Possible Technical Modifications on Pre-2000 Marine Diesel Engines for NOx Reductions

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Title:

Possible Technical Modifications on Pre-2000 Marine Diesel Engines for NOx Reductions

Abstract:

The present report is based on the contract between the European Maritime Safety Agency (EMSA) and Germanischer Lloyd AG (GL) to conduct a study on possible modifications on existing engines for NOx reductions. In this context the term 'existing engines' is defined as marine diesel engines with a power output of more than 130 kW as applied in the emission regulations of IMO MARPOL Annex VI, Regulation 13, however, installed on ships with a keel-laying date **before** 1st of January, 2000, and still in service.
The study addresses technical possibilities to reduce NOx emissions and presents a statistical assessment of the NOx reduction potential of the existing fleet in service. Since there will be engines anyway which cannot be modified with reasonable effort, options for granting exemptions or the acceptance of alternative measures are discussed. The study further contains a proposal for a survey and certification regime.

Department: MPU (Combustion Engines – Environmental –)

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Contents

List of abbreviations

AERO	Alternative Emission Reduction Option
BLG	Bulk, Liquid and Gases Sub-Committee
CO	Carbon monoxide
CO_2	Carbon dioxide
EIAPP	Engine International Air Pollution Prevention
EMSA	European Maritime Safety Agency
g	gram
GL	Germanischer Lloyd AG
GT	gross tons
h	hour
HC	Hydro Carbons
HFO	Heavy fuel oil
IAPP	International Air Pollution Prevention
IMO	International Maritime Organization
ISO	International Organization for Standardization
kg	kilogram
kW	kilo Watt
kWh	kilo Watt hour
LSHFO	Low sulphur heavy fuel oil
MARPOL	International Convention for the Prevention of Maritime Pollution
MEPC	Marine Environment Protection Committee
MW	Mega Watt
NO	Nitrogen oxide
NO_2	Nitrogen dioxide
NOx	Nitrogen oxides (NO, NO_2)
NOx Technical Code	Technical Code on Control of Emission of Nitrogen Oxides from Marine Diesel Engines
PM	Particulate Matter
P	Power
P_W	weighted Power
R&D	Research and Development
RO	Recognized Organization
rpm	revolutions per minute
SCR	Selective Catalytic Reduction
SECA	Sulphur Emission Control Area
SFOC	Specific Fuel Oil Consumption
SOLAS	International Convention for the Safety of Live at Sea
TBO	Time Between Overhaul
TF	Technical File
v	Speed
WGAP	Working Group on Air Pollution

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Executive Summary

Introduction

The present report is based on the contract between the European Maritime Safety Agency (EMSA) and Germanischer Lloyd AG (GL) to conduct a study on possible modifications on existing engines for NOx reductions. In this context the term 'existing engines' is defined as marine diesel engines with a power output of more than 130 kW as applied in the emission regulations of IMO MARPOL Annex VI, Regulation 13, however, installed on ships with a keel-laying date **before** 1st of January, 2000, and still in service, hereinafter referred to as 'Pre-2000 Engines'.

Recognizing the need to prevent and control air pollution from ships due to the fact that ship emissions in many cases contribute to air quality problems on land even if they are emitted at sea, the International Maritime Organization (IMO) in 1997 adopted Regulations for the Prevention of Air Pollution from Ships in a Protocol to the MARPOL Convention for the Prevention of Pollution from Ships. The regulations are included in Annex VI to the International Convention and entered into force on May 19th, 2005.

Regulation 13 of Annex VI specifies limit values for the emissions of nitrogen oxides (NOx) from diesel engines with a power output of more than 130 kW installed on ships constructed on or after 1 January 2000. Engines of the applicable performance installed on ships constructed before that given date are concerned as far as they undergo a 'Major Conversion' after the given date and which would have an adverse impact on the engine's emission characteristics.

The Marine Environment Protection Committee (MEPC) at its 53rd session in July 2005 recalled that the Air Pollution Conference in 1997 by Conference resolution 3 invited the Committee, as a matter of urgency, to review the NOx emission limits at a minimum of five years after the entry into force of Annex VI. Considering developments since 1997 and the need to further reduce the emissions from ships the MEPC instructed the Bulk, Liquid and Gases Sub-Committee (BLG) to begin a comprehensive review of Annex VI. The Terms of Reference provided for the BLG Sub-Committee *inter alia* contain the task to consider reducing NOx emissions from Pre-2000 Engines. The consideration shall take account of current available technology with regard to further reduce air pollution from ships. It was noted that the contribution of ship emissions to air quality problems in many parts of the world is growing, and that many Governments are considering potential local, national or international measures to address ship emissions. It was repeatedly stated that emissions from marine diesel engines are of concern to the international community because of their negative effects on the environment, such as eutrofication, acid deposition, and nitrification, and also the possible adverse impact on human health and life quality.

Extensive discussions on several proposals and comments on how to deal with Pre-2000 Engines took place during the BLG Committee sessions as well as at the intersessional meetings of the Working Group on Air Pollution (BLG-WGAP 1&2). The group reached preliminary conclusion that emission modifications are technically feasible for several Pre-2000 large bore engines, however, also noted that other Pre-2000 Engines would not be appropriate for modifications. It was further noted that there would be significant practical difficulties due to the unavailability of parts for certain engines. Consequently, it was underlined to clarify how those engines which are incapable of modification could be handled without distortion of competition. The Group realized that for incorporating regulations for Pre-2000 Engines into MARPOL Annex VI there would be the need to amend the NOx Technical Code in order to simplify the relevant survey and certification procedures for this category of engines and, of course, even to address them explicitly.

The limit values as specified in the actual version of MARPOL Annex VI, Regulation 13, hereinafter referred to as 'IMO NOx Tier I', are considered to be set as the goal for a potential reduction level for Pre-2000 Engines.

In order to provide objective information on the subject, the approach and methodology of this study highlights sequentially the most important aspects to be considered when addressing the existing fleet with regard to potential possibilities to reduce the emissions of nitrogen oxides (NOx emissions) from the marine diesel engines installed on vessels still in service. The investigations assume that it is considered to bring certain Pre-2000 Engines in compliance with the applicable IMO NOx Tier I standard.

Inventory of possible technical modifications to reduce NOx emissions from Pre-2000 Engines

This inventory of possible technical modifications to reduce NOx emissions from Pre-2000 Engines is based on publications by the engine manufacturers and related research projects during the past years' discussions with regard to potentials to reduce the NOx emissions from Pre-2000 Engines, in the course of the investigations made concerning the reduction potentials of future new engines.

Modifications performed on board after the ship has been put in service may be subject to additional surveys. Dependent on the scope of modifications made to a diesel engine, the original certification might cease to be valid and, as a consequence, new tests need to be made prior to re-issue of an engine's class certificate. When considering measures to reduce the NOx emissions from a diesel engine it has to be verified whether the original engine certification possibly is affected.

The emissions of NOx can be reduced by engine internal measures as well as by engine external measures or a combination of measures. Emission abatement systems of any kind of technology known in general lead to higher fuel consumption, directly by increasing the engines fuel consumption (Diesel dilemma) or indirectly due to increasing energy consumption of auxiliary systems. All additional subsystems like water treatment or heating systems demand additional energy.

Basing on the suggestion that possible NOx emission limits for Pre-2000 Engines are oriented at the existing NOx Tier I limits for marine diesel engines, emphasis is placed on engine internal measures. It may be recalled that even the discussions for setting NOx Tier II standards for new engines are focussed on engine internal measures.

A list of NOx-influencing parameters is provided in the NOx Technical Code, Chapter 6. Engine parameters which apply for 2-stroke and 4-stroke engines are listed in this study and a quick view on a theoretical NOx reduction potential is given.

More advanced techniques such as water based abatement systems include more extensive modifications involving ship modifications. Additional water treatment installations and pipe working are necessary. Water based abatement systems may be suitable for 4-stroke engines but they are not considered as suitable for 2-stroke engines.

Exhaust gas after treatment systems are not taken into account in detail. Exhaust gas recirculation systems which reroute a part stream of the exhaust gas back to the combustion chamber also are not regarded as this technique including exhaust gas cleaning and cooling devices might be considered as a kind of after treatment system, too.

Engine manufacturers worldwide and engine manufacturers' associations have been contacted by the authors of this report in order to validate the feasibility of possible technical modifications on Pre-2000 Engines. A questionnaire was distributed to fourteen engine manufacturers in Europe, Asia and North America representing the full range of marine diesel engine types, large bore slow speed engines, medium speed engines and high speed engines.

It turned out that due to the high number of Pre-2000 Engines and due to unknown emission levels of Pre-2000 Engines the vast majority of the engine manufacturers are not able to answer the questionnaire to the full extent. In many cases no related information is achievable, in some cases general information on engine types was provided and in few cases only more in depth information is available.

Replacement engines are a particular species of Pre-2000 Engines. In order to anticipate the installation of uncertified, non IMO NOx Tier I compliant engines on ships constructed before 1 January 2000, Regulation 13(2) of MARPOL Annex VI may be amended. It may be granted to replace uncertified Pre-2000 Engines by identical, uncertified engines, if the date of build of the engine is before 1 January 2000. However, where a replacement engine differs from the original engine in terms of type or model or performance even, the replacement engine must comply with the IMO NOx Tier I requirements irrespective the engine's date of build.

Range of Pre-2000 Engines

When considering the existing fleet it is essential for the decision making to know about the overall potential of NOx reduction. The second section of this study places emphasis on a statistical investigation of the current world fleet, the number of vessels to be considered, the number of diesel engines with regard to their size and power output installed in the vessels and, finally, the statistical NOx emissions from the vessels. These values then are compared with an estimated NOx reduction potential, taking into account different implementation scenarios of respective regulations.

The statistical analysis of the current world fleet is based on a ship database containing 112,148 ships. The data of the database has been reduced to consider ships only which may be relevant for any new IMO NOx regime and for which relevant engine data is reported. The remaining statistical base containing 35,128 ships has been validated as representative.

The ships within the remaining statistical base are assessed with respect to selected engine criteria which are engine stroke, engine rpm, engine power and cylinder displacement. Information on the number of ships with these engines, on the number of engines of specific build and on the share of the engines in the NOx emissions is provided. Finally, a general view on the share of specific engine groups in the NOx emissions of all Pre-2000 Engines and in all engines is drafted in a graphical way. The reduction potential of NOx emissions and the number of engines to be modified to achieve this reduction are opposed in a benefit / effort - scenario.

Reviewing the results it is to be considered that the NOx reduction potential for each group of engines is a theoretical best case potential. It is made the assumption that all considered Pre-2000 Engines are reduced in NOx emissions by 30 % in average. Having in mind that 30 % NOx reduction is not considered achievable with the available technical modifications and having further in mind, that not all Pre-2000 Engines are modifiable it seems realistic that in reality the provided NOx reduction potentials could be obtained at a range of 50 % of the presented results.

Introducing a NOx regime for Pre-2000 Engines requires solutions for technical modifications, the necessary engine components and capacities for the installation of the components to the engine. The complexity of possible engine modifications depends on the specific solution for the respective engine model and cannot be estimated in general. To avoid any problem of resources among the parties involved (ship owners, engine manufacturer, ship yards, administrations / recognized organizations) a stepwise implementation of a possible

NOx regime for Pre-2000 Engines should be favoured. Information on the consequences of such stepwise implementation is provided within the 'Phasing-in' figures of the statistical analysis.

Exemptions and alternative options for Pre-2000 Engines inappropriate for modification

Having in mind that probably not all Pre-2000 Engines are capable to be modified in a way to become compliant with the applicable IMO NOx Tier I limit values by reasonable means/efforts, alternative scenarios on how to address such 'Exemptions' are suggested. When discussing this matter it is of utmost importance to have in mind that any distortion of competition must be avoided. The following ideas are addressed within this study to reflect this point adequately.

- Exemptions
- Incentives
- Emission trading
- Use of low sulphur heavy fuel oil LSHFO
- Use of distillate fuel
- Exhaust gas aftertreatment systems
- Engine power de-rating

Survey and certification requirements

The fourth section of the study provides a proposal for a survey and certification regime which could be adapted for engines that fall under a new NOx regulation. It is without saying that such a regime will be required, however, the potential to keep tests, survey and certification as simple as possible will be investigated. The difficulty in this approach is to find a solution which grants certain simplification on the one hand without undermining the credibility of the official certification on the other side.

The basic principles of the survey and certification requirements for Pre-2000 Engines are orientated at the current requirements of the NOx Technical Code. It is one main issue to introduce a practice oriented, reliable and also credible survey and certification regime. As experienced for approximately 10 years application of the NOx Technical Code it seems to be obvious to apply the main principles of the Code in almost the same manner. The introduction of an additional certification scheme could itself create a number of new issues which will need to be resolved. Further, alternative survey and certification requirements for Pre-2000 Engines could potentially put the established requirements for post-2000 engines in question.

0 Introduction

0.1 Contract

The present report is based on the contract between the European Maritime Safety Agency (EMSA) and Germanischer Lloyd AG (GL) to conduct a study on possible modifications on existing engines for NOx reductions. In this context the term 'existing engines' is defined as marine diesel engines with a power output of more than 130 kW as applied in the emission regulations of IMO MARPOL Annex VI, Regulation 13, however, installed on ships with a keel-laying date **before** 1st of January, 2000, and still in service, hereinafter referred to as 'Pre-2000 Engines'.

0.2 Background

Recognizing the need to prevent and control air pollution from ships due to the fact that ship emissions in many cases contribute to air quality problems on land even if they are emitted at sea, the International Maritime Organization (IMO) in 1997 adopted Regulations for the Prevention of Air Pollution from Ships in a Protocol to the MARPOL Convention for the Prevention of Pollution from Ships. The regulations are included in Annex VI to the International Convention and entered into force on May 19th, 2005.

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Extensive discussions on several proposals and comments on how to deal with Pre-2000 Engines took place during the BLG Committee sessions as well as at the intersessional meetings of the Working Group on Air Pollution (BLG-WGAP 1&2). The group reached preliminary conclusion that emission modifications are technically feasible for several Pre-2000 large bore engines, however, also noted that other Pre-2000 Engines would not be appropriate for modifications. It was further noted that there would be significant practical difficulties due to the unavailability of parts for certain engines. Consequently, it was underlined to clarify how those engines which are incapable of modification could be handled without distortion of competition. The Group realized that for incorporating regulations for Pre-2000 Engines into MARPOL Annex VI there would be the need to amend the NOx Technical Code in order to simplify the relevant survey and certification procedures for this category of engines and, of course, even to address them explicitly.

The limit values as specified in the actual version of MARPOL Annex VI, Regulation 13, hereinafter referred to as 'IMO NOx Tier I', are considered to be set as the goal for a potential reduction level for Pre-2000 Engines.

0.3 Methodology

In order to provide objective information on the subject, the approach and methodology of this study highlights sequentially the most important aspects to be considered when addressing the existing fleet with regard to potential possibilities to reduce the emissions of nitrogen oxides (NOx emissions) from the marine diesel engines installed on vessels still in service. The investigations assume that it is considered to bring certain Pre-2000 Engines in compliance with the applicable IMO NOx Tier I standard.

1. Technical options to reduce the NOx emissions from marine diesel engines in service:
   At certain opportunities some engine manufacturers indicated technical potential for modifying Pre-2000 Engines with the aim to reduce their NOx emissions with no or little CO_2 trade-off only.
   The first section of this study provides information collected from different sources on the issue, taking into account answers on a questionnaire sent out by the authors received from the industry including specific comments.

2. Statistical investigation of the world's merchant fleet:
   When considering the existing fleet it is essential for the decision making to know about the overall potential of NOx reduction. The second section of this study places emphasis on a statistical investigation of the current world fleet, the number of vessels to be considered, the number of diesel engines with regard to their size and power output installed in the vessels and, finally, the statistical NOx

emissions from the vessels. These values then are compared with an estimated NOx reduction potential, taking into account different implementation scenarios of respective regulations.

3. Ideas of handling ‘Exemptions’:
   Having in mind that probably not all Pre-2000 Engines are capable to be modified in a way to become compliant with the applicable IMO NOx Tier I limit values by reasonable means/efforts, alternative scenarios on how to address such ‘Exemptions’ are suggested. When discussing this it is of utmost importance to have in mind that any distortion of competition must be avoided. The ideas provided so far try to reflect this point adequately.

4. Survey and certification regime:
   The fourth section provides a proposal for a survey and certification regime which could be adapted for engines that fall under a new NOx regulation. It is without saying that such a regime will be required for, however, the potential to keep tests, survey and certification as simple as possible will be investigated. The difficulty in this approach is to find a solution which may grant certain simplification on the one hand without undermining the credibility of the official certification on the other side.

The results of the investigation finally are summarised in order to provide guidance on how to address Pre-2000 Engines, taking into account the efforts to be made by all parties involved:
- The IMO by developing respective amendments to MARPOL Annex VI as well as to the NOx Technical Code;
- The Flag State Administrations by introducing a new survey and certification regime;
- Classification Societies firstly by implementation of a survey and certification regime when acting as a Recognised Organisation RO on behalf of the Administration and, secondly, by verification of engine modifications which potentially affect class requirements including performance of additional acceptance tests and re-issue of engine class certificates;
- Ship owners by proving compliance with the new regulations, with or without the assistance of the engine manufacturer;
- Engine manufacturers by providing appropriate solutions including the respective material and components for the ship owners;
- Repair companies and even ship yards by providing resources for the applicable modification work.

1 Inventory of possible technical modifications to reduce NOx emissions from Pre-2000 Engines

1.1 General remarks

A marine diesel engine is subject to extensive drawing and construction verification procedures and exhausted test bed testing at the manufacturer's site before Classification Societies are going to confirm the general approval for an engine type to be suitable to be installed on classified sea-going vessels in principle. Each subsequent built individual engine has to undergo work trials under the supervision of the respective class surveyor. During these trials operating values for certain load points have to be measured, recorded and compiled in an acceptance protocol. The protocol issued by the engine manufacturer as well as the class certificate form part of the engine's documents to be kept on board. After installation on board a ship further tests need to be performed during a sea trial showing that the engine's application on board with all its auxiliary and safety devices fulfils all requirements, statutory as well as class issues.

Modifications performed on board after the ship has been put in service may be subject to additional class surveys. Dependent on the scope of modifications made to a diesel engine, the original certification might cease to be valid and, as a consequence, new tests need to be made prior to re-issue of an engine's class certificate. When considering measures to reduce the NOx emissions from a diesel engine it has to be verified whether the original engine certification possibly is affected.

This inventory of possible technical modifications to reduce NOx emissions from Pre-2000 Engines is based on publications by the engine manufacturers and related research projects during the past years' discussions with regard to potentials to reduce the NOx emissions from Pre-2000 Engines, in the course of the investigations made concerning the reduction potentials of future new engines.

The investigations related to existing engines assume that the current applicable IMO NOx Tier I standard represents the goal for the NOx level to be set for Pre-2000 Engines. To achieve this goal emphasis is laid on engine internal measures which potentially could be applied, however, other means are also addressed.

Most of the possible technical modifications addressed have primarily been developed for the introduction on post-2000 engines. Most of those measures which are considered applicable for Pre-2000 Engines were developed within the mid 90s when existing engine types were further developed in order to being compliant with IMO NOx Tier I.

If engine modifications are carried out with the aim to reduce the NOx emissions it must be considered that this will have an influence on the engine's combustion process. The air necessary for the combustion of fuel contains oxygen as well as nitrogen. The formation of nitrogen oxides (NO, NO_2) during the combustion process mainly depends on the combustion temperature (including hot spots), pressure, and the duration of the combustion, i.e. time. The parameters, however, have an essential influence also on other engine specific operational data, as engine thermal efficiency and the formation of fuel dependent exhaust gas components. The complete combustion at high mean temperatures and high combustion pressure normally results in high engine efficiency, low specific fuel consumption and thus low emissions of carbon dioxide (CO_2). Consequently, the optimisation of diesel engines towards high efficiency results in high emissions of NOx. This correlation is well known as the 'Diesel dilemma'. From this, it may be assumed that efforts to reduce the NOx emissions from Pre-2000 Engines may lead to an increase in fuel consumption and moreover the emissions of CO_2. From experience with the designs of certain large bore engines from the nineties of the past century an increase of fuel consumption of 2 to 5 grams per kilowatt and hour (2 – 5 g/kWh), or 1 to 3 % by mass respectively, may be expected for these kind of engines.

Figure 1 shows the trends of NOx emissions and specific fuel consumption for diesel engines.

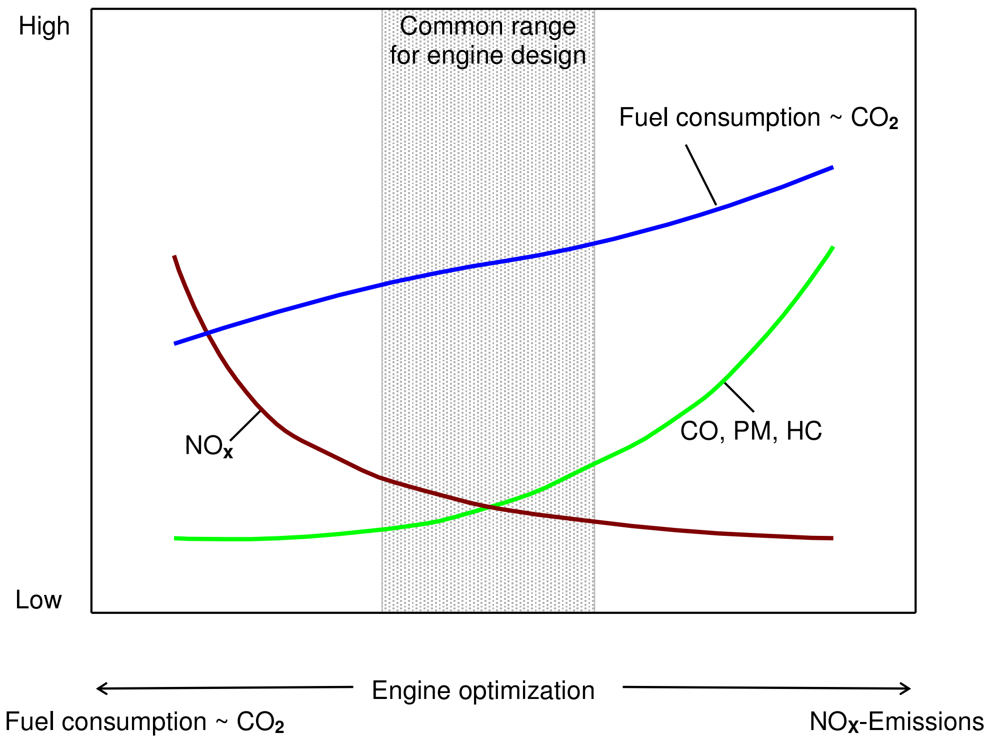

Figure 1: Exhaust gas emissions from diesel engines - 'Diesel dilemma'

The blue curve in Figure 1 shows the trend of specific fuel consumption which correlates to the engine's CO_2 emissions, the brown curve shows the trend of NOx emissions. Further, it is known that emissions like CO, PM (Particulate Matter) and HC (Hydro Carbons) would increase in case of NOx reduction, too. Advanced engine technologies installed in new engine developments strive for a balance between these trends as far as possible but the given correlation remains valid. In particular, if old fuel optimised engines are modified retroactively, potential benefits of one kind may result in penalties with regard to others.

The emissions of NOx can be reduced by engine internal measures as well as by engine external measures or a combination of measures. Looking into the energy efficiency as was done above with regard to engine internal measures, also other methods to reduce NOx are not free of charge.

Emission abatement systems of any kind of technology known in general lead to higher fuel consumption, directly by increasing the engines fuel consumption or indirectly due to increasing energy consumption for auxiliary systems. All additional sub-systems like water treatment or heating systems demand additional energy. Taking the energy balance into account to its full extent the energy necessary for the production of further additives e.g. urea in cases of SCR technology must be considered.

In cases where due to engine optimization the NOx emissions can be reduced keeping the engine efficiency constant, it must be considered that without emission reduction the efficiency would be even higher. It is state of knowledge that NOx reduction is hardly possible without penalty in overall efficiency. This problem is widely addressed in current research of future combustion technology.

Section 1.2 and Section 1.3 below provide a general view on possible technical modifications to reduce NOx emissions from 2-stroke and 4-stroke engines. Basing on the suggestion that possible NOx emission limits for Pre-2000 Engines are oriented at the existing NOx Tier I limits for marine diesel engines, emphasis is placed on engine internal measures. Again, it may be recalled that even the discussions for setting NOx Tier II standards for new engines are focussed on engine internal measures. Exhaust gas after treatment systems are not taken into account in detail. Exhaust gas recirculation systems which reroute a part stream of the exhaust gas back to the combustion chamber also are not regarded as this technique including exhaust gas cleaning and cooling devices might be considered as a kind of after treatment system, too. Furthermore it is known that the introduction of such a system needs extensive development or even research work for each engine type.

Based on the evaluation of a questionnaire which was sent to 14 engine manufacturers by the authors of this study Section 1.4 provides information on the technical feasibility of possible engine modifications.

1.2 2-stroke engines

A list of NOx-influencing parameters is provided in the NOx Technical Code, Chapter 6. Engine parameters which apply for 2-stroke engines are listed below and a quick view on a theoretical NOx reduction potential is given:

- injection timing (fuel cam, injection pump)

  Retarded injection timing will lead to up to a certain NOx reduction. The retarded injection timing leads to lower peak temperatures which are responsible for NOx generation. Due to increasing exhaust gas temperatures caused by retarded injection timing the application of this method and the achievable NOx reduction potential is limited in practice. If applicable, the NOx reduction potential may be estimated up to 10%. The danger of exhaust valve and turbo charger damages is high if the injection timing is retarded too much, in particular for older engine types. Hence, the limit values for retarded injection timing have to be released by the engine manufacturer to ensure ship safety. The adjustment of the injection timing itself can be conducted easily during normal maintenance without any extra costs. Increasing operational costs due to higher fuel consumption are expected. As a consequence of the higher exhaust gas temperature the time between overhaul might be less for exhaust valves and turbo charger.

- injection nozzle

  The optimization of spray generation leads to homogenous air-fuel mixtures with better combustion quality. A homogenous combustion has fewer hot spots where NOx is generated. In particular, in long-stroke low-speed 2-stroke engines it is comparatively difficult to ensure homogenous mixture generation. This is the reason why modern 2-stroke engine types are equipped with up to three injection nozzles. Injection nozzles play an important role in the formation of air-fuel mixtures. The optimization of injection nozzles can lead to a better spray pattern. Special valves prevent the dripping of fuel after the injection. These features can result in lower peak temperatures and lower NOx generation. Low NOx valves are tested and available for some newer engine types. The manufacturer of these valves points out that the impact of the valves on the NOx emissions has to be tested for each engine type and that the valves are not ready for older engine constructions yet. Tests have demonstrated that a NOx reduction of 20% is achievable on selected engine models. However, it must be noted that in most cases a re-adjustment of the engine might become necessary.

  If suitable injection nozzles for NOx emission reduction are available the modification of the respective engine type may be effective with regard to costs and time needed for retrofit as the modification could be conducted during regular maintenance. Injection nozzles are subject to regular exchange during maintenance. Hence, if no further modification is necessary, the implementation of suitable injection nozzles might be a comparatively easy way to reduce NOx emissions from certain engine types.

- combustion chamber (cylinder head, piston crown, liner)

  The modification of the combustion chamber design is considered as more advanced measure and seems not appropriate for Pre-2000 Engines. There might be a limited number of Pre-2000 Engines which can be brought in compliance with post-2000 engines by exchange of combustion chamber components but the number of these engines is estimated as negligible. The modification of the combustion chamber needs extensive research and testing efforts, in particular if modifications are to be introduced with regard to the engine emissions. It needs to be taken into account that in such cases the engine type approval as granted by the Classification Society may be affected with all its consequences to engine testing.

- compression ratio

  The modification of the compression ratio is considered as complex as the modification of the combustion chamber. The compression ratio can be changed e.g. by modifications of the piston or of the cylinder head. The implications on engine design and power output need advanced engineering input. This modification is considered as more advanced and is not appropriate for Pre-2000 Engines.

- turbocharger type and build

  The turbocharger has influence on the generation of NOx as the charge air pressure and temperature are linked to the combustion temperature. In combination with modifications of the other mentioned NOx influencing parameters different turbocharger settings might become necessary. Modifications on the turbo charger potentially might be performed in conjunction with a change of injection nozzles or a derating of an engine.

- charge air cooler / charge air pre-heater

  The charge air cooler design affects the charge air temperature and is therefore linked to the NOx generation of the engine. In combination with modifications of the other mentioned NOx influencing parameters different charge air cooler designs might be necessary. This modification may not be regarded as a stand alone measure.

- valve timing

  The inlet valve timing of 2-stroke engines is not adjustable, as the geometry of the inlet port in the cylinder liner and the piston determine the opening and closing timing. For loop-scavenged 2-stroke engines the exhaust valve timing is not adjustable too, as the geometry of exhaust port in the cylinder liner and the piston determine the opening and closing timing. For uniflow-scavenged 2-stroke engines only the exhaust valve timing is adjustable. However, the adjustment of the exhaust valve timing is considered for the recent, electronically controlled 2-stroke engines only. A modification of valve timing is considered not to be appropriate for Pre-2000 Engines.

The NOx reduction potential by engine internal optimization of future 2-stroke engines may be considered up to 15-20% related to IMO NOx Tier I standard [B 2] [B 7]. Internal engine optimization for new engines includes a mixture of the above mentioned parameters including combustion chamber modifications and advanced electronic controls. Whilst the improvements are feasible for new engines retrofitting Pre-2000 Engines is limited [B 7]. It can be assumed that advanced technologies intended for new engines cannot be adopted to all Pre-2000 Engines due to the complexity of engine technology. However, it may be assumed that certain NOx reducing measures which have been introduced for engine types in the late nineties of the past century can be adopted for those engine models which are direct pre-runners of the IMO NOx Tier I compliant engines.

The implementation of emission reducing measures to new engines is estimated to increase the costs for new engine developments by 10-30%, depending on the applied technology [B 1] [B 7]. The engine manufacturers have not estimated the costs for the modification of Pre-2000 Engines yet. The level of excess costs depends on the extent to which modifications can be adopted on Pre-2000 Engines. The diversity of engine models and suitable modifications does not allow any general assumption.

The impact of emission reducing measures on the performance of new engines is considered low. It is to be considered that the impact of emission reducing measures on the performance of Pre-2000 Engines, where new technologies cannot be applied to their full extent, might be higher, due to the reasons mentioned in Section 1.1 [B 2] [B 7].

The optimization of individual components, such as the injection nozzle, does not guarantee benefits in respect of NOx emissions. Even though NOx reduction is achievable due to the better spray pattern of advanced injection nozzles, for example, any new nozzle type is to be developed, tested and released by the engine manufacturer for each applicable engine type.

It must be considered that different engine types need different injection nozzles. One injection nozzle type can lead to positive results with one engine type whilst other engine types generate even higher NOx emissions with the same nozzle. The emission behaviour must be demonstrated on test beds. Hence, for each engine type any benefit due to nozzle changes is to be confirmed by emission measurements.

Engine parts related to the geometry of the combustion chamber are expensive in development and construction. In particular the development of such engine parts is difficult if not impossible for 2-stroke Pre-2000 Engines. Further, any exchange of such parts is linked to major scope of work at the engine. Any modification of parts related to the combustion chamber is deemed as theoretical but not feasible solution.

In general, Pre-2000 Engines with main design principles complying with post-2000 engines are potentially suitable to be brought in compliance with IMO NOx Tier I standard by adjustments of engine parameters combined with certain advanced engine components. Engines whose further development and even production ended before the introduction of NOx reduction measures can hardly be brought in compliance with the applicable IMO NOx Tier I limit. Even the actual emission behaviour of such engines hardly can be estimated. Extensive investigations would need to be performed to assess the engine's emission behaviour and to consider appropriate NOx reduction measures.

Loop-scavenged 2-stroke engines were commonly produced until the early or even mid eighties of the past century but then disappeared due to their limited potential for further development. Within the early eighties 2-stroke engines with higher stroke-bore ratio have been developed. Uniflow-scavenged engines instead of loop-scavenged engines were introduced to a large extent. Despite the fact that improving development was discontinued in the mid 1980's already, engines following the former loop-scavenged design principle were still further built. For loop-scavenged engines even less data is available than for pre-2000 uniflow-scavenged engines. The establishment of measures for loop-scavenged engines for compliance with IMO NOx Tier I standard is considered as even more difficult than for uniflow-scavenged engines, if not impossible. Loop-scavenged engines are phasing out gradually since the vessels they are installed in come close to the end of their typical lifetime.

In addition to engine internal optimization water based emission abatement systems may be suitable for retrofit of Pre-2000 Engines. These systems can be assessed on a case-by-case basis only, as the framework to be considered depends on individual basic conditions, such as used fuel type or space available.

Water based abatement systems reduce NOx emissions by lowering the combustion temperature due to the evaporation enthalpy of the injected water. The water can be injected directly to the combustion chamber, it can be brought in together with the fuel as water-in-fuel emulsion or it can be taken in together with the moisturized intake air. In connection with all water based emission abatement systems possible in engine water condensation is to be considered. In particular if these systems are retrofitted on engines which were originally designed for operation without such systems attention is to be drawn on this matter. The use of low sulphur fuels is recommended [B 2] [B 7].

Technologies using water as an agent to reduce the combustion temperatures and thus leading to reduced NOx emission are described in more detail in Section 1.3 – 4-stroke engines – since for these type of engines more applications and more experience exist.

Possible NOx reduction measures on 2-stroke engines are listed in Table 1 below.

Measure	New engines		Pre-2000 Engines				
	NOx reduction potential	Additional construction costs	Applicability	NOx reduction potential	Effort for installation		Operational costs
					Time	Costs	
Injection timing	n/a	n/a	Limits due to thermal stress must be investigated.	limited	Adjustment during actual maintenance work based on manufacturer's instruction possible	No additional costs	Increased SFOC Due to higher thermal stress less TBO for exhaust valve and turbo charger possible
Injection nozzles	n/a	n/a	To be verified for each engine model.	up to 20%	Installation during actual maintenance work engine re-adjustment necessary in most cases	Only if new nozzles are more expensive than former nozzles	Higher SFOC possible, depending on required NOx reduction
Internal engine optimization[1]	up to 15%	up to 30%	Possibly applicable on Pre-2000 Engines with same design as post-2000 engines	if applicable to full extent, same as new engine	Major conversion, depending on the extent of modification	Depending on the extent of modification	
Direct water injection	up to 50%	up to 20%	As retrofit-measure doubted; Low sulphur fuel recommended (1.5%).	if applicable to full extent, same as new engine	Conversion of the injection and control system. Installation of water treatment system	Depending on the extent of modification	Higher SFOC of up to 4% Energy consumption of water treatment.
Water-in-fuel injection	up to 30%	up to 10%	Case-by-case basis.	if applicable to full extent, same as new engine	Conversion of the injection and control system. Installation of water treatment system		Higher SFOC of up to 2% Energy consumption of water treatment.
Intake air humidification	up to more than 40%	up to 15%	Case-by-case basis. Complete charge air system to be considered. Large air humidification units may prohibit the installation in existing engine rooms. Low sulphur fuel recommended (1.5%).	if applicable to full extent, same as new engine	Major construction work of the engine room necessary. Docking necessary.	Weeks, to be calculated on a case-by-case basis	Higher SFOC of up to 8%

Table 1: Possible technical modifications to reduce NOx emissions from 2-stroke Pre-2000 engines

[1] Combination of injection timing, injection nozzle, combustion chamber, compression ratio, turbocharger, charge air cooler and valve timing

1.3 4-stroke engines

A list of NOx-influencing parameters is provided in the NOx Technical Code, Chapter 6. Engine parameters which apply for 4-stroke engines are listed below and a quick view on a theoretical NOx reduction potential is given:

- injection timing (fuel cam, injection pump)

  Retarded injection timing will lead to NOx reduction. The retarded injection timing leads to lower peak temperatures which are responsible for NOx generation. Due to increasing exhaust gas temperatures caused by retarded injection timing the application of this method and the achievable NOx reduction potential is limited in practice. If applicable, the NOx reduction potential is estimated up to 10-15%. The danger of exhaust valve and turbo charger damages is high if the injection timing is retarded too much, in particular for older engine types. Hence, the limit values for retarded injection timing have to be released by the engine manufacturer to ensure ship safety. The adjustment of the injection timing itself can be conducted easily during normal maintenance without any extra costs. Increasing operational costs due to higher fuel consumption are expected. As a consequence of the higher exhaust gas temperature the time between overhaul might be less for exhaust valves and turbo charger.

- injection nozzle

  The potential for NOx reduction by injection nozzles is considered low for 4-stroke engines. The central arrangement of the injection nozzle, the high turbulence of charge air caused by the inlet valve channel and the relatively small combustion chamber with a smaller stroke-bore ratio compared to slow speed 2-stroke engines leads to better conditions at 4-stroke engines with regard to a homogenous fuel-air mixture generation in comparison to 2-stroke engines. The impact of further injection nozzle development is considered low with regard to NOx emissions.

- combustion chamber (cylinder head, piston crown, liner)

  The modification of the combustion chamber design is considered as more advanced measure and seems not appropriate for Pre-2000 Engines. There might be a limited number of Pre-2000 Engines which can be brought in compliance with post-2000 engines by exchange of combustion chamber components but the number of these engines is estimated as negligible. The modification of the combustion chamber needs extensive research and testing efforts, in particular if modifications are to be introduced with regard to the engine emissions. It needs to be taken into account that in such cases the engine type approval as granted by the Classification Society may be affected with all its consequences to engine testing.

- compression ratio

  The modification of the compression ratio is considered as complex as the modification of the combustion chamber. The compression ratio can be changed e.g. by modifications of the piston or of the cylinder head. The implications on engine design and power output need advanced engineering input. This modification is considered as more advanced and as not appropriate for Pre-2000 Engines.

- turbocharger type and build

  The turbocharger has influence on the generation of NOx as the charge air pressure and temperature are linked to the combustion temperature. In combination with modifications of the other mentioned NOx influencing parameters different turbocharger settings might be necessary. In particular, the introduction of the Miller Cycle demands for turbocharger with higher charge air pressure. This modification is considered as more advanced and as not appropriate for Pre-2000 Engines.

- charge air cooler / charge air pre-heater

  The charge air cooler design affects the charge air temperature and is therefore linked to the NOx generation of the engine. In combination with modifications of the other mentioned NOx influencing parameters different charge air cooler designs might become necessary. This modification may not be regarded as a stand alone measure.

- valve timing

  In general the valve timing of 4-stroke engines is such that the inlet valves close after the bottom death centre. Due to the dullness the flow of charge air continues and ensures a maximum of air load within the combustion chamber. A more advanced valve timing of 4-stroke engines can be such that the inlet valves close early, before the piston reaches the bottom death centre. This leads to an expansion of the charged air, which cools down the temperature. The described valve timing is called Miller Cycle which was originally invented for performance enhancement but has shown NOx reduction potential, too. To compensate the loss of charge pressure advanced turbo charging systems might become necessary including two stages charging with inter cooling. This modification is considered as more advanced and is inappropriate for Pre-2000 Engines.

The NOx reduction potential by engine internal optimization for future 4-stroke engines can be considered as much as 20-30% related to IMO NOx Tier I standard [B 2]. Internal engine optimization for new engines would include a mixture of the above mentioned parameters including combustion chamber modifications and advanced technologies such as electronic controls and Miller Cycle. Whilst the improvements are feasible for new engines retrofitting to Pre-2000 Engines is limited [B 7]. It can be assumed that advanced technologies developed for new engines cannot be adopted to Pre-2000 Engines due to the complexity of engine technology.

The implementation of emission reducing measures to new engines is estimated to increase the costs for new engine developments by 10-30%, depending on the applied technology [B 2]. The engine manufacturers have not estimated the costs for the modification of Pre-2000 Engines yet. The level of excess costs depends on the extent to which modifications can be adopted on Pre-2000 Engines. The diversity of engine models and suitable modifications does not allow any general assumption.

The impact of emission reducing measures on the performance of new engines is considered low. It is to be considered that the impact of emission reducing measures on the performance of Pre-2000 Engines, where new technologies cannot be applied to their full extent, might be higher, due to the reasons mentioned in Section 1.1 [B 2] [B 7].

In addition to engine internal optimization water based emission abatement systems may be suitable for retrofitting of 4-stroke engines.

Direct water injection is estimated to have a NOx reduction potential of 30 ~ 50%. This technology is within the development phase still and not proven in practice to full extent yet. Hence, the estimated NOx reduction potential is to be taken with care [B 2] [B 7].

The NOx reduction potential of direct water injection is quoted as 1% NOx reduction per 1% water content whereas the maximum water content is limited to up to 50% of the fuel quantity. The fuel penalty is estimated low but not finally confirmed [B 7].

Additional requirements of direct water injection are clean water, a water injection system, potentially requiring new cylinder heads for all cylinders, and changes at the control system. The effort for the installation of a water injection system on a Pre-2000 Engine depends on the design of the engine, in particular the cylinder heads, and the design of the water injection system. Injection systems which inject water and fuel through one nozzle in a certain time sequence were tested already and would limit modifications on the injection system.

The NOx reduction potential of water-in-fuel emulsion techniques is known and quoted as 1% NOx reduction per 1% water content whereas the maximum water content is limited to 10-30% of the fuel quantity. The fuel penalty is estimated as 1-2% per 10% NOx reduction [B 2] [B 7].

Additional requirements of water-in-fuel emulsion systems are clean water, additives for use with diesel fuel oil, a water heating systems for use with heavy fuel oil and a number of fuel and control system changes. An emulsifier device needs to be installed which shall guarantee a homogenous and stable emulsion of water and fuel. Potential problems are seen during stopping and starting of the engine [B 7].

There are systems installed on ships, however, many cases are known where the systems are taken out of operation due to operational difficulties as well as aspects of reliability. Not at least the production of huge amounts of clean water onboard turned out to be problematic in long-term application.

Humidification of the intake air is estimated to have a NOx reduction potential of 40% or even more. This technology is within the development phase still and applied in practice in few cases. Hence, the estimated NOx reduction potential is to be taken with care. The systems are large and not easy to retrofit. In normal operation the charge air cooler is not necessary anymore but it must be considered that they eventually should be kept for emergency operation. New turbochargers may be required. The large size of the air humidification unit limits the suitability for retrofit on Pre-2000 Engines. Even though the system does not have to be installed directly at the engines the need for space is considered to be problematic [B 2] [B 7].

The water used for intake air humidification does not necessarily need to be clean water, even sea water may be used [B 7]. The installation of additional sea water pipes inside the ship needs to be considered under safety aspects.

In cases where fresh water is necessary for water abatement systems special attention should be paid to the additional power consumption for fresh water treatment. The power consumption of evaporation systems is up to 6 %[2] of the primary energy.

Keeping the efforts for development of retrofit-kits, construction and installation, including certification of the modified Pre-2000 Engines in mind the costs might become economically unreasonable in many cases, especially for the smaller high speed 4-stroke engines (>1,000 rpm).

Possible NOx reduction measures on 4-stroke engines are listed in Table 2 below.

[2] Assumptions: Water-fuel share 50/50, calorific value of diesel 40 MJ/kg, enthalpy of evaporation of water 2500 kJ/kg

Measure	New engines		Pre-2000 Engines				
	NOx reduction potential	Additional construction costs	Applicability	NOx reduction potential	Effort for installation		Operational costs
					Time	Costs	
Injection timing	n/a	n/a	Limits due to thermal stress must be investigated.	10%	Adjustment during actual maintenance work based on manufacturer's instruction possible	No additional costs	Higher SFOC of up to 8% Due to higher thermal stress less TBO for exhaust valve and turbo charger possible
Injection nozzles	Not known, different to 2-stroke engines	n/a	n/a				
Internal engine optimization[3]	up to 30%	up to 30%	Possibly applicable on Pre-2000 Engines with same design as post-2000 engines	if applicable to full extent, same as new engine	Major conversion, depending on the extent of modification	Depending on the extent of modification	
Direct water injection	up to 50%	up to 20%	Case-by-case basis. Low sulphur fuel recommended (1.5%).	if applicable to full extent, same as new engine	Conversion of the injection and control system. Installation of water treatment system, new cylinder heads	Depending on the extent of modification	Higher SFOC of up to 4% Energy consumption of water treatment.
Water-in-fuel injection	up to 30%	up to 10%	Case-by-case basis.	if applicable to full extent, same as new engine	Conversion of the injection and control system. Installation of water treatment system		Higher SFOC of up to 2% Energy consumption of water treatment.
Intake air humidification	up to 40%	up to 15%	Case-by-case basis. Complete charge air system to be considered. Large air humidification units may prohibit the installation in existing engine rooms. Low sulphur fuel recommended (1.5%).	if applicable to full extent, same as new engine	Major re-construction of the engine room necessary. Docking necessary.	Estimation not possible	Higher SFOC of up to 8%

Table 2: Possible technical modifications to reduce NOx emissions from 4-stroke Pre-2000 engines

[3] Combination of injection timing, injection nozzle, combustion chamber, compression ratio, turbocharger, charge air cooler and valve timing

1.4 Technical feasibility of engine modifications

Engine manufacturers worldwide and engine manufacturers' associations have been contacted by the authors of this report in order to validate the feasibility of possible technical modifications on Pre-2000 Engines. A questionnaire as attached in Appendix A was distributed to fourteen engine manufacturers in Europe, Asia and North America representing the full range of marine diesel engine types, large bore slow speed engines, medium speed engines and high speed engines.

In order to obtain a general view on the number of engine types the Pre-2000 Engines have been categorized as follows:

- Type A: Pre-2000 Engines which do comply with IMO NOx Tier I standard already.
- Type B: Pre-2000 Engines which do not comply with IMO NOx Tier I standard but can be brought in compliance by retrofit measures or adjustments.
- Type C: Pre-2000 Engines which do not comply with IMO NOx Tier I standard and can not be brought in compliance by retrofit measures or adjustments by reasonable efforts.

Due to the diversity of existing ships in service, the huge number of installed Pre-2000 Engines and the range of possible modifications the expression 'Reasonable effort' can hardly be rated in an objective way. 'Reasonable efforts' in this context is interpreted in a way that for the modification of a Pre-2000 Engine none of the following criteria applies:

- The Pre-2000 Engine is not further developed and important information is missing. The impact of NOx reducing measures is not predictable for this engine type and no comparable engine is available for test bed investigations. The number of engines of this type in operation is limited and the installed power of engines of this type in operation is less than 500 MW.
- The modification of a Pre-2000 Engine implies the exchange of major engine components, such as crankcase, crankshaft, camshaft, cylinder heads and would have a major impact on the engine's class certificate.
- The modification of a Pre-2000 Engine implies major re-construction of the engine room or of the ships structure.
- The costs for the measures are close to or even exceed the costs for a new engine.

Information on the technical feasibility of engine modifications was given by 8 of the 14 engine manufacturers contacted. All contacted manufacturers (licensors) of large bore 2-stroke engines (3) have replied on the questionnaire.

It turned out that due to the high number of Pre-2000 Engines and due to unknown emission levels of Pre-2000 Engines the vast majority of the engine manufacturers are not able to answer the questionnaire to the full extent. In many cases no related information is achievable, in some cases general information on engine types was provided and in few cases more in depth information is available.

In principle, in depth information on engines built before 1980 is not achievable in any case. According to the engine manufacturers these engines are considered as ‘historical’ engines with only a few engines still in service per engine model. The engine manufacturers assume that these engines are in or at least close to compliance with IMO NOx Tier I standard but there is no data available at all. Addressing these engines, it seems that the environmental benefit achievable by engine testing and modification is entirely disproportionate to the effort for making them compliant, if they even would turn out to be compliant.

As the NOx emissions of most Pre-2000 Engines have not been measured even on test bed it can not be estimated by the engine manufacturers yet how many engines can comply with IMO NOx Tier I standard without any modification. There are several Pre-2000 Engines which have been certified according to the NOx Technical Code on a voluntary basis. The total number of these engines is to be considered negligible.

From a technical perspective most engines can be brought in compliance with IMO NOx Tier I standard, in principle. However, for individual models or engines the associated efforts and consequences may be prohibitive. Particularly engines following former design principles, most of these engines built and delivered before the mid 1980’s, are to be considered carefully.

In general Pre-2000 Engine models which have been built in similar design and at similar ratings before and after the introduction of IMO NOx Tier I standard could more easily be converted to the Tier I compliant stage than engine models which were developed and built only earlier.

The development of the retrofit technologies requires considerable efforts and investments from the engine manufacturers, in particular for those engines that have never been built in a Tier I compliant stage. This includes extensive validation on existing vessels due to the lack of test bed accessibility of those models in order to make sure that the measures to be introduced do not have a negative impact on engine reliability and operational safety. Thus, sufficient lead time would be needed for the required development.

The necessary lead time for the development of modification kits and the costs per engine cannot be estimated at this stage. However it is outlined that the engine development to low-NOx engines within the 1990's took a lot of manpower with expensive engine and component tests. These developments cannot easily be adopted without any restrictions for Pre-2000 Engines and without further tests and measurements. The ship and engine owners would possibly be faced with huge costs per engine to finance the necessary investigations and developments, not to mention possible off-hire times for the vessel.

The information from the engine manufacturers is provided in Table 11 in Appendix B. Below Table 3 summarises in figures the information received.

	2-stroke engines	4-stroke engines
Total number of Pre-2000 Engines	~ 10,475	~ 51,800
Share of Type A engines	~ 11 %	~ 35 %
Share of Type B engines	~ 40 %	~ 14 %
Share of Type C engines	~ 49 %	~ 51 %

Table 3: Engine manufacturers' information on Pre-2000 Engines – Summary

There has been no unique regulation or standard for exhaust gas measurements of marine engines until the standard ISO 8178, Part 1, had been published in 1996. Consequently, the level of uncertainty with respect to NOx emission levels of Pre-2000 Engines is high even in cases where emission values are available. Such values mostly are not comparable to emission data achieved under reference conditions specified in the standard, not to mention the use of the appropriate test cycle.

In general it may be concluded from the aforesaid that the share of 2-stroke engines appropriate for reasonable modification is bigger than the share of 4-stroke engines which could be modified by 'Reasonable efforts'.

1.5 Replacement engines

A particular species of Pre-2000 Engines are replacement engines. There are engines installed on ships which due to several reasons need to be replaced during the lifetime of a ship.

One reason could be routine replacement in cases where an engine is taken from board the ship for major overhaul work ashore. In such cases it may occur that the engine is replaced by an identical 'spare engine' of same type and model with same engine set-up, connected to the ship's existing piping and wiring system without any modification. Such engine replacements are common practice on high speed ferries, for example. The replacement engines normally are of similar age as the original engine and should not be subject to any additional requirements as the original engine. After a certain period in service these engines again are replaced by the overhauled original engine.

Another reason for an engine replacement could be the break-down of an engine. In accordance with the official text it is common practice that old, (second hand) engines of same type, model and engine set-up replacing the original engine do not need to fulfil the requirements of MARPOL Annex VI, Regulation 13 if the date of engine build is before 1 January 2000 and no modifications to the ship's piping and wiring system become necessary.

However, if an engine is replaced by a new engine built on or after 1 January 2000 the engine needs to be IMO NOx Tier I compliant even if the replacement engine is of same type and model as the original engine. According to MARPOL Annex VI, Regulation 13, Chapter (2)(a)(i) 'new' replacement engines are regulated under the definition of 'Major Conversion'.

Where a replacement engine differs from the original engine in terms of type or model or performance even, the replacement engine must comply with the IMO NOx Tier I requirements irrespective the engine's date of build.

An engine certified for compliance with IMO NOx Tier I may be replaced by a NOx compliant engine only and needs to be certified.

In most cases high speed or medium speed 4-stroke diesel engines used for auxiliary drives need to be replaced occasionally. Large bore 2-stroke engines normally remain in the vessel during the whole lifetime of the ship even in cases of severe damage onboard repair is conducted rather than replacement.

Engines installed on pre-2000 ships in addition to the original engines in any case should be compliant with the IMO NOx Tier I requirements, irrespective the age of the engine.

2 Range of Pre-2000 Engines

2.1 Particulars on information sources and ship database

The statistical analysis of Pre-2000 Engines is based on the data of the Lloyd's Register Fairplay WSE Database, Version 9,51 released in July, 2007 [B 8]. Within the database ships of the current world fleet are registered and information about the propulsion system is given. The information concerning the installed engines is focused on the main engines of the ships. Information on auxiliary engines is not covered. Hence, all following analyses refer to propulsion engines only.

The Fairplay database contained 112,148 ships at the date of investigation. Prior the analysis with respect to certain assessment criteria the database was reviewed in order to deal with comparable data sets only. Resulting from selection criteria the data used from the database is reduced to 35,128 ships which are propelled by diesel engines which may be considered for a new requirement. For these ships the database contains full information on the installed propulsion engines. The review of the database and the selection criteria are described in the following.

2.1.1 Data reduction

In a 1st step ships which are not considered to be relevant for a new IMO NOx regime have been deleted. The following selection criteria have been applied and the affected ships were deleted:

- Ships with engines other than diesel engines, e.g. gas turbines (refer to MARPOL Annex VI, Regulation 13).
- Ships which are recorded as scrapped or lost but which are still listed in the database.
- Ships delivered before 1950.
- Ships with a propulsion power per engine of 130 kW or less (refer to MARPOL Annex VI, Regulation 13).
- Ships with 400 gross tons or less (refer to MARPOL Annex VI, Regulation 5).

The screening of the database has reduced the amount of considered ships by 46,520 ships to 65,616 ships.

In a 2nd step of this approach all ships for which relevant propulsion engine data for analyses is not given completely have been deleted. By this it is ensured that for all different assessment criteria as described in Section 2.2 the same statistical base is used. The following ships have been deleted in the 2nd step:

- Ships, where the main engine's stroke is reported not to be 2- or 4-stroke (false entries).

- Ships, where the engine speed in rpm is not given.
- Ships, where the number of main engines is not defined.
- Ships, where cylinder bore and stroke of the main engine is not defined.

This screening of the database has reduced the amount of considered ships by further 30,488 ships to 35,128 ships.

Finally, for the purpose of the study, the analysis considers 35,128 ships with 45,005 diesel engines installed having a total of 312,378 MW installed propulsion power.

Table 4 provides a general view on the above mentioned selection criteria and the sum of ships which are affected. The table is to be read column by column. The screening process started with the criteria left 'Engine type not diesel' proceeding to the right. The number of ships which were deleted within the respective screening step can be found in the respective line of the screening criterion. The total number of deleted ships within the category is highlighted in light grey for each screening criterion. The numbers below the total number indicate how many ships could be assigned to other screening criteria as well. The sum of all numbers does not necessarily equalize the total number as multiple assignments are possible. The total numbers for each screening criterion depends on the sequence of the screening process. The final sum of deleted ships is independent of the order of the screening criteria.

Sequence of screening →

Number of ships assigned to other screening criteria ↓

	Step 1 Ships which are not relevant for a new IMO NOx regime						Step 2 Ships where relevant engine data is incomplete				
	Engine type not diesel	Ship scrapped or lost	Delivery date before 1950	Engine <130 kW	Ship <400 GT	**Sum Step 1**	Engine stroke unknown	Engine rpm unknown	Number of engines unknown	Engine cylinder bore and stroke unknown	**Sum Step 2**
Engine type not diesel	3,881	0	0	0	0		0	0	0	0	
Ship scrapped or lost	19	605	0	0	0		0	0	0	0	
Delivery date before 1950	214	14	1,344	0	0		0	0	0	0	
Engine <130 kW	7	12	210	687	0		0	0	0	0	
Ship <400 GT	311	111	966	590	40,003		0	0	0	0	
Sum Step 1						**46,520**					
Engine stroke unknown	-	25	303	64	6,497		5,212	0	0	0	
Engine rpm unknown	40	396	1,184	519	26,996		4,869	24,937	0	0	
Number of engines unknown	3,482	50	674	102	9,604		4,258	1,682	282	0	
Engine cylinder bore and stroke unknown	-	30	362	79	7,476		5,072	430	7	57	
Sum Step 2											**30,488**

Table 4: Screening process of the ship database

2.1.2 Data validation

Reviewing the database and deleting parts of the data may lead to distortion of the results. All engines installed on ships deleted during the two steps of the screening process are not regarded for further analyses. Ships deleted in the 1st step do not influence the results of this analysis as these ships and the installed engines are considered not to be relevant for a new IMO NOx regime. Ships deleted in the 2nd step may be relevant for a new IMO NOx regime but cannot be considered as relevant data on the installed engines is not available.

A review on the data validation is provided in Figure 32 in Appendix C. There are four sets of data defined:

- Deleted ships 1: Ships within 'Deleted ships 1' were deleted during step 1 of the screening process. These ships are considered not to be relevant for a new IMO NOx regime. Hence, the deletion of these ships does not influence the results of the analyses and needs not to be considered for the validation of the remaining statistical base.

- Deleted ships 2: Ships within 'Deleted ships 2' were deleted during step 2 of the screening process. For these ships relevant information on the installed engines is not available completely. A new IMO NOx regime may be relevant for engines installed on these ships. It must be validated how the deletion of these ships influences the results of the analyses.

- Statistical base: Ships within the 'Statistical base' remain for further analyses and are the base of all further statistical analyses. For these ships relevant information on the installed engines is available completely. A new IMO NOx regime may be relevant for engines installed on these ships.

- Overall: Ships within 'Overall' are the sum of ships within 'Deleted ships 2' and 'Statistical base'. This group of ships is necessary for the validation of the 'Statistical base'.

In order to validate the informal value of the 'Statistical base', the ships within 'Deleted ships 2' and within the 'Statistical base' were analysed with regard to the share of Pre-2000 Engines and post-2000 engines in the installed propulsion power. The results of the analyses of 'Deleted ships 2', the 'Statistical base' and 'Overall' are provided in Figure 32. The calculation of the result of 'Overall' is provided in Appendix C. The 'Statistical base' is considered as representative for further analyses with regard to the installed propulsion engines if the distribution of Pre-2000 Engines and post-2000 engines within the 'Statistical base' and within 'Overall' is within the same range.

The share of Pre-2000 Engines and post-2000 engines in the installed propulsion power differs from within 'Overall' (58/42) to within the 'Statistical base' (50/50) but is within the same range. The error band is less than 16% of the result. Hence, the confidence level of the 'Statistical base' may be regarded sufficient. All ships within 'Statistical base' form the statistical base for the following analyses.

2.2 *Particulars on the statistical analysis of the ship database*

The analysed ship database is based on ship data of the current world fleet. For the purpose of this study information on the propulsion engines installed on these ships is necessary. Information on the propulsion engines is available completely for ships defined as statistical base in Section 2.1 only. In the following the statistical base is assessed with regard to the propulsion engines installed on the considered ships.

2.2.1 *Calculation of the NOx emissions*

It is the aim of the analysis to provide information on the current world fleet with regard to the number of vessels to be considered, the number of diesel engines with regard to their size and power output installed in the vessels and the allocated NOx emissions with regard to different propulsion engine assessment criteria. The number of ships and the number of engines are values which are available out of the database directly. The NOx emissions are not provided within the statistical base but were calculated in an approach as explained in the following.

For the purpose of this study the calculated NOx emission of diesel engines results from two parameters. The engine speed in rpm and the installed engine power in kW. Both parameters are available out of the statistical base.

1. **Parameter 'engine speed in rpm':** The speed dependent maximum allowable NOx emission for marine diesel engines is according to the IMO NOx curve. In Figure 2 information on the methodology of the calculation of the NOx emission level is provided for a marine diesel engine of 514 rpm engine speed. Assuming that the emission level of the diesel engine is exactly the limit value of the IMO NOx curve an emission level of 12.9 g/kWh is calculated.

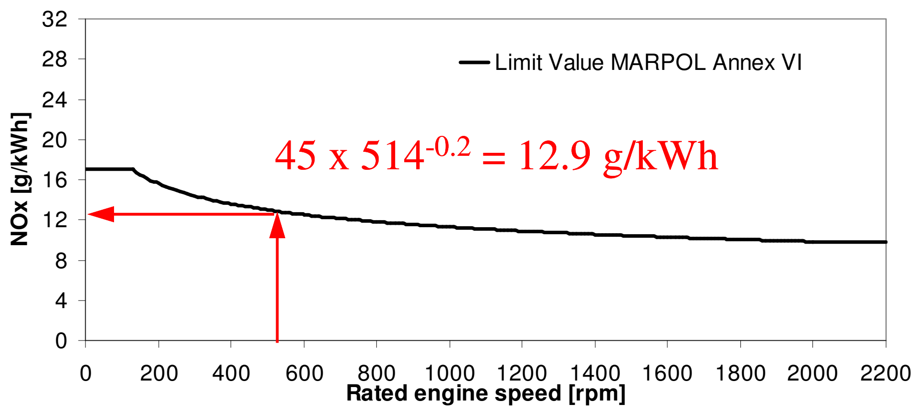

Figure 2: Calculation of the statistical NOx emission from marine diesel engines

2. **Parameter 'installed engine power in kW':** The installed engine power in kW is recorded for all engines installed on ships within the statistical base. The installed engine power is weighted according to the weighting factors for main propulsion application (Test Cycle E2 / E3) given in the NOx Technical Code, Chapter 3 and in Table 5 hereof. The weighted power represents a standardized load cycle of the respective application.

Test Cycle type E2 / E3	Power	100%	75%	50%	25%
	Weighting factor	0.2	0.5	0.15	0.15

Table 5: Weighting factors for main propulsion application (Test Cycle E2 / E3)

As an example, the following equation shows the calculation of the weighted power of a marine diesel propulsion engine of 10,000 kW installed power.

$$P_W = (0.2 \times 10{,}000 + 0.5 \times 7{,}500 + 0.15 \times 5{,}000 + 0.15 \times 2{,}500)\ kW = 6{,}875\ kW$$

The NOx emission is calculated out of the two parameters explained above. Referring to the above mentioned examples the NOx emission is calculated as follows:

$$NOx\ emission = 12.9\ g/kWh \times 6{,}875\ kW = \underline{88.7\ kg/\ h}$$

The NOx emission is calculated for each engine installed on ships within the 'Statistical base'. In the following the calculated NOx emission is used as an estimation of the NOx emissions.

The benefit of the calculated NOx emissions approach as NOx emission estimation is that engines are rated according to their emission behaviour. The given correlation between engine speed and NOx emission level is considered in the limiting IMO NOx curve.

The approach taking the calculated NOx emissions is based on the assumption that the NOx emission level of each engine within the statistical base meets exactly the maximum allowable NOx emission level for marine diesel engines according to the IMO NOx curve. An example for the calculation of the NOx emissions is shown above and in Appendix D. Assessing the results of the statistical analysis the effect of the made assumption should be considered. The emission level of post-2000 engines is on or below the level of IMO NOx Tier I standard whereas Pre-2000 Engines are considered to exceed the limit value. It is not known how many of the Pre-2000 Engines and how far they exceed the limit value of the IMO NOx curve. Further information on the emission level of Pre-2000 Engines is provided in Section 2.5.

2.2.2 Assessment criteria for the analysis of the ship database

The engines installed on ships within the statistical base are assessed to different engine criteria based on the proposals in documents BLG 11/5/22, BLG 11/5/26, BLG-WGAP 2/2/12 and BLG-WGAP 2/2/13.

Engine stroke: The engines are differentiated with regard to stroke (2-stroke and 4-stroke).

Engine rpm: The engines are differentiated with regard to speed in revolutions per minute (rpm).

Engine power: The engines are differentiated with regard to installed power per engine in kW.

Cylinder displacement: The engines are differentiated with regard to displacement per cylinder in litre.

Against the background of the huge amount of engines in service as well as the manpower needed for retrofit activities a stepwise introduction of possible requirements for Pre-2000 Engine is proposed in documents BLG 11/5/26, BLG-WGAP 2/2/12 and BLG-WGAP 2/2/13. The distribution of the Pre-2000 Engines with regard to the date of build is given to provide information on the effect of 'Phasing-in'-scenarios. In the following the expression 'Phasing-in' is used to refer to the proposed stepwise introduction of a possible requirement.

Figure 3 provides a general view on the different analysis methods which were carried out.

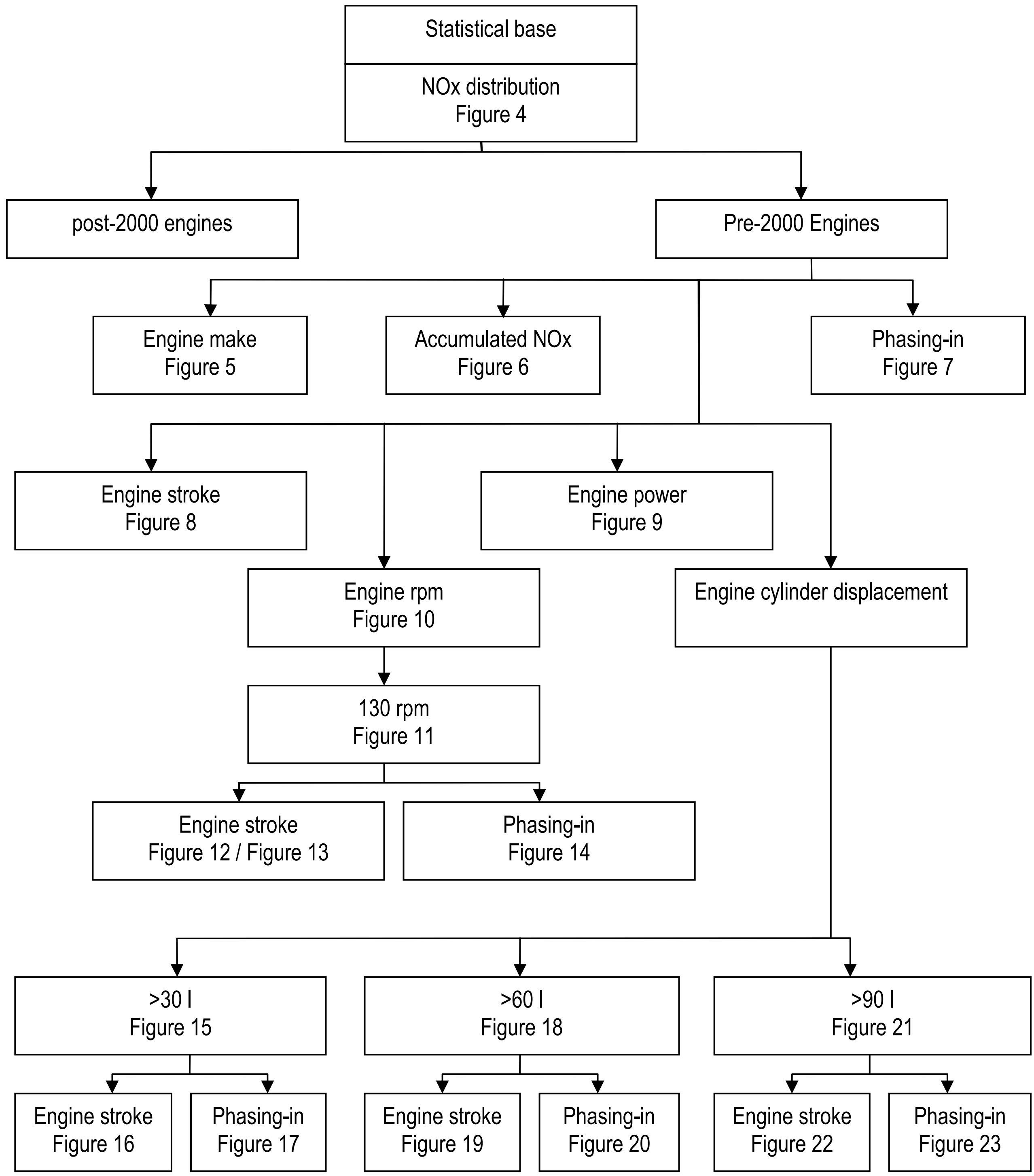

Figure 3: General view on the statistical analysis of the ship database

Due to the screening of the database as described in Section 2.1 the results of all analyses are based on the same statistical base. This ensures that the results may be compared directly.

2.3 Results of the statistical analysis of the ship database

The database remaining after the screening described in Section 2.1 is analysed with regard to the share of Pre-2000 Engines and their distribution with regard to the engine parameters listed in Section 2.2. In the following the results of different analyses for different engine groups are described. The headline of each section indicates the considered engine group.

In all figures the share of the respective engine group in the number of ships is indicated in grey, the share in the number of engines in blue and the share in the NOx emissions in brown. Additional in Figure 4 the share in the installed propulsion power is indicated in turquoise.

2.3.1 All engines (Pre-2000 Engines and post-2000 engines)

In order to analyse the share of Pre-2000 Engines in the total NOx emissions from marine diesel engines all engines of the statistical base are considered in the first step. The share of Pre-2000 Engines in the fleet's total installed propulsion power of all engines is shown in Figure 4.

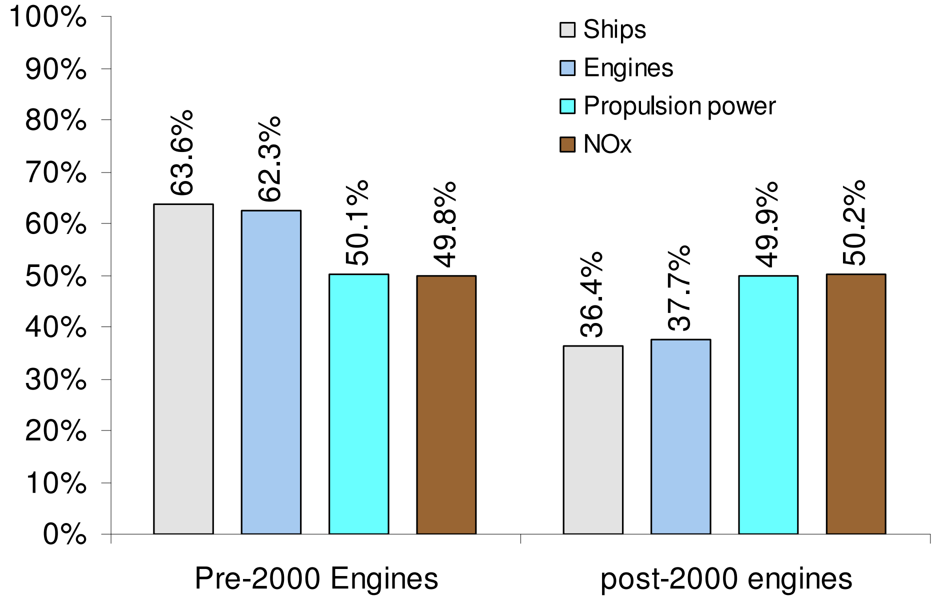

Figure 4: Share of the Pre-2000 Engines in all engines of the statistical base

The share of Pre-2000 Engines in the installed propulsion power is 50.1% of the total installed propulsion power on ships built between1950 and 2007. The share of Pre-2000 Engines in the NOx emissions is 49.8% of the total NOx emissions from engines installed on ships built between 1950 and 2007. The share of number of ships with

Pre-2000 Engines in the total number of ships is 63.6%. The share of number of Pre-2000 Engines in the total number of engines is 62.3%.The result of this analysis shows that approximately half of the NOx emissions from all main propulsion engines installed on ships is allocated to Pre-2000 Engines. At the same time the share of ships with Pre-2000 Engines in the number of all ships is comparatively high. This result is valid for the point of time of the release of the database, July 2007. It is to be considered that the share of NOx emissions from Pre-2000 Engines in all NOx emissions and the share of number of ships with Pre-2000 Engines in the number of all ships will become less, as older ships will be decommissioned and new ships will be put into operation.

2.3.2 All Pre-2000 Engines

Pre-2000 Engines were built by 94 different engine manufacturers. The number of 94 different engine manufacturers does not consider the merging of engine manufacturers. Differentiating engine models with regard to their NOx emission level the number of models is unknown. At this stage engine manufacturers can hardly estimate how many Pre-2000 Engine models suit in existing NOx engine groups from post-2000 engines and how many new engine groups need to be established for the Pre-2000 Engines. Since Pre-2000 Engines of same model do not necessarily belong to the same NOx engine group the number of new engine groups cannot be estimated without more in depth information by the engine manufacturers.

Considering the engine manufacturers with regard to the amount of NOx emissions assigned to Pre-2000 Engines of their build the share in Pre-2000 Engines is as shown in Figure 5.

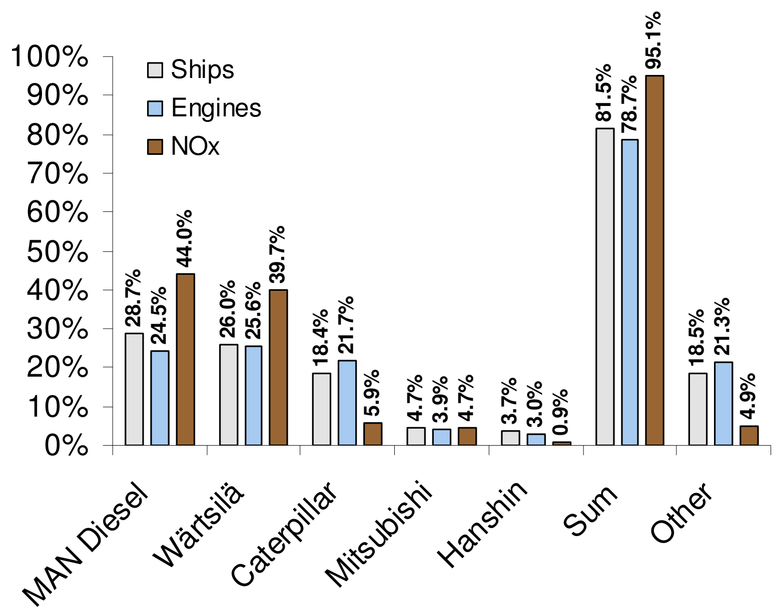

Figure 5: Share of engines from selected engine manufacturers in all Pre-2000 Engines

The merging of engine manufacturers is considered in this figure. It can be seen that 95.1% of the NOx emissions from Pre-2000 Engines can be allocated to engines of build from 5 engine manufacturers. This approach seems to simplify the diversity of engine models. However, it is to be kept in mind that the relatively high share of these engine manufacturers in Pre-2000 Engines can partly be reconnected to several co-operations and take over activities. The manufactures partly cover several former engine brands which elevates their share and the number of engine models. At this stage it cannot be judged how this has influenced the engine documentation and development but it is to be considered that there are several engine models which are not documented and developed further. Even within this group of engine manufacturers it may be expected that not for all engine models retrofit kits and documentation for certification can be made available, even if the engines would technically be suitable for modification. Further there are several engine builders which produce engines of the above mentioned make in licence which might complicates the allocation of these engines to NOx engine groups.

The analysis of Pre-2000 Engines considers a wide time frame from 1950 to 1999. The allocation of Pre-2000 Engines to the time is important information and is shown in Figure 6. The view of Figure 6 is such that the relevant values are accumulated. The time axis is starting in the year 1999 reaching back to the year 1950. The accumulated values are showing at which point of time most of the respective value is captured. This is the case once the increase of the trend is flattening.

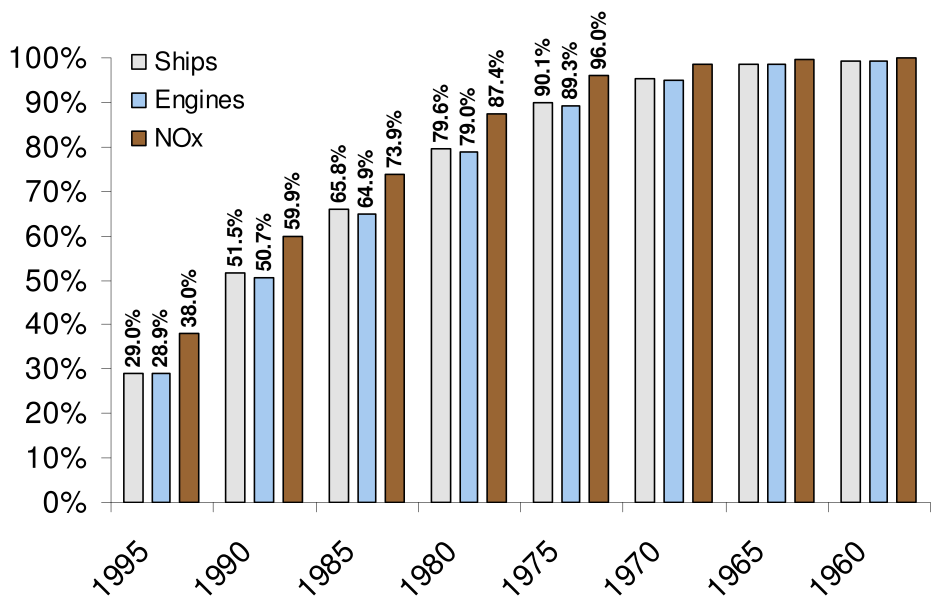

Figure 6: Pre-2000 Engines age distribution - accumulated values

It may be recognised that the increase of the trends is flattening within the decade of the 1970ies. Within each 5-year step from year 1999 to year 1980 the share in NOx emissions is increasing by more than 10 % points. Beginning with the 5–year step from year 1980 to year 1975 the increase is less than 10 % points. A limitation of time from year 1999 back to year 1980 is taking into account a share of 87.4% in the NOx emissions of Pre-2000 Engines. In particular, engines installed on ships built from year 1999 to year 1995 take a share of 38.0 % in the NOx emissions from all Pre-2000 Engines.

A Phasing-in scenario would allow a smoother implementation of a new emission regime for Pre-2000 Engines. Engines of newer date of build with a realistic potential to be brought in compliance would be considered first, followed by older engine models. This would allow to further investigate technical solutions for modifications of older engines and to schedule resources at the involved facilities over a wider time frame. Figure 7 shows how many Pre-2000 Engines and how much of the respective NOx emissions could be captured if a Phasing-in scenario would be applied for all Pre-2000 Engines.

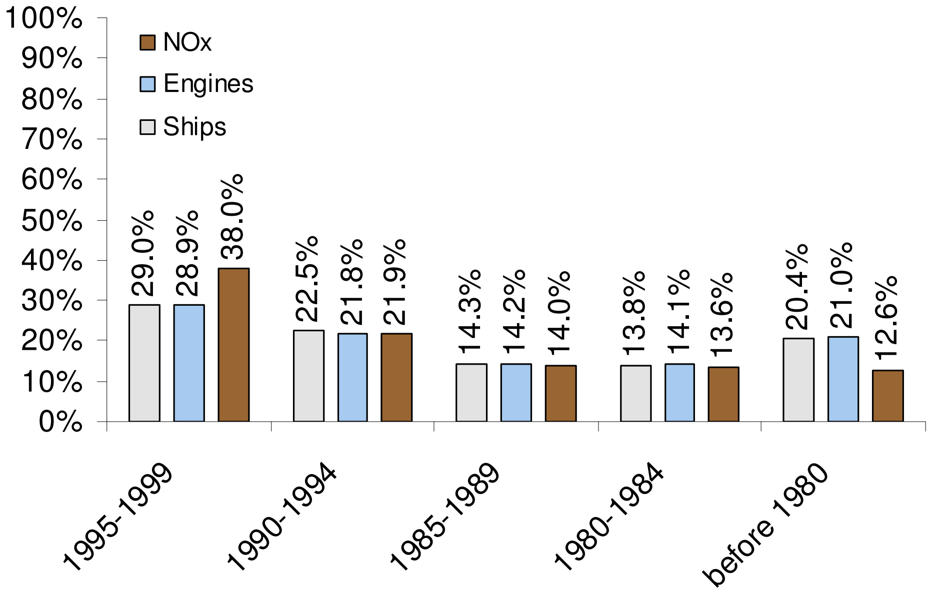

Figure 7: Phasing-in implementation of all Pre-2000 Engines

The shares provided in Figure 7 refer to all Pre-2000 Engines from 1950 to 1999. The analysis shows that 38% of the NOx emissions of Pre-2000 Engines are captured if engines built from 1995 to 1999 are regarded in the first instance. The next group of engines to be considered built from 1990 to 1994 takes a share of 21.9 % in the NOx emission of all Pre-2000 Engines. At the end, the remaining group of engines to be considered built before 1980 takes a share of 12.6 % in the NOx emission of all Pre-2000 Engines. All these values correspond to the numbers provided in Figure 6, where the values are accumulated.

The share of 2- and 4-stroke engines in all Pre-2000 Engines is provided in Figure 8. The share of 2-stroke engines in the NOx emissions is 78.7 % whilst the share in the number of engines is 41.2 %. The share of 4-stroke engines in the NOx emissions is 21.3 % whilst the share in the number of engines is 58.8%. Slow speed 2-stroke engines have the highest specific NOx emission level and the highest installed power per engine. Hence, these engines take a bigger share in the NOx emissions of all Pre-2000 Engines than 4-stroke engines. At the same time the share in the number of ships and in the number of engines is comparatively low. Further, it can be seen that the number of 2-stroke engines per ship is less than the number of 4-stroke engines per ship. With 2-stroke engines a share of 50.1 % in the number of ships have a share of 41.2 % in the number of engines installed, whilst with 4-stroke engines a share of 49.1 % in the number of ships have a share of 58.8 % in the number of engines installed. In practice, most 2-stroke propulsion engines are single engine arrangements.

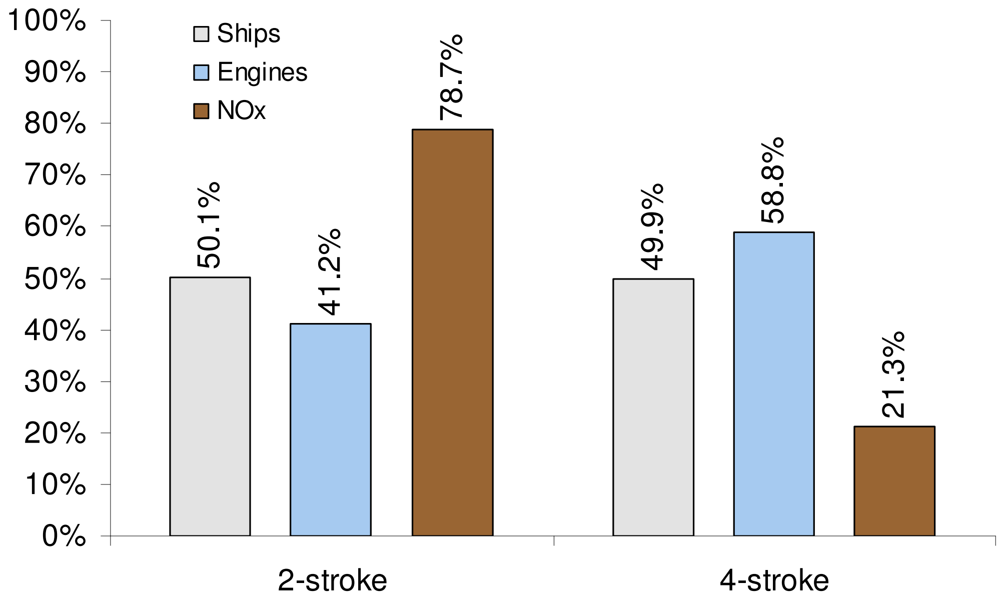

Figure 8: Share of 2- and 4-stroke engines in all Pre-2000 Engines

The distribution of all Pre-2000 Engines with regard to the engine power is shown in Figure 9. The group of engines of 11,000 kW and above takes a share of 40.2% in the NOx emissions and a share of 10.7% in the number of engines. The sum of the values of all engines of 5,000 kW and above gives a share of approx. 82 % in the NOx emissions and a share of approx. 38 % in the number of engines.

Figure 9 shows that the share in number of ships and engines with regard to engine power runs contrarily to the share in NOx emissions. This result corresponds to the results of stroke and speed related analyses. The given correlation between installed engine power, engine speed and specific NOx emission level is the same for all analyses made.

Further, it can be seen that the ratio of share in the number of ships to share in the number of engines decreases with less propulsion engine power. In correlation with the result of the analysis with regard to 2-stroke engines this shows that in general propulsion engines with less power are installed in higher numbers per ship while bigger engines are installed in fewer numbers per ship.

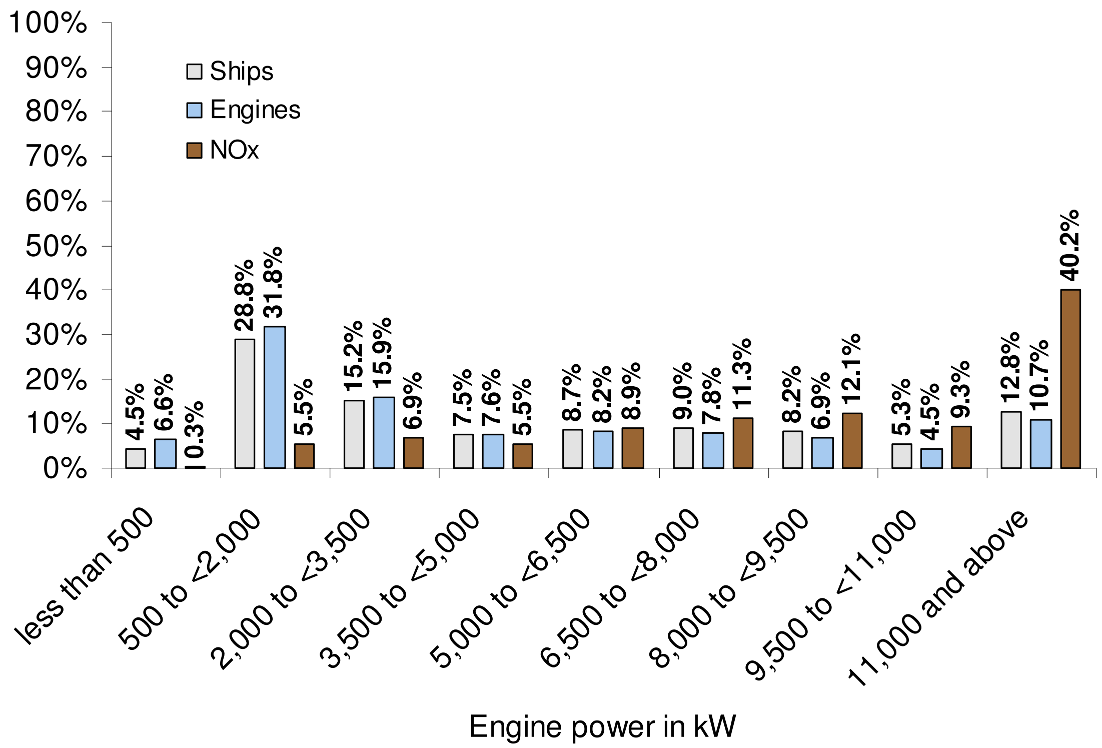

Figure 9: Distribution of Pre-2000 Engines with regard to engine power

Figure 10 shows the allocation of all Pre-2000 Engines related to the engine speed range. The range of speed is categorized in low speed, medium speed and high speed engines according to [B 10]. The low speed engines with less than 300 rpm take a share of 79.3% in the NOx emissions of all Pre-2000 Engines. The share in the number of engines is 41.9% of all Pre-2000 Engines. The share of the high speed engines in the total NOx emission of all Pre-2000 Engines is low (1.6%) whilst the number of high speed engines takes a considerable share (14.7%) in the Pre-2000 Engines.

The result provided in Figure 10 can be explained with the given correlation between specific NOx emission and engine speed and with the correlation between engine size and engine speed. Engines with less engine speed have higher specific NOx emissions and are in general of higher installed power. Hence, slow speed engines have the highest per engine NOx emissions. Further, Figure 10 shows that the achievable benefit in NOx emission reduction is almost negligible for high speed engines whilst the connected effort is comparatively high.

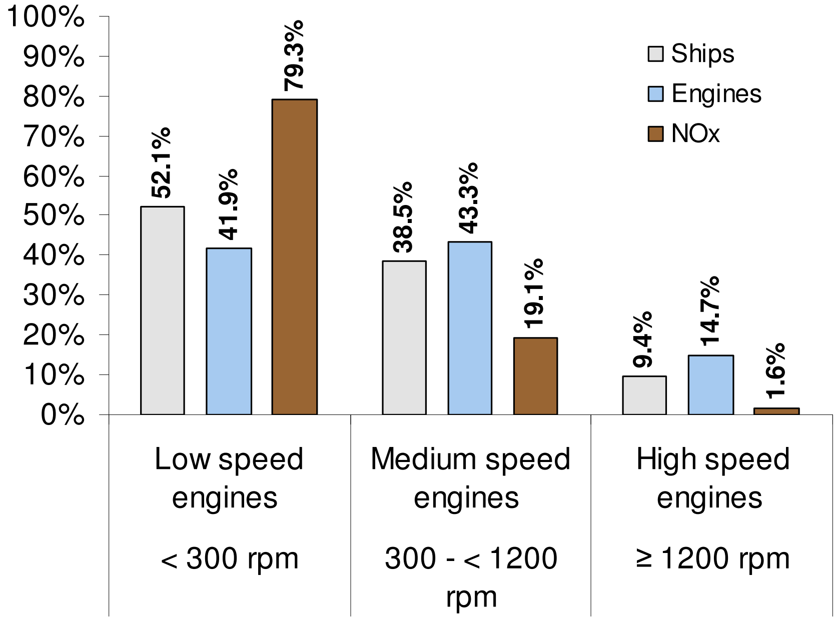

Figure 10: Distribution of Pre-2000 Engines with regard to engine speed

2.3.3 Pre-2000 Engines of less than 130 rpm

In document BLG 11/5/22 it is proposed to consider Pre-2000 Engines of less than 130 rpm only. Looking at Figure 24 it can be seen that the IMO NOx curve has a break point at exactly 130 rpm. The maximum allowable NOx emission value for engines with less than 130 rpm is 17 g/kWh. This is the highest allowable emission value. Hence, engines with the highest specific NOx emissions are considered by this proposal.

Referring to document BLG 11/5/22 the share of engines of less than 130 rpm engine speed in all Pre-2000 Engines is analyzed in Figure 11. The share of engines of less than 130 rpm in the total NOx emission of all Pre-2000 Engines is 44.0 % and 14.4 % in the number of engines. This result indicates that a considerable amount of the NOx emissions of the Pre-2000 Engines can be assigned to engines with less than 130 rpm while the number of concerned engines and ships remains comparatively low.

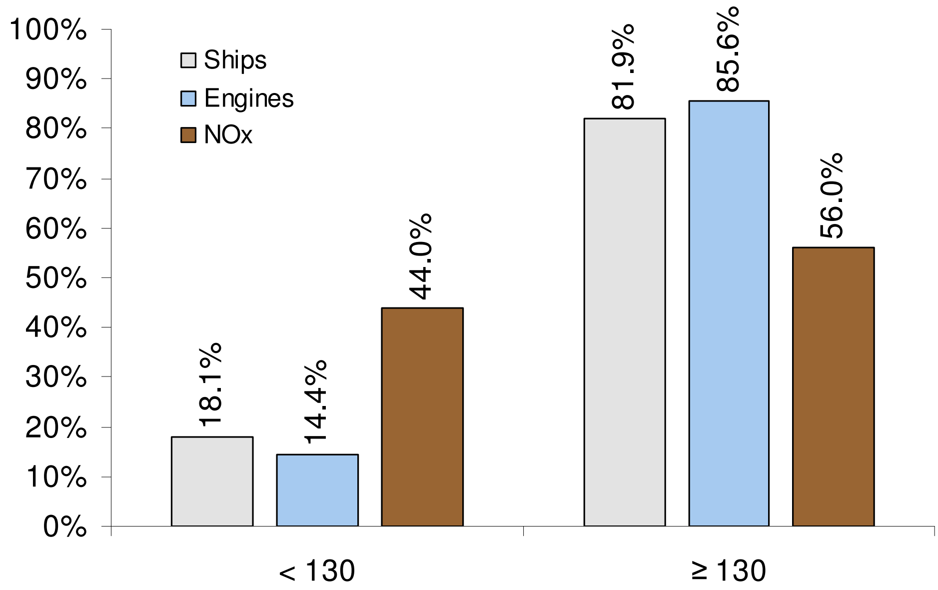

Figure 11: Split-up of Pre-2000 Engines at an engine speed of 130 rpm

The share of 2- and 4-stroke engines in engines of less than 130 rpm and engines of 130 rpm and more is shown in Figure 12 and Figure 13. Whilst the engines of less than 130 rpm in principle are all 2-stroke engines (99.8 %) the number of engines of 130 rpm and more are split between 2-stroke engines (21.6 %) and 4-stroke engines (78.4 %). With regard to the NOx emissions the share of 2-stroke engines is 99.9 % in the NOx emissions of Pre-2000 Engines of less than 130 rpm and 40.9 % in the NOx emissions of Pre-2000 Engines of 130 rpm and more.

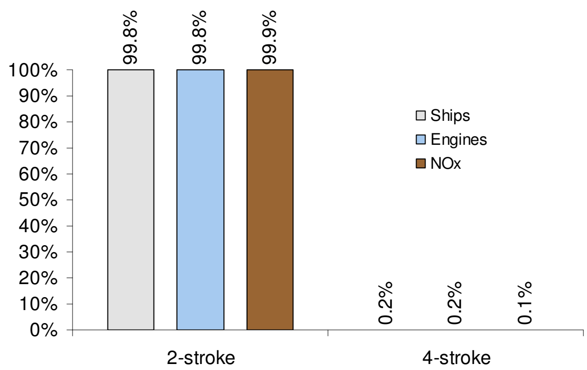

Figure 12: Share of 2- and 4-stroke engines in Pre-2000 Engines of less than 130 rpm

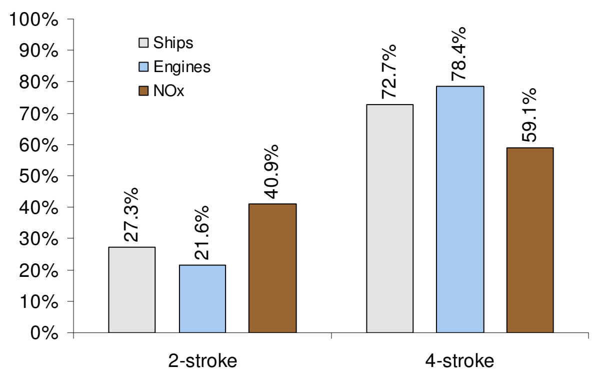

Figure 13: Share of 2- and 4-stroke engines in Pre-2000 Engines of 130 rpm and more

Figure 14 shows how many Pre-2000 Engines of less than 130 rpm and how much of the respective NOx emissions would be captured if a Phasing-in scheme would be applied. Pre-2000 Engines of less than 130 rpm represent 100 % of the referred value.

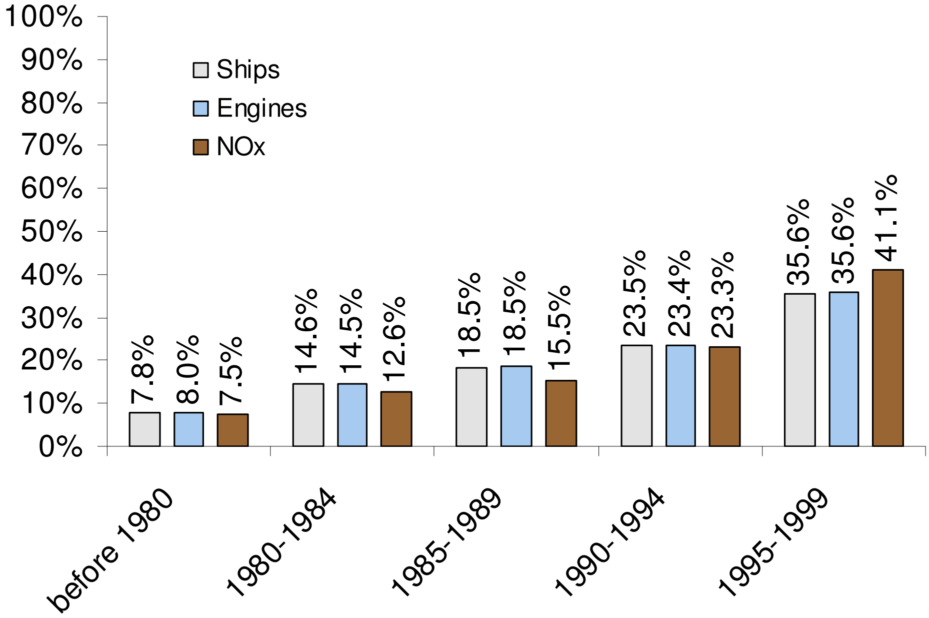

Figure 14: Phasing-in implementation of Pre-2000 Engines of less than 130 rpm

2.3.4 Pre-2000 Engines of 30 / 60 / 90 litres per cylinder and more

The analyses with regard to the engine cylinder displacement for instance refer to document BLG-WGAP 2/2/12. Splitting the group of all Pre-2000 Engines subsequently at 30 litres (Table 6), 60 litres (Table 7) and 90 litres (Table 8) per cylinder the share of the respective engine groups in the number of ships, in the number of engines and in the NOx emissions is provided. Further the shares of 2-stroke and 4-stroke engines in the respective engine groups and details for Phasing-in scenarios are provided.

Figure 15 shows that the group of engines of 30 litres per cylinder and more have a share of 92.5 % in the NOx emission and covering 64.9 % of the number of engines. Engines of 60 litres per cylinder and more (Figure 18) have a share of 87.3 % in the total NOx emission and covering 49.8 % of the number of engines. Engines of 90 litres per cylinder and more (Figure 21) have a share of 82.4 % in the total NOx emission and covering 42.1 % of the number of engines.

For Pre-2000 Engines of 30 litres per cylinder and more the share of 2-stroke engines is 61.0 % in the number of engines and 84.8 % in the NOx emissions as shown in Figure 16. The share of 4-stroke engines is 39.0 % in the number of engines and 15.2 % in the NOx emissions.

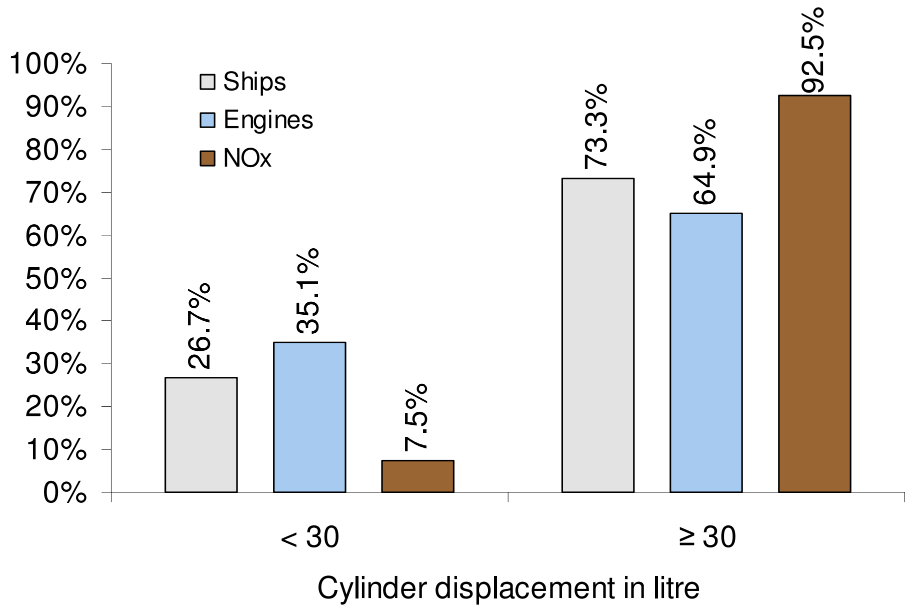

Figure 15: Split-up of Pre-2000 Engines at 30 litres per cylinder

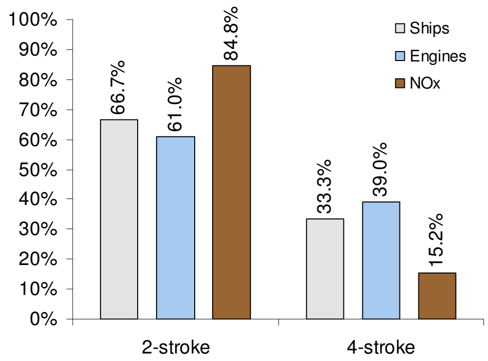

Figure 16: Share of 2- and 4-stroke engines in Pre-2000 Engines of 30 litres per cylinder and more

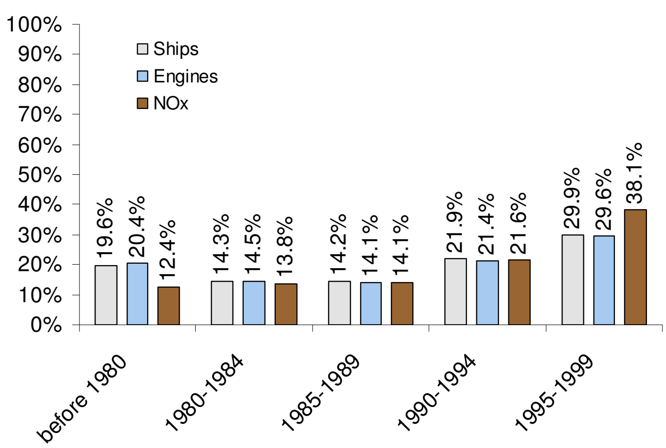

Figure 17: Phasing-in implementation of Pre-2000 Engines of 30 litres per cylinder and more

Table 6: Pre-2000 Engines of 30 litres per cylinder and more

For Pre-2000 Engines of 60 litres per cylinder and more the share of 2-stroke engines is 77.7 % in the number of engines and 89.5 % in the NOx emissions as shown in Figure 19. The share of 4-stroke engines is 22.3 % in the number of engines and 10.5 % in the NOx emissions.

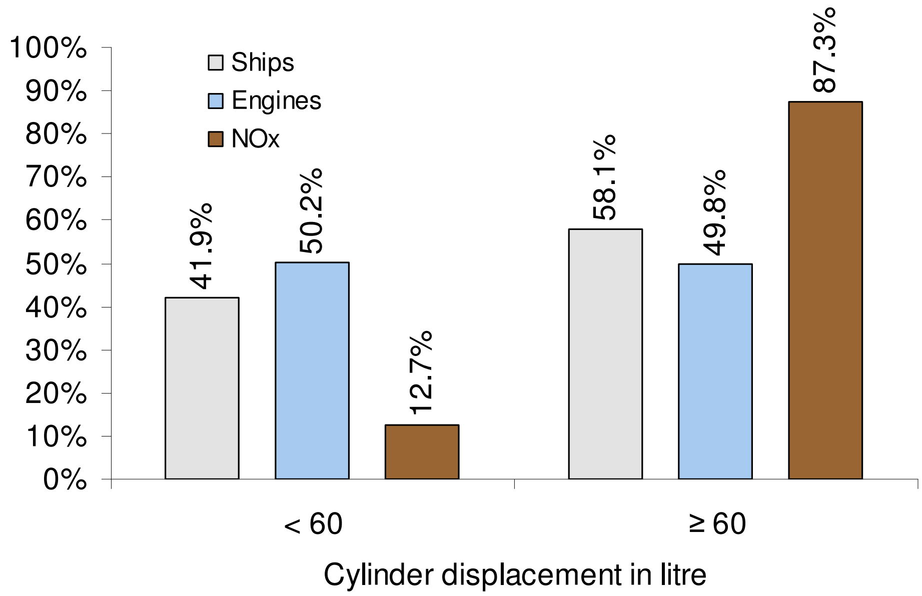

Figure 18: Split-up of Pre-2000 Engines at 60 litres per cylinder

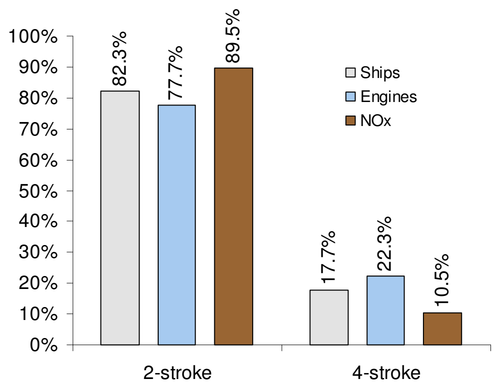

Figure 19: Share of 2- and 4-stroke engines in Pre-2000 Engines of 60 litres per cylinder and more

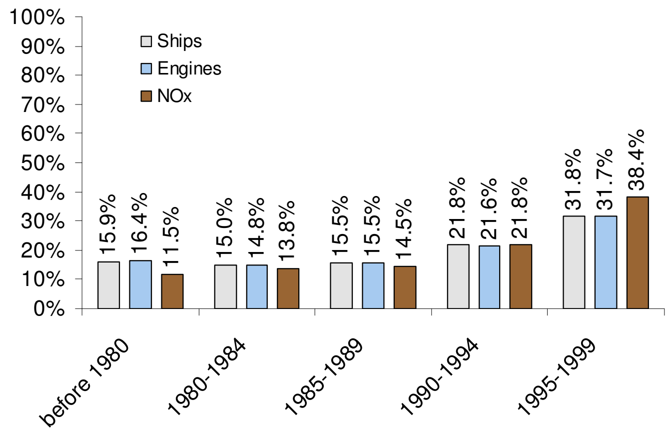

Figure 20: Phasing-in implementation of Pre-2000 Engines of 60 litres per cylinder and more

Table 7: Pre-2000 Engines of 60 litres per cylinder and more

For Pre-2000 Engines of 90 litres per cylinder and more the share of 2-stroke engines is 90.5 % in the number of engines and 94.5 % in the NOx emissions as shown in Figure 22. The share of 4-stroke engines is 9.5 % in the number of engines and 5.5 % in the NOx emissions.

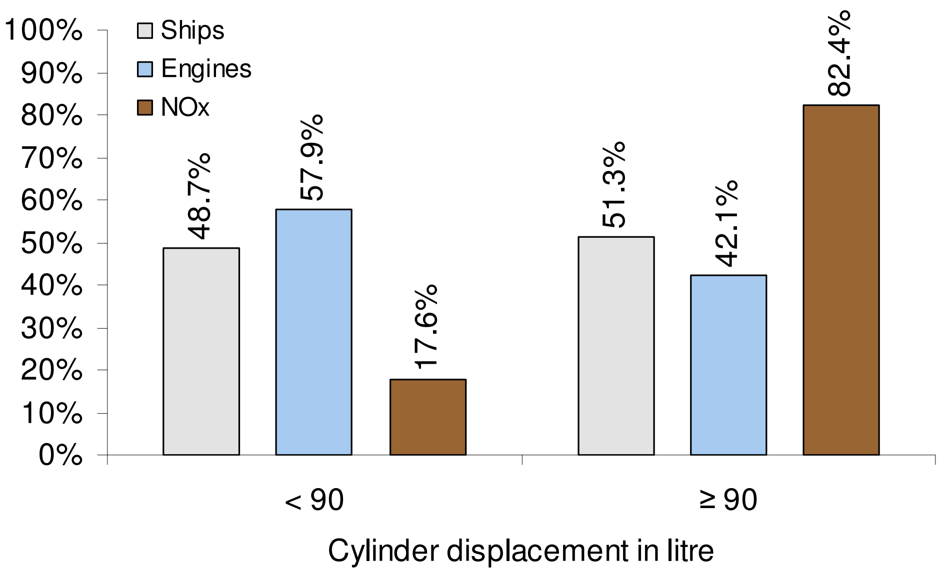

Figure 21: Split-up of Pre-2000 Engines at 90 litres per cylinder

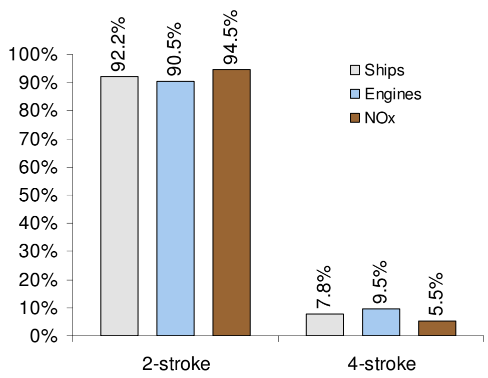

Figure 22: Share of 2- and 4-stroke engines in Pre-2000 Engines of 90 litres per cylinder and more

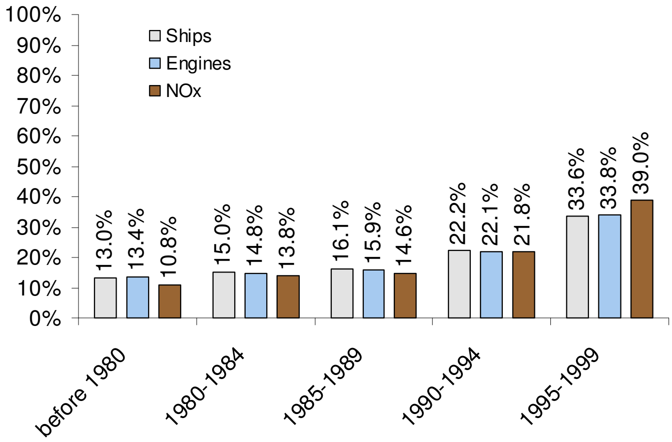

Figure 23: Phasing-in implementation of Pre-2000 Engines of 90 litres per cylinder and more

Table 8: Pre-2000 Engines of 90 litres per cylinder and more

2.4 Implementation of modifications on Pre-2000 Engines

The modification of Pre-2000 Engines requires the development and testing of appropriate components or other means of NOx reduction, the production of them and the installation to the engine. To perform these measures resources within the R&D- departments, the component production lines and the service and maintenance centres of the engine manufacturers are prerequisite.

Taking into account the information given by several engine manufacturers it can be assumed that the resources within all the above mentioned sectors are fully engaged at least until 2010 with today's orders. In case of continuing economic growth the extra work load seems not feasible all at once. To avoid any problem of resources among the parties involved (ship owners, engine manufacturer, ship yards, administrations / recognized organizations) a stepwise implementation of a possible NOx regime for Pre-2000 Engines should be favoured.

As long as retrofit means are limited to engine internal measures, shipyard capacity probably will not be required to a larger extent.

Any Phasing-in scenario for implementation as proposed e.g. in document BLG 11/5/26 seems appropriate to ensure feasibility of the implementation of a IMO NOx regime for Pre-2000 Engines.

2.5 Assessment of analysis results

The assessment of the analysis results has the aim to give information on NOx reduction potentials for various scenarios. The reduction potential is estimated on the base of the analysis results and on the base of the NOx reduction target. The NOx reduction target is explained in the following.

2.5.1 NOx reduction potential

The IMO NOx Tier I limit value for NOx emissions was introduced for engines installed on ships constructed on or after 1 January 2000 with a power output of more than 130 kW. It was the aim to reduce the NOx emissions of the considered engines by 30% compared to the average emission level of diesel engines delivered in 1992. The average emission level of diesel engines delivered in 1992 was not known but had been estimated in the course of drafting MARPOL Annex VI as shown in the shaded area in Figure 24. It is to be considered that NOx emissions of engines built before 2000 were not necessarily measured according to the rules defined in the NOx Technical Code. Hence, NOx emission tests carried out before 2000 are to be handled with care, primarily if the measuring equipment is not known or not according to the requirements of the NOx Technical Code. Even, the international standard for exhaust gas measurements from diesel engines was available only in 1996 (ISO 8178: 1996).

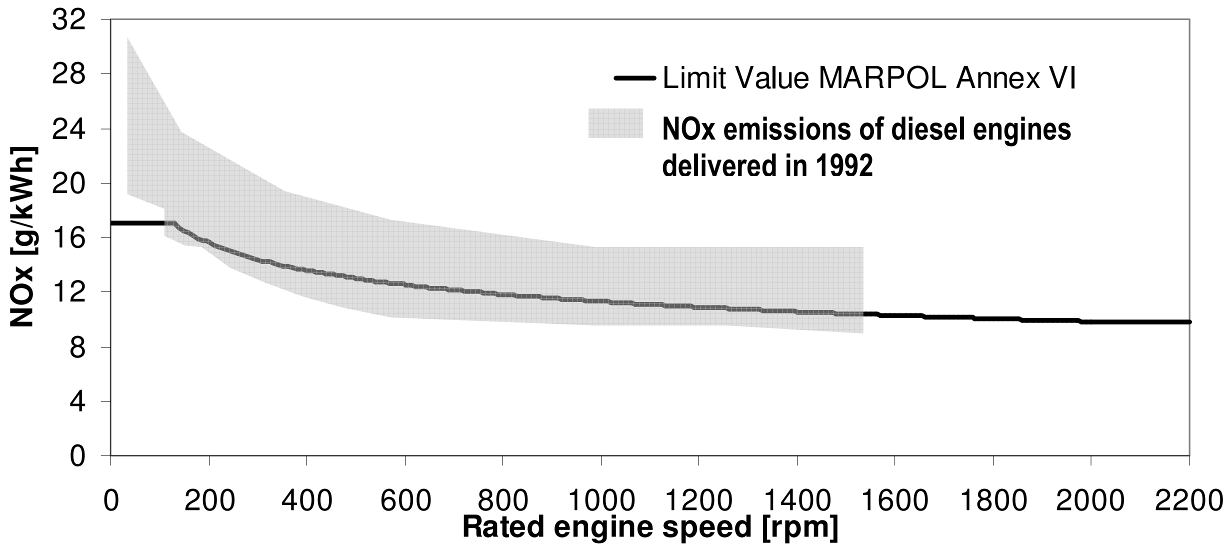

Figure 24: NOx emission limit of MARPOL Annex VI, Regulation 13

The NOx emission level of Pre-2000 Engines is not equal for all engines. Depending on the date of build the emission level is changing due to various requirements for new engine development. Figure 25 is showing the qualitative trends of emissions for the relevant period of time. It can be observed that the engines with highest NOx emissions were constructed during the time between the mid 70s until the mid 90s. Older engine constructions until the mid 70s were not yet optimized in terms of efficiency. The fuel consumption is higher than of later engine types with relative high emissions of CO and HC. The emissions of NOx of such engines are comparatively low. Optimization of the combustion process as consequence of increasing fuel prices due to the fuel crisis led to less fuel consumption and less CO and HC emissions, however, unfortunately to increasing NOx emissions. In the early 90ies of the past century engine constructions with lower NOx emissions at steady fuel consumption without or with limited increase of the other emissions were developed as consequence of the continuing discussions about NOx emission standards [B 9].

Figure 24 shows that several Pre-2000 Engines delivered in 1992 do comply with IMO NOx Tier I standard already. In combination with the information provided in Figure 25 it is allowed to conclude that Pre-2000 Engines of other date of build than 1992 comply even in higher numbers as the NOx emission level in 1992 is within the highest range of the trend.

However, for further estimates it is assumed that the IMO NOx Tier I standard is 30% below the average emission level of all Pre-2000 Engines. Hence, if IMO NOx Tier I standard shall apply to Pre-2000 Engines the NOx emissions of Pre-2000 Engines are to be reduced by 30% in average. The reduction target is 30% of the NOx emissions of Pre-2000 Engines. Reviewing the results it must be considered that 30% reduction of NOx emissions from all Pre-2000 Engines is the maximum theoretical achievable NOx reduction potential. In reality less reduction is to be expected.

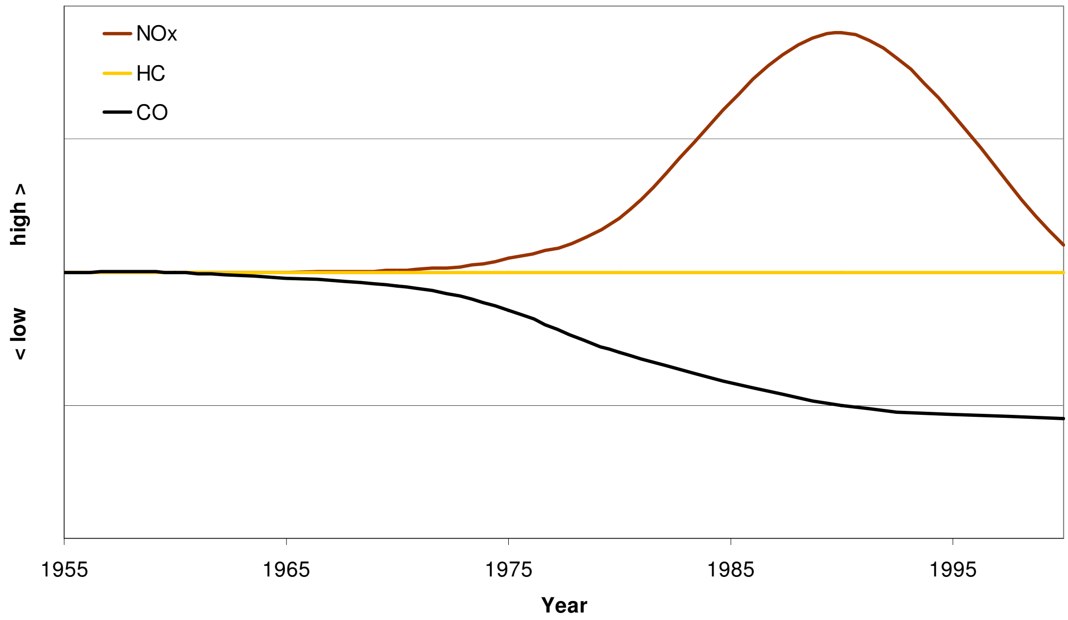

Figure 25: Qualitative historical view on diesel engine emissions

2.5.2 Presentation of the results

For various engine groups within the Pre-2000 Engines the maximum theoretical achievable NOx reduction potential is calculated. The calculation is based on the result of the statistical analysis and on the reduction target of 30% NOx reduction. The reduction potential for each scenario is provided as share in the NOx emissions of Pre-2000 Engines only and as share in the NOx emissions of all engines. The reduction potential for each scenario is shown as summary below and in Appendix E.

The presentation of the share in the NOx emissions of Pre-2000 Engines only is such that the NOx emissions from all Pre-2000 Engines from 1950 and 2007 are set as 100% value. All Pre-2000 Engines are set as total number of engines.

The left, brown column represents the NOx emissions of all Pre-2000 Engines. The reduction target of 30% NOx emission reduction is indicated by a horizontal line, separating 30% of the column. The separated area of the left column is the NOx reduction potential if the NOx emissions from all Pre-2000 Engines could be reduced by 30%. In cases where not all Pre-2000 Engines are considered but various engine groups only the NOx reduction potential decreases. The vertical line within the separated area indicates the share of various engine groups in all Pre-2000 Engines. Hence, the resulting area which is coloured in a darker brown represents the NOx reduction potential for each specific engine group considered. The number within the area indicates the NOx reduction potential as share in the NOx emissions from all Pre-2000 Engines.

The right, blue column represents the number of all Pre-2000 Engines. The vertical line indicates for various engine groups the share of engines to be modified in all Pre-2000 Engines. Hence, the resulting area which is coloured in a darker blue represents the engines to be modified to reach the NOx reduction potential of the considered engine group. The number within the area indicates the share of engines to be modified in the number of all Pre-2000 Engines.

Figure 26 provides detailed information on the methodology of the presentation of the results.

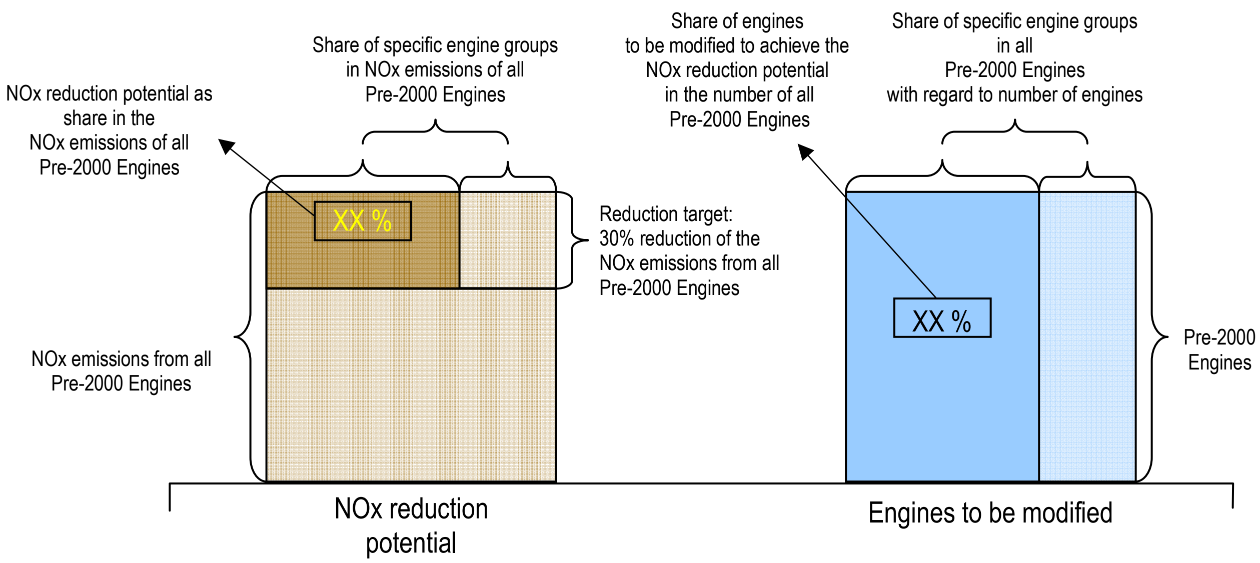

Figure 26: Methodology of the presentation of results with respect to the NOx reduction potential as share in NOx emissions from <u>all Pre-2000 Engines</u>

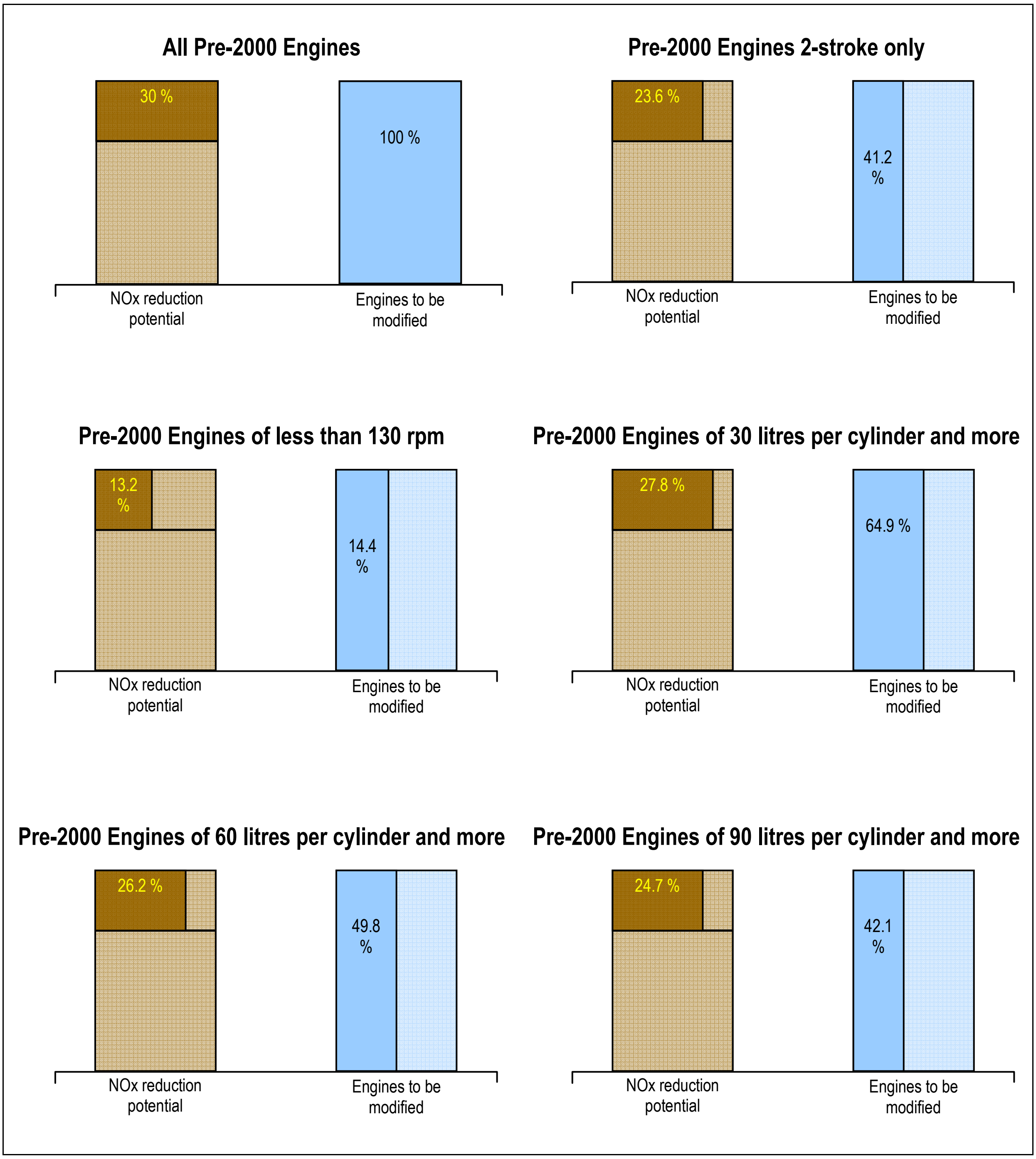

Table 9: NOx reduction potential as share in NOx emissions from all Pre-2000 Engines

The presentation of the share in the NOx emissions from all engines is such that the NOx emissions from all engines from 1950 and 2007 are set as 100% value. The number of all engines is set as total number of engines. In the left column the NOx reduction potential is provided as share in the NOx emissions from all engines. The share of engines to be modified in the number of all engines is provided in the right column.

Figure 27 provides detailed information on the methodology of the presentation of the results with respect to the NOx reduction potential as share in NOx emissions from all engines.

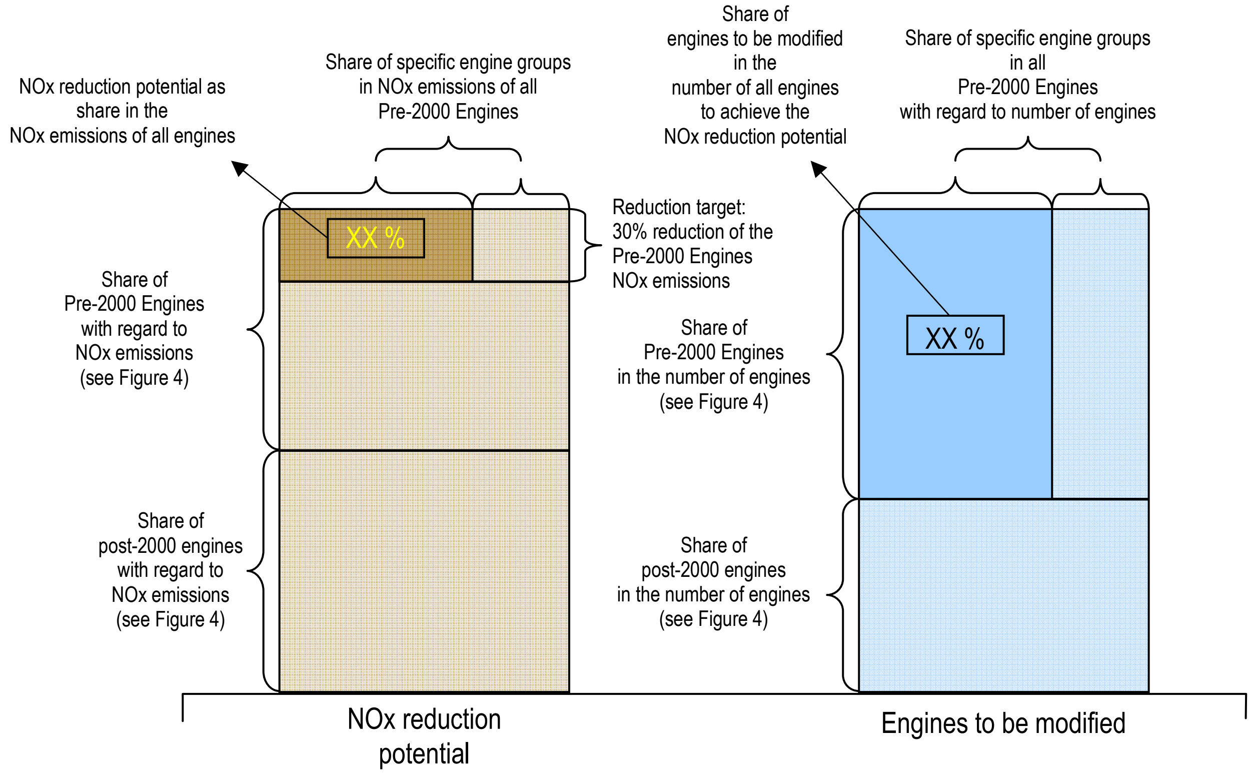

Figure 27: Methodology of the presentation of results with respect to the NOx reduction potential as share in the total NOx emissions from all engines

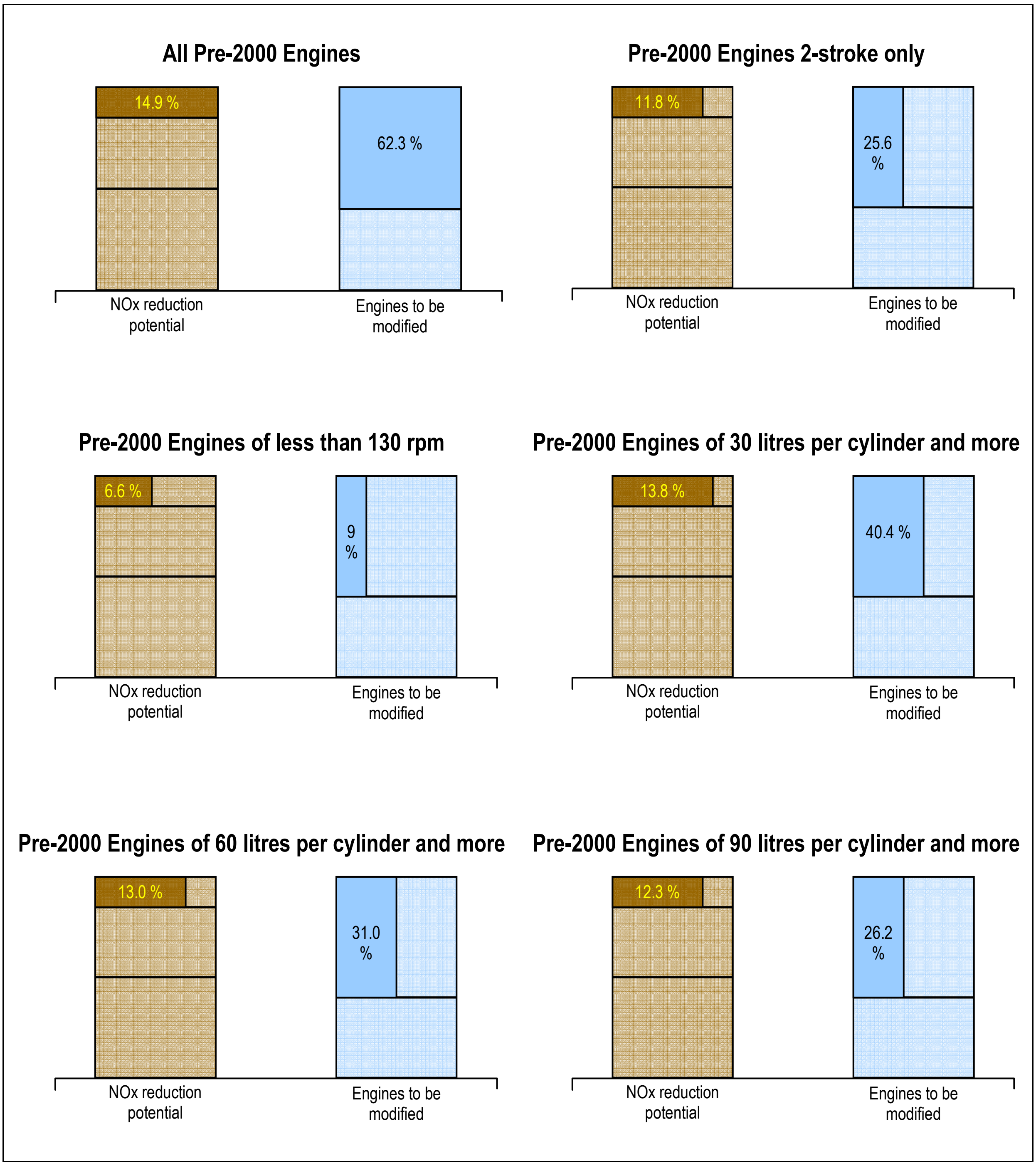

Table 10: NOx reduction potential as share in NOx emissions from all engines

3 Exemptions and alternative options for Pre-2000 Engines inappropriate for modification

Even knowing that nothing is impossible theoretically and practically, it may be confirmed that some economic and ecologic limits even are set to refrain from doing everything what is possible. Outlined in IMO documents BLG WGAP 2/2/12 and BLG WGAP 2/2/13 there will be engines which can not be brought in compliance with the applicable IMO NOx Tier I limits with reasonable efforts irrespective whether all Annex VI engines would fall under a possible new regulation or a limited range/category of Pre-2000 Engines only. Hence, some kind of regulations or guidelines on how these exemptions should be handled need to be established. However, it has to be kept in mind that distortion of competition must be avoided. In the following some options are provided on how engines which are not capable to be modified in order to make them IMO NOx Tier I compliant could be addressed.

1. Exemptions

   The ship owner may have the option to provide evidence that the engine to which possible new regulations would apply can not be modified in a way to make it IMO NOx Tier I compliant with reasonable efforts. 'Reasonable efforts' in this context is interpreted as specified in Section 1.4, i.e. that for the modification of a Pre-2000 Engine none of the following criteria applies:

   - The Pre-2000 Engine is not further developed and important information is missing. The impact of NOx reducing measures is not predictable for this engine type and no comparable engine is available for test bed investigations. The number of engines of this type in operation is limited and the installed power of engines of this type in operation is less than 500 MW.
   - The modification of a Pre-2000 Engine implies the exchange of major engine components, such as crankcase, crankshaft, camshaft, cylinder heads and would have a major impact on the engine's class certificate.
   - The modification of a Pre-2000 Engine implies major re-construction of the engine room or of the ships structure
   - The costs for the measures are close to or even exceed the costs for a new engine

   This approach seems to be easy applicable, however, two points of concern may be raised:

   a. This option might create a loophole to by-pass the requirements
   b. This option may lead to distortion of competition. Probably there are cases where ships of same type and size or even sister ships owned by different lines are equipped with engines of different make. It might happen that the one engine manufacturer provides the option to modify the engine accordingly while the second maker does not. Hence, one owner need to invest in retrofit measures, the competitor does not.

2. Incentives

   Referring to a.m. example, the introduction of an incentive scheme could compensate (or even more than that) the original disadvantage the first ship owner has faced. The introduction of incentive regimes, however, could not globally be introduced by the IMO, hence, it could not be specified in an IMO regulation. However, it could be considered whether the IMO may prepare some kind of respective guidelines to be applied by flag states, as appropriate. At least, the IMO could urge Port States to charge increased port fees and fairway dues from ships which fall under the new requirements and which cannot comply.

3. Emission trading

   Emission trading could potentially form an option to compensate non-conformity with Pre-2000 Engines regulations. With regard to the implementation, similar aspects as in above item 2 may be considered.

4. Use of low sulphur heavy fuel oil (LSHFO)

   Since money does not necessarily help to improve the air quality, non-compliant ships might be required to run the engine in question **continuously** in all sea areas on low sulphur fuel as specified for use whilst operating in designated Sulphur Emission Control Areas (SECA). This currently would imply that the ship could be prohibited to burn any fuel exceeding a sulphur content of 1.5% m/m.

   The use of low sulphur fuel would of course not have an essential impact on the NOx emissions but would help to reduce pollutant emissions to air in another way.

5. Use of distillate fuel

   A further option for the owner could be to use distillate fuel with a maximum sulphur content of currently 1.5 % m/m (SECA limit) on the engine which would be affected by new Pre-2000 Engine regulation. The effect would be similar to that described under item 4 above. A slight reduction in the emissions of NOx could be expected here, too, because the nitrogen content of distillates in most cases is less than the nitrogen content in heavy fuel. By using distillate fuel a lower potential for the formation of NOx during the combustion may be anticipated whereas the reduction potential is small.

   A sub-option under this item could be to run **all** auxiliary diesel engines and boilers on board with distillate fuel only.

6. Exhaust gas aftertreatment systems

   As a technical option other than those addressed in Chapter 1 the ship owner may consider to install and operate any kind of exhaust gas aftertreatment device appropriate for the use on board, i.e. applicable class requirements (including SOLAS) must be fulfilled. The system should be capable to reduce the NOx emissions from the engine(s) in question at least to a level as required by a new regulation. The operation of the system shall be monitored when the engine it is applied to is running. The monitoring shall be recorded. Taking into account the provisions of the NOx Technical Code as specified in 2.3.7 and 2.3.8, testing procedures and certification need to be considered carefully.

7. Engine power de-rating

The de-rating of an engine is applicable and acceptable to propulsion engines only. De-rating of an auxiliary diesel engine driving a generator for electricity supply on board would impact the safety of the ship due to an increased risk of a 'black out' (total loss of electrical energy on board).

When talking about de-rating of a propulsion engine, reduction of the ship's speed is concerned. The correlation between the ship's speed and the power demand for propulsion is

$$P \sim v^3 \qquad \text{with P := propulsion power; v := ship speed}$$

This correlation is also known as 'nominal propeller law'. The exponent may slightly vary depending on the ship's shape or resistance respectively. Due to this correlation, a reduction of the ship's speed results in a drastic reduction of propulsion power (examples below are approx. figures):

Speed reduction:	**Power reduction**
10 %	75 %
15 %	63%
20 %	54 %

Reduction of ship speed can be achieved by reducing the propeller pitch and keeping the propeller/engine speed constant or by keeping the propeller pitch constant and reducing the propeller/engine speed.

Ship owners will consider a fixed de-rating of the ship's speed only if a reduced speed would match into the sailing list of their fleet. If a ship owner would decide so, dependent on the ship type several aspects need to be considered:

a. Classification issues are concerned
b. The propulsion engine needs to be de-rated what will affect the engine class certificate
c. De-rating of an engine in most case does not mean to limit the maximum fuel rack position only on but will result in major engine modification (e.g. Turbocharger nozzle ring, injection nozzles) in order to optimise the engine for the reduced power and to keep the engine reliable for long term operation.

Speed reduction, i.e. reduced engine output would result in a reduced exhaust gas mass flow, of course, and by this the emitted pollutant exhaust gas components are reduced by mass as well. When it comes to the engine itself and the assessment of its emission behaviour it must be considered that the reference emission are specified as engine specific values expressed in grams per kilowatt and hour (g/kWh). So it may happen that a de-rated engine's specific emission value is even higher than before. Resulting from the aforesaid, a de-rated engine needs to be certified based on its de-rated set-up rather than on its original (100%) adjustment.

4 Survey and certification requirements

4.1 General aspects

As mentioned in above Section 1.1 already this is to remind that a marine diesel engine is subject to extensive drawing and construction verification procedures and exhausted test bed testing at the manufacturer's facilities before Classification Societies are going to confirm the general approval for an engine type being suitable to be installed on classified sea-going vessels in principle. Each subsequent built individual engine has to undergo work trials under the supervision of the respective class surveyor. During these trials operating values for certain load points have to be measured, recorded and compiled in an acceptance protocol. The protocol issued by the engine manufacturer as well as the class certificate form part of the engine's documents to be kept on board. After installation on board a ship further tests need to be performed during a sea trial showing that the engine's application on board with all its auxiliary and safety devices matches all applicable requirements, statutory as well as class issues.

Modifications performed on board after the ship has been put in service may be subject to additional surveys. Dependent on the scope of modifications made to a diesel engine, the original certification might cease to be valid and, as a consequence, new test need to be made prior to re-issue of an engine's class certificate. When considering measures to reduce the NOx emissions from a diesel engine it has to be verified whether the original engine certification possibly is affected.

Flag State Administrations or Recognised Organisations acting on behalf of Administrations must keep in mind always the dependency between engine class certificate and modifications possibly affecting the class issues when any modification to an engine is planned. Modifications might require the performance of additional acceptance tests and re-issue of engine class certificates.

4.2 Basic principles for the survey and certification regime

If it comes to the implementation of requirements for NOx emission controls for Pre-2000 Engines one main issue will be the introduction of a practice oriented, reliable and also credible survey and certification regime. As experienced for almost 10 years application of the IMO's 'Technical Code on Control of Emission of Nitrogen Oxides from Marine Diesel Engines' (NOx Technical Code) it seems to be obvious to apply the main principles of the Code to Pre-2000 Engines in almost the same manner.

The practical pre-requisites for the certification of Pre-2000 Engines, however, may be expected to be much more complex in many cases than for new engines where the engine manufacturer in the vast majority of applications takes care for the preparation of the required engine's Technical File, all necessary supplementary documentation and drawings as well as the emission testing. With regard to the Pre-2000 Engines it is noted by the IMO group dealing with the issue that the certification, including emission testing, compilation of the Technical File and verification procedures, appropriate to such engines is to be 'simplified', as compared to the provisions of the existing NOx Technical Code. It has to be recognised, however, that there are limits beyond which verification and survey cannot be reduced without loosing any credibility. Consequently, it is anticipated that in practice the degree to which the procedures really can be simplified may be limited. The introduction of an additional certification scheme could itself create a number of new issues which will need to be resolved.

The engine group concept as provided in Chapter 4 of the NOx Technical Code may be applied for Pre-2000 Engines similarly, the engine family concept, however, should not be applied.

As aforementioned, there will be engines which fall under the possible Pre-2000 Engines requirements which cannot be brought in compliance with the IMO NOx Tier I limits by engine modifications with reasonable effort. Thus, as indicated in Chapter 3 of this study, the ship owner should have the possibility to compensate the lack of NOx reduction by engine modification by an alternative emission reduction option (AERO), to be approved by the Administration. Such an alternative emission reduction method then, of course, would also be needed to be verified, assessed and certified. This approach is reflected in the proposed survey and certification regime as well.

The authors have worked out proposal for a possible survey and certification regime for different scenarios:

- Certification of an engine which could be covered by an approved engine group, i.e. 'Member Engine'
- Drawing approval and emission test followed by group approval and 'Parent Engine' certification
- Emission testing followed by certification as 'Single Engine'
- Certification of Alternative Emission Reduction Options, 'AERO'

The flow chart as given in Figure 28 below provides a simple general view on the certification process and form the basis for the more detailed procedures drawn in the subsequent flow charts.

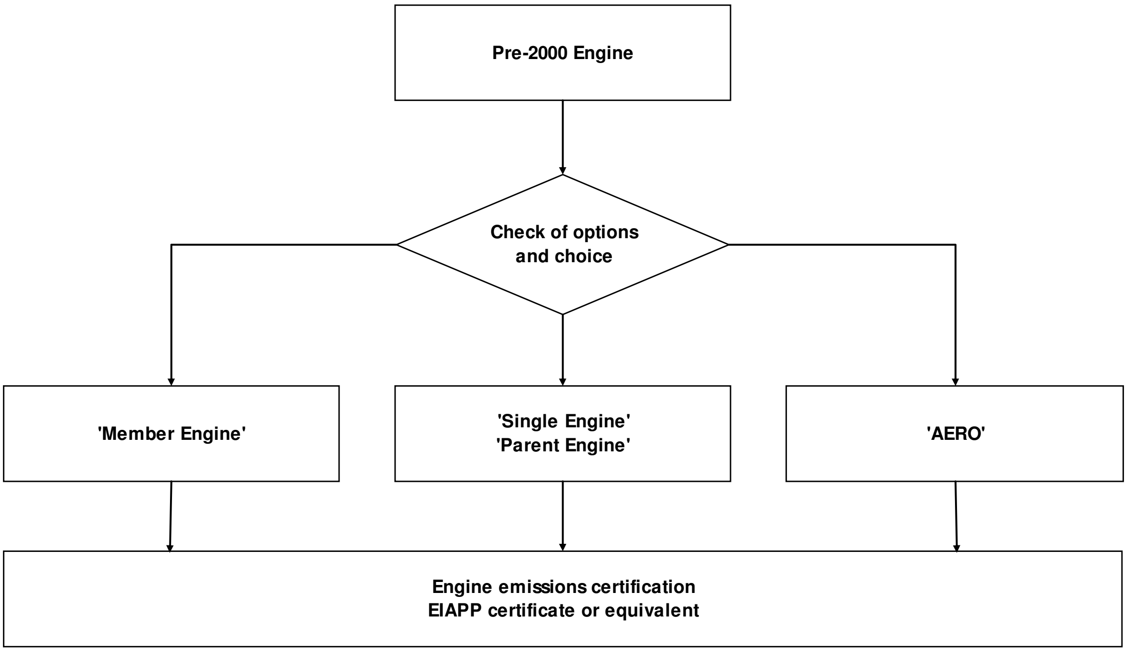

Figure 28: General view on the certification process

It is not of relevance for the certification procedure whether the possible new regulations for Pre-2000 Engines apply to all engines or to a certain range of engines only. Those engines to which they would apply in any case need to be provided with an EIAPP certificate, or equivalent (dependent on the flag state requirements). The certificate shall confirm either that the Pre-2000 Engine complies with the applicable NOx emission limit or that an alternative emission reduction option as approved shall be applied.

The engine owner should have the choice between the following options, if applicable:

1. ‘Member Engine’ certification
   The Pre-2000 Engine can be certified as a Member Engine of an existing Engine Group.

2. ‘Single Engine’ or ‘Parent Engine’ certification
   An emission test will become necessary on board the ship or on a test bed.

3. Certification of an alternative emission reduction option (AERO)
   The ship owner shall have the option to select an alternative method to be applied to the engine in question or the ship, for instance if option 1 or 2 is not possible.

These options are described in more detail in the following sections. The complete flow chart of the proposed survey and certification regime is shown in Appendix F.

4.1 Member Engine certification

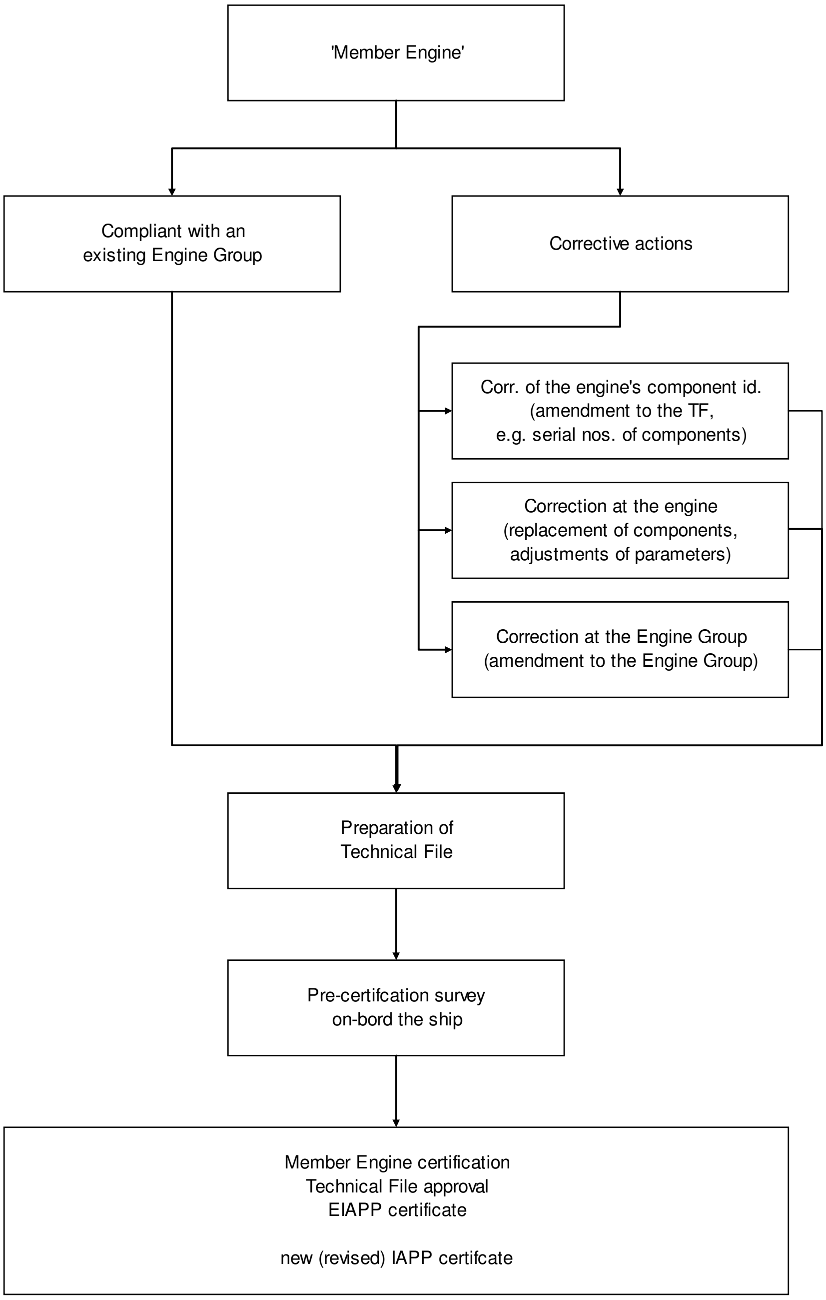

Figure 29: Member engine certification flow chart

A Pre-2000 Engine may be certified as a 'Member Engine' of an existing approved engine group if the engine in principle is covered or can be brought in a configuration that it meets the engine group specifications (rating, emission relevant components and adjustments).

Thus, an emission test of the Pre-2000 Engine is not necessary, however the engine's Technical File needs to prepared and approved prior obligatory pre-certification survey.

Most of the existing approved engine groups are designated to the engine manufacturer's property. The ship owner in these cases should turn to the engine manufacturer for application for the certification of the Member Engine (Pre-2000 Engine) at the flag state Administration or an organisation acting on their behalf (Recognised Organisation). Thus, a co-operation between engine owner (ship owner) and engine manufacturer will become necessary in almost any case.

4.1.1 Compliant with an existing Engine Group

If the Pre-2000 Engine turned out to meet all specifications of an existing approved engine group the engine may become a Member Engine of the relevant engine group. This option requires the commonly used Member Engine certification procedure according to MARPOL Annex VI, NOx Technical Code.

4.1.2 Corrective actions

Corrective actions are possible if the Pre-2000 Engine differs from the specification of the relevant Engine Group. The following possibilities could be applied solely or in combination.

1. Correction of the engine's component identification
   If a Pre-2000 Engine complies with the specification of an existing Engine Group but the component marking does not correspond to the identification numbers stated in the engine group's basic Technical File an amendment to the engine specific Technical File should be made. Pre-requisite for such an amendment to the engine specific Technical File must be a verification providing evidence that the relevant components used in the engine are identical in terms of emission behaviour to the components approved for the engine group. In any case a component marking is necessary to identify the components. An amendment shall be added to the Technical File which contains a reference list of actual component marking and the identification numbers approved for the engine group.

2. Correction at the engine
   If a Pre-2000 Engine does not comply with the specification of an existing Engine Group the relevant components and/or adjustments can be changed to reconcile the engine with the specification of the Engine Group.

3. Correction at the Engine Group
   If a Pre-2000 Engine does not comply with the specification of an existing approved engine group the relevant engine group specification may be extended in order to reconcile the engine with the

specification of the engine group. It must be proven, however, that the NOx emission value of the group's Parent Engine will not be exceeded if new components or alternative adjustment options for the engine are intended to be added to the engine group specification. Evidence could be provided by results of an emission test, a parameter sensitivity test or a even by theoretical investigation.

4.1.3 Pre-certification survey on-board the ship

According to the requirements of the NOx Technical Code the engine has to be surveyed to ensure that the engine, as designed and equipped, complies with the applicable NOx emission limit, i.e. a verification shall be performed confirming that the engine's rating, its components, adjustments and the documentation comply with the requirements.

It is suggested that after entry into force of the proposed new regulations for Pre-2000 Engines the survey should take place at the ships intermediate survey or renewal survey, whichever occurs first (or later; this is to be finally regulated by IMO)

4.1.4 Member Engine certification

If the Pre-certification survey has proven that the Pre-2000 Engine is compliant the engine may be certified as it is common practice in accordance with the NOx Technical Code. The Technical File shall be approved and the EIAPP certificate or equivalent shall be issued.

Furthermore, the ship's International Air Pollution Prevention certificate (IAPP) needs to be re-issued containing the information of the certified Pre-2000 Engine.

4.2 Engine emissions evaluation

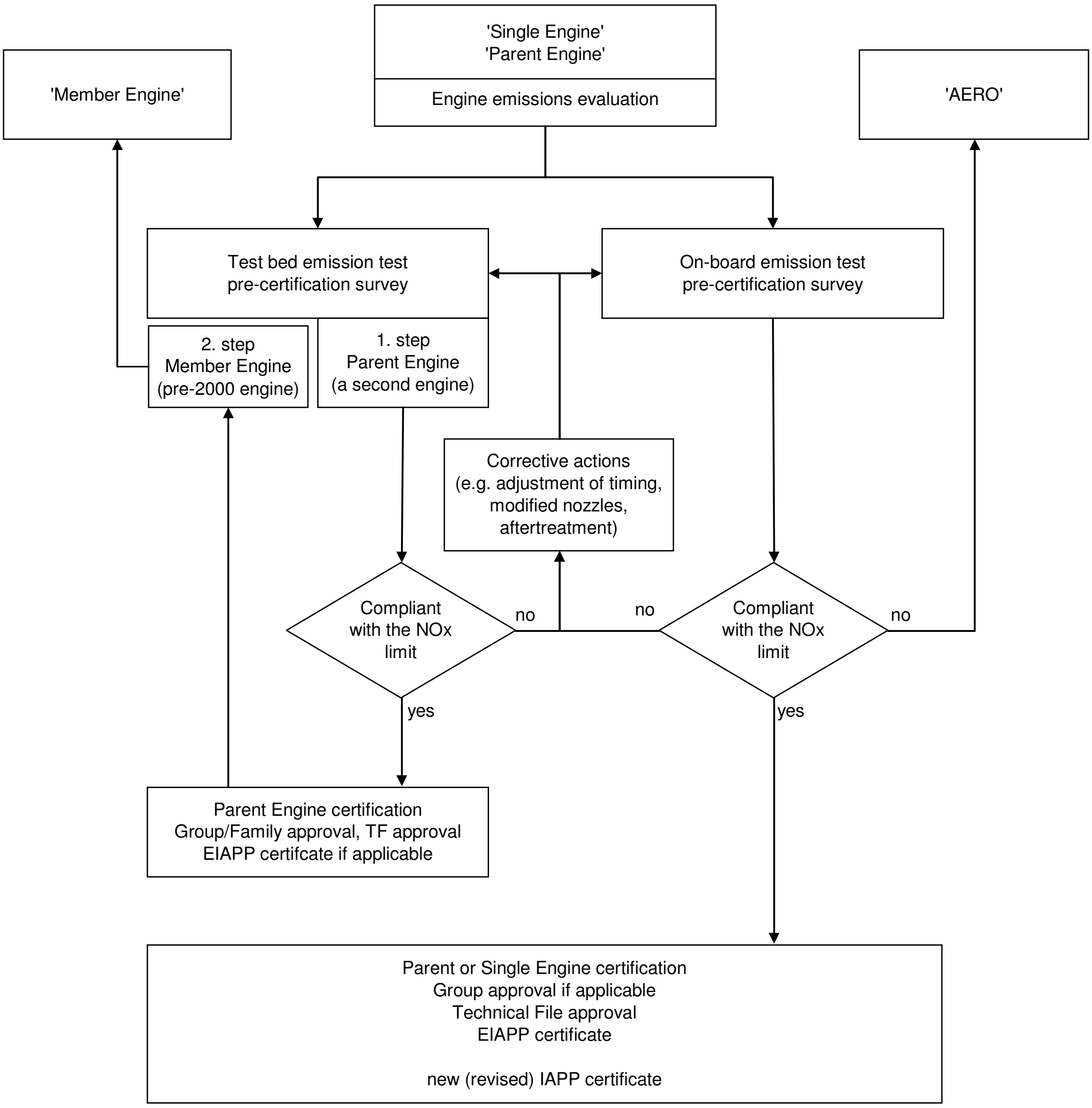

Figure 30: Engine emissions evaluation flow chart

The evaluation of the NOx emissions of an engine becomes necessary if the pre-requisites for a Member Engine certification according to Chapter 3.1 are not applicable. In these cases an emission test has to be performed according to the requirements of the NOx Technical Code, Chapter 5. An emission test may be performed on a test bed or on-board the ship. The tested engine may subsequently be certified as 'Parent Engine' of a new engine group or as a 'Single Engine'.

The current MARPOL Annex VI, Regulation 13, and the NOx Technical Code in its actual version do not apply for Pre-2000 Engines. Therefore, component identification numbers as introduced for IMO NOx compliant engines in most cases are not available. It is recommended to investigate whether it is possible to show compliance of the engine by verification of engine operating parameters. That could be lead to an additional system of On-Board Verification Procedure according to Chapter 6 of the NOx Technical Code or possibly to a combination with the 'Parameter Check Method'. The 'Simplified measurement method' or the 'Direct NOx monitoring method' as provided in the Code may be applied as well for annual, intermediate and renewal surveys, however, they are not appropriate for the initial certification survey.

4.2.1 Test bed emission test

The test bed emission test is applicable if it is either possible to take an engine off board the ship for modification or a similar engine in terms of type, model, rating and set-up is available on a test bed. It must be considered that the performance of an emission test on board is difficult and costly if the requirements of the NOx Technical Code for certification purposes are applied. In fixed pitch propeller applications it is even not possible to match with the required test cycle requirements. Test bed testing of an engine would open the option to establishing a new engine group designating the tested engine as 'Parent Engine'. The Pre-2000 Engine on board would then be considered as 'Member Engine' and certified accordingly. The guidelines for selection of an engine group set out in Chapter 4 of the NOx Technical Code need to be applied.

The emission test of the Parent Engine has to show compliance with the applicable NOx limit. If necessary, corrective actions shall be undertaken. Subsequently, the tested engine may be certified as 'Parent Engine' including approval of the Technical File and approval of the engine group.

4.2.2 On-board emission test

If there are no other possibilities available to prove an engine's compliance with the IMO NOx Tier I requirements the Pre-2000 Engine may be tested on-board the ship. Basis for the emission test on board shall be the requirements of the NOx Technical Code, Chapter 5. However, as aforementioned it is considered to be a fact that for fixed pitch propeller applications test cycle E3 for propeller law operated main engines can not be performed in accordance with the requirements. Ideas on how to handle this problem may be developed but are not within the scope of this study.

4.2.3 Parent Engine certification

Where a tested engine is intended to become the 'Parent Engine' of an engine group, the applicable documentation, the basic Technical File and the engine group will be approved, full compliance with the requirements provided. Subsequently, the ‘Parent engine’ and ‘Member Engines’ of the designated group may be certified on a serial number basis, satisfying surveys provided.

4.2.4 Single Engine certification

Where a tested engine is not intended to become the ‘Parent Engine’ of an engine group, the applicable documentation, the engine specific Technical File and the engine group will be approved, full compliance with the requirements provided and the engine’s certificate may be issued. This kind of certification does not cover any ‘Member Engines’.

4.3 Application of alternative options for Pre-2000 Engines not suitable for Tier I compliance

If the ship owner chooses an alternative option or if an engine fails to comply with the requirements of IMO NOx Tier I, alternative emission reduction options (AERO) could be applied if approved by the Administration. Chapter 3 provides further details of such possible options. Alternative emission reduction methods, of course, would also be needed to be verified, assessed and certified. How to proceed in this case is proposed in the following.

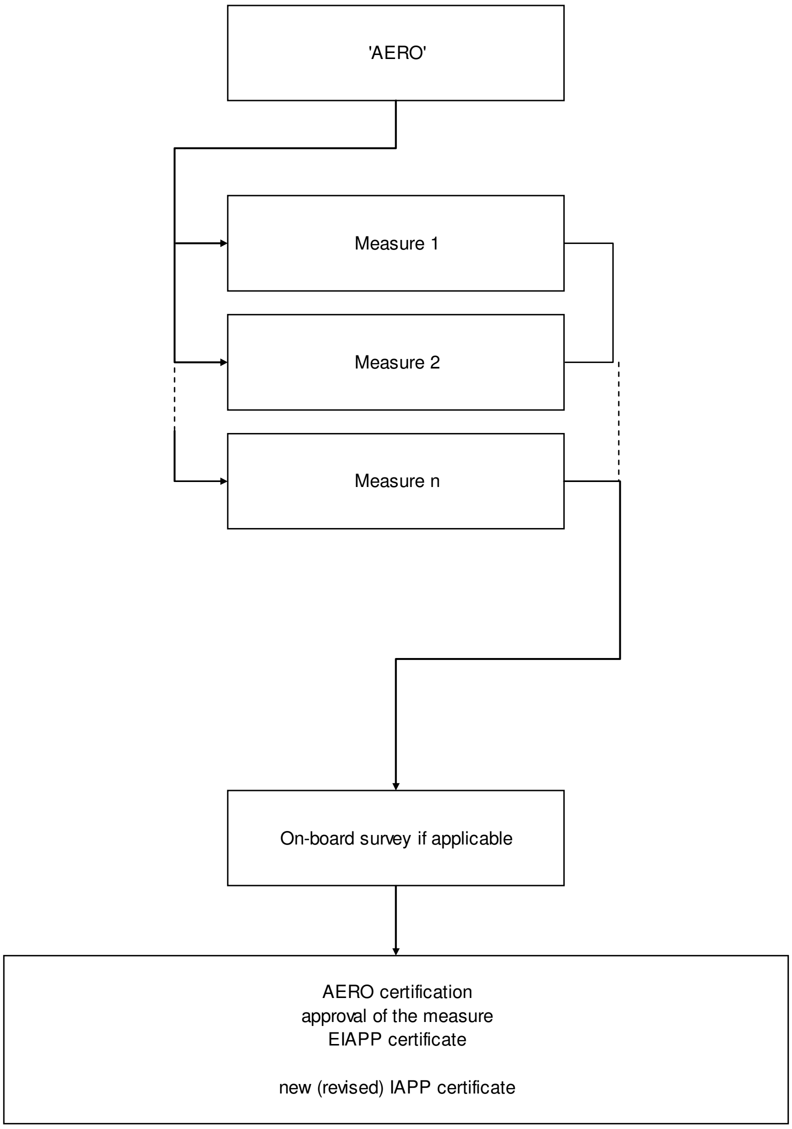

Figure 31: Alternative measures certification flow chart

The ship owner should have the option to choose the Pre-2000 Engine survey and certification regime. Thus, alternative emission reduction options should be defined very carefully.

4.3.1 On-board survey

Depending on the alternative emission reduction method a survey on-board the ship shall be performed based on a certain kind of Technical File.

4.3.2 Alternative Measures certification

The application of the alternative emission reduction method shall be approved as an 'AERO' for an Pre-2000 Engine not complying with the IMO NOx Tier I limits. A modified Engine International Air Pollution Prevention certificate (EIAPP) may be issued accordingly. Furthermore, the ship's International Air Pollution Prevention certificate (IAPP) needs to be re-issued containing the information on the AERO certification.

5 Conclusion

In order to provide objective information on the discussions held at IMO on how to deal with Pre-2000 Engines this study summarizes possible technical modifications to reduce NOx emissions, identifies the range of engines for modification, specifies alternative emission reduction options and lines out possible survey and certification requirements for Pre-2000 Engines.

Basing on the suggestion that possible NOx emission limits for Pre-2000 Engines are oriented at the existing NOx Tier I limits for marine diesel engines, emphasis is placed on engine internal measures. It may be recalled that the discussions for setting NOx Tier II standards even for new engines are focussed on engine internal measures.

The inventory of possible technical modifications to reduce NOx emissions from Pre-2000 Engines shows that the range of applicable techniques is limited. Taking engine internal measures into consideration only the scope of practical feasible measures is reduced to the adjustment of the ignition timing and the optimization of the injection nozzles. These measures are not applicable on all Pre-2000 Engines in general but have to be developed and tested on a case-by-case basis. The NOx emission reduction potential of injection nozzle optimization is considered higher for large bore 2-stroke engines than for 4-stroke engines whilst retarded injection timing is probably better suited for smaller 4-stroke engines.

The exchange of components of the combustion chamber seems to be inappropriate for both, 2-stroke and 4-stroke engines. In addition to extensive research, development and testing it needs to be taken into account that the engine type approval as granted by the Classification Society may be affected.

More advanced techniques such as water based abatement systems include more extensive modifications involving ship modifications. Additional water treatment installations and pipe working are necessary. Special attention should be paid to the additional power consumption for fresh water treatment. Water based abatement systems may be suitable for 4-stroke engines but they are not considered as suitable for 2-stroke engines.

Exhaust gas after treatment systems are not taken into account in detail. Exhaust gas recirculation systems which reroute a part stream of the exhaust gas back to the combustion chamber also are not regarded as this technique including exhaust gas cleaning and cooling devices might be considered as a kind of after treatment system, too.

It can be concluded that up to a certain degree engine internal technical modifications to reduce NOx emissions from Pre-2000 Engines are theoretically possible but penalties in fuel consumption and high development, installation and operational costs put these measures in question. In some selective cases easy to install solutions are available. Hence, the aim to reduce NOx emissions from Pre-2000 Engines by 30 % in average is rated as optimistic approach. Further, the influence on the safety of ships and on ship and engine certificates issued by the Classification Society is to be considered carefully.

Replacement engines are a particular species of Pre-2000 Engines. In order to anticipate the installation of uncertified, non IMO NOx Tier I compliant engines on ships constructed before 1 January 2000, Regulation 13(2) of MARPOL Annex VI may be amended. It may be granted to replace uncertified Pre-2000 Engines by identical, uncertified engines, if the date of build of the engine is before 1 January 2000. However, where a replacement engine differs from the original engine in terms of type or model or performance even, the replacement engine must comply with the IMO NOx Tier I requirements irrespective the engine's date of build.

The statistical analysis of a ship database with regard to Pre-2000 Engines installed on these ships provides information on the distribution of the engines in respect to different assessment criteria and their share in the NOx emissions. The data of the database is reduced to consider ships only which may be relevant for a new IMO NOx regime and for which relevant engine data is reported. The remaining statistical base is validated as representative.

The ships within the remaining statistical base are assessed with respect to selected engine criteria which are engine stroke, engine rpm, engine power and cylinder displacement. Information on the number of ships with these engines, on the number of engines of specific build and on the share of the engines in the NOx emissions is provided. Finally, a general view on the share of specific engine groups in the NOx emissions of all Pre-2000 Engines and in all engines is drafted in a graphical way. The reduction potential of NOx emissions and the number of engines to be modified to achieve this reduction are opposed in a benefit / effort - scenario.

The general view on the share of specific engine groups in NOx emissions is provided in Table 9 related to the NOx emissions from all Pre-2000 Engines and in Table 10 related to the NOx emissions from all engines. Assessing the results with respect to the best benefit / effort ratio, where NOx reduction potential is regarded as benefit and engines to be modified is regarded as effort, leads to the conclusion that the scenario where engines of less than 130 rpm are considered only is most effective, followed by the scenario where engines of 90 litres per cylinder and more are considered only. However, it is to be kept in mind that the group of engines of less than 130 rpm consists mostly of 2-stroke engines (99.8 % in the number of engines). The group of engines of 90 litres per cylinder and more consists of 2-stroke engines (90.5 %) and 4-stroke engines (9.5 %) and, hence, considers both types of diesel engines. Further, it is to be considered that the NOx reduction potential as share in NOx emissions from all engines is comparatively low for engines of less than 130 rpm (6.6 %), considering the NOx reduction potential of engines of 90 litres per cylinder and more (12.3 %).

The results of the other specified groups of engines (2-stroke engines only, engines of 30 / 90 litres per cylinder and more only) are less effective with regard to the benefit / effort ratio. Further, the total NOx reduction potential of these engine groups is not remarkable higher. Even, the NOx reduction potential of all Pre-2000 Engines together is within the same range (14.9 % NOx reduction potential, as share in NOx emissions from all engines), having the worst benefit / effort ratio.

Taking the above mentioned considerations into account it seems to be most effective to address engines of 90 litres per cylinder and more with new requirements. With regard to the benefit / effort ratio and the level of the NOx reduction potential of this engine group a considerable compromise can be achieved.

Reviewing the results it is to be considered that the NOx reduction potential for each group of engines is a theoretical best case potential. It is made the assumption that all considered Pre-2000 Engines are reduced in NOx emissions by 30 % in average. Having in mind that 30 % NOx reduction is not considered achievable with the available technical modifications and having further in mind, that some Pre-2000 Engines already comply with Tier I standard and others are not modifiable it seems realistic that in reality the provided NOx reduction potentials could be obtained at a range of 50 % of the presented results.

The extent to which the theoretical NOx emission reduction potential is achievable depends on the considered engine group. The inventory of possible technical modifications to reduce NOx emissions from Pre-2000 Engines indicates that the reduction potential by reasonable efforts is lower for 4-stroke engines than for 2-stroke engines. For both types of engines the engine manufacturers estimate a number of approx. 50 % of the Pre-2000 Engines not to be modifiable (see Table 3).

Introducing a NOx regime for Pre-2000 Engines requires solutions for technical modifications, the necessary engine components and capacities for the installation of the components to the engine. The complexity of possible engine modifications depends on the specific solution for the respective engine model and cannot be estimated in general. To avoid any problem of resources among the parties involved (ship owners, engine manufacturers, ship yards, administrations / recognized organizations) a stepwise implementation of a possible NOx regime for Pre-2000 Engines should be favoured. Information on the consequences of such stepwise implementation is provided within the 'Phasing-in' figures of the statistical analysis. It is concluded that possible new requirements for Pre-2000 Engines should not come into force before the year 2011 or even 2012 in order to have sufficient lead time for the investigation of the emission behaviour of Pre-2000 Engines and to develop NOx emission reducing measures which may be applied to Pre-2000 Engines. Further, the effective date for each individual engine should be linked to the date of renewal of the ship's International Air Pollution Prevention certificate (IAPP certificate) or the scheduled Intermediate survey, whichever occurs earlier, however in no case later than 24 months after the date of entry into force of the new requirements.

Pre-2000 Engines which do not need to be modified because they are in compliance with the NOx Tier I standard already may ease the implementation process of new requirements. These engines do not require further development or modified components. However, these engines still have to follow the certification procedures described in Chapter 4 of this study. The engine manufacturers estimate a number of approx. 11 % of 2-stroke Pre-2000 Engines and of approx. 35 % of 4-stroke Pre-2000 Engines to be compliant with NOx Tier I standard (see Table 3).

Distortion of competition is to be avoided. It is assumed that there are Pre-2000 Engines which cannot be brought into compliance with the applicable limits. Exemptions and alternative options should be considered in order to provide a possibility to keep the ships in question in operation. It is to be considered if alternative emission reduction options (AERO) as described in Chapter 3 can be chosen by the ship owner as general alternative or if alternative options apply in cases only where Pre-2000 Engines are not modifiable. The introduction of AERO as an alternative approach provides a feasible possibility for each ship to comply with the requirements.

The basic principles of the survey and certification requirements for Pre-2000 Engines are orientated at the current requirements of the NOx Technical Code. It is one main issue to introduce a practice oriented, reliable and also credible survey and certification regime. As experienced for approximately 10 years application of the NOx Technical Code it seems to be obvious to apply the main principles of the Code in almost the same manner. The introduction of an additional certification scheme could itself create a number of new issues which will need to be resolved. Further, alternative survey and certification requirements for Pre-2000 Engines would put the established requirements for post-2000 engines in question.

An Engine International Air Pollution Prevention certificate (EIAPP) shall be issued for each Pre-2000 Engine, based on an approved Technical File and an initial engine survey. In order to avoid certification testing of every Pre-2000 Engine for compliance with the applicable NOx emission limit the engine group concept may be applied. The engine group concept may include a test engine on the test bench. The test engine should allow the assessment and validation of the effectiveness of measures to reduce the NOx emissions from Pre-2000 Engines.

The NOx Technical File shall include a description of these measures including test results, a specification of the applicable components and settings including engine performance data, and shall be approved by the Administration. A description for applicable on-board verification shall also be provided.

There are Pre-2000 Engines which potentially comply with the applicable NOx limits. If the ship owner with or without the aid of the engine manufacturer is in the position to provide evidence thereof, a reduced Technical File stating the engine specification may be approved and a EIAPP certificate issued. The applicant shall also have the option to perform a simplified measurement according to Chapter 6 of the NOx Technical Code under supervision of an authorised surveyor to show compliance.

Bibliography

[B 1] IMO Annex VI of MARPOL 73/78: 'Regulations for the Prevention of Air Pollution from Ships' and 'NOx Technical Code'

[B 2] Document BLG 11/5, Annex 5

[B 3] Document BLG 11/5/22

[B 4] Document BLG 11/5/26

[B 5] Document BLG-WGAP 2/2/12

[B 6] Document BLG-WGAP 2/2/13

[B 7] Outcome of the CIMAC Exhaust Emission Controls Working Group (EEC WG5)

[B 8] Lloyd`s Register Fairplay WSE Database, Version 9.51, Database Jul 2007

[B 9] CLEAN Forschungsvorhaben, FM 99.006, 1999

[B 10] Klaus Mollenhauer: Handbuch Dieselmotoren, 2. Auflage , Springer-Verlag Berlin Heidelberg 2002

Appendix A

Return per fax to +49 (0) 40 36149 7321
or email rene.cengiz@gl-group.com

IMO NOx standard Tier I
Questionnaire on pre-2000 Existing Engines

General engine information

1. How many marine diesel engines were delivered before 2000 and are assumed still to be in service?

2. How many Existing Engines comply with IMO NOx Tier I standard (Category I) and how can evidence be provided that they do so?

3. How many non-compliant Existing Engines can be brought in compliance by retrofit measures or readjustments (Category II)?

4. How many non-compliant Existing Engines can not be brought in compliance by retrofit measures or readjustments (Category III)?

5. The engine group / engine family concept according to Chapter 4 of the NOx Technical Code may be applied. How many engine groups for a.m. categories could be established?

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Detailed engine information

The Excel sheet attached to this mail may be used to give further detailed information on specific engines.
Please list all pre-2000 Existing Engines giving following details, if possible:

- Engine designer
- Engine manufacturer
- Engine model
- Engine application (main engine, auxiliary engine, emergency engine)
- Engine build date
- Engine stroke
- Engine rated power output
- Engine rated speed
- Cylinder bore and stroke
- Engine Category (I, II, III, see above)

For engines / engine groups modifiable please estimate the following details:

- Lead time to develop retrofit measures
- Lead time to bring retrofit measures to market
- Costs per engine modification in €
- Off-time per engine modification in days (best case scenario)

	Engine designer	Engine manufacturer	Engine type	Engine model	Engine application	Engine of build date [yyyy]	2- / 4- stroke	Engine rated power output [kW]	Engine rated speed [rpm]	Cylinder bore [mm]	Cylinder stroke [mm]	Engine category* (I, II, III)	Estimated lead time to develop retrofit measures [days]	Estimated lead time to bring retrofit measures to the market [days]	Estimated costs per engine modification [€]	Estimated off-time per engine modification (best case scenario) [days]

*according to questionnaire

Table 11: Engine manufacturers' information on Pre-2000 Engines

	2-stroke engines 10,475 engines			4-stroke engines 51,800 engines					
	I	II	III	IV	V	VI	VII	VIII	IX
Engines delivered before 2000 and still in operation	**100 %**	**100 %**	**	**100 %**	**100 %**	**	**100 %**	**100 %**	**100 %**
Type A engines	**~ 3 %**	**~ 25 %***	**	**~ 61 %**	**unknown**	**	**> 1 %**	**~ 6 %**	**unknown**
Type B engines	**~ 51 %**	**~ 20 %**	**	**~ 19 %**	**unknown**	**	**~ 15 %**	**~ 12 %**	**~ 8 %**
Type C engines	**~ 46 %**	**~ 55 %**	**	**~ 20 %*** **	**unknown**	**	**~ 85 %**	**~ 82 %**	**~ 92 %**
NOx engine groups to be established	**~ 200** (best case)	**no estimate**	**	**> 15**	**unknown**	**	**~ 30**	**unknown**	**unknown**
Comments				Engine types with a total engine type installed power exceeding 500 MW regarded only (~ 1/3 of all pre-2000 Existing Engines of this build)					

Type A: Pre-2000 Existing Engines which do comply with IMO NOx Tier I standard already
Type B: Pre-2000 Existing Engines which do not comply with IMO NOx Tier I standard but can be brought in compliance by retrofit measures or adjustments.
Type C: Pre-2000 Existing Engines which do not comply with IMO NOx Tier I standard and can not be brought in compliance by retrofit measures or adjustments by reasonable efforts.

* Minor modification necessary
** General comments were submitted
***Major modification necessary

Appendix C

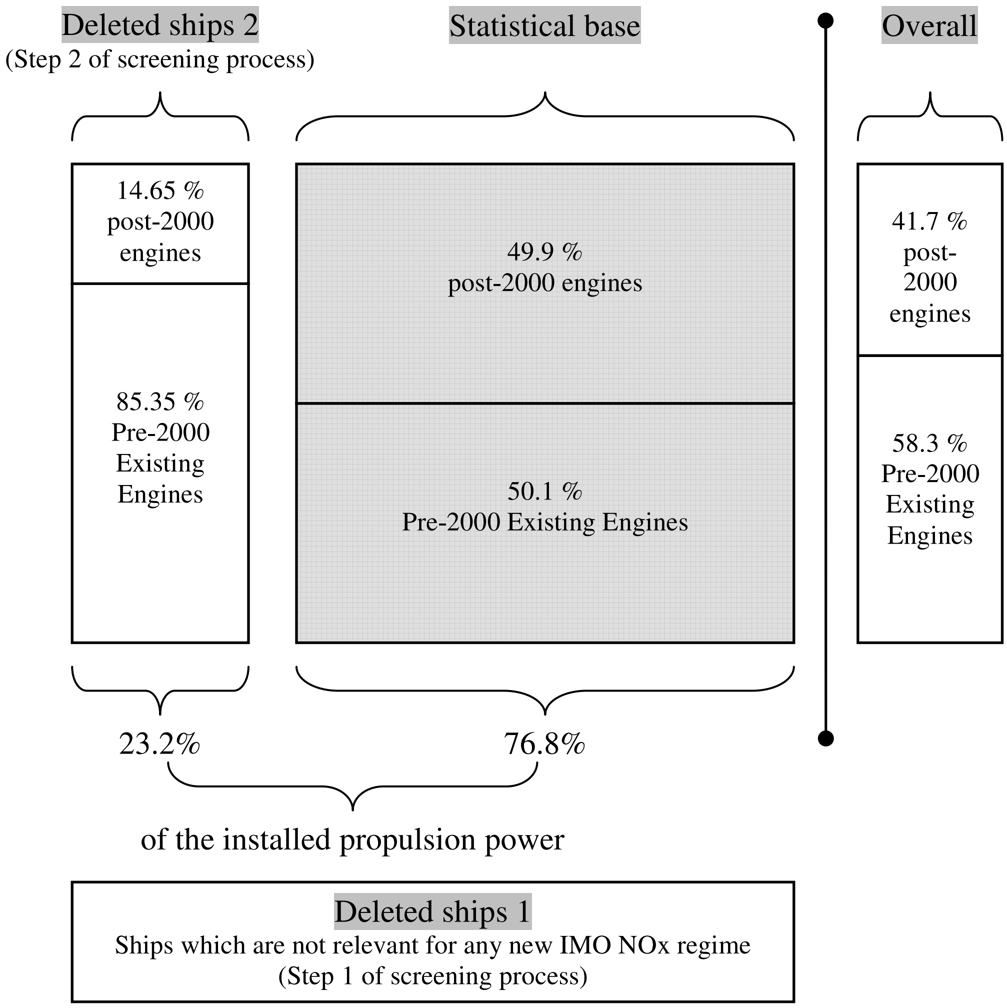


Figure 32: Screening and validation of the database

Calculation of the overall share of post-2000 engines in the installed propulsion power:

$$\frac{14.65 \times 23.2 + 49.9 \times 76.8}{100} = 41.7\%$$

Calculation of the overall share of Pre-2000 Engines in the installed propulsion power:

$$\frac{85.35 \times 23.2 + 50.1 \times 76.8}{100} = 58.3\%$$

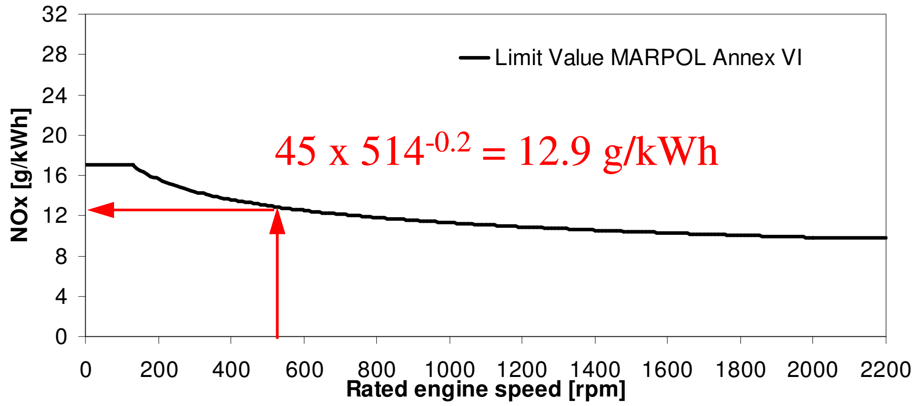
Appendix D

<u>Assumption:</u> The specific NOx emission of <u>each</u> engine is exactly the limit value of MARPOL Annex VI, Regulation 13

<u>Example:</u> The calculation is conducted for an engine of

- 514 rpm rated speed and
- 10,000 kW rated power.

<u>Calculation of the NOx limit value:</u>



<u>Calculation of the weighted power:</u>

Test Cycle type E2 / E3	Power	100%	75%	50%	25%
	Weighting factor	0.2	0.5	0.15	0.15

P_W = (0.2 x 10,000 + 0.5 x 7,500 + 0.15 x 5,000 + 0.15 x 2,500) kW = 6,875 kW

<u>Calculation of the weighted NOx emission:</u>

Weighted NOx emission = 12.9 g/kWh x 6,875 kW = <u>88.7 kg/ h</u>

Appendix E

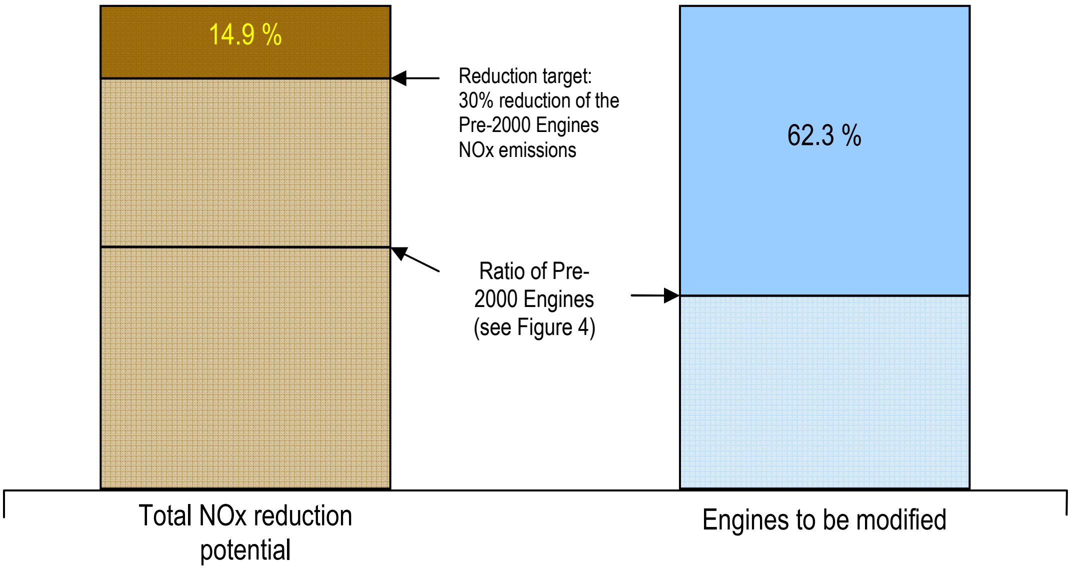


Figure 33: NOx reduction potential of all Pre-2000 Engines

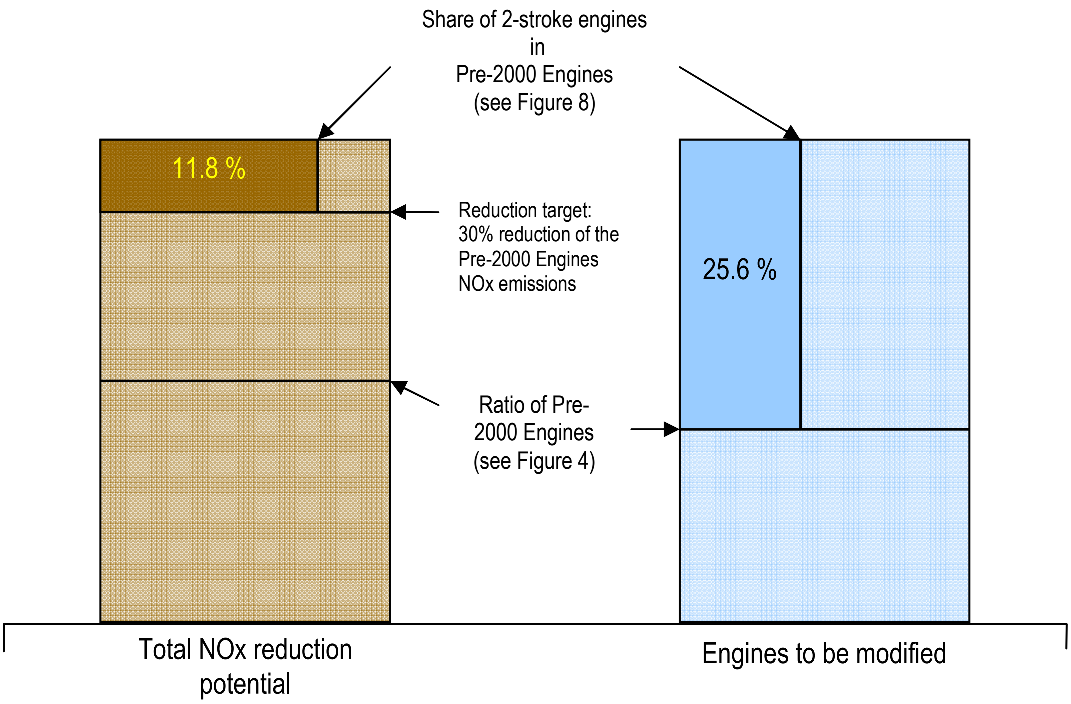


Figure 34: NOx reduction potential of 2-stroke Pre-2000 Engines only

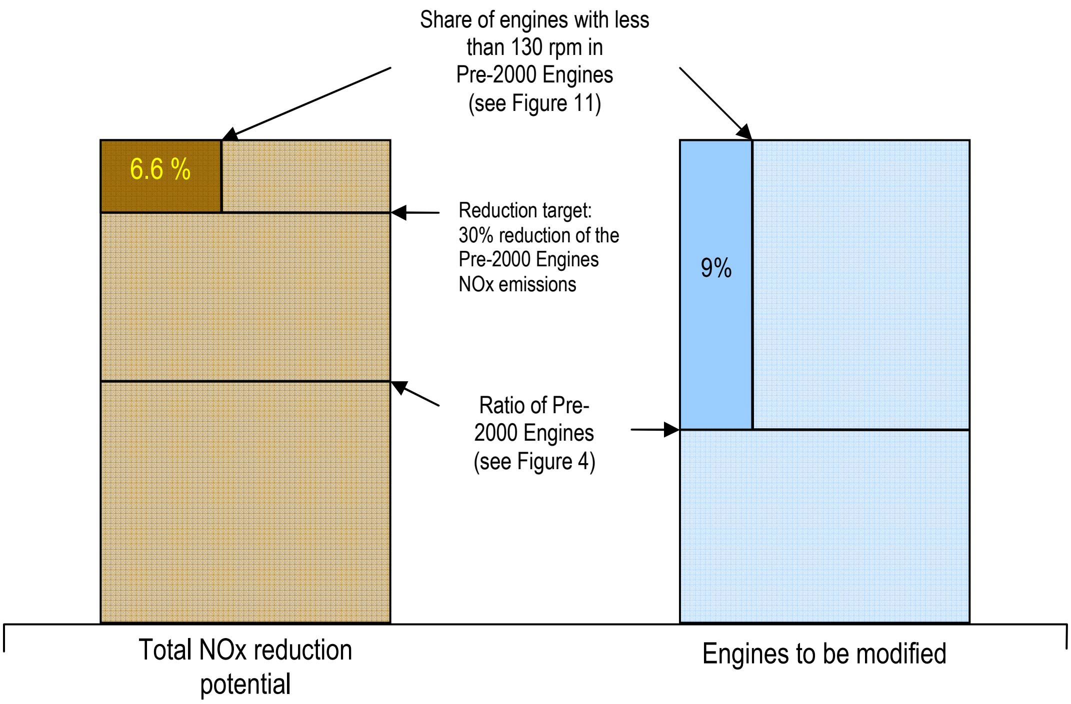


Figure 35: NOx reduction potential of Pre-2000 Engines of less than 130 rpm only

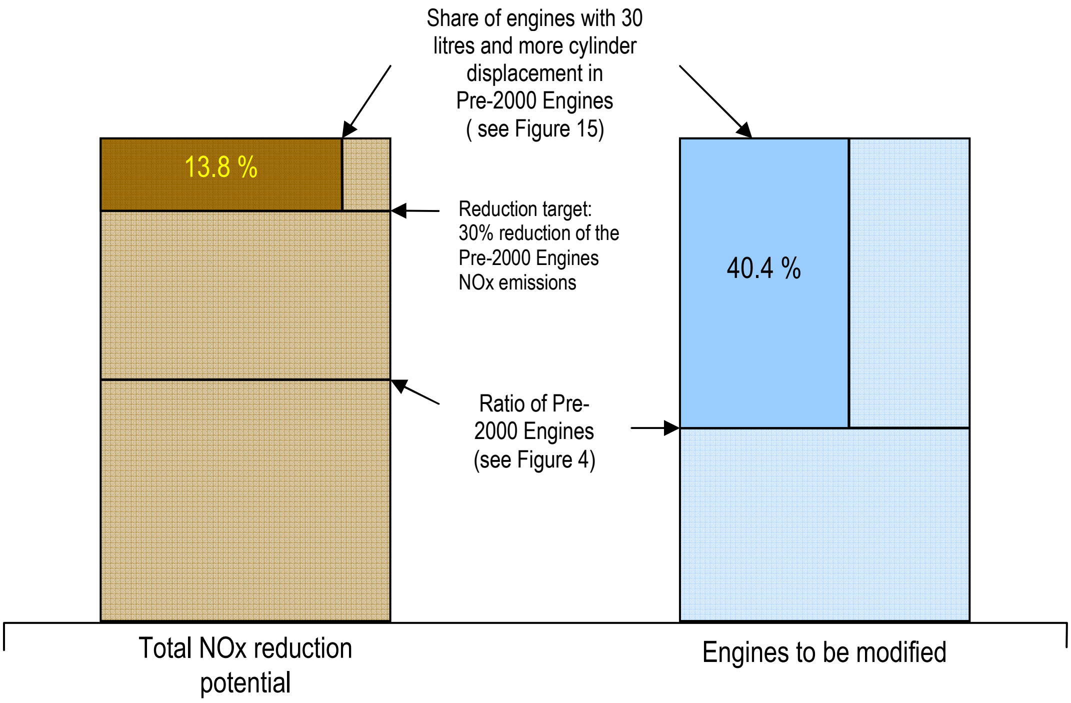


Figure 36: NOx reduction potential of Pre-2000 Engines of 30 litres per cylinder and more only

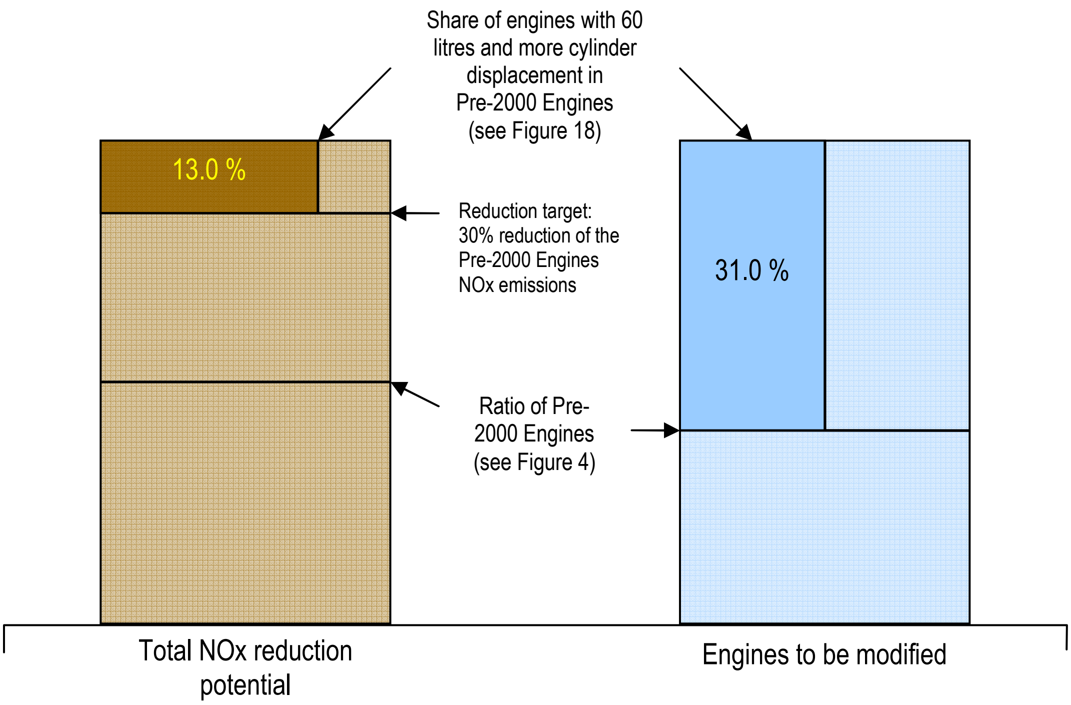


Figure 37: NOx reduction potential of Pre-2000 Engines of 60 litres per cylinder and more only

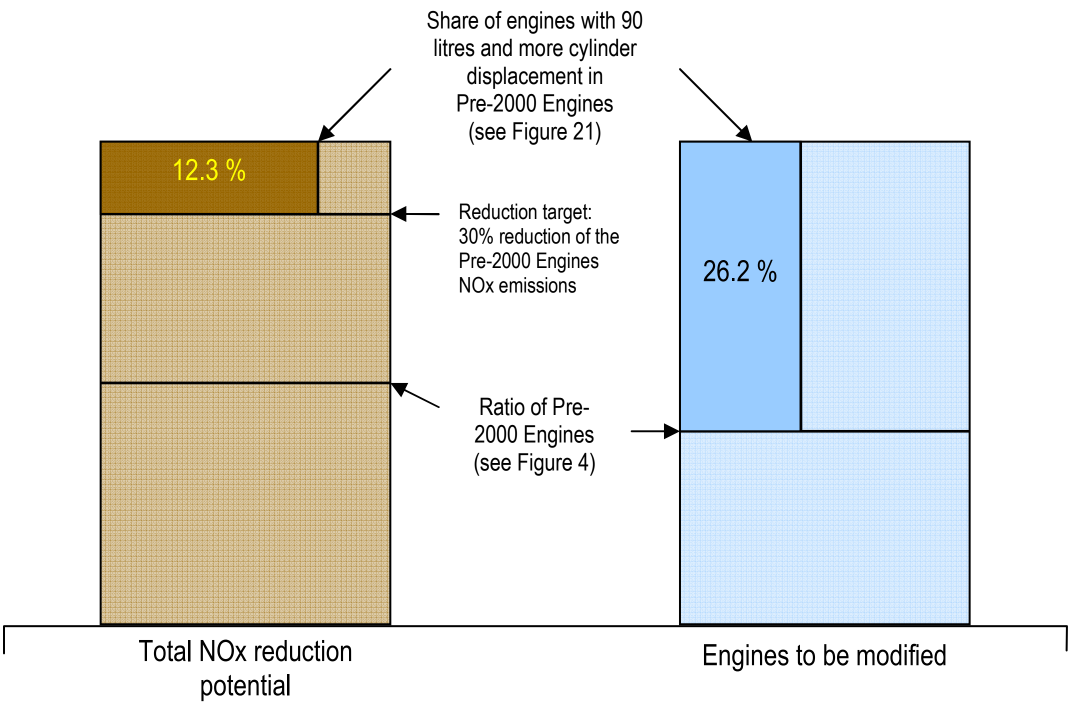
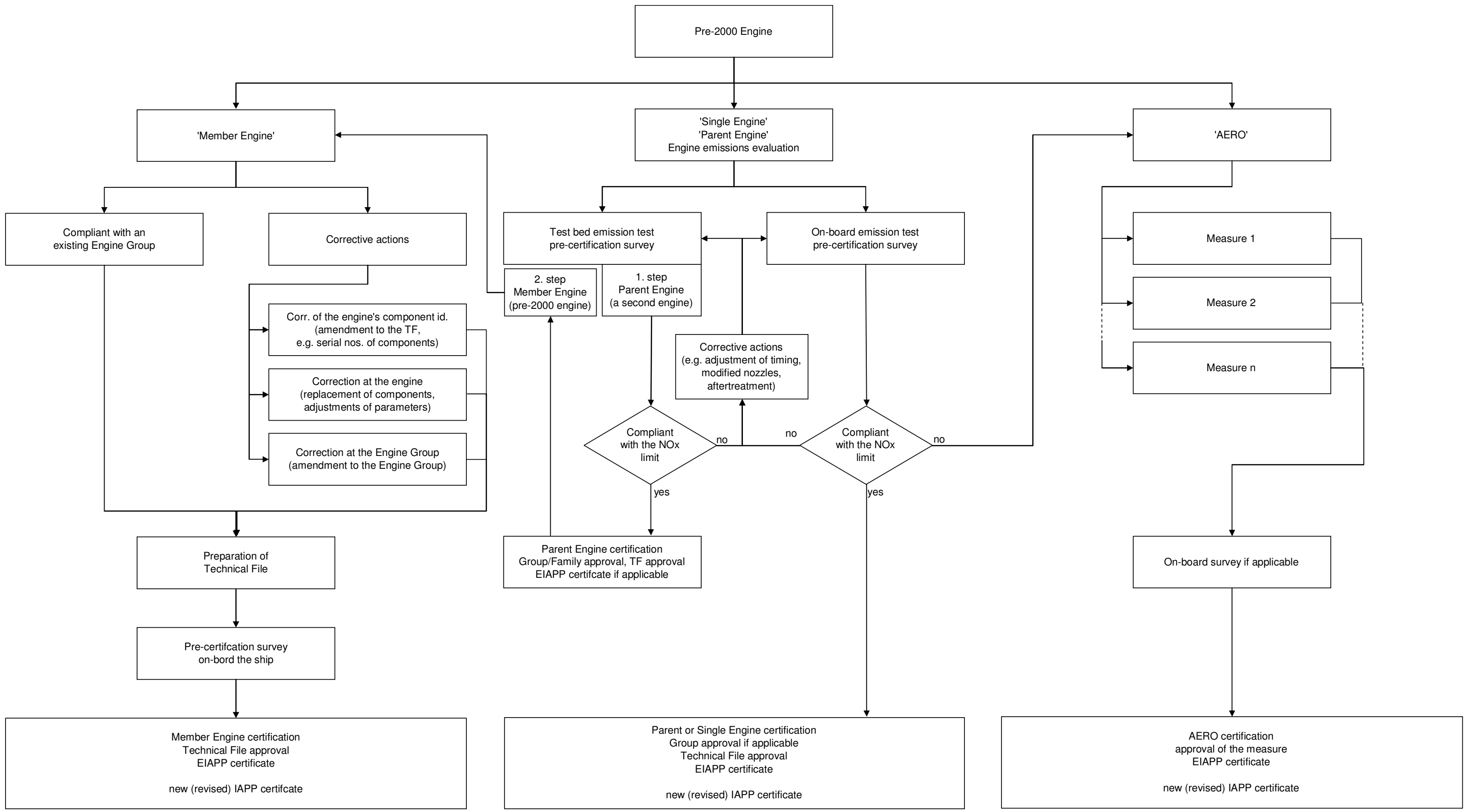


Figure 38: NOx reduction potential of Pre-2000 Engines of 90 litres per cylinder and more only


Pre-2000 Engine
'Member Engine'
'Single Engine'
'Parent Engine'
Engine emissions evaluation
'AERO'
Compliant with an
existing Engine Group
Corrective actions
Test bed emission test
pre-certification survey
On-board emission test
pre-certification survey
Measure 1
Measure 2
Measure n
2. step
Member Engine
(pre-2000 engine)
1. step
Parent Engine
(a second engine)
Corr. of the engine's component id.
(amendment to the TF,
e.g. serial nos. of components)
Correction at the engine
(replacement of components,
adjustments of parameters)
Correction at the Engine Group
(amendment to the Engine Group)
Corrective actions
(e.g. adjustment of timing,
modified nozzles,
aftertreatment)
Compliant
with the NOx
limit
no
no
Compliant
with the NOx
limit
no
yes
yes
Preparation of
Technical File
Parent Engine certification
Group/Family approval, TF approval
EIAPP certifcate if applicable
On-board survey if applicable
Pre-certifcation survey
on-bord the ship
Member Engine certification
Technical File approval
EIAPP certificate
new (revised) IAPP certifcate
Parent or Single Engine certification
Group approval if applicable
Technical File approval
EIAPP certificate
new (revised) IAPP certificate
AERO certification
approval of the measure
EIAPP certificate
new (revised) IAPP certificate