Kari Anne Tveitaskog

Assessment of methods for quantification of exhaust emissions from marine diesel engines

Master Thesis

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Assessment of methods for quantification of exhaust emissions from marine diesel engines

Master Thesis

Carried out at: **Department of Marine Technology**

Advisor: **Harald Valland**

Norwegian University of Science and Technology
Faculty of Engineering Science and Technology
Department of Marine Technology

Kari Anne Tveitaskog
Trondheim, June 2010

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MASTER THESIS

for
Stud.techn. Kari Anne Tveitaskog
Spring semester 2010

Assessment of methods for quantification of exhaust emissions from marine diesel engines

Vurdering av metoder for kvantifisering av eksosutslipp fra marine dieselmotorer

Background

While emissions from land based sources in many cases have been reduced in recent years, emissions of NOx, SOx, and PM from ships has increased. International shipping now contributes to somewhere around 15% of global NOx emissions, and there is a substantial pressure to reduce NOx emissions from ships. EU and USA have both established air quality standards with established maximum levels of fine particles. These levels are exceeded in many coastal and harbour areas, and reductions of PM emissions from ships is an important objective. Nevertheless, while NOx emissions from ships is regulated and more stringent NOx emission limits are forthcoming, emissions of PM from ships is not likely to be regulated.

It is widely accepted that many NOx reduction measures will result in increased levels of other emissions. In particular, reductions of NOx may result in increased emissions of CO2, CO, unburned hydrocarbons and particulates. The magnitude of the effect on CO2 is fairly well established; however the consequence of NOx reduction measures on the various aspects of PM emissions from ships is largely unknown.

To get a better understanding of the effect of PM emissions from ships these emissions must be more accurately characterised. Accurate measurements of the number of particles and the size-distribution are needed for marine diesel engines using typical marine fuels, including heavy fuel oil. Assuming future regulation of PM emissions it is important to assess realistic procedures for evaluation of PM emissions, for example by means of test cycles.

Emissions of NOx must be evaluated according to measurement procedures defined in NOx Technical Code (2008). The test cycles applied are based on steady state engine operation at certain predefined operating points (speed and power). The weighing factors applied in the Technical Code may differ from the actual operating profile of a particular ship. The NOx emission according to the standard may be higher or lower than the real world value.

Overall Aim and Focus

This assignment has emphasis on two objectives: measurement and characterization of PM emissions, and evaluation of NO_x emissions in accordance with current standards.

The assignment should be prepared based on following points:

Evaluation of NOx emissions in accordance with current standards:

- Collect operating profile data from shipping companies.
- Compare existing test cycles with real life operating profiles from different ship types
- Estimate real life emissions of NOx using engine specific emission data.
- Evaluate relationship between NOx emissions based on test cycle and real life NOx emissions.

Measurement and characterization of PM emissions:

- Collect measurement data for PM emissions
- Determine PM emissions during transients
- Evaluate the magnitude of transient operation in relevant vessel types.
- Evaluate use of test cycle for certification in regards to future legislations

The MSc-assignment will be performed in cooperation with MARINTEK, where senior engineer Erik Hennie is the contact person.

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

The report should be written as a research report, with an abstract, conclusions, contents list, reference list, etc. During preparation of the report it is important that the candidate emphasizes 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.

It is assumed that the student should take initiative for establishing satisfactory contact with his teacher and eventual advisors.

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.

Three -3- copies of the report are required. A complete copy of all material on digital form on CD-ROM in Word-format or other relevant format should be handed in together with the written material.

The MSc-report must be delivered no later than June 14, 2010.

Department of Marine Technology, 2010-03-15

Harald Valland
Professor

Preface

This thesis is written as a requirement for completion of the Master of Science degree in Marine Technology, at the Norwegian University of Science and Technology. The assignment has been completed in cooperation with MARINTEK.

The process of writing this thesis was a process of learning. As questions were answered, new questions were raised. The assignment was carried out with a time limitation, inevitably leaving some stones left unturned.

The main objective of the thesis was to make an assessment of procedures for quantification of exhaust emission in relation to certification, with emphasis on NO_X and PM emissions.

The assignment was initially meant to include extensive laboratory testing in order of evaluating influences from NO_X abatement technologies on PM formation, as part of an ongoing research by MARINTEK. Due to engine modifications and other external measures, the laboratory testing was not possible to the extent that it was planned. As this became clear early in the process, the main objective of the thesis was altered to the objective presented here.

In the process of this assignment there was a need for collecting data from external parties. Information was gathered from several companies where not all material received was equally comprehensive. This gives that there were some degree of uncertainty when utilizing the information for comparison.

I would like to thank my advisor, Professor Harald Valland at the Institute of Marine Machinery, NTNU, and my advisor at MARINTEK, Erik Hennie for all support and discussions during the assignment. I would also like to thank Jørgen B. Nielsen at MARINTEK for support with laboratory testing and evaluation of findings. Lastly I would like to thank Mr. Andy Wright, consultant at FOBAS London, and Dr. Øyvin Melhus, Head engineer at Ecoxy AS for letting me interview them in order of achieving a greater understanding of the regulative framework concerning exhaust emissions from diesel engines.

Trondheim 14.06.2010

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Kari Anne Tveitaskog

Abstract

The focus on exhaust emissions has increased the last decades. In the coming years emission restrictions on nitrogen oxides (NO_X) will be intensified while restrictions on PM are still pending consensus. With this, it becomes increasingly important that the emission measurements achieved during engine certification reflects the emissions formed during real engine operation. This study presents results of an assessment of measurement procedures for quantifying NO_X and PM emissions from marine diesel engines for certification purposes. The present methods for quantifying NO_X are questioned and the feasibility of applying the same measurement procedures for determining PM emissions is investigated. The study is based on the currently in use measurement procedures with focus on the application of steady state test cycles.

For NO_X emission concern, the current test cycle was compared to cycles that were constructed based on specific vessel operation of a platform supply vessel, an anchor handling vessel and an oil tanker. Comparing the vessel specific cycles and the test cycle showed considerable differences in the chosen loads and weighting of them. Calculations where done on total weighted NO_X emissions based on the test cycle and the constructed cycles. The results, giving difference in total weighted emissions comparing vessel specific cycles and test cycle, were not as distinctive as first thought. The difference found showed an increase or decrease in emissions of approximately 10 %. There were uncertainties to the calculations due to the specific NO_X emissions used. The data had been collected from two engines, which might not be representative for a general average of specific emissions. New evaluations should be done with more extensive emission data.

An evaluation was done concerning application of the steady state test cycle for PM emission measurements. The focus was on evaluating if there are operational conditions inducing PM emissions that are not reflected in the use of test cycle. To evaluate this concern laboratory measurement of PM distribution during transient operation was conducted. The laboratory results gave inconclusive results, thus previous studies on the matter was reviewed. It was found from a study conducted on a ferry, that there was 6.5 times the number of particles formed during manoeuvring than during the sailing period. To determine the extent of manoeuvring and thereby transient operation, an assessment was made on operation of selected car ferries along the Norwegian coastline. It was found that manoeuvring constituted 5.5 minutes of a complete voyage, whereas an average of the total voyage duration was found to be 19.5 minutes. For the vessel from the external study, manoeuvring amounted to a total of 60 minutes, while sailing constituted 150 minutes. By taking the duration of the manoeuvring and sailing into account, a new relationship of PM number was found to be 2.6 times the amount of particles during manoeuvring than during sailing. For the given vessels, this constitutes that 70% of the particles formed for a voyage can be attributed to the manoeuvring phase. The findings give that application of a steady state test cycle for these vessels would give a poor reflection of the total emitted particles, and thus a generally applied test cycle should include transient loads in addition to the steady state. Current test cycles used for NO_X quantification is with basis from my results unsuited for PM measurements.

Abbreviations

AHV – Anchor Handling Vessel

DI – Direct fuel Injection

DP – Dynamic positioning

ECA – Emission Control Area

EIAPP – International Air Pollution Prevention Certificate

HFO – Heavy Fuel Oil

IMO – International Maritime Organization

ISO – International Organization of Standardization

MARPOL – International Convention for the Prevention of Pollution from Ships

ME – Main Engine

MEPC – Marine Environmental Protection Committee

MGO – Marine Gas Oil

NO_X – Nitrogen oxides

PM – Particulate Matter

PSV – Platform Supply Vessel

SCR – Selective Catalytic Reduction

SECA – Sulphur Emission Control Area

SFOC – Specific Fuel Oil Consumption

SO_X – Sulphur oxides

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1 Introduction

During the last decade the focus on emissions to air has escalated, especially in regards to nitrogen oxides (NO_X) and sulphur oxides (SO_X). Recently particular matter (PM) entered the discussion with new concerns. Research has found that particles can have adverse health effects, where the main concern is particle size and amount of particles distributed. The most common method to measure PM has until now been gravimetric measurements, measuring weighted mass deposited on a filter. New methods have recently been developed that can measure the number distribution of particles with respect to their size.

The International Maritime Organization (IMO) as well as local governments has enforced restrictions on the emissions of NO_X and SO_X, and it is possible that similar restrictions will be proposed for particle emissions in the not so distant future.

Recent estimates indicate that around 95% of the world fleet is powered by marine diesel engines [1], and as the most commonly used fuel at present is heavy fuel oil of poor quality, there are evident room for improvement in regards to emission reduction.

In the coming years the emission restrictions from IMO regarding both NO_X, SO_X and possibly PM will be strengthened. With this, it becomes increasingly important that the emission measurements achieved during engine certification reflects the emissions induced by real engine operation.

1.1 Goals of the Master Thesis

The main subject for discussion in the thesis is the test cycles represented in MARPOL's NO_X Technical Code. The test cycles are applied for NO_X emission measurements for engine certification to show compliance with the stated emission limits according to regulations. The test cycle E2, generator mode, is evaluated from two points of view. Firstly regarding NO_X emissions, and secondly regarding PM emissions considering the possibility of applying a test cycle for future PM legislations.

There are two goals of this master thesis, as the assessments to be made are divided into two areas of interest, namely NO_X emissions and PM emissions.

In regards to NO_X emissions, the goal is to evaluate the present application of the test cycle. The evaluation will concern how well the given test cycle reflects real engine operation.

Concerning PM the goal is to evaluate if the existing test cycle could be applied to determine PM emissions as well.

To achieve the main goals of the master thesis objectives where formulated for assessments to be done for Part One, regarding NO_X emissions, and Part Two, regarding PM emissions.

1.1.1 *NO_X objectives – Part One*

The test cycle is applied in the certification process to enable NO_X emissions measurements for a distinct set of load points and weighting of them. The test cycle is generally applied, meaning that the planned use of the engine is not taken into account. Marine vessels come in many forms with a variety of tasks and it is of interest to see how well the stated loads and weighting of the test cycles correlate with real engine operations. To be able to evaluate this, the following points will be completed:

- Gather information of vessel operation
- Construct cycles based on real operation of appointed vessel types
- Evaluate if the load points and weighting of the test cycle is representative for real engine operation based on appointed vessel types
- Retrieve engine characteristics on specific NO_X emissions
- Calculate weighted NO_X emissions for both the test cycle and the constructed cycles
- Compare weighted NO_X emissions based on the operational cycles against weighted NO_X emissions based on the test cycle

1.1.2 *PM objectives – Part Two*

PM emissions are not regulated by IMO at the time being, but it is a possibility that restrictions will be enforced in the coming years as the understanding of PM behaviour is increased and measurement methods are being developed. One operation condition that is highlighted in this thesis is transient operation. Transient behaviour occurs in phases of rapid load changes in scenarios such as manoeuvring or operation in dynamic positioning (DP) mode. Transient operation is not included in the existing steady state test cycles. If it could be shown that these phases are of importance to the total PM emissions, then the use of a steady state test cycle would give misleading results and thus, not be applicable.

In this thesis it is of interest to investigate whether or not transient condition should be taken into consideration for potential PM measurements. To be able to evaluate if transient behaviour is of importance for PM formation, the following points will be completed:

- Laboratory testing to evaluate PM development during transient condition
- Literature review of similar investigations
- Gather information on operation of relevant vessel types
- Evaluate the presence of transient operation modes for relevant vessels
- Determine the scope of PM emissions due to transient operation
- Evaluate the application of test cycles for potential PM measurement procedures

1.2 Methodology

Reaching the goal of the master thesis depends strongly on gathering sufficient information from external parties on vessel operation, specific NO_X emission data, and obtaining data on PM development during transient operation. To achieve this, enquiry will be sent out to several relevant shipping companies in cooperation with fellow master student Magnus Selås. This is done in order to retrieve operational data for different vessel types. To obtain data on PM development, laboratory testing will be executed in the MARINTEK laboratory.

It is also planned to carry out interviews with both legislative representative and executive representative in order to gain further insights to the actual working principals of the NO_X Technical Code and its certification process.

1.3 Structure of the thesis

The main goals of the thesis is divided into two main parts, therefore the report is structured likewise. The report has been organized as following;

- Regulatory framework concerning exhaust emissions from marine diesel engines – chapter 2
- Part One, discussing the objectives concerning measurements of NO_X emissions and application of the test cycle – chapter 3
- Part Two, covering the objectives concerning PM emissions and possible use of test cycle for measurements – chapter 4
- Overall evaluation of findings in Part One and Part Two. Discussion of the results and what consequence the findings have for the use of test cycles – chapter 5
- Conclusion and suggestion of further assessments on the topic – chapter 6 and chapter 7

2 Regulatory Framework for Exhaust Emissions

The focus of this chapter is to present the governing restrictions for exhaust emissions according to the International Maritime Organization (IMO), and how they are enforced. As the framework for emission control has been laid out, the issues involving the emission control procedures that are addressed throughout this thesis are presented.

2.1 IMO MARPOL

IMO was founded in 1959 with the mandate to develop and maintain regulatory framework for shipping in order to improve maritime safety. Today the regulations of IMO involve safety, environmental concerns, maritime security, legal matters, technical co-operation and the efficiency of shipping. IMO has today 169 member states [2].

IMO does not have authority to enforce conventions by themselves. As a convention is accepted, it is the member states that are responsible for the implementation in their country, being primarily responsible for enforcing conventions on own vessels and their crew.

In order to get conventions or amendments accepted by the member states, the "tacit acceptance" procedure is used. This means that an amendment will enter into force on a given date unless a specified number of the member states have objected to the amendment.

The International Convention for the Prevention of Pollution from Ships (MARPOL) was adopted by IMO in 1973 and would evolve to what it is today where it addresses pollution from ships by oil, noxious or harmful cargo spills, sewage, garbage and lastly the prevention of pollution to air. These different pollutants are addressed in Annex I to VI in the MARPOL convention [3].

2.2 MARPOL Annex VI, regulation 13

MARPOL Annex VI was adopted by the MARPOL Convention in 1997 and entered into force May 2005. MARPOL Annex VI concerns the matter of regulations for the prevention of air pollution from ships, more precisely limiting the SO_X and NO_X contained in the exhaust gas, as well as prohibiting deliberate emissions of ozone depleting substances.

Regulation 13 of Annex VI states limits for NO_X emissions for marine diesel engines with a power output of 130 kW or more, and installed on ships constructed on or after 1st of January 2000, as well as engines that has undergone major modification after the given date [3].

Amendments were adopted by the Marine Environmental Protection Committee (MEPC) of IMO to Annex VI that stated stricter emission levels as well as revised NO_X Technical Code which will enter into force on 1 July 2010[2].

TIER I is the current emission level that needs to be met, whereas TIER II will be put into force 1st of January 2011 lowering the limit of permissible NO_X emission. TIER III is a great leap comparing with TIER II demanding a reduction of 80% from the TIER I level of emission. Whereas TIER I and TIER II are global restrictions, TIER III will yield only for emission control areas (ECA) when enforced 1st of January 2016 [4]. At the time being there are two ECA areas defined; the Baltic Sea and the North Sea which entered into effect in May 2006 and November 2007 respectively [5]. The ECA areas mentioned are recognised for now as Sulphur Emission Control Areas (SECA) controlling SO_X emissions, as the control of NO_X in these areas will not enter into force before TIER III in 2016.

NO_X emission limits as stated in IMO Annex VI - Regulations for the Prevention of Air Pollution from Ships, regulation 13 are presented in Table 1.

NO_X emission limits	TIER I After 01.01.2000	TIER II After 01.01.2011	TIER III After 01.01.2016
n < 130 rpm	17.0 g/kWh	14.4 g/kWh	3.4 g/kWh
130 rpm < n < 2000 rpm	45 · n^(-0.2) g/kWh	44 · n^(-0.23) g/kWh	9 · n^(-0.2) g/kWh
n > 2000 rpm	9.8 g/kWh	7.7 g/kWh	2.0 g/kWh

Table 1: MARPOL NO_X emission limits

2.3 NO_X Technical Code

The NO_X Technical Code, which is short for "Technical Code on Control of Emissions of Nitrogen Oxides from Marine Diesel Engines", was adopted in September 1997 by the "Conference of Parties to the International Convention for the Prevention of Pollution from Ships". The NO_X Technical Code entered into force on 19 May 2005.

Whereas MARPOL Annex VI regulation 13 states emission limits of NO_X, the NO_X Technical Code states mandatory procedures for testing, survey and certification of marine diesel engines. If compliance is shown to the emission limits, one achieve an International Air Pollution Prevention Certificate (EIAPP) [2]. As stated in MARPOL Annex VI regulation 5b [4], "*The survey of engines and equipment for compliance with the regulation 13 of this Annex shall be conducted in accordance with the NO_X Technical Code.*"

The testing procedures as given in the NO_X Technical Code are adopted from the international standard ISO 8178. Whereas ISO 8178 covers a greater area of application, a selection of applications is implemented in the NO_X Technical Code for the sole purpose of evaluating marine diesel engines.

2.4 Certification procedures

The NO_X Technical Code states a procedure for test bed measurements, as well as procedures for demonstrating compliance after installation. As testing on-board can prove limited in scope and accuracy, the initial testing is executed on test bed. When installed, engine parameters are checked against the engine's technical file in order to verify that operating values are the same as before instalment. Simplified measurements are done of the exhaust gas for onboard confirmation test and renewals to verify if the engine is still in compliance with the NO_X emission limit [6].

2.4.1 *Test bed measurements*

When a test is carried out, gaseous emissions from the raw exhaust are analyzed throughout a test sequence with variable load parameters. The test sequences that are used are referred to as test cycles. For marine application the NO_X Technical Code states four possible test cycles; E2, E3, D2 and C1, which is applied based on the engine type that are to undergo certification. Test cycles E2 and E3 are generally applied for main engine propulsion and D2 and C1 are applied for auxiliary engines. The focus throughout this report is on the E2 test cycle which is applied for main propulsion, constant speed, marine diesel engines.

The test cycle E2 consists of four modes with variable load, and each mode has a given weighting factor. The weighting factors states a share or percentage for each load point, assigning a value to the load point in terms of how much it would constitute during regular engine operation.

By testing with several load points the test cycle covers a wide area of operation, whereas the weighting of the modes are given in order for the test cycle to be representative of the normal operation of the engine. By having to test for several load points, one also avoids engines being fully optimized for one operation point [7].

	TEST CYCLE E2			
Mode number	1	2	3	4
Speed	100 %	100 %	100 %	100 %
Power	100 %	75 %	50 %	25 %
Weighting factor	0.2	0.5	0.15	0.15

Table 2: E2 test cycle

The test is carried out by operating the engine at steady state in each mode in ascending order for a minimum of 10 minutes duration on each mode.

It should be noted that test cycle E3 that is applied for propeller-law operated engines, is weighted equally and apply the same load points but not at constant speed. However this test cycle is not targeted in this thesis.

2.5 Restriction on PM emissions

At present time there are no direct restrictions on PM emissions for ships through MARPOL Annex VI like there are for NO_X and SO_X. As PM formation and measurements of particle distribution is a complex matter, it is unknown whether it is feasable to quantify and enforce a PM emission limit. Though there are no direct measures taken to reduce PM at the moment, an indirect reduction of PM occurs when sulphur emissions are reduced by regulations, as a share of the PM emissions is induced by the presence of sulphur [5].

2.6 Issues to be addressed

As the objective of this thesis is to evaluate the testing procedures for NO_X emission and simultaneously evaluate possibility of applying similar procedures for PM emissions, some areas of the stated procedures have been highlighted with regards to its application.

Due to difference in regulation of the two emission species, the evaluation is done first with respect to NO_X emissions, and secondly with respect to PM emissions. Both evaluations are targeting the use of the E2 test cycle as given in the NO_X Technical Code.

2.6.1 *Concerns regarding NO_X emission measurements*

The main concern when evaluating the test cycle in regards to NO_X emission measurements, is the realism of the test cycle. Different vessel types can have very different operational pattern, raising the question if the use of the same test cycle for the different types of vessels can give misleading results in concern to actual emission levels.

The test cycles used in NO_X Technical Code originate from the international standard ISO 8178-4. the first principle of the standard is quoted: "*The first principle is to group applications with similar engine operating characteristics in order to reduce the number of test cycles to a minimum, <u>but ensure the test cycles are representative of actual engine operation</u>*"[8]. It is assumed that, since the test cycles originate from the ISO standard, the same principles should apply when considering the NO_X Technical Code procedures. In this thesis I will investigate whether or not the first principle of the given standard is met.

2.6.2 *Concerns regarding potential PM emission measurements*

Particulate matter is at the moment not regulated under MARPOL, and no emission limits are set for marine diesel engines. Still, as this may become a possibility in the foreseeable future, it is of interest to evaluate possible methods for emission control. The formation of particles is dependent on the combustion process, as the formation of NO_X, and for that reason it could be necessary to evaluate PM distribution with variable engine operations.

In this thesis the objective for evaluating potential measurement procedures for PM emissions, will target the possibility of applying a test cycle for PM emission quantification with main focus on the PM behaviour during transient operation. Transient operation is not incorporated in the yielding test cycles for marine applications, but international standard ISO 8178-11 has been developed for the purpose of enabling comparable test-bed measurements of gaseous and particulate exhaust emissions from engines in no road machinery during transient conditions. As an objective in this thesis it will be evaluated if the PM development indicates a need for testing during transient conditions.

3 Part One – Nitrogen Oxides

In the following section the basic principles of NO_X formation will be discussed, followed by data collected on the formation of NO_X, dependent on engine load. To be able to evaluate the accuracy of the test cycles used during certification, operational information of different vessel types have been collected and is presented in the text. The real operational profiles are then compared to the E2 test cycle based on weighted NO_X emissions.

The focus of Part One is to investigate whether there are any significant differences in total NO_X emissions, if the test cycle would be altered in an attempt to better resemble actual vessel specific operational profiles.

3.1 NO_X formation

Nitrogen oxides called NO_X consists of NO and NO_2, where nitric oxides are the dominating specie. NO_X is considered a hazardous pollutant that is known to reduce air quality and forms acid rain contaminating lakes and soil. The formation of NO in near-stoichiometric fuel-air mixtures follows the main principal reactions of the Zeldovich mechanism [9].

$$O + N_2 = NO + N$$

$$N + O_2 = NO + O$$

$$N + OH = NO + H$$

NO_X is a pollutant that is driven by the combustion process dependent on nitrogen and oxygen from the intake air, however there can be a small amount of nitrogen in the fuel used for marine diesel engines that contribute to the total amount of NO_X emitted. NO_X formation has three driving forces, namely temperature, available oxygen and residence time, and the formation takes place when ambient nitrogen as well as fuel nitrogen reacts with oxygen at a high temperature. Turbochargers with intercoolers are often used with diesel engines and by this influence both temperature and oxygen levels in the combustion by exploiting the exhaust gas to increase the inlet air density [10].

3.1.1 *Steady state operation*

NO_X is formed in the high-temperature burned gases and the rate of formation increases with the temperature. In general it would be expected that NO_X formation is increased from low load steady state operation to high load steady state, since high load leads to high peak pressures and thus higher temperature. Combining this with greater regions of close-to-stoichiometric burned gas, one get increased emissions of NO_X [10]. Yet this is not necessarily consistent with real-life measurements as will be given examples of in chapter 3.3. Due to tuning of engine and use of turbocharger, the emission levels of high load operation can be reduced, at cost of higher emissions in the low load operating conditions. Matching of the turbocharger, meaning avoiding surging, has strong influence on the exhaust emissions, where airflow through the cylinders is increased. By proper matching a compromise between the operation conditions of high load and low load is achieved. Optimizing by matching is often done with regards to reducing emissions at high loads which constitute the most of an operation period, especially in terms of certification [11].

3.1.2 *Transient operation*

Little information was found on how NO_X behaves during rapid load changes, but it was expected that due to lower temperatures with lower engine loads and reduced air flow, the NO_X formation would be lower during load change compared to steady state operation. To support these statements literature was reviewed, and a recent research paper investigating NO_X and PM emissions during manoeuvring [12] had found that NO_X emissions fluctuated during manoeuvring, but at lower concentrations than during full speed operation. As the emission during transient operation is generally lower than during steady state, there is no conflict with the fact that transient operation is neglected for testing procedures.

3.2 Test cycle versus vessel operational cycle

The load points and weightings that are given in the E2 test cycle as presented in chapter 2.4.1 are equal for each test executed without regarding the actual present or future application of the engine [13]. The monotonous use of the test cycle raises questions whether there would be any significant differences in the NO_X emission values if one would optimize the choice of loads and weighting of them to match the real operation of a given engine.

3.2.1 *Test cycle E2*

The origin of the test cycle E2 is not elaborated in the NO_X Technical Code, but it is understood that the purpose of using a set of simplified test cycles, one achieve a comparable set of measurements making it possible to compare engines independently of where and when the test was executed. As mentioned previously the test cycle consists of four load points and a given weighting of each mode.

	TEST CYCLE E2			
Mode number	1	2	3	4
Speed	100 %	100 %	100 %	100 %
Power	100 %	75 %	50 %	25 %
Weighting factor	0.2	0.5	0.15	0.15

Table 3: E2 test cycle

To be able to evaluate whether the test cycle E2 is representative for real operation, operational information of three vessel types was gathered in an attempt to create cycles reflecting specific vessel operational patterns. The vessel types included in this study is a platform supply vessel (PSV), anchor handling vessel (AHV) and an oil tanker. The operational profiles investigated are mainly based on vessels operating with diesel electric propulsion systems (with the exception of evaluation of an oil tanker) and would under normal circumstances be certified with respect to the E2 test cycle.

In Figure 1 the E2 test cycle is illustrated for easy comparison with the constructed vessel specific operational cycles.

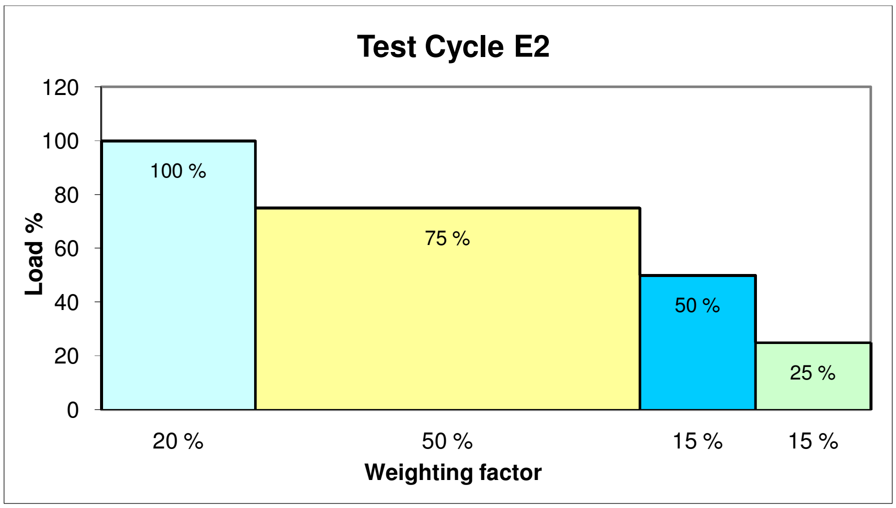

Figure 1: Profile of E2 test cycle

3.2.2 *Operational cycle – Platform Supply Vessel*

An operational profile of the platform supply vessel (PSV) Stril Myster was given by Simon Møkster Shipping AS, as a response to a survey sent out to several shipping companies in cooperation with master student Magnus Selås.

The vessel is equipped with a diesel electric propulsion system consisting of five Catapillar 3516B engines delivering each 1901 kW at 1800 rpm, and five Alconza 5064 generators. One of the engines is arranged for "take me home", implying that it us utilized solely as a back-up solution and therefore not included in the data [14]. The information that was received from the ship owner consisted of logged data on engine load factor versus time (appendix A). The engines had very similar data on load and duration; therefore it was assumed that one engines data would be representative for a full operation period and is illustrated in Figure 2.

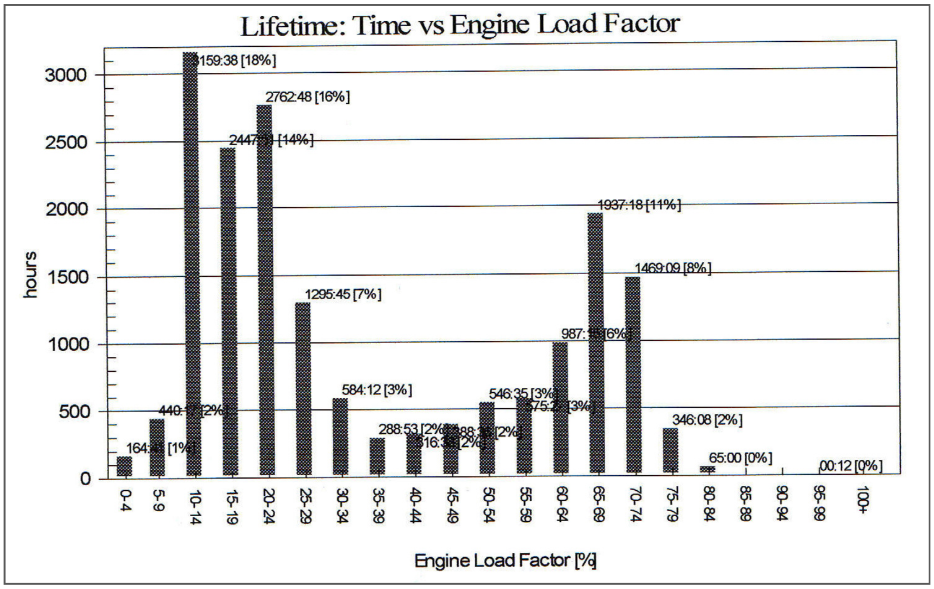

Figure 2: PSV - operational data

The given data covered the full load range of the engine making it possible to construct two simplified operational cycles for the PSV. One cycle was made based on the same load points as the E2 test cycle (Table 4), and another that is optimized with regards to the load points that are most frequent for the given engine (Table 5).

PSV - E2 load points				
Mode number	1	2	3	4
Power	100 %	75 %	50 %	25 %
Weighting factor	0.00	0.26	0.13	0.61

Table 4: Weighting of PSV operation with E2 load points

PSV - Optimal load points					
Mode number	1	2	3	4	5
Power	70 %	60 %	30 %	20 %	15 %
Weighting factor	0.19	0.09	0.10	0.30	0.32

Table 5: Weighting of PSV operation with optimal load points

It was found that by basing the profile on the E2 load points, the real amount of time spent with these loads only represented 19% of the total operational time, in contrast to the profile based on the most occurring loads representing 50% of the total operation (see appendix A). This is off course only measured for a single vessel and its operation, but it is an indication in this case of how poorly the real operation is represented in the original E2 test cycle.

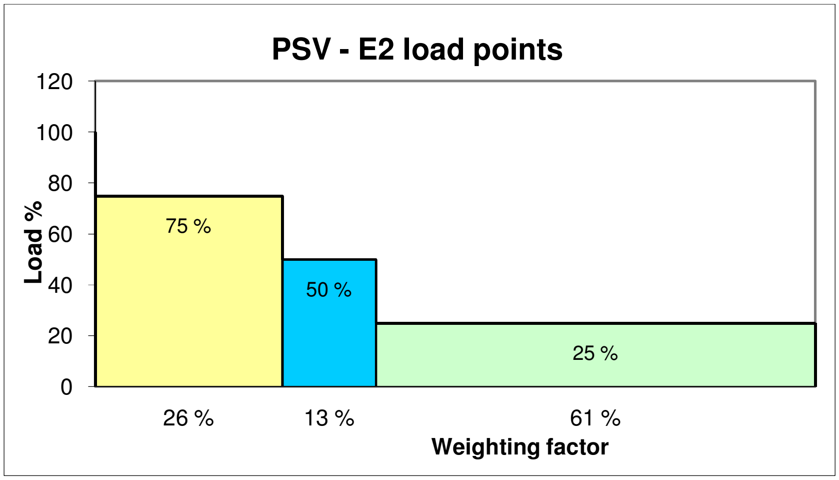

Figure 3: Profile of PSV load and weighting with E2 load points

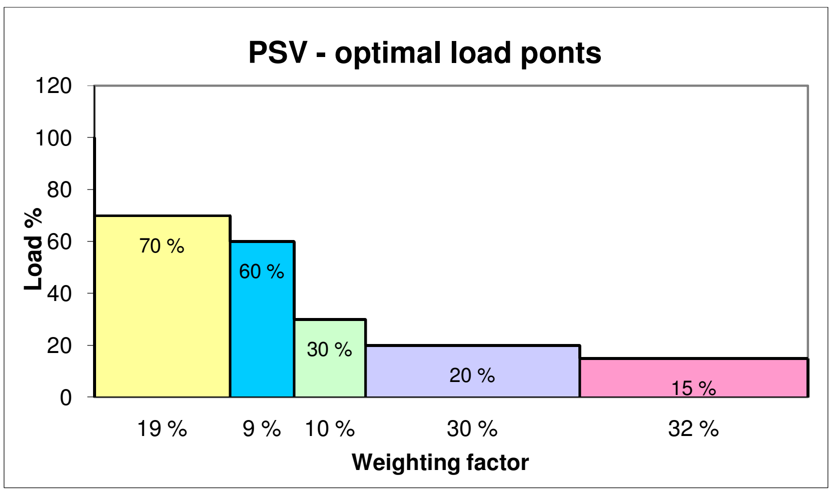

Figure 4: Profile of PSV load and weighting with optimal load points

When comparing Figure 3 and Figure 4 it is evident that the PSV profile cycle based on optimal load points have a better reflection of the load points that is used. Both profile cycles for the PSV have great differences comparing with the E2 test cycle shown in Figure 1 whereas the main differing factor being the increased amount of low load operation. It is acknowledged that the 100% load of the E2 test cycle is difficult to attain and could be presented with lower loads, such as 90%. But as one can see in Figure 2 showing the operational data from the PSV, the load on the engine is rarely above 80%, and therefore the 100% load is not included in the weighting for the PSV.

3.2.3 *Operational cycle – Anchor Handling Vessel*

Information on operation of an anchor handling vessel (AHV) was obtained by contacting Dr. Hilmar Æsøy from the University College in Ålesund and is presented in Table 6. In contrary to the operational profile for PSV, this operational data is not based on a single vessel, but is an example of typical operation of an anchor handling vessel. There are great variations in load for the operation conditions. This makes it necessary to use average values, as the information attained is not logged data for a complete operation sequence. Factors that are critical for the engine load of this kind of ship is sea depth at operation, type of anchoring to be placed and the type of operation to be executed [15].

Condition/ operation:	Max power (MW)	Min power (MW)	Average power (MW)	Ca. share of tot. op. duration (%)
Anchor handling	25	5	12	25
Transit	10	2	5	30
DP/standby	15	2	8	35
At port	5	1	2	10

Table 6: Operational information of AHV

The use of average values increases the uncertainties to the data as the given average might not represent an actual load point that is often in use.

With background in the operational information for an AHV, an operational cycle was constructed and presented in Table 7 (calculations can be found in appendix B).

AHV - Optimal load points				
Mode number	1	2	3	4
Power	50 %	45 %	40 %	30 %
Weighting factor	0.25	0.35	0.30	0.10

Table 7: Weighting of AHV operation with optimal load points

One immediately difference from the E2 cycle is that the load points used are all medium load with little deviance. This can be explained by the use of average values giving that the full extent of operation cannot be presented correctly. Another possible explanation to the great extent of medium load is the fact that anchor handling vessels are being instructed to have a surplus of available power as a safety measure.

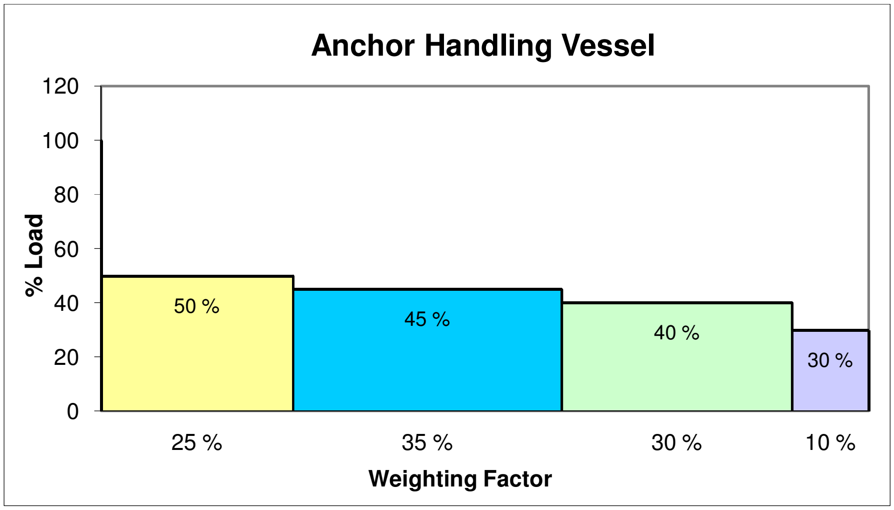

Figure 5: Profile of AHV load and weighting with optimal load points

The profile of the AHV given in Figure 5 is closer to the E2 cycle than the PSV-profiles, but there are still great differences due to the extent of medium load operation.

3.2.4 *Operational cycle – Oil tanker*

The operational profile of a tanker or a bulk vessel often represents an operational profile with long periods of high loads as they travel long distances at rated speed. Data was received from the shipping company Knutsen OAS Shipping AS on a round trip of a Suezmax size shuttle tanker. In addition an alternative route was recommended to illustrate a vessel in intercontinental trade. The route used for this vessel was Rotterdam (Holland) to Maracaibo (Venezuela) representing a voyage of 4418 nautical miles. As well as duration estimates for different operations, data was also given on fuel consumption during different operating conditions (appendix C).

Transit speed was assumed to be 13.5 knots while loaded and 14.5 knots in ballast. A specific fuel oil consumption (SFOC) was given to be 164 g/kWh, and was assumed to be constant enabling calculation of power output for the different operations based on fuel consumed (calculations can be found in appendix C). A constant SFOC is unlikely, but an increase in SFOC would normally occur with lower loads, which constitute a small part of the tanker operation profile, as well as a potential difference in SFOC will not amount to a great difference in the power output value.

Table 8 illustrates an operational profile constructed by the information given for the vessel travelling between Rotterdam and Maracaibo. The profile reflects only the main engine loads, as these large vessels are often equipped with auxiliary engines or boilers that are utilized during loading/ off-loading and when situated in port. Auxiliary engines are certified using other test cycles than E2 and is therefore not evaluated in this thesis.

Simplified trip, ME load	Duration		Fuel cons.	Power ME	
Operation:	[h]	%	[t/day]	[kW]	% of MCR
Manoeuvring	15	2.3	10	2420	14.2
Transit - loaded	327	50.5	69.3	14581	85.3
Transit - ballast	305	47.1	73.6	15486	90.6
	647	100.0			

Table 8: Operational information of tanker

The operations that are done by main engine (ME) for the oil tanker, is manoeuvring and transit. Due to difference in transit speed between loaded and ballast condition, the operation of transit has been divided into two different operation conditions. With knowledge on the operation of the oil tanker, an operational cycle was created and is given in Table 9.

Tanker Optimal load points			
Mode number	1	2	3
Power	90 %	85 %	15 %
Weighting factor	0.47	0.51	0.02

Table 9: Weighting of tanker operation with optimal load points

With this vessel being a long-distance-carrier, it is natural that the main operation of the vessel consists of long periods with high load.

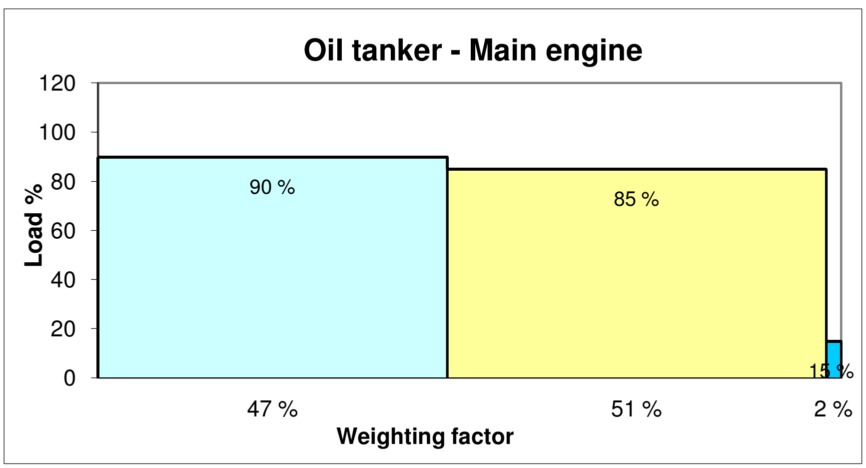

Figure 6: Profile of tanker load and weighting with optimal load points

Figure 6 shows the profile of the tanker where high load operation constitutes almost the entire operation cycle. This is of course dependent on the length of the voyage, and if the length had been shortened, the manoeuvring phase would have increased. Comparing the profile with the E2 cycle (Figure 1) there are obvious dissimilarities.

3.3 Specific NO_X emission values

To be able to compare the potential NO_X emission differences between the E2 test cycle and the profile cycles based on different vessel types, it is necessary to use the same specific NO_X emission data for each cycle. By using specific NO_X emission data held constant for each test cycle, one can calculate and compare the total weighted emission for each cycle.

The emission values may differ from engine to engine, therefore for the sake of evaluating accuracy of the results, measurement data was collected from two different engines with a total of three measurement sets. When the weighted NO_X emissions are calculated for all the cycles, it is done for each of the three data sets in parallel. This enables comparison of weighted NO_X emissions, as well as the sensitivity of the calculations is detected.

The NO_X emission values used gives NO_X in grams per kilowatt hour, and is measured at five load points, namely at 10%, 25%, 50%, 75% and 100%.

3.3.1 *Bergen KR3 Engine*

The MARINTEK laboratory is equipped with a Bergen KR3 engine with an output of 660 kW, at a rate of 900 rpm, from which specific NO_X emission measurements where obtained with the help of advisor at MARINTEK, Erik Hennie .

Due to recent modifications of the engine, including a new turbocharger, data was collected both before and after modification. The measured specific NO_X emissions are given in Table 10 for KR3 engine with old turbocharger, and in Table 11 for the KR3 engine with new turbocharger. The data from the KR3 engine with old turbocharger will from here on be referred to as "A-old T/C", whereas data from the KR3 engine with new turbocharger will be referred to as "B-old T/C".

Engine Type		KR3 ENGINE - old turbo				
Speed	[%]	100	100	100	100	100
Power	[%]	100	75	50	25	10
Specific NO_X emissions	g/kWh	8.90	9.90	11.20	13.90	17.80

Table 10: Specific NO_X emissions – "A-old T/C": KR3 engine with old turbo

Engine Type		KR3 ENGINE - new turbo				
Speed	[%]	100	100	100	100	100
Power	[%]	100	75	50	25	10
Specific NO_X emissions	g/kWh	10.10	10.70	11.00	12.70	14.10

Table 11: Specific NO_X emissions – "B-old T/C": KR3 engine with new turbo

It is evident from the tables that the new turbocharger has affected the NO_X emissions when comparing the measurements from before and after modifications. The specific NO_X emissions deviate less for "B-new T/C" than for "A-old T/C" implying a better matching with the new turbocharger.

3.3.2 *Rolls Royce Bergen B32 Engine*

The second engine data that is used in the calculations of NOx emissions is from a B32:40L9P engine produced by Rolls Royce. By contacting Rolls Royce, information was obtained on test bed measurements results which made it possible to calculate the specific NOx emissions as given in the table below (see appendix D for data and calculations). The B32 engine operates with a rated speed of 750 rpm, and gives a power output of 3000 kW. The dataset of specific emission from the B32 engine will from here on be referred to as "C-B32".

Engine type		B32 Engine				
Speed	[%]	100	100	100	100	100
Power	[%]	100	75	50	25	10
Specific NO_X emissions	[g/kWh]	8.82	8.77	8.18	8.46	9.50

Table 12: Specific NOx emissions – "C-B32": B32 engine

By assuming that the NOx development over the different load points is a continuous function, a graph over the given data for the two engines was constructed as shown in Figure 7. By doing so it is possible to extract information on specific NOx emissions for other load points then the ones that are given.

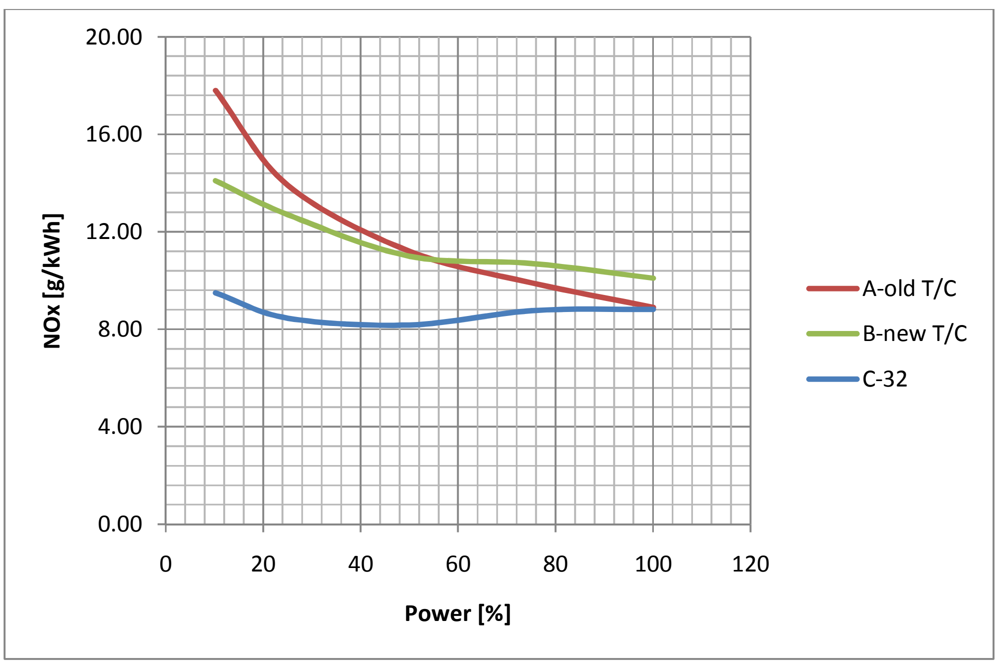

Figure 7: Specific NOx emission distribution

As shown in the figure above, there are evident variations in the specific emissions from the three different data sets.

3.4 Weighted NO_X emissions

By using the specific NO_X emission values from the three data sets, as well as the weighting for each operational cycle, total weighted NO_X emission values where calculated. As there are three different data sets of specific NO_X emissions, the calculations where done for all the cycles using one data set at a time. The weighted NO_X emissions are calculated by multiplying the weighting of a given load with the specific NO_X emission value for the same load point. When all the weighted NO_X emissions are found, they are summarized and give the total weighted emission. In Table 13, Table 14 and Table 15, below, a summary of the resulting calculations is given, whereas a more elaborated set of calculations are given in appendix E.

The weighting and chosen load points are individual for each cycle as proposed in chapter 3.2, where cycles were defined for each type of vessel operation in questioning. When the total weighted NO_X emission for each cycle was determined, the operational cycles was compared with the original E2 test cycle to evaluate whether or not any deviance could be found.

Total emission NO_X: Data set "A-old T/C"		
Cycle:	Tot. weighted NO_X emissions [g/kWh]	Difference from E2
E2	10.50	-
PSV - E2 loads	12.51	19.2 %
PSV - optimal loads	13.94	32.8 %
AHV - optimal loads	11.81	12.5 %
Tanker - optimal loads	9.54	-9.1 %

Table 13: Total NOx emission for cycles using engine data "A-old T/C"

Total emission NO_X: Data set "B-new T/C"		
Cycle:	Tot. weighted NO_X emissions [g/kWh]	Difference from E2
E2	10.93	-
PSV - E2 loads	11.96	9.5 %
PSV - optimal loads	12.54	14.8 %
AHV - optimal loads	11.40	4.3 %
Tanker - optimal loads	10.49	-4.0 %

Table 14: Total NOx emission for cycles using engine data "B-new T/C"

Total emission NO_X: Data set "C-32"		
Cycle:	Tot. weighted NO_X emissions [g/kWh]	Difference from E2
E2	8.35	-
PSV - E2 loads	8.50	1.8 %
PSV - optimal loads	8.75	4.8 %
AHV - optimal loads	8.19	-1.8 %
Tanker - optimal loads	8.83	5.8 %

Table 15: Total NOx emission for cycles using engine data "C-32"

As observed from the tables above, the calculated weighted NO_X emissions generally show increased emissions when comparing with the E2 test cycle. Still, the deviance in the results gives that the specific NO_X emission data represented by "A-old T/C", "B-new T/C" and "C-32" is crucial to the results.

By calculating the total NO_X emissions both before and after modification of the KR3 engine, the influence that the engine characteristics can have on the comparison between cycles becomes evident. It is recognized that the calculations based on the NO_X emission data from the KR3 engine with old turbocharger ("A-old T/C") reflects a less than optimal combustion process, but in the means of comparison, it is an important example of how the total emissions are not solely influenced on the weighting of load points.

3.4.1 *Results regarding PSV operation cycle*

The most comprehensive diversity in the results is found for the PSV with a cycle based on optimal loads. The difference when comparing the calculations for this cycle and the E2 test cycle varies between a 30% increase using engine data "A-old T/C", (Table 13), to a 5% increase using data set "C-32" (Table 15). The overall trend is that the emission level is higher when the more realistic profile is used, in comparison to the E2 test cycle used for certification. For the PSV-cycle based on E2 load points, the difference from the E2 test cycle was less, but still shows the same trend of increased emissions.

3.4.2 *Results regarding AHV operation cycle*

The results found for the profile based on an AHV, showed some interesting differences. Using engine data set "A-old T/C" and "B-new T/C", the emissions where elevated in comparison to the E2 test cycle. But with data set "C-32", there was a small decrease in emissions compared to the E2 test cycle. Still, the differences found between the AHV cycle and the E2 test cycle is small compared to the differences between the PSV cycles and the E2 test cycle.

3.4.3 *Results regarding tanker operation cycle*

When evaluating the differences found between the E2 test cycle and the cycle based on an oil tanker, it is for engine data set "A-old T/C" and "B-new T/C" found a reduction in emission for the tanker cycle. For engine data set "C-32" there is found an increase in emissions. The trend here is then the opposite of the trend for the AHV. For the tanker operation cycle the difference compared to the E2 test cycle was never above 10% neither increase or decrease.

3.4.4 *Evaluation of uncertainties*

It is important to emphasize that results obtained are not meant to represent a certain vessel type. This is rather an attempt to show by specific examples, that there are vessels for which the existing method for certification (using the E2 test cycle) can be imprecise.

The sensitivity of this emission evaluation is quite high. There are uncertainties regarding the weighting of the loads in the operational cycles, as the data it is based on are estimates and average values, especially in the case of AHV. Another important uncertainty is related to the specific NO_X emission values. The values that are used might not be representative for an average set of specific NO_X emission values, as the data was collected from only two engines. It was attempted to retrieve more extensive engine data, but that proved difficult. The data that was used in this assessment showed variations, and consequently gave variable results.

Also, it was assumed that the specific emission values for the different load points represented a continuous curve to enable determination of NO_X values at different load points than the ones given. There could be a peak in NO_X formation between the load points measured that would, in this case, not be accounted for. If total NO_X emissions with other load points than the ones used in the E2 test cycle should be examined, the uncertainty would be less if actual NO_X emission measurements were done at the exact load points.

3.5 Discussion of results - Part One

By using data of specific NO_X emissions to compare total weighted emissions for a variety of operation cycles as done here, the sensitivity of applying the E2 test cycle for certification can be evaluated. By keeping the specific NO_X emissions constant and varying the weighting and the load points, one can determine if there is a difference in total emissions.

It was revealed while collecting data, that the NO_X emission characteristics from different engines can have great variations from engine to engine, and this again makes it difficult to generalize what should be assumed to be a representative set of data. The results from calculating NO_X emissions using different loads and weighting, and the deviation found from the test cycle is completely dependent on the engine data collected, and consequently introduce uncertainty to the results.

When comparing total NO_X emissions for different operational cycles with the E2 test cycle the results that were found was inconclusive. Due to variety in the specific NO_X emission data collected from the KR3 and the B32 engine the outcome from the calculations for the different vessel profiles showed a wide spread in difference from the E2 test cycle. It is evident from the deviations comparing the calculations using data set "A-old T/C", "B-new T/C" and "C-32" in chapter 3.3 that the specific NO_X emissions, which are the base for the calculations, have a strong influence on the result. However for the PSV cycles weighted NO_X emissions are higher than E2 cycle emissions for calculations by all three specific emission data sets.

Even though the variations between the different operation cycles seemed considerable compared to the E2 test cycle as they were presented in chapter 3.2, the difference found in emission levels were mostly less than 10% increase or decrease.

If it would be of interest to further investigate the deviations in NO_X emissions using cycles based on operational profile versus test cycle used for certification, determining a representative NO_X emission data set would be a critical factor which needs to be resolved.

4 Part Two – Particulate Matter

The formation and behaviour of PM is a topic that lately has generated a lot of attention in concern of exhaust emissions. In this section, particulate matter and how it behaves during engine operation will be presented. A topic that is of interest is the PM formation during transient engine loads. Laboratory tests have been carried out to investigate this matter and the results are presented in the text. Information has also been collected on operation of vessels, which are of interest regarding high occurrence of transient operation. As knowledge is gained on the PM formation, and the scope of transient operation for distinct vessels is known, an assessment can be made of the importance of transient operation induced particles.

The test cycles used for certification in regards to NO_X emissions are made up by four load points of steady state operation, whereas transient operation is not included. NO_X formation, as discussed in part one, is not elevated during transient operation in comparison to steady state operation. It is therefore understandable that the NO_X emissions during transient operation are neglected in the certification process.

Transient operation might not be of interest to evaluate in regards to NO_X, but it could be of importance when evaluating PM emissions. This considering PM behaves opposite of NO_X as high NO_X formation generally corresponds to low emissions of PM [11].

The focus of Part Two is to evaluate if the test cycles that are applied for NO_X emission determination are applicable for PM emission determination as well. The evaluation is mainly emphasizing the questions of whether or not PM emissions that can be attributed to transient operations are of such extent that they should <u>not</u> be neglected.

4.1 Particulate matter - background

The subject of particulate matter and its origin is a more complex subject than the formation of NO_X emissions. This was discussed in the project thesis that was done previously to the master thesis. The paragraphs below present parts of the literature reviewed in the project thesis.

4.1.1 *PM origin*

PM is for legislative purposes defined as the material that is deposited on a filter trough which a volume of diluted exhaust gas has passed [16].

Particles from diesel engines are created mainly from soot, sulphates, volatile hydrocarbons and compounds from unburnt fuel. These again are divided into primary particles formed in the combustion process, and secondary particles which are formed in the atmosphere as the exhaust is diluted. When considering PM emissions from ships, the quality of the fuel plays an important role in the chemical composition of the emission product. The content of sulphur in marine fuels vary by quality and can be as high as 4,5%. This can lead to the formation of large sulphur particles and, as illustrated in Figure 8 [5], also increase the amount of water associated with sulphate. Residual oil also contain a large quantity of polyaromatic hydrocarbons which is identified as having a connection with the formation of soot particles [17]. Analysis that have been done of the chemical composition of soot particles [18] found that the particles mainly consisted of carbon with smaller contribution of oxygen, vanadium, nickel and silocone, which was assumed to originate from burning heavy fuel oil (HFO).

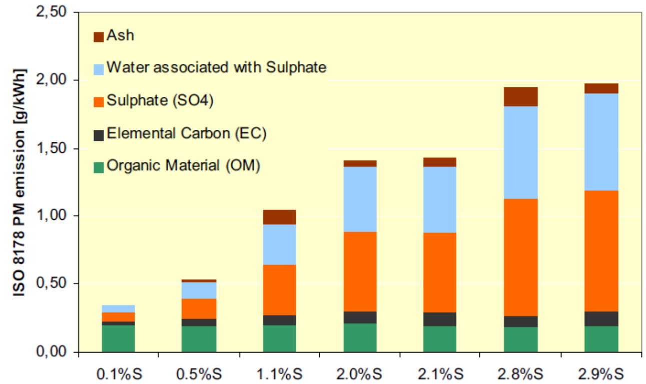

Figure 8: Chemical composition of PM emissions

4.1.2 *Health aspects*

The particles size is a variable concerning the health impact, and physically absorption in the human body. The coarse particles are deposited in the upper respiratory tract, nasal and oral cavities, while the fine particles is brought further down to our upper pulmonary system. The ultrafine particles on the other hand, is allowed by their small size to travel to the lower pulmonary and to the alveolar region where gas exchange takes place between the bloodstream and the lung [19].

Previous studies have recognized the large surface area, small size and contaminasion of transition metals to be the main qualities of ultrafine particles that provokes respiratory illness [20]. By this the particles generated by combustion in marine diesel engines stands out as more hazardous than other combustion generated particles. Based on global estimates it is found that shipping emits between 1.2 and 1.6 million tons of PM annually, and results from recent studies indicate that as much as 60'000 deaths annually due to cardiopulmonary deceases as well as lung cancer globally can be attributed to shipping induced PM emissions [21].

4.2 PM formation

The exact formation process of particles, as measured in number and size, is yet to be completely uncovered as much research is put into this topic at the time being. Therefore I will not speculate in the specifics, but present some overall factors that are known to influence the formation of PM.

4.2.1 *Steady state operation*

PM is formed dependently on the combustion process and it is a generally accepted phenomenon that soot is formed due to incomplete combustion in the engine, being a consequence of a lower than stoichiometric air/fuel equivalence.

Diesel combustion is generally a lean combustion process, which means that there is a high flow rate of air making sure there is excess oxygen. However direct fuel injection (DI) is commonly used for large scale diesel engines allowing formation of local fuel rich areas in the combustion which can cause soot formation [11].

The behaviour of PM with varying engine load is typically low PM emissions during steady state operation at high engine load, and higher PM formation with lower engine loads. As the load is low, smoke is formed in the fuel rich zone downstream in the liquid core of the fuel spray. Here, the air to fuel ratio is lower, therefore lack of oxygen locally causes soot formation. At high loads there is increased motion of the combustion air generating better mixing of the air and injected fuel. This reduces the fuel rich areas and thus, less incomplete combustion and less PM [22].

4.2.2 *Transient operation*

The general acceptance concerning PM emissions during transient operation is that with great engine variations, such as while manoeuvring when approaching or leaving port, there is formed visible dark smoke suggesting fuel rich combustion. Load variations can interfere with the performance of the turbocharger, reducing the air supply and by that create larger areas in the combustion chamber with fuel rich mixture.

When it comes to particle distribution during transient operation, little information is published, and this matter is the main target for investigation in Part Two of this thesis.

4.3 Laboratory testing

To be able to investigate variations in PM development with varying engine loads, a laboratory test was carried out 18th of February with assistance of MARINTEK'S Jørgen B. Nielsen. The test was carried out in the engine laboratory at the Marine Technology Centre.

The measurements that were done in the laboratory consisted of number distributions of PM with respect to particle size. Measurements where made both during transient and steady state operation to enable comparison between the two conditions.

At the moment there are not any established procedures for how PM distributions should be measured, and for that reason the quantity of emissions is not the main concern for these tests, but rather the relationship between the distributions for different phases of engine operation.

The testing was originally focused on measuring NO_X and PM in concern of applying a selective catalytic reduction (SCR) system for NO_X emission reduction[1], therefore some changes were made as we went along to enable measurement of PM emissions with the SCR system running.

4.3.1 *Engine and measurement equipment*

The engine that was used in the test was a 660 kW Bergen Diesel KR3. This is a four stroke turbocharged with intercooler engine, operating with an engine speed of 900 rpm, which is able to run on both heavy fuel oil (HFO) and marine gas oil (MGO).

The laboratory is equipped with two sets of measuring systems for determination of particle size distribution, the Dekati and the TSI equipment. The PM distribution measurements was done both by the Dekati and the TSI measuring systems, but during transient phase only the Dekati equipment was used to record particle behaviour and is therefore the source of the data presented in the results. Information of the working principals of the two PM measuring systems can be found in appendix F.

4.3.2 *Measurement test runs*

Initially it was planned to complete two test runs, first with MGO then with HFO, with steady state operation at 25%, 50%, 75% and 100% of the load measuring PM with each load held for 15 minutes. To record PM behaviour during transient operation, the periods of load shift were measured. As the testing initially was focused on measurements while operating a SCR system, the load point of 25% was aborted as, even when operated at 30 % load, the exhaust temperature was too low for the SCR system to start functioning. It was then decided to carry on with the testing for the load points of 50%, 75% and 100%, and two test sequences was eventually run.

[1] Explanation on use of SCR system can be found in project thesis, written as preparation to the master thesis [23].

One test sequence consisted of 15 minutes of steady state operation on each of the loads 50%, 75% and 100%. The load increase between two load points took 15 -20 minutes to stabilize, which was recorded as transient conditions. For the particle sampling the dilution temperature was set to 400˚ Celsius, and an approximate dilution ratio was set to 1:50. For verification a Horiba NO_x analyser was also used for determining the dilution ratio. At a temperature as high as 400 ˚Celsius it could be assumed that all volatile organic compounds would be evaporated, and the PM emissions that are measured are therefore a “base-level” emission.

Measurements were done of the exhaust gas both before and after the SCR system, but as the influence of the SCR system is not of interest in this thesis, only the measurements done before the SCR system have been taken into consideration when evaluating the PM distributions.

4.3.3 *Purpose and expectations*

The purpose of measuring transient phase during load shifts was to investigate if there could be any noticeable peak in particle development as the load was increased or decreased.

As particles were measured both during steady state condition and transient condition it enabled comparison of PM development before, after and during load shifts. Before evaluating the measurement data it was expected that one could see an increase in PM formation during load changes based on the background information found on PM formation as presented in chapter 4.2.

4.4 Laboratory test results

As the data from the laboratory testing was collected, it was treated and made accessible with the help of Dekati software. The graphs on the following pages shows particle distribution accounting for number of particles distributed over a size range.

4.4.1 *First test sequence with MGO:*

For comparison between the distributions, the steady state (SS) condition before and after a certain load shift occurred is presented in the charts as well as the measurements conducted during the given transient load (T).

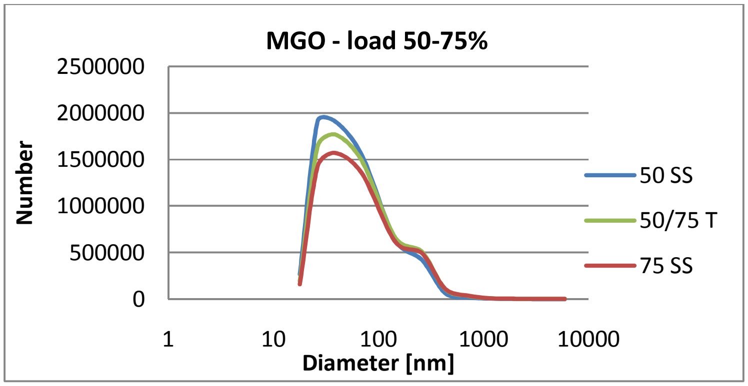

Figure 9: PM distribution, MGO 50-75% load shift

In Figure 9 the PM distribution for steady state (SS) operation at 50% and 75% can be seen, as well as the transient period (T) while the load was increased. The findings for this load shift show surprisingly a decrease in particle number from 50% steady state to the transient phase, followed by a further decrease when measuring for 75% steady state operation.

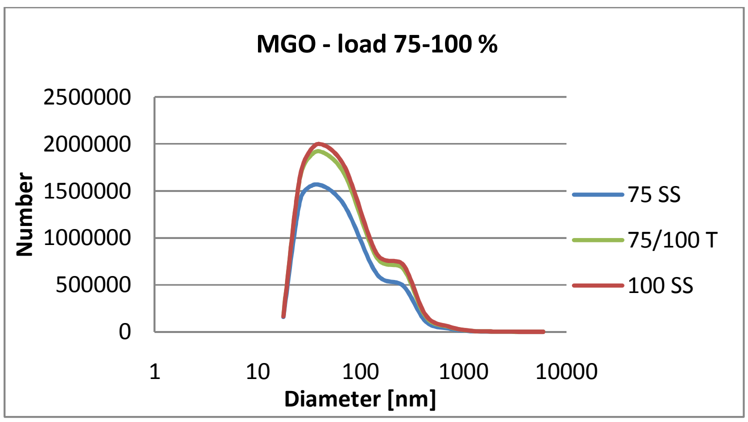

Figure 10: PM distribution, MGO 75-100% load shift

When increasing the load from 75% to 100% there is, in contrary to the previous load shift, an increase in particle number.

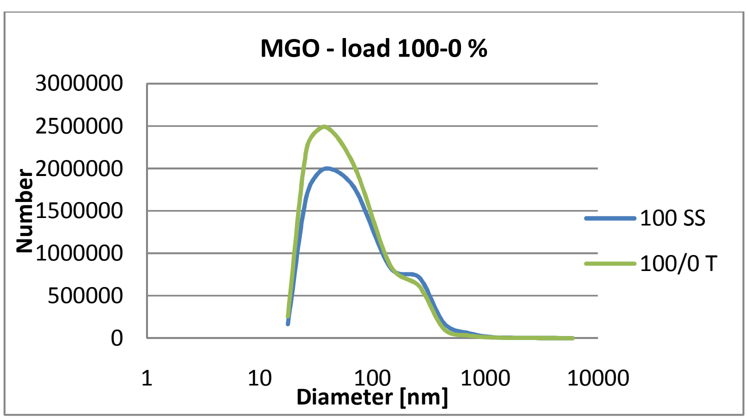

Figure 11: PM distribution, MGO 100-0% load shift

The PM behaviour while the engine was slowed down, as shown in Figure 11, was rather surprising. It was expected that the number of particles would be higher while the load was high in contrary to when the torque on the engine was reduced from 100% to close to 0%. Still, the results show an opposite behaviour than that expected as the particle number is higher for the load reducing period than for the 100% steady state operation.

4.4.2 *Second test sequence with HFO:*

The second test sequence was run using HFO. After the problems encountered during the 30% load point in the first test sequence, this operation mode was neglected in the second test sequence as well. PM formation is drastically increased by using HFO for fuel, as one can see in the vertical axis giving the number of particles.

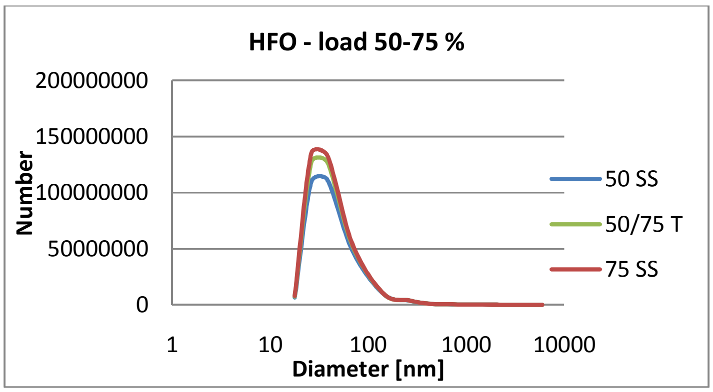

Figure 12: PM distribution, HFO 50-75% load shift

The first load shift tested for with HFO was from 50% steady state to 75% steady state operation given in Figure 12. It was interesting to find that in contrary to the same load shift for MGO, the highest particle number is now for the condition of steady state of the highest load, 75%.

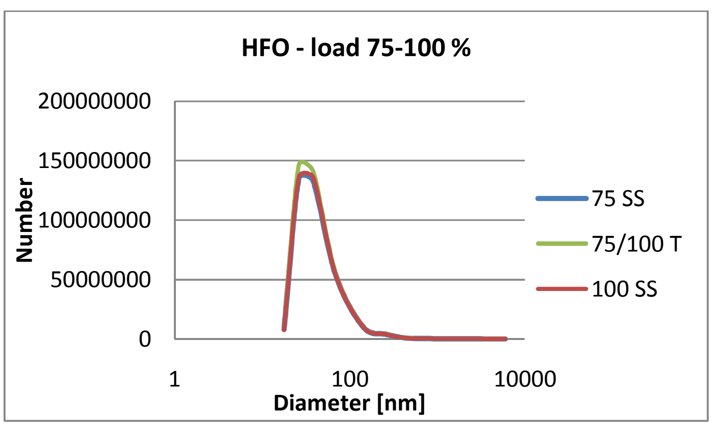

Figure 13: PM distribution, HFO 75-100% load shift

The next load shift tested with HFO was between 75% and 100% of load. This is the only result that illustrates what was initially expected from each test, namely that the transient phase would show an increased particle number compared to steady state operation. Even though this was achieved for this case the increase is not substantial, and it was not a persistent trend throughout the testing.

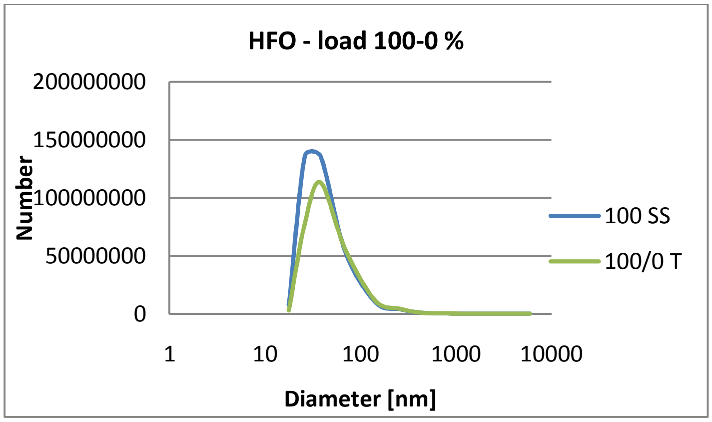

Figure 14: PM distribution, HFO 100-0% load shift

Again, as the engine load was decreasing from 100% the measurements for HFO testing showed an opposite trend than what was found with MGO. In Figure 11 for the MGO-test, the particle number is higher for the transient phase, whereas the situation is opposite using HFO as shown in Figure 14 where the highest particle number is presented by the steady state operation.

4.4.3 *Overall laboratory result evaluation*

Throughout the test results it is apparent that there is an actual change in number of particles as the size distribution is kept more or less constant for most of the measurements. If there had been a change in size distribution between the measurements, the curve would have shown a narrower or wider spread in the size range.

There is a lot of diversity in the test results, both comparing the different load shifts using the same fuel, and when comparing the same load shifts but with different fuel in use. The expected peaks of PM formation during load shift were not present. On the contrary, the results showed in several cases that the transient phase did not present the greatest PM formation.

The results found were unexpected in regards to the expectations and based on the theory of particle development during transient phases as manoeuvring. As it was not possible to have more testing done in the laboratory, the testing could not be repeated and re-examined.

4.4.4 *Review of measurement accuracy*

One issue concerning the results of the test runs is that it was only possible to make one set of measurement for each fuel. Without a more substantial amount of data, the reliability of the data is limited, as there is no information on reproducibility. Another factor is that the load point of 30% was aborted for both test sequences, reducing the range of testing.

When reviewing the data collected it was noticed that the data indicated an increase in particle development AFTER the SCR unit, which was unexpected. Even though the measurements taken after the SCR unit was not of interest for this study, this finding made one question the results, and investigate why the error occurred. It was then discovered by Jørgen B. Nielsen who supervised the measurements, that there was a leakage in the hose delivering the exhaust gas measured before the SCR unit to the particle measuring instruments. Due to negative pressure in the hose, surrounding air was sucked in and basically increased the dilution of the exhaust gas pre-SCR unit. Since the transient and steady state measurements were taken under the same conditions, the proportion between the two measures is still regarded as unchanged, even if there was increased dilution. Therefore, as the measurements after SCR are not of any interest, the relative increase in PM emissions comparing transient with steady state operation can still be evaluated in spite of the leakage.

4.5 Offshore testing – DP mode

There possibility for investigating PM distribution from testing offshore on the shuttle tanker, Navion Oceania, undergone by MARINTEK was discussed. Unfortunately due to many delays this was not possible before the deadline of the master thesis. There are many factors that influence the possible transients during DP mode, but measurements of PM distribution would have given an opportunity to quantify the contribution of total PM during operation for one vessel under known circumstances.

4.6 Research on PM formation

As the results gained during laboratory testing did not shed any further light on the behaviour of PM during transient operation and more laboratory testing was not possible, literature was reviewed in order to find out if there were any studies conducted on the matter.

4.6.1 *PM formation during manoeuvring*

A study carried out by Hulda Winnes and Erik Fridell at the Department of Shipping and Marine Technology of Chalmers University of Technology [12], investigated emissions of NO_X and PM from vessels during manoeuvring. The measurements of their study were conducted on the main engines of a product tanker and a ferry, both running on HFO. Manoeuvring was defined as "from engine start-up until steady state full speed condition was held for one minute". Corresponding definition was made for engine shut-down, in order of consistency throughout the tests. The ferry presented in the paper is in regular service sailing between two ports and there was carried out seven series of measurements each covering a period from engine start-up till engine shut-down. The research conducted on the ferry will be the main focus for discussion in this chapter due to the available measurements-data covering a full operation.

The results of Winnes and Fridell showed a substantial increase in particle number concentrations during manoeuvring as illustrated in Figure 15 extracted from their research report.

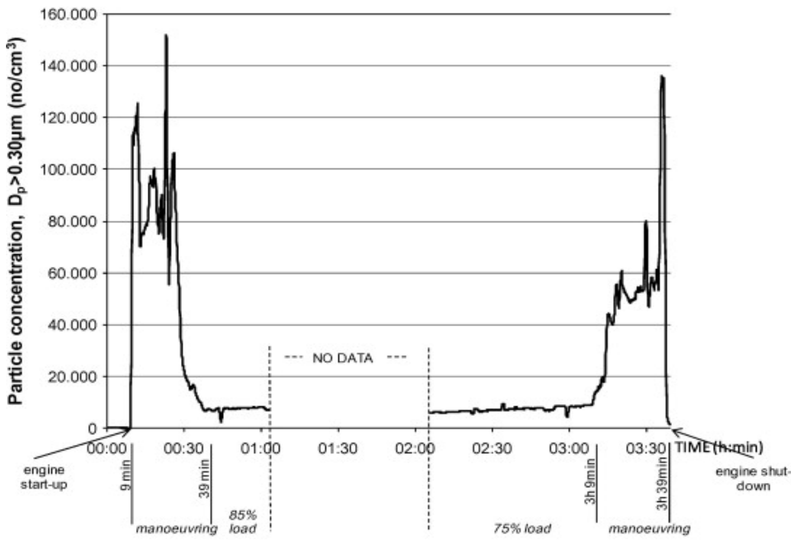

Figure 15: Number concentration of PM during ferry journey

As the figure illustrates, the manoeuvring phases is responsible for a substantial number of particles being formed whereas during service speed sailing, the number of particles are low. A pattern for all the engines included in the testing was found showing that during full speed there was a larger share of particles of diameter of more than 0.40 µm compared to the manoeuvring phase. This statement suggests that the periods which contributed most to the high number of particles also emitted the smallest particles.

For the ferry the average specific emission of PM during manoeuvring was 0.20 g/kWh, and 0.12 g/kWh during full speed steady state. The increase in specific emissions during manoeuvring are smaller than first expected, but one have to take into account that the specific PM emissions are based on particle mass and not amount in means of numbers of emitted particles. As mentioned before, there as larger shares of bigger particles during steady state, implying that if one wants to consider the number of particles formed, the specific emission gives a misleading impression of the actual emission.

In regards to the number distribution of particles, a rough estimation was done, based on information given in Figure 15, of the particle number to compare manoeuvring and transit condition. In Table 16 the estimates are presented, where a mean value is used for manoeuvring as Figure 15 shows some differences in manoeuvring while leaving port in comparison to approaching port.

Operation	Manoeuvring leaving	manoeuvring approaching	mean manoeuvring	transit
Particle conc. [no/cm3] in thousands	80	50	65	10
Relationship emission			6.5	1

Table 16: Particle concentration relationship between operations

The resulting relationship between amounts of particles formed gives that during manoeuvring there is formed approximately 6.5 times as many particles compared to high load, steady state operation.

4.7 Operational profiles

In the previous section the effect transient operation conditions can have on particle formation was presented. To be able to evaluate if the PM emission during transient operation can have a substantial effect on the total emissions during a full operational cycle, it is necessary to determine how extensive the transient operation periods are in regards to an complete operation.

Transient operation represents rapid load changes in the engine and occurs during acceleration, manoeuvring as well as during dynamic positioning (DP) mode. Transient operation will not be as substantial for every vessel as there is great diversity in vessel operation, but the types of vessels that can be of interest to investigate is vessels that operates a great deal on DP mode and ferries.

Platform supply vessels, standby vessels may have long periods operated in DP mode, but engine load during DP can vary from day to day being effected by external influences. Weather is an important factor as calm weather can give low loads where rough weather can demand more of the engine to stay in position. Due to these variations it is difficult to quantify transient in DP mode. Passenger ferries operate in calmer sea and have a predictable sailing pattern. Even though different routes have different lengths, the acceleration from port and manoeuvring can be presumed to be very similar for different vessels of comparable size.

4.7.1 *Ferry profile – CASE 1*

In the research paper by Winnes and Fridell [12], the full sailing period for the ferry was given, and can therefore be used to determine how extensive the manoeuvring period is with regards to the complete voyage. Still, little information is given on where this ferry sails and whether it is representative for a typical ferry operational profile. The duration of the complete voyage for the ferry represented in the research paper is approximately 150 minutes, with manoeuvring phase amount to a total of 60 minutes. This ferry will be from now on referred to as CASE 1.

4.7.2 *Ferry profile – CASE 2*

In order to get a better basis for comparison, information was gathered on short-voyage car ferries representing typical ferries along the Norwegian coastline. In Norway domestic ships in regular service for public transportation purposes comprise a total of 336 vessels, where 190 vessels are car ferries [24].

To be able to get an estimate of a mean voyage duration for car ferries along the Norwegian coastline, an average was calculated from Fjord1 [25] vessels sailing in the areas of Sunnmøre and Sogn og Fjordane (appendix G) as these are coastal areas with high density in car ferries. The average value of voyage duration was found to be 19.3 minutes for the ferries in the given areas.

By contacting the transportation company Tide AS, information was attained of a complete operational cycle for a car ferry sailing between Venjaneset and Hattvik in the Norwegian county, Hordaland. By having engine operational specifics of a complete voyage it is possible to estimate how much of the voyage duration manoeuvring constitutes.

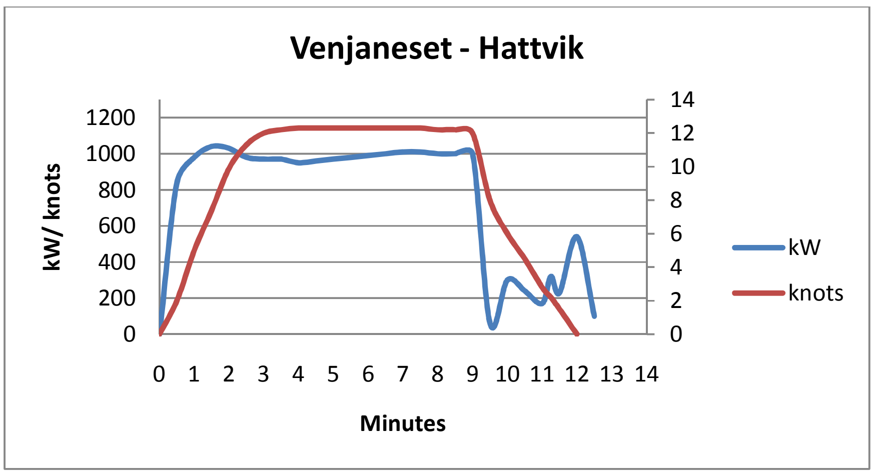

Figure 16: Engine operation data, Norwegian car ferry (1)

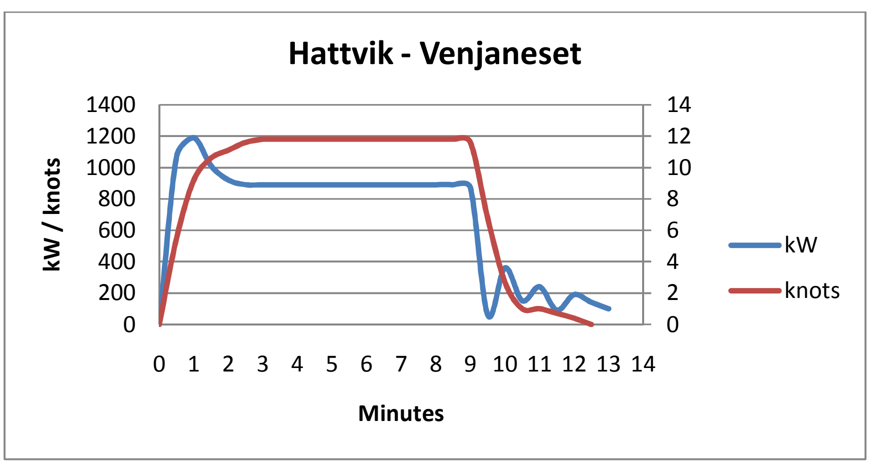

Figure 17: Engine operation data, Norwegian car ferry (2)

Figure 16 and Figure 17 illustrate how the engine load as well as speed varies throughout a voyage back and forth between the two ports. The information that is gained from this data is that the phase of acceleration from harbour until sailing speed is reached, lasts about 2 minutes, and when approaching the destination a period of manoeuvring is evident due to the variable engine load and speed illustrated. The manoeuvring phase when approaching port lasts approximately 3.5 minutes defining the phase as from start of load decrease until port is reached. The original data that was given by Tide ASA can be found in appendix H.

The voyages illustrate the extent of operation that can be considered transient, for this particular case being a total of approximately 5.5 minutes. If one would assume that the acceleration and manoeuvring periods found in this case is representative for most car ferry voyages along the Norwegian coastline, the factor that will influence the share of transient operation is the steady state sailing period. By assuming an equal share of manoeuvring as for the given example, the manoeuvring phase would, with average voyage duration of 19.3 minutes, represent close to 30% of the total operation.

The voyage profile representing a Norwegian car ferry will from now on be referred to as CASE 2, with the assumption of a mean duration of 19.3 minutes, whereof 5.5 minutes is spent manoeuvring.

4.8 Extent of PM emission during maneuvering

By applying the relationship of particle concentration found in chapter 4.6.1 (Table 16), and calculating the PM formation with respect to the duration of the given phases, one obtains the "real" relationship of emission.

In Table 17 the duration of manoeuvring and transit is given for both CASE 1 and CASE 2. By multiplying the phase durations with the particle number factor for the same phase, the duration is accounted for. This means that by taking the duration of manoeuvring and sailing into account to the PM emission ratio, one obtain a new ratio of emission giving the real contribution of each phase to number of particles emitted.

	Operation	Manoeuvring leaving	manoeuvring approaching	total manoeuvring	transit
Case 1	Duration [min]	30	30	60	150
	PM number relationship /factor			6.5	1
	PM factor multiplied with duration			390	150
	REAL PM relationship			2.6	1
	Percentage PM contribution to total			72%	28%
Case 2	Duration [min]	2	3.5	5.5	13.8
	PM number relationship /factor			6.5	1
	PM factor multiplied with duration			35.75	13.8
	REAL PM relationship			2.6	1
	Percentage PM contribution to total			72%	28%

Table 17: Calculations of particle formation for a voyage

The results found when taking the duration into account are very interesting. Initially the relationship between PM concentration during manoeuvring and transit was 6.5 to 1. This relationship then represents if the duration of the two phases was equal. But even when the duration has been accounted for and the factor between the two phases decrease, the relationship is still 2.6 to 1. This gives that by the data and information collected, the transient phase, which is recognized as manoeuvring, is the phase during a voyage, for the given ferries, that is responsible for approximately 70% of the particles formed.

It is also quite interesting that the result is exactly the same PM emission relationship for CASE 1 and CASE 2. CASE 1 is obviously a larger vessel travelling longer distances, while CASE 2 is a relatively small car-ferry travelling short distances.

4.8.1 *Evaluation of uncertainties*

As the measurement data used for determining the relationship between PM formation during manoeuvring and steady state operation is collected from a research paper, it is difficult to make an assessment of the uncertainties that could lay in the measurements, and by that constitute an uncertainty in using their findings.

When determining an average duration for manoeuvring as in CASE 2, an assumption was made that the duration found of manoeuvring could be considered representative for short-distance car ferries. This statement is a simplification, and should be investigated further as there most likely are examples where the manoeuvring when approaching or leaving port is easier or more demanding.

The average voyage duration for CASE 2, was found based on a selection of ferries. An attempt was made to get an estimate based on all ferries in domestic routes by contacting Tor Harald Eliassen at the Norwegian Public Roads Administration, department for ferry transportation. Mr. Eliassen informed that they are now in a process of developing a ferry statistics database, but unfortunately this was not yet finalized. As the statistics for all domestic car ferries were not complete it was decided to collect data from a transportation company Fjord1, who operate a great share of the domestic car ferries in Norway. By this, the average voyage duration that was found for CASE 2 could be made more precise as the information needed is made available.

4.9 Discussion of results – Part Two

4.9.1 *Particle formation*

The results of the laboratory testing did not live up to its expectations, as there were no significant peaks in the transient conditions. The findings were discussed with Jørgen B. Nielsen who supervised during the testing, and it was evaluated that the rate of load change, and the load increase was to slow and too little to influence the combustion process to the extent that one would see a peak in PM formation.

The tests that was done in the laboratory showed little importance of load changes in regards to formation of PM, whereas the tests done on site in the article of Winnes and Fridell [12] showed extensive PM formation due to the transient behaviour of manoeuvring. It was found a ratio of 6.5 to1 in number of emitted particles during manoeuvring compared to number of emitted particles during high load steady state operation.

Reviewing the laboratory results and the findings in previous research, the question was raised of what defines transients. Definition of transient test cycle according to the international standard ISO 8178-11 - "Test-bed measurements of gaseous and particulate exhaust emissions from engine used in non road mobile machinery under transient test conditions" is as given: "*Test cycle with a sequence of normalized speed and torque values that vary relatively quickly with time*". To be able to define how much particle development depends on transient conditions, one first would have to define transient condition more accurately. The definition given in ISO 8178-11 *"...values that vary relatively quickly with time*" is open for interpretation. How rapid does the load changes have to be before it influences the combustion process? Does the formation of PM intensify with increased rate of load variations? These are questions that would be interesting to look further into in order of gaining a greater understanding of the influence transient operation has on PM formation.

4.9.2 *Extent of transient operation*

When evaluating the extent of transient conditions, the main focus was on manoeuvring operations. The operation of ferries was targeted, as the operation of these vessels consists a considerable part of manoeuvring and thereby operation with variable loads.

CASE 1 was the vessel from the research paper which consisted of a manoeuvring phase of a total of 60 minutes, and a high load steady state sailing period of 150 minutes. The initial relationship in PM concentrations between these two phases was found to be 6.5 to 1(Table 17), meaning that the PM concentration during manoeuvring was 6.5 times the magnitude of the PM concentration during sailing. When considering the duration of the two phases the relationship of particle number became 2.6 to 1, giving that PM concentrations during manoeuvring constitutes 2.6 the amount of particles as formed during sailing.

CASE 2 represented a car ferry operating along the Norwegian coastline where an average manoeuvring duration was estimated to be 5.5 minutes with an average total duration of 19.3 minutes, giving that the duration for sailing would be 13.8 minutes. By applying the same initial PM concentration relationship 6.5 to 1 and taking the duration of the two phases into account, the relationship became 2.6 to 1, still giving highest concentration levels for the manoeuvring phase.

It is peculiar that the same relationship was found for both cases, when it is clear that the two cases represent different vessels with different voyage lengths. But none the less, the findings based on the data that has been collected are very interesting giving that approximately 70% of amount of particles formed, during the voyage of CASE 1 and CASE 2, is attributed the manoeuvring phases.

There are uncertainties to the results that are found, and the PM concentration measurements are done for a single vessel, reviewing the findings should, therefore be done with caution. But as an initial assessment, the results presented reflects that the phase of manoeuvring should be further investigated in terms of making an quantitative assessment of PM emissions for variable engine loads.

5 Evaluation of main findings

This chapter presents an evaluation of the results obtained in Part One and Part Two in regards to application of the test cycle for emission measurement procedures. The topics that are discussed are both of present concern and of future concerns on the subject of emission control.

To better understand the working principles of the certification process, interviews were conducted with Mr. Andy Wright with the Marine Consultancy Services, FOBAS, and with Dr. Øyvin Melhus with Ecoxy AS[2]. The two interview objects represent two opposing sides, Mr. Wright being involved in the development of the NO_X Technical Code, thereby the certification process, whereas Dr. Melhus represents the executive part having to utilise the certification process in the measurements offered by Ecoxy AS. The written interviews are included in appendix I and J, and the information gained from these two interviews is used in the evaluation of the findings.

5.1 NO_X emissions and the test cycle

The findings in Part One of this thesis showed that there is a deviation between total weighted NO_X emissions when evaluating operational profiles against the E2 test cycle used for certifications. Still, the results were inconsistent as the specific NO_X emission data used for the calculations showed great variations which was reflected in variations of the final result. Overall the deviance from the E2 test cycle was for most of the cases less than 10%.

5.1.1 *Realism of the test cycle*

The main concern when evaluating the E2 test cycle in regards to NO_X emissions, was whether or not it reflected real engine operation. To evaluate the authenticity of the E2 test cycle, operational cycles were constructed for specific examples of platform supply vessel, anchor handling vessel and an oil tanker. The comparison between the different vessels specific operational cycles and the E2 test cycle showed great differences in load points and the weighting of them. Though there were observed great differences in the loads and weighting, the differences were not equally great when evaluating the total weighted NO_X emissions calculated for each cycle.

[2] Ecoxy AS performs emission measurements, monitoring and reporting, as well as offer consultancy services regarding energy efficiency and turbo machinery.

5.1.2 *Cost of complex measurements*

In the response to a written interview, one of the arguments of Mr. Andy Wright concerning alterations of the test cycles was that an increased complexity in the test cycles would consequently lead to increased costs of the certification process.

Increasing the complexity of the certification procedures needs to be justified by an evident reduction, and with the results obtained in this thesis it is questionable if the gain justifies the means with the present NO_X emission limits. If further assessments where to be done in this matter, it would be of interest to evaluate the costs of introducing more complex testing procedures versus the gain in terms of reduced NO_X emissions.

5.1.3 *Emission reducing measures*

When further restrictions on NO_X emission limits will be enforced with TIER II and TIER III, the usage of NO_X reducing measures will introduce another factor when evaluating the use of the test cycle for certification. When modifications are done in order to reduce NO_X emissions, it is done in order of gaining certification in line with the yielding or a future TIER demand. This again means that the engine modifications are done with respect to emission reductions as measured when applying the test cycles, and not with respect to the actual emissions and operating conditions. An argument against the present use of test cycles would in this case be that the reductions obtained when measured with the test cycles, might be a poor reflection of the real reduction as the modifications done are most likely optimized for the certification and not for the real operation.

The consequence of implementing NO_X reducing measures, while certification is done using test cycles could be of interest for further studies. As there is observed deviance without considering NO_X reducing measures, one possible scenario is that these differences would increase if the engine were to be operated as for the platform supply vessel, but the modifications are optimized with respect to the load points of the test cycle. If it would be the case that the reduction is not to the level it is supposed to, according to the emission limits, then the issue of cost takes another turn. One could argue that the investments made in engine modifications could be better spent when the modifications are done with respect to a misleading test cycle.

5.1.4 *ECA areas*

One of the questions in the interview concerned on what grounds the loads and weighting were selected for the test cycle. Mr. Wright replied that weighting factors are selected based on surveys of typical engine loads in service. It was assumed that this survey was done on a global scale.

When the TIER III NO_X emission limits come into force in 2016, it will solely be implemented in the emission control areas (ECA), where the North Sea is included. The North Sea is an area of extensive offshore oil production operation recruiting unconventional marine vessels.

As mentioned it is assumed that survey of engine loads in service was done on a global scale, but what if regional operation of engines in service, focusing on ECA areas was to be evaluated? The ECA areas will be the areas with the most stringent emission control, and effort should therefore be placed in assuring that the emission reduction obtained on paper is a good reflects the real reduction in operation.

As an indication of the engine operation that is most represented in the North Sea, data was collected from Statistics Norway [26] of an operation survey conducted on short sea and domestic sea transport from 2006. These statistics show that the vessel types with highest occurrence in operation is offshore supply and anchor handling vessels. Following is car ferries and tugs as given in Figure 18 from Statistics Norway, being an indication of the operation occurring in the North Sea. Have in mind that the results of Part One showed greatest increase in emissions for the PSV-operational cycle when compared with the test cycle.

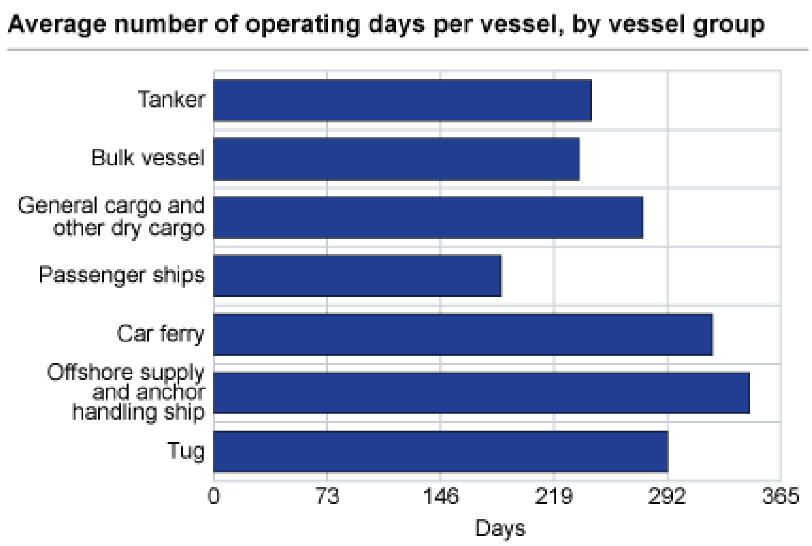

Figure 18: Operating survey on short sea and domestic sea transport, Norway 2006

As mentioned earlier, increasing the complexity of the test cycles would increase the costs, which needs to be justified. It might be unrealistic to suggest that all marine engines should be tested for its exact use, but a more realistic approach could be to evaluate regional activity such as in ECA areas. One essential objection to this is that the future application for an engine is not always determined at the point of certification, let alone the areas of vessel operation. But as the TIER III demands are applied on the ECA areas, certification against the TIER III demands would indicate planned operation in ECA areas, giving that it should be possible to evaluate regional operation.

5.2 PM emissions and the test cycle

The main objective of Part Two in this study was to evaluate the PM formation during transient operation in comparison to steady state operation. Measurements of PM during steady state operation was not evaluated for this thesis, the focus was rather placed on assessing the importance of transient operation in regards to PM emissions. When evaluating the use of test cycles for potential PM emission measurements, it was of interest to uncover if there are operational conditions essential for the PM formation that is <u>not</u> reflected in the existing procedures.

5.2.1 *PM formation during manoeuvring*

The results of studying PM development with engine operation shows that the phase of manoeuvring is an important period in terms of amount of PM formed. The research paper[12] that was examined in order to determine PM concentration, with respect to engine operation, also showed that the contribution during high load steady state was small in comparison to the transient condition.

5.2.2 *Extent of transient operation*

The amount of manoeuvring is highly connected with the operation of the vessel. A ferry may have a considerable share of manoeuvring as it leaves and enters port with relatively short sailing periods. Whereas a cargo vessel or oil tanker has long transit periods leaving the manoeuvring share at a minimum. Transient operation is also expected to be evident during DP operation mode which is utilized in great extent for stand by vessels, anchor handling vessels, etc, but measurements confirming this were not ready in time of the thesis hand in.

The use of ferries and the type of voyage they represent, with high occurrence of manoeuvring, might not comprise a lot in a global assessment. Even so, the operation of ferries is closely connected with populated areas and voyages along the coastline where ambient particles might pose the greatest threat.

5.2.3 *Applicability of test cycles*

When assessing if the use of a test cycle is applicable for PM emission quantification, the transient periods are of importance, and is not evaluated by the steady state test cycles that exists.

Transient operation is as mentioned highly dependent on the vessel type, which can constitute a big part of the operation for some vessels. For other vessels it can be a minor contribution to an operational profile. Testing during transient conditions is applied in the automotive industry, but it represents a far greater challenge for implantation in the test cycle for marine diesel engine. Transient operation is nearly impossible to generalize for a certification purpose due to great variety in marine operations. The engine measurements itself can prove to be difficult to carry out as there is a great need of parameter control to induce rapid load changes.

The existing steady state test cycles are generally applied, meaning without consideration to the planned operational profile of engine tested. Since the transient conditions might be a minor concern for several vessel types it is unlikely that transient phases would be included in a generally applied test cycle. Under these circumstances engines utilized in vessels with high occurrence of transient operation, will have great deviations from test cycle emission measurements and real life emissions..

6 Conclusion

This thesis has discussed the utilization of test cycles with respect to NO_X emissions as well as PM emissions.

Test cycles are already utilized for certification procedures to determine compliance with NOx emission regulations. The issue addressed in this thesis was whether or not the generally applied test cycle can reflect the variety of engine operation in real life.

On the matter of evaluating existing E2 test cycle against constructed cycles based vessel operation, the initial comparison showed great differences in terms of chosen loads and weighting of them. The findings when comparing the weighted NO_X emissions was deviating showing no obvious trend. Most of the calculations on vessel specific cycles showed less than a 10% increase or decrease in weighted emissions compared to the test cycle. The deviations in the results can be attributed to the specific NO_X emissions data used, as there were considerable differences between the three data sets. The findings in weighted NO_X emissions were not as extensive as initially thought. It was expected to see a greater consequence of using different loads and weighting than the original E2 test cycle. Still, further assessments should be done with more substantial data to evaluate the realism of the test cycles, due to the uncertainties in the findings of this thesis.

Concerning PM emissions, the findings in this thesis indicate that the implementation of the existing test cycles for PM measurements cannot be done directly. The results obtained on the matter of PM suggest that the phase of manoeuvring is an important contributor to the amount of PM. As manoeuvring represents rapid load changes, thereby transient operation, the existing steady state test cycles can give a poor representation of the total emitted PM, especially for vessels with a noticeable amount of transient operation. Thus a generally applied test cycle should include transient loads in addition to the steady state. Implementation of current test cycles is with basis from my results unsuited for PM measurements.

7 Further work

7.1 NO_X emissions

One main concern to the results regarding NO_X emissions found in this thesis was the deviance in the specific NO_X emission data that was decisive for the total weighted emissions. It would be of interest to gather more engine data with the means of determining a representative mean value of specific NO_X emissions, which would give more representative total weighted emissions.

Another assessment in regards to NO_X emissions and the test cycles should be concentrated in determining the deviance between operation cycles and the test cycle when engine modifications have been done in order of achieving TIER II or TIER III emission limits. If there are found results supporting that deviations in total weighted NO_X emissions increase, it would be interesting to do an assessment of what effect this will have concentrating on ECA areas.

An evaluation should also be done on the cost of altering the certification process, as well as a feasibility study on implementation. If alterations where to be done, it is necessary to assess if the gain justifies the cost.

7.2 PM emissions

It would be of interest to run new tests in an engine laboratory to further try to determine the formation of PM due to transient operation. While instead of the small load changes that was done for this thesis, one should try to make more drastic load changes, or rather try to simulate the load changes that are represented in the ferry profiles.

Testing during DP mode was not executed in time for it to be evaluated in this thesis, but investigation of the PM formation during DP mode is interesting to look further into.

The definition of transient operation could be further investigated by attempting to determine more precisely how transient operation effects PM formation and determination of a relationship to the behaviour of load change and the behaviour of PM.

As if was found in this thesis that manoeuvring operations are an important contributor to PM formation, it would be of interest to map the operation of manoeuvring for different vessel types, and make an assessment of the extent of it.

Again, ECA areas could be a target for evaluation when looking further into PM formation induced by manoeuvring as the existing, and most likely the coming ECA areas, are coastal areas close to population.

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[25] Fjord1. *http://www.fjord1.no/default.asp?page=336*.

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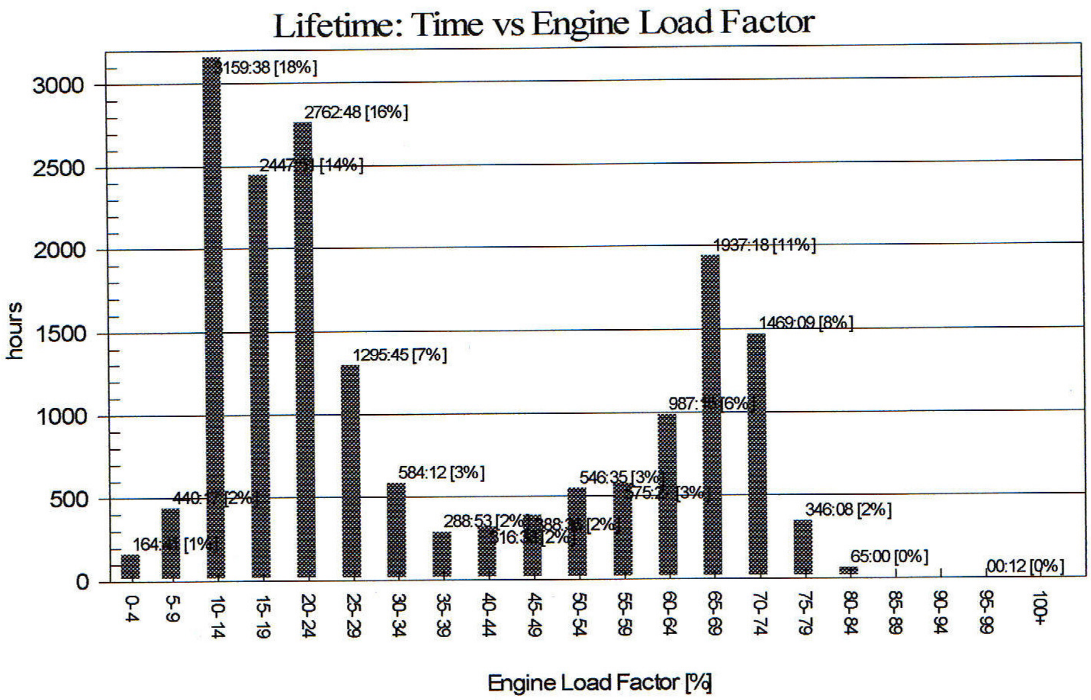
9 Appendix

Table of contents

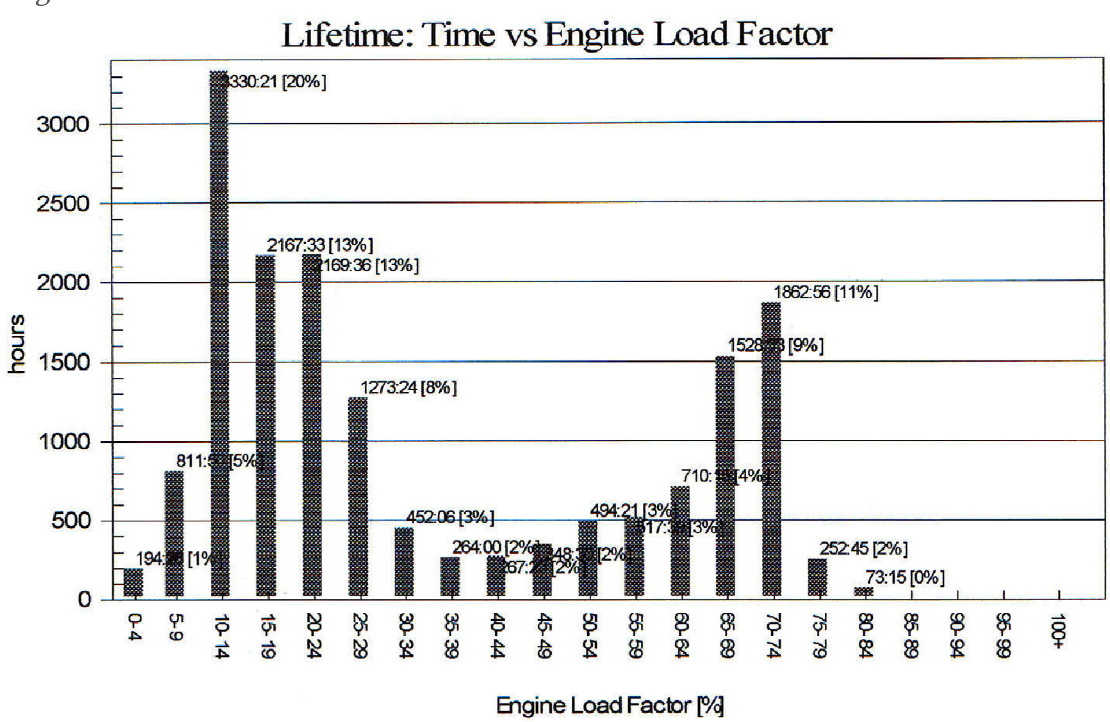
A. PSV – Operational profile background

Engine Load factor PSV – Stril Myster

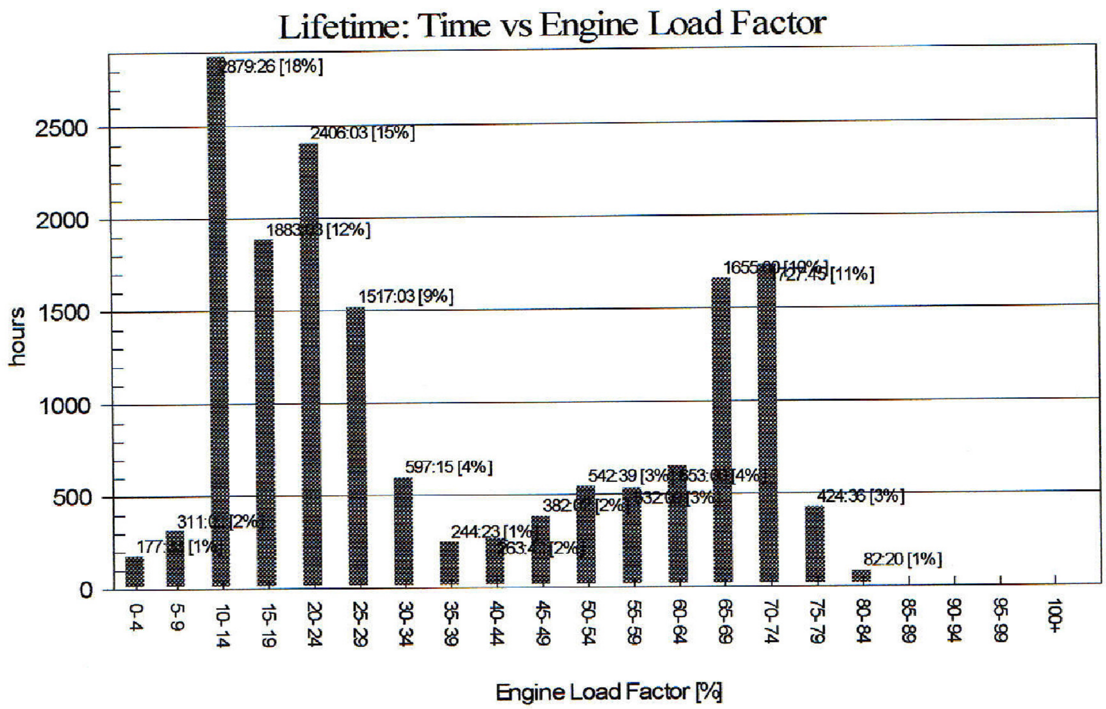
Engine number 1



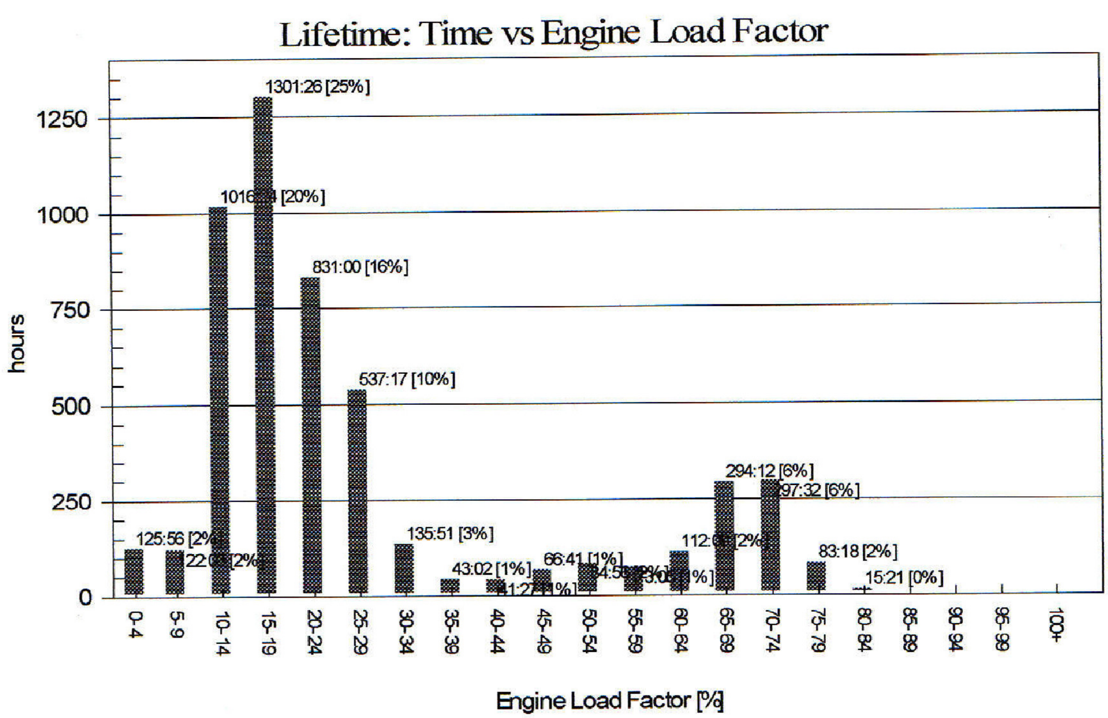
Engine number 2



Engine number 3



Engine number 4



Source: Reply from Simon Møkster Shipping AS on survey sent out in cooperation with fellow master student, Magnus Selås.

Calculations

One weighting was done considering the original load points as given in test cycle E2, where the time spent in these given loads for the engine in questioning made up the new weighting.

Weighting for PSV based on original test cycle load points:

Load %	compatible with mean	load duration	Weighting
%	%	% of total time	
100	90 to 100	0	**0.00**
75	70 to 79	5	**0.26**
50	45 to 54	2.5	**0.13**
25	20 to 29	11.5	**0.61**
		19	**1.00**

To be able to compromise the full operation data given above into a simplified operation cycle five load points was selected basing it on the load points that are engaged the most.

Weighting for PSV based on optimal load points:

Load %	compatible with mean	load duration	Weighting
%	%	% of total time	
100	90 to 100	0	**0.00**
70	65 to 74	9.5	**0.19**
60	55 to 64	4.5	**0.09**
30	25 to 34	5	**0.10**
20	15 to 24	15	**0.30**
15	10 to 19	16	**0.32**
		50	1

As one can see from the figures above, the profile based on the original E2 load points only comprise 19 % of the total operation time, in comparison to the optimized load points that represents 50 % of the total operation.

B. AHV – Operational profile background

Information collected on Anchor Handling Vessel

Data from typical North Sea operating vessel

Kondisjon/operasjon:	Makspower (MW)	Minpower (MW)	Ca.gjennomsnitt (MW)	Ca. andel av total driftstid (%)
Ankerhåntering	25	5	12	25
Transit	10	2	5	30
DP/standby	15	2	8	35
Ved kai	5	1	2	10

- Variations can be great depending on type of operation executed, ocean depth, type of anchoring etc.
- Can assume maximum load capacity is 25 MW
- Can assume effect is divided on 4 equal size diesel engines, and that they are operated as necessary, for example 2 engines during transit and 4 engines during anchor handling.

Source: Professor Vilmar Æsøy

Calculations

	Max. power	**Min. power**	**Average power**	**time spent**	**Engines in use**	**% of available load**
Operation	MW	MW	MW	%		
Anchor handling	25	5	12	25	4	48.0 %
Transit	10	2	5	30	2	40.0 %
DP/ standby	15	2	8	35	3	42.7 %
At port	5	1	2	10	1	32.0 %

Assumptions:	Number engines	Engine output each [MW]
	4	6.25

Calculated based on average power, and on neccesary available engines

C. Tanker – Operational profile background

Assumptions:

Rotterdam - Maracaibo 4418 Nm
transit loaded 13.5knots
transit ballast 14.5 knots

sfoc =	**164**	**g/kWh**
MCR =	**17090**	**kW**

Assuming sfoc constant enabling calculations of power output

Round trip	Duration		Fuel cons.	
	[h]	%	[t/day]	
Landing port	*4*	0.6	***10***	
Loading	*20*	2.9	*22*	AUX
Leaving port	*3*	0.4	*10*	
Transit - loaded	*327*	47.7	***69.3***	
Landing port	*4*	0.6	*10*	
Discharging	*18*	2.6	*68*	AUX
Leaving port	*4*	0.6	*10*	
Transit - ballast	*305*	44.5	***73.6***	
Total	685			

formula for power output:

[kW] = ([t/day]*1000000) / (SFOC*24h*1.05*1.15)

1.05 = NOx correction factor
1.15 = sea margin*
*included for transit condition

Simplified trip, ME load	Duration		Fuel cons.	Power ME	
Condition:	[h]	**%**	[t/day]	[kW]	**% of MCR**
Manouvering	15	**2.3**	10	2420	**14.2**
Transit - loaded	327	**50.5**	69.3	14581	**85.3**
Transit - ballast	305	**47.1**	73.6	15486	**90.6**
	647	100.0			

Assume no shaft generator in use

Power represents main consumption to proulsion

Information given by Knutsen OAS Shipping AS

D. Information on NOx emission specifics, engine B32

Information received from Rolls Royce:

|	Rolls-Royce Marine AS, Engines-Bergen					
Engine type	B32:40L6P CD					
Rated speed		750	[rpm]			
Rated power		3000	[kW]			
Bore		320	[mm]			
Stroke		400	[mm]			
Cylinder number and configuration		6	Inline			
Mode:						
Speed	[%]	100	100	100	100	100
Power	[%]	100	75	50	25	10
Ambient data:						
Atmospheric pressure, pB	[kPa]	98.46	98.46	98.46	98.49	98.49
Intake air temperature, Ta	[℃]	22.2	23.9	23.1	23.9	25.4
Relative humidity of intake air, Ra	[%]	44	44.3	47.9	44.2	44.3
Air temperature for Ra calc.	[℃]	22.1	22.5	22.6	22.2	21.9
Gasseous emission data:						
NOx concentr. (wet), NOW, NO2W	[ppm]	887	847.2	755.2	634.9	358.8
CO concentration (dry), COD	[ppm]	45.3	51	90.8	198.1	169.8
CO2 concentration (dry), CO2D	[%]	6.22	6.07	6.07	5.63	4.03
O2 concentration (dry), O2D	[%]	12.29	12.55	12.57	13.19	15.31
HC concentration (wet), HCW	[ppm]	85.3	122.7	182.8	248.2	287.3
Engine data:						
Speed	[rpm]	751	751	749	749	749
Engine Power	[kW]	3001	2256	1500	753	306
Corrected Fuel flow	[g/s]	160.81	120.97	84.06	48.18	25.86
Temperature intercooled air, Tsc	[℃]	55.2	55.2	54.8	54	53.3
Temp. intercooled air ref., Tsc ref	[℃]	60	60	60	60	80
Fuel elemental analysis						
Carbon	Wbet	86.68	[%-mass]			
Hydrogen	Walf	13.3	[%-mass]			
Nitrogen	Wdel	0.007	[%-mass]			
Oxygen	Weps	0.1	[%-mass]			
Sulphur		0.05	[%-mass]			

Calcuations using The Norwegian Maritime Directory's scheme for reporting of source specific NOx emission factor

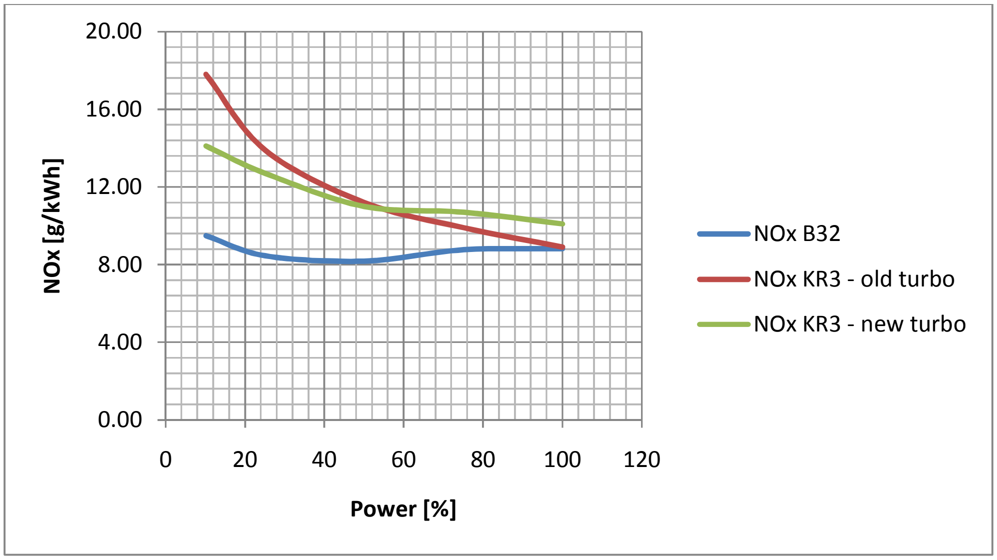
MOTOR						
	Nom. Effekt	Nom turtall	Applikasjon		Antall	
B32:40	< kW>	<rpm>	<hoved/hjelp>			
Drivstoff (MGO/HFO/LNG)	% H	% C	% S	% N	% O	Referanse
MGO	13.3	86.68	0.05	0.007	0.1	ISO 8178
Test syklus (E2/E3/D2)						
D2	**Disregard cycle weighting**					
		1	2	3	4	5
DRIFTSPARAMETRE						
Lastpunkt	%	100	75	50	25	10
Turtall	rpm	751	751	749	749	749
Last	kW	3001	2256	1500	753	306
Ladeluft trykk	kPa g					
Ladeluft temp	C	55.2	55.2	54.8	54	53.3
Referansetemp ladeluftkjøler	C	60	60	60	60	80
MÅLTE VERDIER						
CO2	%	6.22	6.07	6.07	5.63	4.03
CO	ppm	45.1	51	90.8	198.1	169.8
NOx	ppm	887	847.2	755.2	634.9	358.8
Relativ luftfuktighet	%	44	44.3	47.9	44.2	44.3
Lufttemperatur	C	22.2	23.9	23.1	23.9	25.4
Barometrisk trykk	kPa	98.46	98.46	98.46	98.49	98.49
Ureaforbruk	l/h					
TILEGGSINFORMASJON (for fartøy med SCR-anlegg)						
SFOC	g/kWh					
BEREGNINGSRESULTAT						
Metningstrykk omgivelser	kPa	2.68	2.97	2.83	2.97	3.24
Absolutt luftfuktighet Ha	g/kg	7.53	8.41	8.67	8.39	9.21
Korreksjon for vann i inntaksluft KW2		0.01196	0.01334	0.01375	0.01331	0.01459
Korreksjonsfaktor for tørr til våt gass KWr2		0.97565	0.97292	0.97210	0.97295	0.97059
Nox Korreksjon for luftfuktighet og temperatur Khd		0.96941	0.98398	0.98597	0.98705	1.06364
Våt gass konsentrasjon						
CO2	%	6.07	5.91	5.90	5.48	3.92
CO	ppm	44.00	49.62	88.27	192.74	165.21
NOX	ppm	865.40	824.26	734.13	617.73	349.10
NOX korrigert	ppm	838.92	811.06	723.83	609.73	371.31
NOx	Kg/tonn fuel	**45.72**	**45.42**	**40.54**	**36.71**	**31.21**

Calculations for determining specific NOx emissions in g/kWh

|	Rolls-Royce Marine AS, Engines-Bergen					
Engine type	B32:40L6P CD					
Maxumum load	kW	3000				
Rated speed		750	[rpm]			
Rated power		3000	[kW]			
Speed	**[%]**	**100**	**100**	**100**	**100**	**100**
Power	**[%]**	**100**	**75**	**50**	**25**	**10**
NOx emissions(from rep. scheme)	*[kg/ton fuel]*	*45.72*	*45.42*	*40.54*	*36.71*	*31.21*
Engine Power	[kW]	3001	2256	1500	753	306
Corrected Fuel flow	[g/s]	160.81	120.97	84.06	48.18	25.86
NOx flow	[kg/h]	26.47	19.78	12.27	6.37	2.91
Specific NOx emissions	**[g/kWh]**	**8.82**	**8.77**	**8.18**	**8.46**	**9.50**

E. Weighted NOx emission calculations:

Specific NOx emissions:



Information extracted from curves on NOx emissions on other load point then the ones given, assuming continues curves.

	KR3 - OLD TURBO	KR3 NEW TURBO	B32 - ENGINE
Power	NOx	NOx	NOx
[%]	[g/kWh]	[g/kWh]	[g/kWh]
10	**17.80**	**14.10**	**9.50**
15	16.40	13.60	9.08
20	15.00	13.15	8.70
25	**13.90**	**12.70**	**8.46**
30	13.20	12.30	8.33
35	12.60	11.90	8.24
40	12.10	11.60	8.19
45	11.60	11.25	8.17
50	**11.20**	**11.00**	**8.18**
55	10.85	10.85	8.25
60	10.55	10.80	8.37
65	10.35	10.80	8.53
70	10.10	10.75	8.67
75	**9.90**	**10.70**	**8.77**
80	9.70	10.60	8.81
85	9.50	10.50	8.83
90	9.30	10.35	8.82
95	9.10	10.20	8.82
100	**8.90**	**10.10**	**8.82**

Test cycle E2

E2 test cycle				
		KR3 -old T	**KR3 - new T**	**B32 -ENGINE**
Load	Weighting	NOx emissions	NOx emissions	NOx emissions
%	[-]	[g/kWh]	[g/kWh]	[g/kWh]
100	0.2	1.78	2.02	1.76
75	0.5	4.95	5.35	4.09
50	0.15	1.68	1.65	1.23
25	0.15	2.09	1.91	1.27
sum	1	**10.50**	**10.93**	**8.35**

PSV – E2 load points

PSV - E2 load points				
		KR3 -old T	**KR3 - new T**	**B32 -ENGINE**
Load	Weighting	NOx emissions	NOx emissions	NOx emissions
%	[-]	[g/kWh]	[g/kWh]	[g/kWh]
100	0	0	0	0
75	0.26	2.57	2.78	2.28
50	0.13	1.46	1.43	1.06
25	0.61	8.48	7.75	5.16
sum	1	**12.51**	**11.96**	**8.50**
Differance from E2		**19.2 %**	**9.5 %**	**1.8 %**

PSV – optimal load points

PSV - optimal load points				
		KR3 -old T	**KR3 - new T**	**B32 -ENGINE**
Load	Weighting	NOx emissions	NOx emissions	NOx emissions
%	[-]	[g/kWh]	[g/kWh]	[g/kWh]
70	0.19	1.92	2.04	1.65
60	0.09	0.95	0.97	0.75
30	0.10	1.32	1.23	0.83
20	0.30	4.50	3.95	2.61
15	0.32	5.25	4.35	2.91
sum	1	**13.94**	**12.54**	**8.75**
Differance from E2		**32.8 %**	**14.8 %**	**4.8 %**

AHV – optimal load points

AHV - optimal load points				
		KR3 -old T	**KR3 - new T**	**B32 -ENGINE**
Load	Weighting	NOx emissions	NOx emissions	NOx emissions
%	[-]	[g/kWh]	[g/kWh]	[g/kWh]
50	0.25	2.80	2.75	2.04
45	0.35	4.06	3.94	2.86
40	0.30	3.63	3.48	2.46
30	0.10	1.32	1.23	0.83
sum	1	**11.81**	**11.40**	**8.19**
Differance from E2		**12.5 %**	**4.3 %**	**-1.8 %**

Tanker – optimal load points

Tanker - optimal load points				
		KR3 -old T	**KR3 - new T**	**B32 -ENGINE**
Load	Weighting	NOx emissions	NOx emissions	NOx emissions
%	[-]	[g/kWh]	[g/kWh]	[g/kWh]
90	0.47	4.37	4.86	4.15
85	0.51	4.85	5.36	4.50
15	0.02	0.33	0.27	0.18
sum	1	**9.54**	**10.49**	**8.83**
Differance from E2		**-9.1 %**	**-4.0 %**	**5.8 %**

F. Particle distribution measurement equipment

Extracted from project thesis delivered December 2009.

Measurement equipment

Marintek's laboratory is equipped with two installations for PM size distribution measurements, one delivered by TSI and one by Dekati.

Dekati

The equipment from Dekati consists of two main components, the Electrical Low Pressure Impactor (ELPI) and the Fine Particle Sampler (FPS). The FPS unit is a two stage dilution system that dilutes and conditions the gas samples before it is sent to the measurement instrument (ELPI), and has an adjustable dilution ratio as well as adjustable temperature [1]. The ELPI is an instrument that combines the technologies of a cascade impactor with charging of particles and electrical detection, which has rapid response time and can operate with particles with a size between 0.007 to 10 μm with 12 channels. As the gas sample is taken it is charged electrically and sent into the impactor where the particles are classified by aerodynamic diameter. The collected charged particles that are distributed in the 12 channels are then detected. This results in real-time measurement of concentration and size distribution where data is then collected and saved by using custom made software for ELPI application [2]. Another possibility the Dekati equipment offers is to run chemical test of the deposited particle samples on the collection plates. This enables one to determine chemical composition of the particle samples after completion of tests.

Figure 1: ELPI unit

TSI

The measuring equipment delivered by TSI is a Scanning Mobility Particle Sizer (SMPS) Spectrometer which again consists of an Electrostatic Classifier and a Condensation Particle Counter (CPC). The method that the SMPS uses to measure size distribution of particles is an electrical mobility detection technique. This means using bipolar charge in the Electrostatic Classifier to charge and then classify the particles according to size, by measuring the particles ability to pass through an

Figure 2: SMPS unit

electrical field [3]. As the particles are classified, the concentration is measured by the CPC. The CPC unit can detect particles down to a size of 4 nanometres in diameter by condensation of the particles using either water or an alcohol. The working principle is that by enlargement of the particles to an optically detectable size, they can be counted as they pass through an optical detector [3]. The SMPS equipment can measure particles in a size range from 0.0025 to 1.0 µm and has 167 size channels [4]. In comparison the ELPI unit only have 12 channels, thus the SMPS offers higher accuracy in the distribution. On the down side, the extensive number of channels also demands more time to generate results, therefore the feedback from the ELPI is much quicker.

Sources:

[1] Dekati. http://www.dekati.fi.
[2] Dekati, "ELPI user manual ver 4.02," ed, 2007.
[3] TSI, "Model 3936 Scanning Mobility Particle Sizer (SMPS) Spectrometer," in *Operation and Service Manual*, ed, 2008.
[4] TSI Incorporated. http://www.tsi.com.

G. Ferry Voyages

Below it an overview made of voyage durations for car ferries sailing in the areas of Sunnmøre and Sogn og Fjordane, along the Norwegian Coastline. Data have been collected from www.fjord1.no where an overview over routes is given.

Fjord 1

Sunnmøre	Sogn og Fjordane
Voyage duration	Voyage duration
[min]	[min]
20	15
20	15
25	10
15	15
15	25
15	15
10	20
25	25
15	35
35	10
20	25
15	25
15	15
20	20
15	40
10	15
15	20
25	15
20	10
35	
15	
20	
15	
25	
460	370
19.2	**19.5**

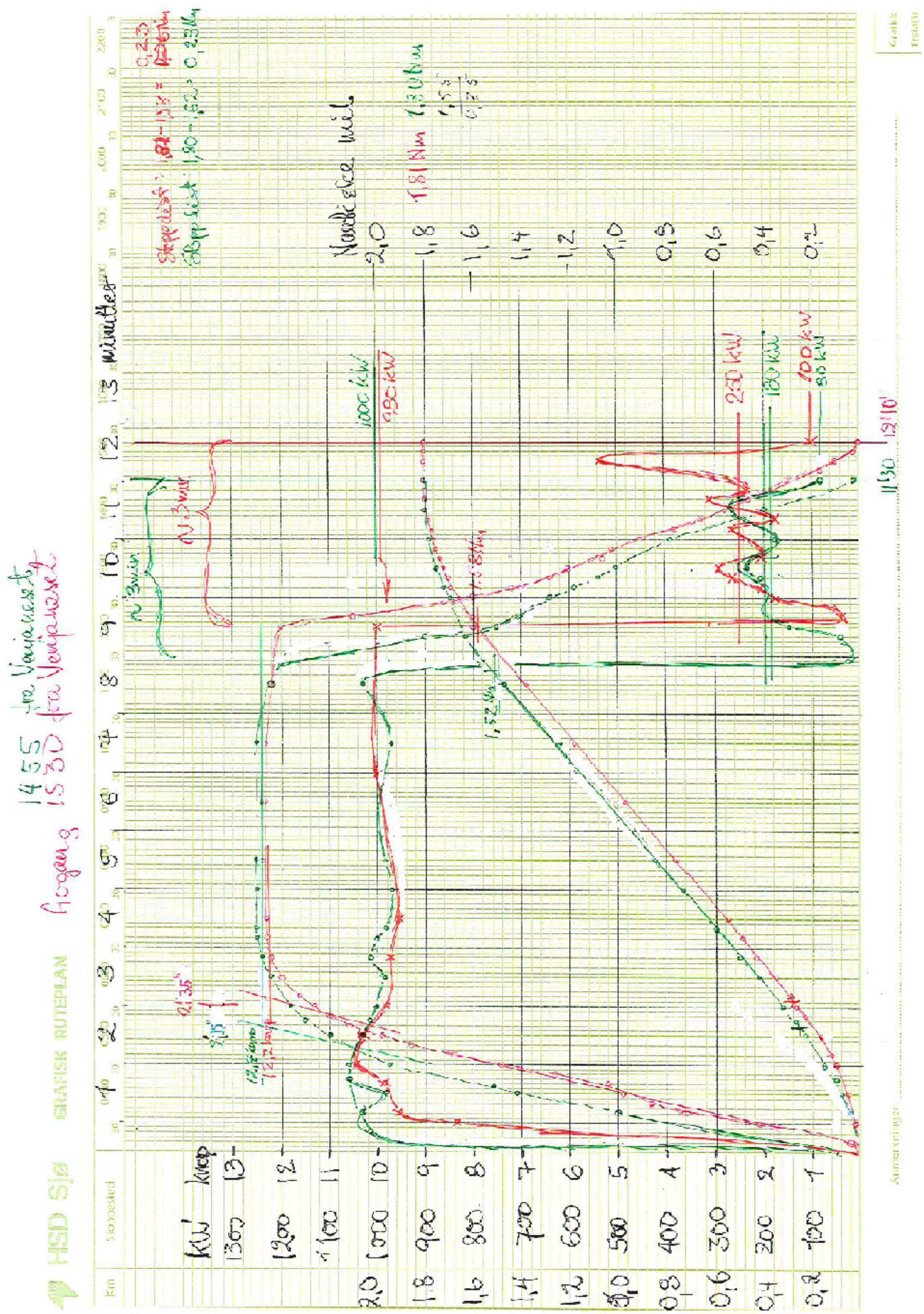
Tot. Average:	**19.3**

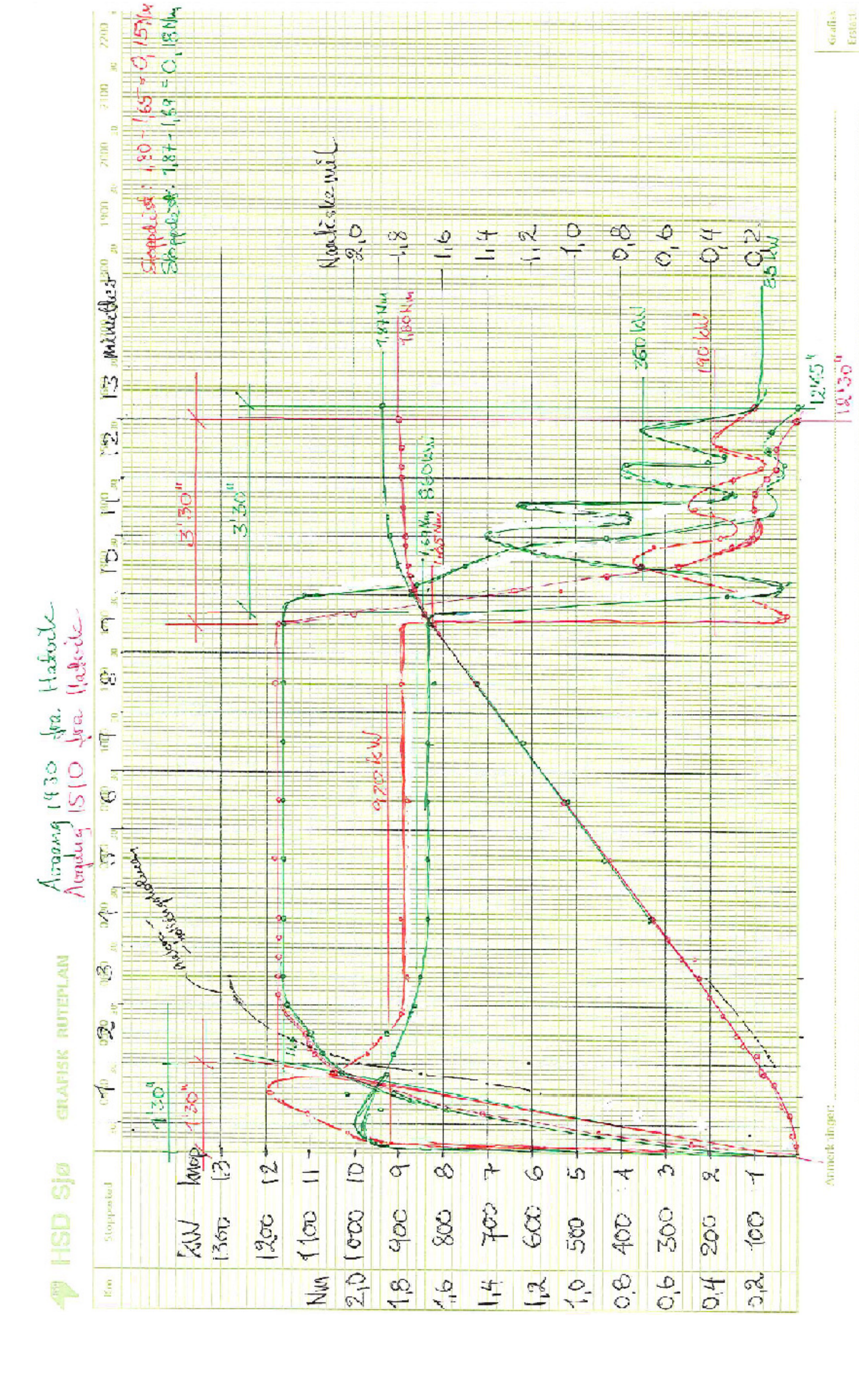
Routes with several stops have been considered multiple voyages where each distance is represented here.

Highest and lowest value has been excluded when estimating mean value.

The average duration for these voyages was found to be 19.3 minutes

H. Original operational data – Tide ferry




HSD Sjø
GRAFISK RUTEPLAN

I. Interview with Mr. Andy Wright

Written interview concerning test cycles used in accordance with IMO NO_X Technical Code

The motive of this interview is to gain information and knowledge on how the procedures of emission measurements are carried out, and how the testing procedures correlate with real life scenario in relation to my master thesis.

If there are any answers that are considered sensitive, it would be possible to restrict the availability of the information. Please notify me of this if necessary.

In accordance with IMO NOx technical code there are four applicable test cycles in respect to the unit to be tested, namely E2, E3, D2 and C1. The focus in this interview is on main engines, hence E2 and E3.

Question 1. The operational profile for different vessel type can have significant differences, for example comparing the profile of a container ship against the profile of a supply/stand-by vessel. When a main engine is tested according to test procedures stated in NOx Tech. Code, does one consider the expected/existing operational profile for the engine? If so, how is it done?

Answer:

The certification of engines in accordance with the NO_x Technical Code is undertaken independent of the ship type onto which that engine is to be installed. Indeed in some instances even at the engine certification stage it may not be known as to what type of ship a particular engine is to be installed - the lower the cost of an engine the lower the likelihood of knowing the intended usage.

Question 2. Could there be a need for a wider spectre of test cycles where it also would be taken into consideration the usage of the engine in order to get a correct value of emission levels?

Answer:

The test cycles given in the NO_x Technical Code are all taken from ISO 8178-4, one of the key objectives behind this ISO standard was to provide a single common basis for engine testing world-wide in order to avoid a widespread duplication of procedures, each possibly differing in certain respects which would render results obtained under one system invalid under another. Regulations such as the NO_x Technical Code (or, for example the US EPA 40CFR94 – emission regulations for engines installed on US flagged commercial ships) would then cross adopt those cycles relevant to the engines to be covered.

While a wider range of marine main propulsion test cycles could produce an emission value which was **slightly** closer to the actual in service value it would be at the cost of increasing the complexity of engine certification process, potentially requiring the emission testing – to the full NO_x Technical Code Chapter 5 requirements – of each engine at the engine builder's works (noting, as per Q1, that often, particularly for the smaller / lower cost engines, the eventual end use is not known at the time of manufacture).

One of the main principles of the NO_x Technical Code is that virtually all engines belong either to an Engine Family or an Engine Group. In these instances the Parent Engine is emission tested to the full rigour of the Code requirements and thereafter all engines produced within the relevant rating range (kW/cyl. & speed) with the NO_x critical components and settings as approved are not emission tested.

Concerning the point raised as to what is the 'correct' emission value.

It must be understood that the emission value (E2 or E3) assigned to a propulsion engine – that which is given on that engine's EIAPP Cert. – is not the emission value of that engine in service even if the engine was subsequently operated exactly in accordance with the test cycles as applied and the mode point weightings given due to:

1. The NO_x Technical Code emission value is that under reference conditions:

   All testing is undertaken using an ISO 8217 'DM' grade fuel irrespective of the grade of fuel that engine will operate on in service. Hence since DM grade fuels will contain no more than a minor proportion of nitrogen (typically less than 0.1%) the effect of fuel nitrogen on eventual NO_x emission is not taken into account – it being generally recognised (although not specifically quantified) that there is a high conversion efficiency of fuel nitrogen to NO_x. However in service, engines which operate on residual fuel oils – where nitrogen content will typically be in the range 0.1 – 0.8% (although can exceed 1.0%) – will consequently emit NO_x at a significantly higher rate.

   The NO_x correction factor (NO_x Technical Code 2008 Equation 17) is applied. This adjusts the emission value to the given conditions of:

   Charge air humidity – 10.71 g/kg

   Intake air temperature - 25°C

   Seawater temperature - 25°C (with due allowance for fresh water cooled charge air coolers)

   Subsequently in service of course engines will operate under ambient conditions which may well vary considerably from the reference values – with consequent effects (+ve or –ve) on the resulting NO_x emissions.

   Furthermore the equation itself is empirical and generalised – the sensitivity of different engines to these conditions is not reflected in its working – and does not represent a universal phenomenon.

2. Engine Family / Engine Group engines

In these instances the emission value given on the EIAPP Cert. for a particular engine is that of the Parent Engine. The Parent Engine is the engine where the combination of rating and NOx critical components and settings applied results in the highest NO_x emission value. Consequently there can be, particularly for medium and high speed engines, engines within an Engine Family or Engine Group which have significantly lower NO_x emission values than that of the Parent Engine.

There are two test cycles applied to marine main propulsion engines – E2 & E3. These are composed of the given torque / speed relationships and the assigned mode point weighting factors.

1. Torque / speed relationship. The NO_x emission value at any load point is sensitive to these factors however the in-service torque / speed relationship may well differ from that given for either the E2 or E3 cycles.

   To take the simpler E3 cycle first. The propeller law relationship given may not be that encountered by the engine in service, the particular design of propeller fitted can result in higher or lower torque at a particular speed as compared to that as given for the E3 cycle with a consequent effect on NO_x emissions.

   The E2 cycle is applied to all diesel-electric propulsion engines and all engines which drive controllable pitch propellers. In the latter case such engines may well include some form of combinator control whereby a wide range of torque / speed combinations are possible within the applicable maximum torque curve (indeed different operators of the same ship may select different speed / torque relationships so as to fit with their feel for ship-handling) – even where such engines are in service operated on what is essentially a propeller law curve they would still have been certified on the constant speed E2 cycle. As given in the NO_x Technical Code 2008 the footnote to Table 1 recognises that constant speed operation on the test bed even may not be possible.

   In service both E3 and E2 certified engines may additionally drive shaft generators with yet further influences on the torque loading at any speed setting.

2. In service it is quite possible that a propulsion engine will not generally operate at one of the four (E2 / E3) mode points – typically a slow speed crosshead engine would be tuned for maximum efficiency at around the 85% MCR load point. Since the load / NO_x emission (g/kWh) profile of an engine does not necessarily follow a simple curve (as would typically be expected for CO or HC emissions) but can feature maximum and / or minimum points within the certified load range any resulting plot of mode point intermediate values will therefore be approximate. Additionally, where there are non-continuous functions (VIT timing, auxiliary blower cut in) in mechanical engines these further complicate the resulting profile and where engines include electronic fuel injection systems there can be no assurance of profile. It should however be noted that

the Revised MARPOL Annex VI has specific text prohibiting either 'defeat devices' or 'irrational control strategies' in order to ensure that the test cycle mode points retain some degree of representative performance. A more extreme example is the US EPA's 'Not To Exceed' requirements as given, for example, in their 40CFR94 regulations.

The overall point therefore is that certification test cycles have that purpose. Considerable caution is therefore necessary in extending certified performance to accurately, and precisely, represent in service performance in the form of 'end of stack' emissions. If the latter is required then in service emission monitoring / testing should be considered – the judgement then being as to whether the additional cost, considerable effort and the resulting reduction in the number of legible data sets is matched by the greater precision obtained. Potentially should the Direct Measurement and Monitoring option (NO_x Technical Code 2008 Chapter 6.4) be adopted, at least to some degree, as the Onboard NO_x Verification Procedure used then more in service data will become available (again noting that the value reported by that method is reduced to reference conditions).

Question 3. When comparing the methods for marine engine testing and automobile engine testing, one see that when testing a car, the test is carried out including both steady state engine loads as well as transient loads in one test run, whereas the test cycles given in NOx Tech. Code are all steady state test cycles. It is well understood that the test methods for automobiles are not compatible with marine diesel engines, but are there taken any considerations to transient conditions for marine engines? (Especially concerning ships that operates in DP mode)

Answer:

No account is taken of transient conditions in the emission certification of engines within the NO_x Technical Code.

Question 4. If there is not taken any considerations to transient mode for marine engines, why so? Is it considered as no need to include transient modes in testing? Is it even thought as feasible to be able to generalize and test for transient mode?

Answer:

There are two principal reasons for absence of transient conditions in the MARPOL Annex VI certification of marine diesel engines:

1. Of the exhaust emission components controlled under MARPOL Annex VI SO_x is directly related to the quantity of fuel used and its sulphur content - SO_x emissions are therefore effectively independent of the combustion source by which they are produced. In contrast NO_x emissions are very much related to the combustion system by which they are produced, indeed NO_x emissions could be taken as a measure of

efficient combustion hence on load change, when combustion conditions are often not optimum, the tendency would be for NO_x emissions to reduce rather than increase as is the case of those exhaust emission components which are the product of compromised combustion – CO, HC and particulates (PT as defined in ISO 8178-1). However CO, HC and PT are not controlled under the NO_x Technical Code (albeit that CO and HC are required to be measured and are used in the subsequent carbon balance calculations). Following load change there will be an immediate effect on NO_x emissions however there is a longer period (measured in minutes) as they settle down at the new load condition due to the time lag as charge air cooler performance, and hence charge air temperature, duly adjusts to that revised load.

2. Additionally although marine propulsion engines may in some circumstances be subject to frequent load changes (DP vessels as cited and during manoeuvring) the overall service time spent under such conditions is in stark contrast to the changes in applied torque / speed of an automotive engine driving typically through a 5 or more gear ratio gearbox and under a range driving conditions (urban, motorway, 'A' class roads, country lanes, etc.). In any case a transient load cycle must itself be only an approximation of the number and rate of load changes which would be encountered by a particular engine in service.

Question 5. Lastly, do you have any comments to on what basis the existing test cycles and weighting factors were defined? Why are they as they are today?

Answer:

The E2 and E3 test cycles are those as given in the 1996 version of ISO 8178, continuity being an essential point to avoid additional testing of no substantial benefit. It is clear that any test cycle must include the 100% load point albeit that in most instances such a value will never be used in service. That 25% load was chosen for the lowest load could be considered to represent the lowest load that a propulsion engine would tend to work on other than during manoeuvring (in this regard an idling load could have been considered but set against this is the length of time typically spent under such loads and the quantity of fuel consumed and hence kg of pollutant emitted). Thereafter inserting two additional mode points at 50% and 75% loads represents a reasonable compromise. Of course if 20% had been taken at the lowest load this would have allowed 20% increments and hence a 5 mode point cycle (as for D2).

It is recalled that the weighting factors were selected based on surveys of typical engine loads in service. Of course each such survey and review thereof would potentially result in a slightly different distribution in detail but with the same overall general trend.

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To summarise, emission testing for certification needs to be such as to result in a common, universally applicable, point of reference with clear guidance given as to the procedures and methods adopted (hence the differences between ISO 8178 and the NO_x Technical Code). While amendments may be (and have been) proposed to the test cycles (mode points and weighting factors) it is questionable as to whether any significant benefits, in reality, would be obtained particularly when compared to the possible fragmentation of the emission testing process world-wide.

In contrast, if it required to know what the real world 'end of stack' emissions are from a particular engine in service then direct monitoring is necessary, however, due to the various influencing factors caution is necessary in extrapolating from such data to represent the subsequent performance of even that engine, let alone other 'similar' engines.

Thank you for your attention and time.

Sincerely,

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J. Interview with Dr. Øyvin Melhus

Written interview concerning test cycles used in accordance with IMO NO_X Technical Code

The motive of this interview is to gain information and knowledge on how the procedures of emission measurements are carried out, and how the testing procedures correlate with real life scenario in relation to my master thesis.

If there are any answers that are considered sensitive, it would be possible to restrict the availability of the information. Please notify me of this if necessary.

In accordance with IMO NO_X technical code there are four applicable test cycles in respect to the unit to be tested, namely E2, E3, D2 and C1. The focus in this interview is on main engines, hence E2 and E3.

Meeting with Øyvin Melhus, Ecoxy

This is not all directly quotations but a summary of the discussion and the information gained by meeting with Dr. Øyvin Melhus, Head Engineer at Ecoxy AS. This text has been edited after a draft of this paper was sent to Dr. Melhus where he verified and commented on the text.

Question 1. The operational profile for different vessel types can have significant differences, for example comparing the profile of a container ship against the profile of a supply/stand-by vessel. When a main engine is tested according to test procedures stated in NO_X Tech. Code, does one consider the expected/existing operational profile for the engine? If so, how is it done?

Answer:

It is described in the "Guidance on NO_X taxation" from the Norwegian Maritime directorate [1] that if the company or ship owner that operates a given vessel can by documentation show to another operational profile than the given weighting in NO_X tech. Code, then one can apply this profile for calculating the emission factor. Make notice that this is relation to the Norwegian NO_X fund, and is not directly related to the NO_X Technical Code.

This tells that if the company or owner sees it as beneficial, they can apply their own profile for weighting, but it is not a demand. Therefore, if the result by own operational profile is expected to give an increase in emissions, one can use the given test cycle to satisfy the emission limits.

So by this, there are not taken any specific accounts to the operation of the vessel in the regulations.

Question 2. Could there be a need for a wider spectre of test cycles where it also would be taken into consideration the usage of the engine in order to get a correct value of emission levels?

Answer:

"The background for NO_X emission regulations is this: the development of ISO8178 in the early 1990s started in parallel with the IMO work for making the regulations which now are known as NO_X Technical Code and a part of the MARPOL regulations at sea. It was a need for testing marine diesel engines against an emission level wherever the engine is operating around the world that was the basis for the standard. When it comes to the use of the emission data achieved by ISO8178 testing to estimate real emissions the case is totally different. It is this application of data you should focus on and argue for being wrong or at least insufficient detailed. You should also pinpoint that even if transients are a major part of the ship operation it will be very challenging to perform such measurements at sea due to reduced ability/instrumentation to control the transient behaviour." Quotation of Øyvin Melhus

Question 3. When comparing the methods for marine engine testing and automobile engine testing, one see that when testing a car, the test is carried out including both steady state engine loads as well as transient loads in one test run, whereas the test cycles given in NO_X Tech. Code are all steady state test cycles. It is well understood that the test methods for automobiles are not compatible with marine diesel engines, but are there taken any considerations to transient conditions for marine engines? (Especially concerning ships that operates in DP mode)

Answer:

The test cycles are as mentioned above all based on steady state. In the applicable test cycles for marine applications, transient behaviour is not considered.

Question 4. If there is not taken any considerations to transient mode for marine engines, why so? Is it considered as no need to include transient modes in testing? Is it even thought as feasible to be able to generalize and test for transient mode?

Answer:

It should not be impossible to measure for transient operation for the case of offshore supply vessels, and other vessels operating in DP mode, but it is very difficult to generalize and therefore reproduce/illustrate in laboratory. As for the ferries that there are collected data for, it might be possible to generalize as there operational pattern is foreseeable and similar for each vessel. On the other hand, there are few countries that have as much local/ inland shipping as Norway, and in the bigger picture it might not be enough to encourage focus on transient measurements.

Question 5. Lastly, do you have any comments to on what basis the existing test cycles and weighting factors were defined? Why are they as they are today?

Answer:

No direct answer to this, but he seemed to agree to the information I have gained from Hennie, on the fact that the test cycles are based on the vessels that represents the highest fuel consumption worldwide, that being long distance transport vessels (tankers/ bulk/ cargo).

He also agreed that to the standard there is no information for which reason the different measures are based on, thus making it difficult to argue the validity of the standard.

[1] *Veiledning om NOx-avgift, 2010*

K. CD content

Report:	- Complete digital master thesis	
Collected data and calculations:	- Part One:	- PSV operational data
		- Oil tanker operational data
		- Operational profiles, data
		- Weighted NOx emissions
		- Emission data B32 Engine
		- Sjofartsdir. Calculations B32
	- Part Two:	- Duration estimate, ferry voyages
		- Calculation ferries, case 1/ case 2
Laboratory measurements Part Two:	- ELPI raw data	
	- ELPI software conversion	
	- Lab. Measurements 18.02.10 ELPI	
Literature:		
	- Corbett et al. 2007	
	- Fridell et al. 2008	
	- Maureen R et al. 2006	
	- Moldonová et al. 2009	
	- Sarvi et al. 2008	
	- Sarvi et al. 2010	
	- Winnes, Fridell 2010	
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Correspondence:	- Correspondence Knutsen OAS Shipping AS	
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