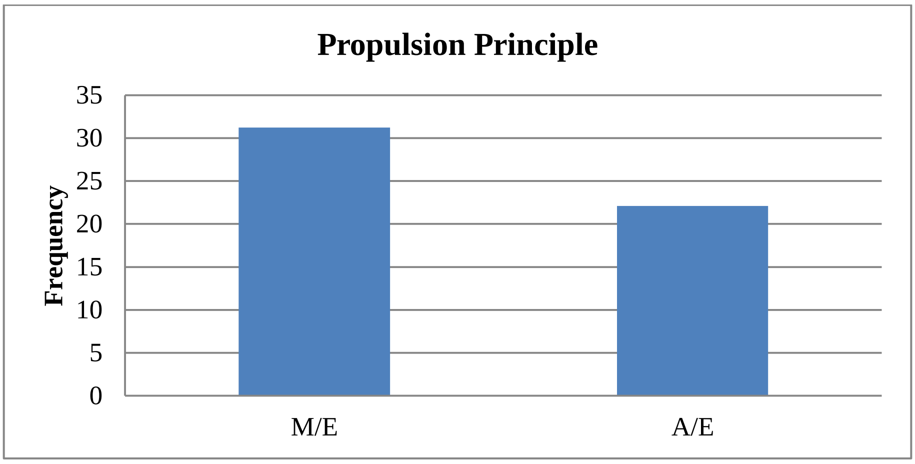
Auxiliary engines non DP-vessels	2000	54	243	2133,06	25,32
	2001	35	295	2591,03	13,51
	2002	50	317	2754,71	18,15
	2003	33	298	2599,87	12,69
	2004	25	249	2176,81	11,48
	2005	126	880	7595,96	16,59
	2006	44	573	4454,70	9,88
	2007	100	673	4615,06	21,67
	2008	68	660	3968,19	17,14
	2009	84	716	3709,52	22,64
	2010	92	1115	4860,39	18,93
	2011	41	1043	3264,88	12,56
	2012	27	849	1899,11	14,22
	2013	7	788	813,41	8,61
	2014	1	193	71,50	13,99
	Summary	**1651**	**11945**	**74026,47**	**22,30**

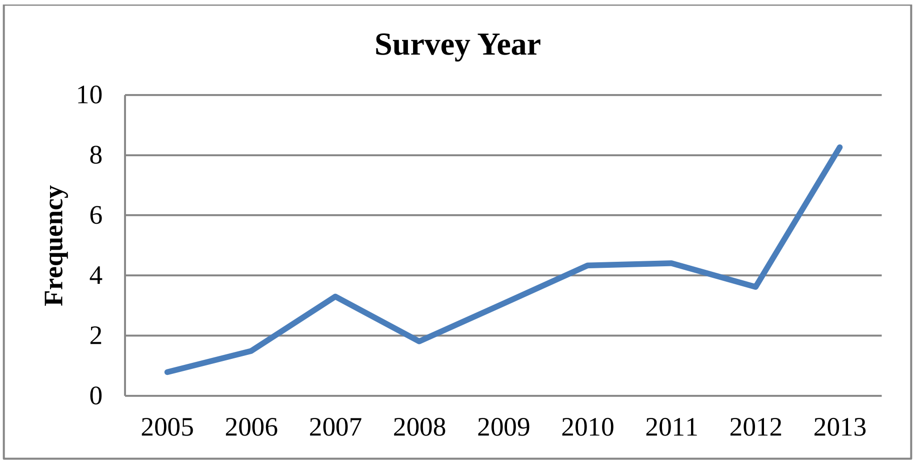
	Main Component Instance Name	Number of Findings	Number of Main Vessel Components	DNV Main Component Age	Main Component Frequency
Main engines ALL vessels		6	31	234,99	25,53
		3	4	35,63	84,20
		0	3	17,55	0,00
		0	1	5,85	0,00
		6	8	71,25	84,20
		9	117	636,21	14,15
		2	16	117,05	17,09
		0	4	35,63	0,00
		0	4	34,21	0,00
		1	6	27,95	35,78
		0	4	25,23	0,00
		3	84	205,26	14,62
		0	4	12,32	0,00
		5	58	274,27	18,23
		1	8	1,36	735,89
		1	2	17,81	56,14
	Summary	**37**	**354**	**1752,58**	**21,11**
Main engines DP-vessels		6	31	234,99	25,53
		3	4	35,63	84,20
		0	3	17,55	0,00
		0	1	5,85	0,00
		6	8	71,25	84,20
		9	117	636,21	14,15
		2	16	117,05	17,09
		0	4	35,63	0,00
		0	4	34,21	0,00
		1	6	27,95	35,78
		0	4	25,23	0,00
		3	84	205,26	14,62
		0	4	12,32	0,00
		5	53	229,74	21,76
		1	8	1,36	735,89
		1	2	17,81	56,14
	Summary	**37**	**349**	**1708,04**	**21,66**

A2 Finding Analysis








Survey Year
Frequency
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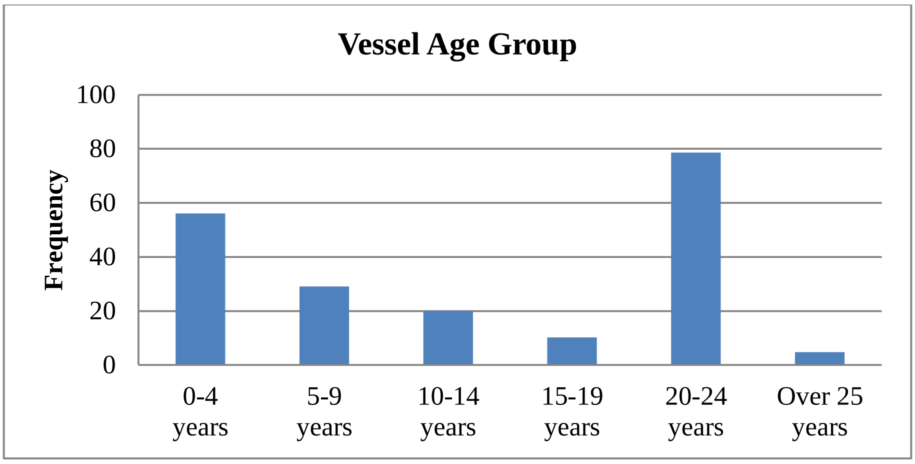
8
6
4
2
0
2005
2006
2007
2008
2009
2010
2011
2012
2013


Vessel Age Group
Frequency
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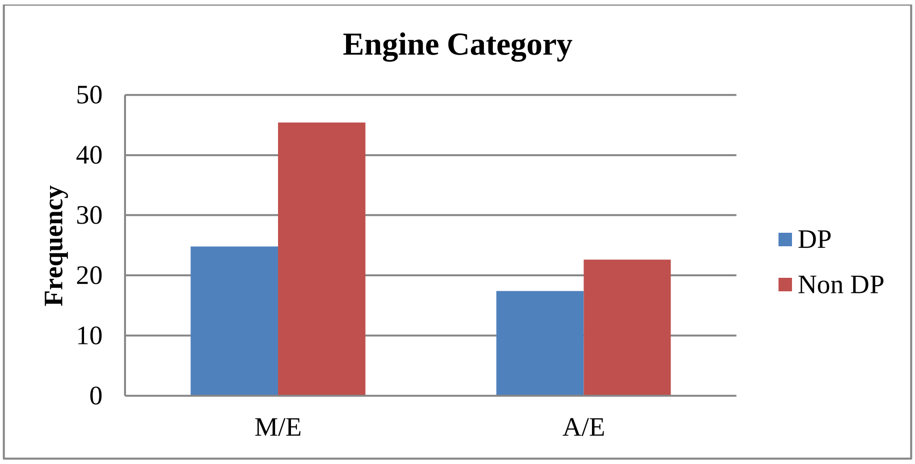
60
40
20
0
0-4 years
5-9 years
10-14 years
15-19 years
20-24 years
Over 25 years


Engine Category
Frequency
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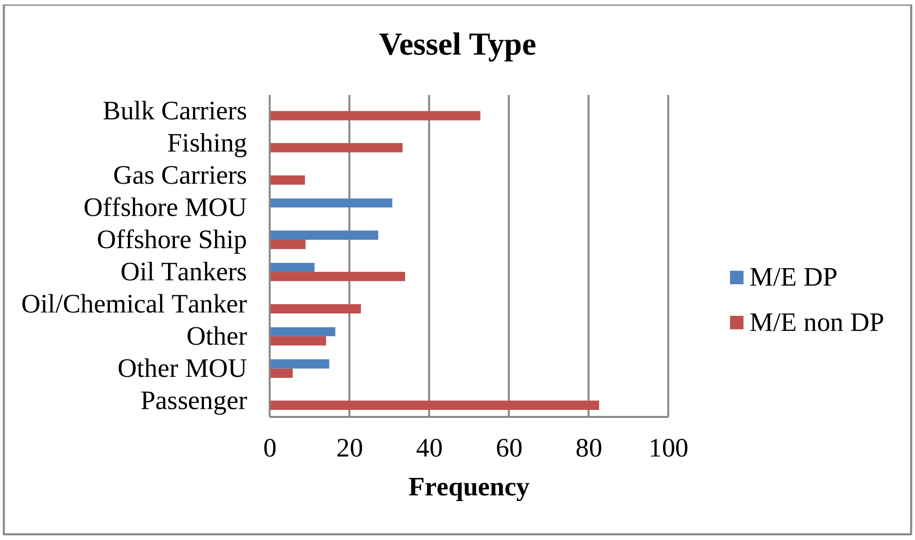
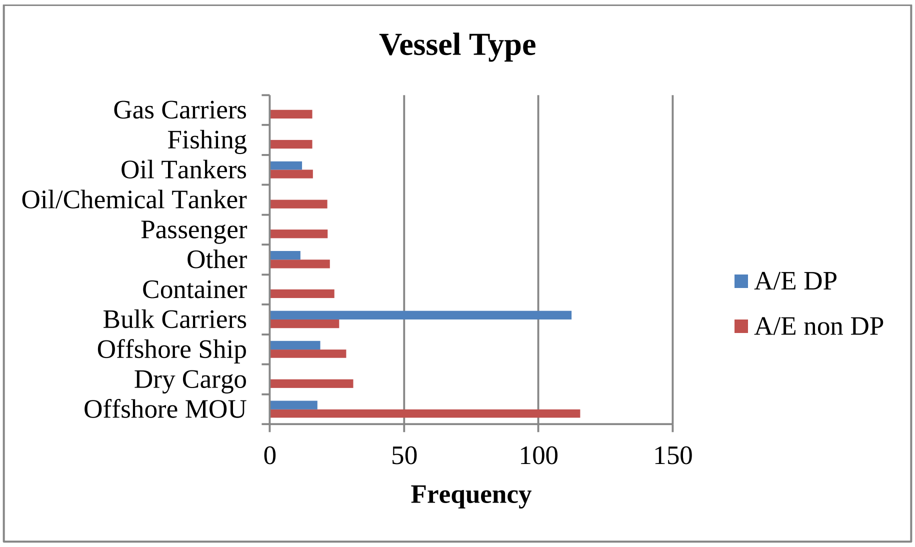
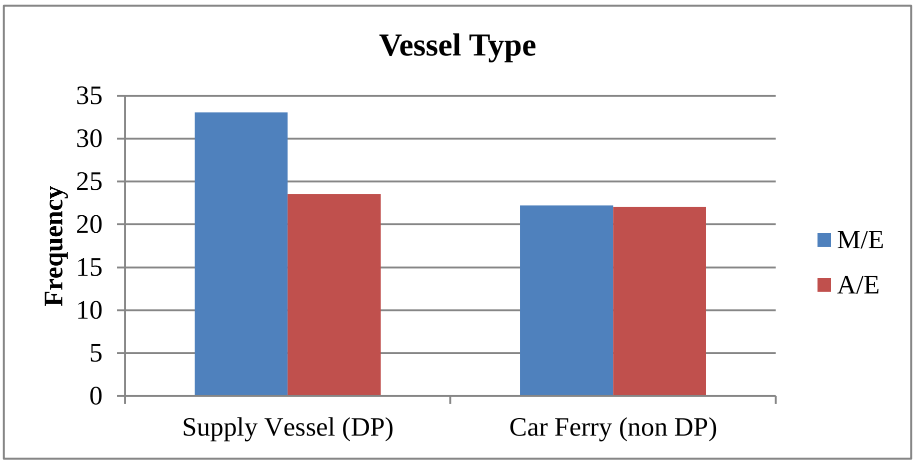
40
30
20
10
0
M/E
A/E
DP
Non DP


Vessel Type
Bulk Carriers
Fishing
Gas Carriers
Offshore MOU
Offshore Ship
Oil Tankers
Oil/Chemical Tanker
Other
Other MOU
Passenger
0
20
40
60
80
100
Frequency
M/E DP
M/E non DP


Vessel Type
Gas Carriers
Fishing
Oil Tankers
Oil/Chemical Tanker
Passenger
Other
Container
Bulk Carriers
Offshore Ship
Dry Cargo
Offshore MOU
0
50
100
150
Frequency
A/E DP
A/E non DP


Vessel Type
35
30
25
20
15
10
5
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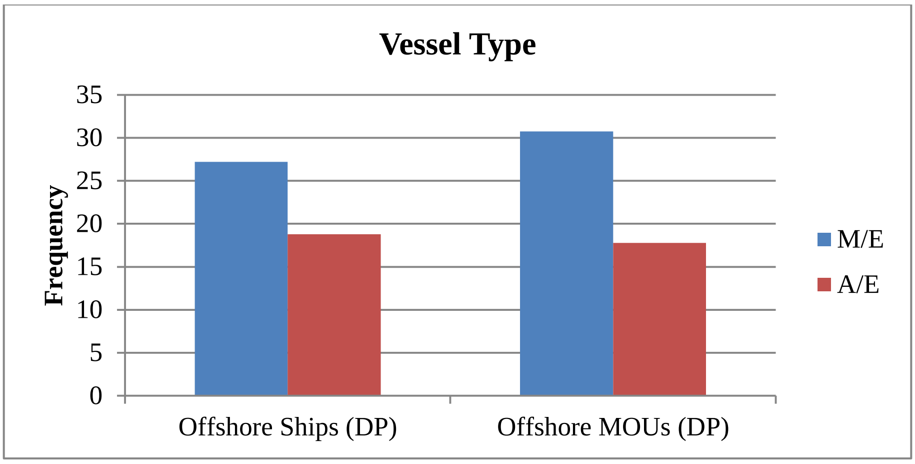
Frequency
Supply Vessel (DP)
Car Ferry (non DP)
M/E
A/E


Vessel Type
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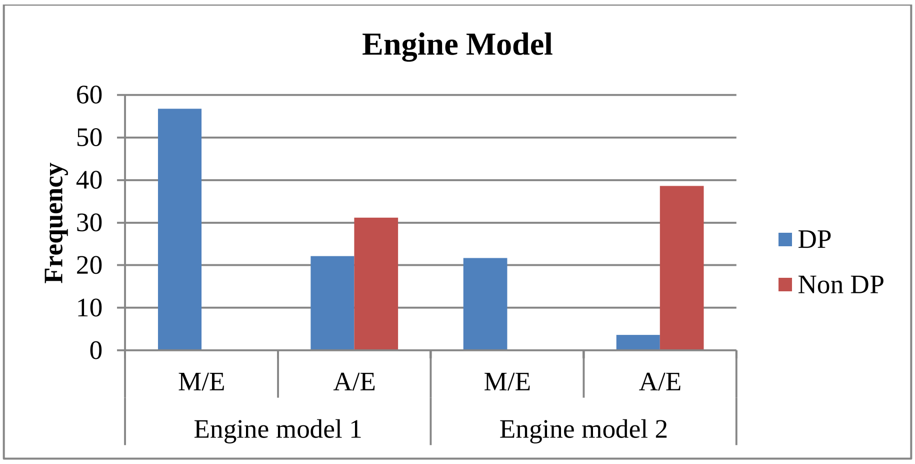
30
25
20
15
10
5
0
Frequency
Offshore Ships (DP)
Offshore MOUs (DP)
M/E
A/E


Engine Model
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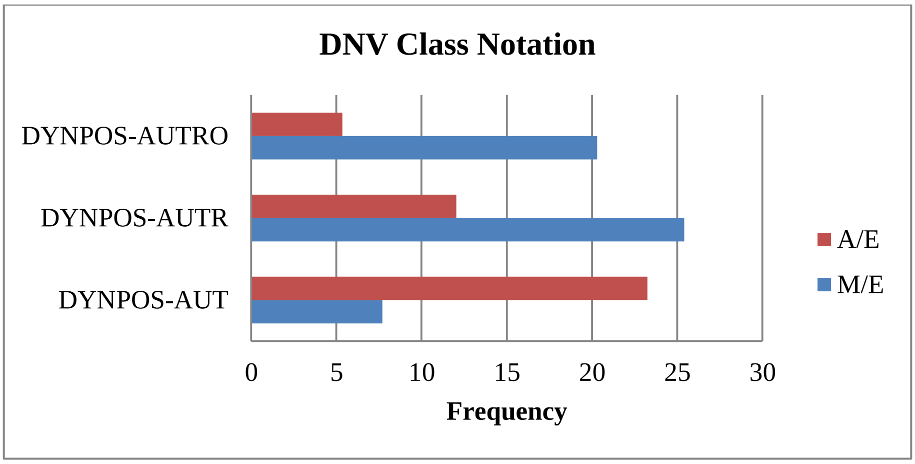
50
40
30
20
10
0
Frequency
M/E
A/E
M/E
A/E
Engine model 1
Engine model 2
DP
Non DP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DYNPOS-AUTR
DYNPOS-AUT
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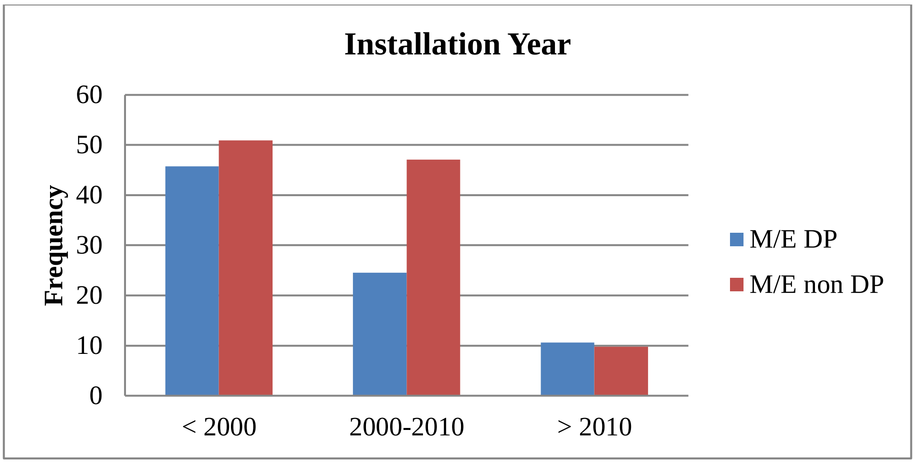
10
15
20
25
30
Frequency
A/E
M/E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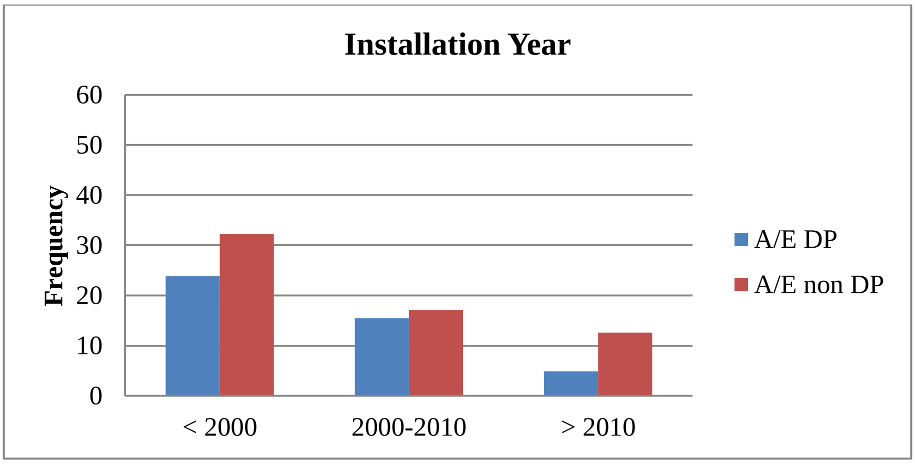
40
30
20
10
0
< 2000
2000-2010
> 2010
M/E DP
M/E non DP


Installation Year
Frequency
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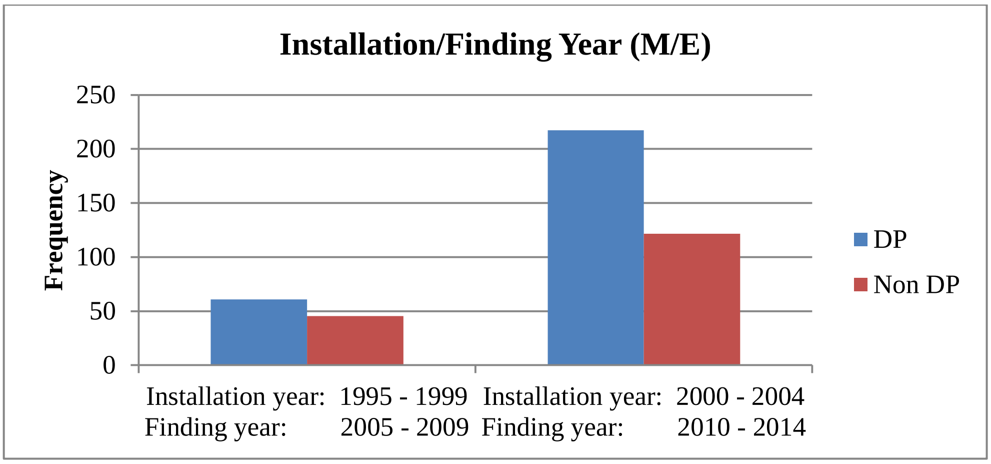
50
40
30
20
10
0
< 2000
2000-2010
> 2010
A/E DP
A/E non DP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Frequency
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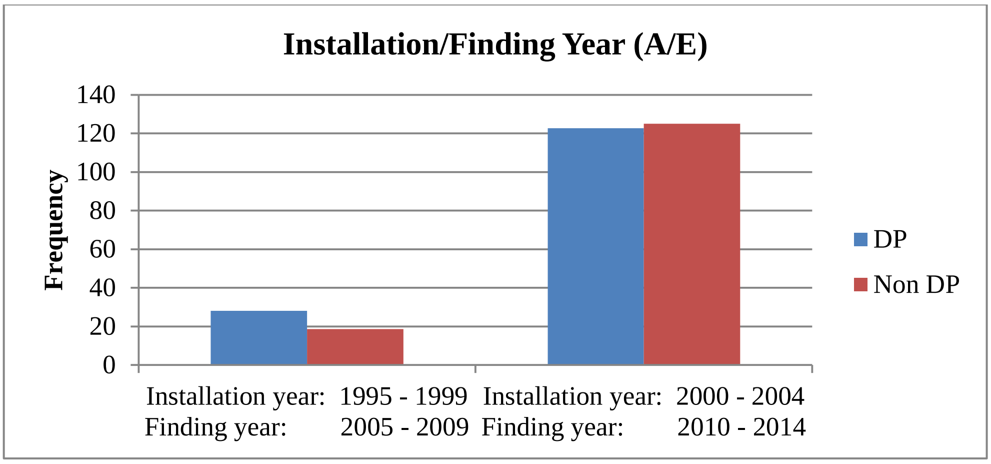
200
150
100
50
0
Installation year: 1995 - 1999
Finding year: 2005 - 2009
Installation year: 2000 - 2004
Finding year: 2010 - 2014
DP
Non DP


Installation/Finding Year (A/E)
Frequency
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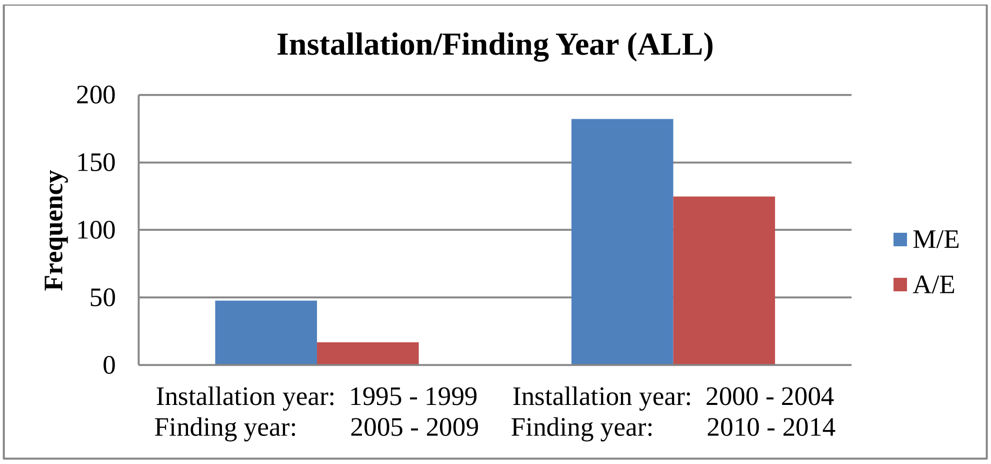
120
100
80
60
40
20
0
Installation year: 1995 - 1999
Finding year: 2005 - 2009
Installation year: 2000 - 2004
Finding year: 2010 - 2014
DP
Non DP


Installation/Finding Year (ALL)
Frequency
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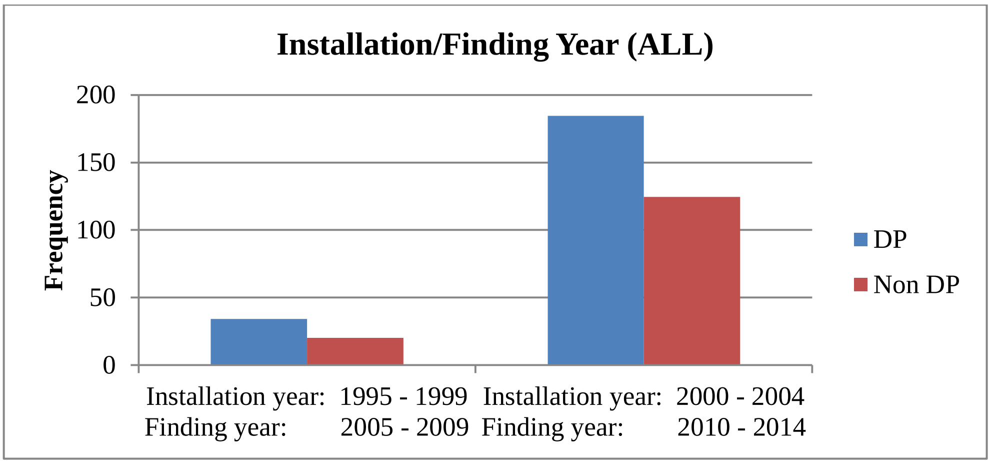
Installation year: 1995 - 1999
Finding year: 2005 - 2009
Installation year: 2000 - 2004
Finding year: 2010 - 2014
M/E
A/E


Installation/Finding Year (ALL)
Frequency
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100
50
0
Installation year: 1995 - 1999
Finding year: 2005 - 2009
Installation year: 2000 - 2004
Finding year: 2010 - 2014
DP
Non DP

A3 Interview

This document contains question regarding low load operations on diesel engines and will be used in a master thesis with working title as stated below:

«Impacts of Low Load Operations on Modern Four-Stroke Diesel Engines in Diesel Generator Configuration»

The master thesis is written by student Espen Dalsøren Tufte in collaboration with DNV GL and NTNU Marine Technology.

Background

Diesel engines in generator mode are normally optimized for operation at high and medium loads. It is suspected that operation at low loads, combined with transient loads, may increase operational problems and increase the damage frequency. It is also suspected that the negative effects of low load operations are aggravated by the recent IMO regulations of exhaust emissions, and in particular NO_X emissions.

The questions below mainly concern modern high speed four-stroke diesel engines in generator configuration.

Low load Operations

1. What is the engine manufacturer's experience with low load operations?
2. Does the engine manufacturer regard low load operations as a real issue?
    a. If so, what factors make low load operations to a problem?
3. Does the engine manufacturer focus/work on issues regarding low load operations?
    a. In that case, what is done?
4. Does the manufacturer recommend any specific countermeasures when operating at low loads to prevent wear and/or damage?
5. Does the manufacturer recommend reduced maintenance intervals when operating at low loads?
    a. In that case, what maintenance regime should be recommended?
6. Does the manufacturer have any knowledge of engine damages where low loads operation is suspected to be the root cause?
    a. If so, please specify.
7. Does the manufacturer have any impression of the damage extent on diesel engines in generator configuration?
    a. In that case, are there any statistics available (engine operating hours, damage types, components, etc.)?

Environmental Measures

8. What challenges has the manufacturer with NO_X optimization, low sulphur fuels (fuel quality) and CO_2 reduction?
9. What mitigation measures does the manufacturer focus on? Primary measures (optimization of the engines) or secondary measures (external systems)?
10. What changes have been made on Tier II engines compared to Tier I engines?
11. Is there any change in the damage frequency for Tier II engines compared to Tier I engines?
12. What challenges can be related to the combination of low load operations, NO_X optimization and low sulphur fuels?

In addition to the questions above are all existing written material on the subjects low load operation, transient loads, environmental measures and fuel quality of particular interest.

Please note that all written/oral material collected may be used in the thesis with consent from the manufacturer.

Thank you very much!

A4 Generator Load Curve