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Sustainable Surface Transport

Retrofitting potentials for diesel engines in inland navigation

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List of Abbreviations

CCNR:	Central Commission for Navigation on the Rhine
DLD:	Dutch Logistic Development
ESP:	ElectroStatic Precipitator
g/kWh:	gram per kWh
IBC:	Intermediate Bulk Container
IMO:	International Maritime Organization
kPa:	kiloPascal (0.01 bar)
kWh:	kiloWatthour is 1 kiloWatt (kiloJoule/second) during 1 hour (i.e. 3.6 MJ)
NOx:	Nitrogenoxides
PM:	Particulate Matter
RNLNC:	Royal Netherlands Naval College
SCR:	Selective Catalytic Reduction
SPB:	Shipping Projects Bureau
STID:	STeam Injected Diesel

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1. ABSTRACT

New engines used in inland navigation on the river Rhine have to fulfil emission regulations. Inland navigation engines have a rather long lifetime. The result is that the full effect of this legislation only becomes visible after a long period of time. It might be interesting to speed up this process by implementing emission reduction technology on existing ship engines, so-called retrofitting.

One of the goals of this study is to investigate which techniques for retrofitting are suitable for which engines. The other goal is to estimate the achieved reduction of emissions by implementing retrofit legislation.

In order to reach these goals it is necessary to group a number of engines, based on available data and necessary parameters. Based on data from milestone report M06.01 of CREATING [Kampfer et al., 2005] a division by engine type is made to analyse which techniques are suitable for retrofitting on which engine. A division by decade in which the engine under consideration is produced is used in the study on impact of retrofit emission legislation. It is noted that emission factors (emission of an engine, often expressed as g emission /kWh engine output) are not readily available for older engines; especially data on particulate matter emissions are limited. In order to get a more detailed picture of the emissions of inland navigation it is advised to investigate these parameters. The exploration of technical possibilities of retrofitting is strongly based on M06.03 Task II of CREATING [Van Rens and De Wilde, 2005] about options for aftertreatment on new engines. In this part all proven techniques from [Van Rens and De Wilde, 2005] and in-cylinder water injection are treated as likely candidates for retrofit. Only NOx reduction technology has been demonstrated on board of an inland navigation ship. Particulate matter reduction is theoretically possible, but is still to be demonstrated on board of an inland navigation ship. It is advised to stimulate research in that area and more in particular demonstration projects. Due to the lack of demonstration of particulate matter reduction technologies on inland navigation ships, as well as the limited availability of emission factors for particulate matter, it was decided not to investigate the influence of retrofit legislation for particulate matter.

For NOx emissions the influence of retrofit legislation has been investigated based on three engine lifetime scenarios. For this calculation it is assumed that the retrofit legislation enters into force 5 years after the same legislation entered into force for new engines. It is advised not to implement retrofit legislation based on CCNR I legislation, because with this retrofit legislation the reduction of emissions is rather limited, with 7% in the most beneficial scenario (for a short overview of all legislation see for example [Kampfer et al., 2005]). This finding corresponds to the findings of [Kliche et al., 2001] and [Schilperoord, 2004]. The influence of retrofit legislation based on EU IIIA/CCNR II with implementation date 2011 or proposed EU IV/CCNR III with implementation date 2016 is much larger, with 12 to 18% NOx reduction over the period 2001 through 2020, depending on the used scenario. In 2 of the 3 scenarios EU IV/CCNR III retrofit legislation has the largest impact on NOx emissions over the period 2001 through 2020. Because the influence of this retrofit legislation remains over the end of the 2-decade period, this retrofit legislation is advised, if proposed EU IV/CCNR III legislation has in fact entered into force in accordance with the present proposition.

2. INTRODUCTION

Newly built ships or ships retrofitted with new engines have to fulfil new emission regulations. However, as illustrated in [Kliche et al., 2001], more than half of the engines in inland navigation ships in the Netherlands and Germany are older than 20 years. Because of the long lifetime of ship engines, it might take a while (depending on the expected lifetime 1.5 to 4 decades) before new engines substitute engines, produced just before the implementation date of emission legislation. Therefore it is interesting to investigate the possibilities of using emission reduction technologies on existing engines, so-called retrofitting, and the implication of retrofitting on total emissions by inland navigation.

The goal of this investigation is twofold. The first goal is to research which techniques are suitable for retrofitting on which inland navigation engine. The second goal is to investigate the reduction of emissions when retrofit legislation is enforced.

In order to assess possible techniques for retrofitting and the impact of retrofit legislation it is necessary to group engines. Therefore first a classification will be made of engines of inland vessels sailing in Europe, based on the report of milestone 1 of this workpackage [Kampfer et al., 2005]. Subsequently the possible engine techniques from [Kampfer et al., 2005] and the pre- and after-treatment techniques from [Van Rens and De Wilde, 2005] will be judged on their potential use for different types of engines. Experiences from retrofitting will be used to shed a light on difficulties associated with retrofitting some techniques. In the end the benefits of forcing retrofit by legislation in terms of not-emitted pollutants will be investigated based on selected scenarios.

3. CLASSIFICATION OF ENGINES USED IN INLAND NAVIGATION

3.1. Introduction

Engines can be classified in many different ways. For the part that assesses the possibility of retrofitting existing technologies, it is most important that data contain information on the emissions of pollutants and some specific characteristics of the engine, like exhaust gas temperature and allowable backpressure. For the part that estimates the influence of emission legislation on existing engines data about remaining engine lifetime and emission of pollutants are necessary.

A list of possible parameters for a division in emission classes is given below:

- engine type (2-stroke vs. 4-stroke, turbocharged vs. atmospheric)
- engine speed (low speed (i.e. 2-stroke), medium speed and high speed)
- power output
- fuel consumption
- emissions of the engine
- the type of vessel they are fitted in
- year of vessel construction
- year of engine construction

Unfortunately not one of the proposed divisions gives information on all above-mentioned elements necessary for judging applicability of retrofit and the influence of (forced) retrofit on total emissions. Therefore two different class divisions will be used in the following chapters. The first division will be by engine type, which roughly links emission parameters with engine characteristics. The second division will be by year of engine construction, which will roughly link emissions by remaining engine lifetime. These classifications will be elaborated further in the next sections.

3.2. Division by engine type

Engines used in inland shipping can be divided in two-stroke engines and four-stroke engines. In a two-stroke engine the charge combusts each moment the piston of a cylinder is at its highest point, called top dead centre, while combustion of the charge in four-stroke engines takes place each second time the piston of a cylinder is at top dead centre. The result is that four-stroke engines can run at higher revolutions per minute than two-stroke engines. Due to the longer residence time of the exhaust gas at high temperatures in a two-stroke engine, the emission of NOx is higher than for four-stroke engines. This is reflected in the engine speed dependant “IMO-curve” for maximum NOx-emissions, as illustrated in Figure 1.

Retrofitting potentials

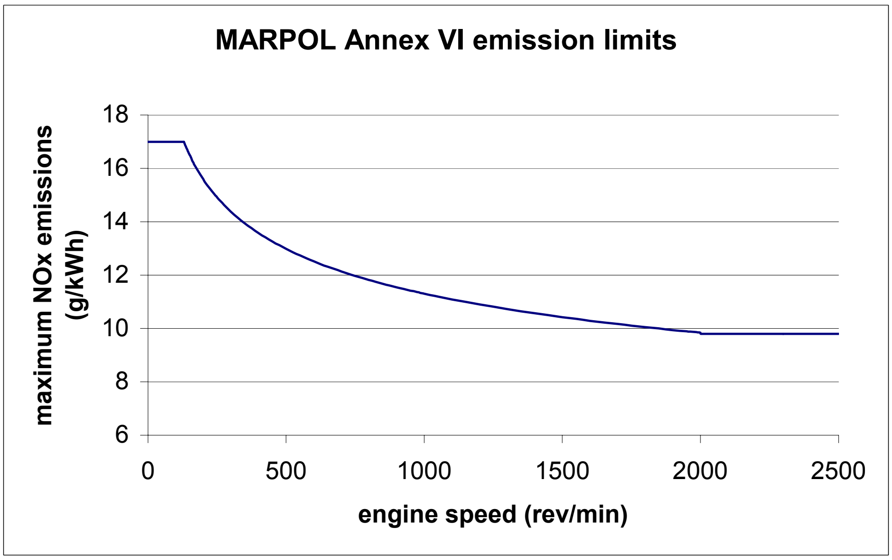

Figure 1. Engine speed dependant maximum NOx emissions according to MARPOL 73/78 Annex VI

Another result of the longer residence time in the cylinder is that exhaust gas temperatures of a 2-stroke engine are lower than the exhaust gas temperature of a four-stroke engine. Historically two-stroke engines are used for shipping, because of their fuel efficiency, long lifetime and direct coupling with the propeller. Due to improvements in four-stroke engines and their mass production by truck manufacturers most new ships are fitted with four-stroke engines. Historically engines are designed for larger pressure drops in the exhaust gas pipe (in the order of 10 kPa). Modern engines are designed for a pressure drop of 3 kPa. Acceptable pressure drop is in itself a design parameter, but for existing engines a fact. Virtually every new engine is a 4-stroke engine. These new engines, especially the turbocharged are sensitive to backpressure. In general it can be said that pressure drop is of less concern with 2-stroke engines, but it is strongly advised to check the manufacturers data on maximum pressure drop in the exhaust gas system anyhow.

An additional division can be made by discerning turbocharged from atmospheric engines. Turbocharged engines use the energy left in the exhaust gas to get more air into the engine. This leads to a higher power output with the same cylinder volume, and higher efficiency, in comparison to an atmospheric engine with the same power output, due to reduced friction. Turbocharged engines are more sensitive to backpressure because of the multiplier effect of the turbine.

A further distinction could be made between direct injected and indirect injected diesel engines. Indirect injected diesel engines produces less particulate matter, but consume more fuel. This division will not be taken into account in this study.

3.3. Division by year of engine construction

[Kliche et al., 2001] did an extensive investigation in the composition of the fleet of inland navigation ships sailing on the river Rhine and the Danube. Their data, illustrated in Figure 2, show that more old ships are sailing than old engines. This means that old ships are often retrofitted with a new engine. The Dutch fleet has newer engines than the German fleet. It seems that retrofitting old ships in Germany mainly took place in the fifties and sixties, whereas retrofitting old ships in The Netherlands mainly took place from the seventies on.

Retrofitting potentials

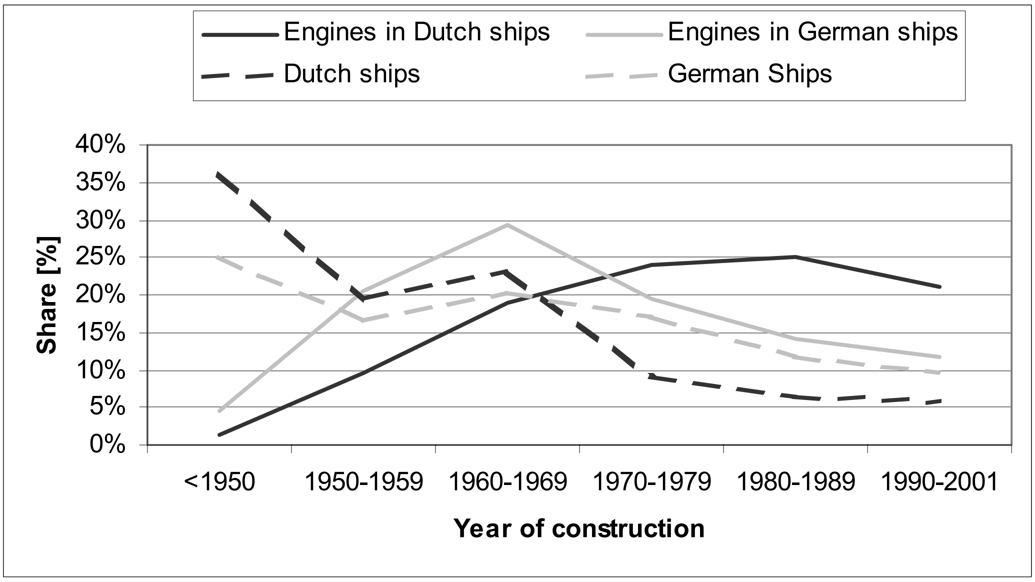

Figure 2. Year of construction of ships versus year of construction of engines for the river Rhine, data from [Kliche et al., 2001]

[Kliche et al., 2001] also showed an interesting graph of the share of engines that fulfilled the CCNR I legislation based on year of construction of the engine.

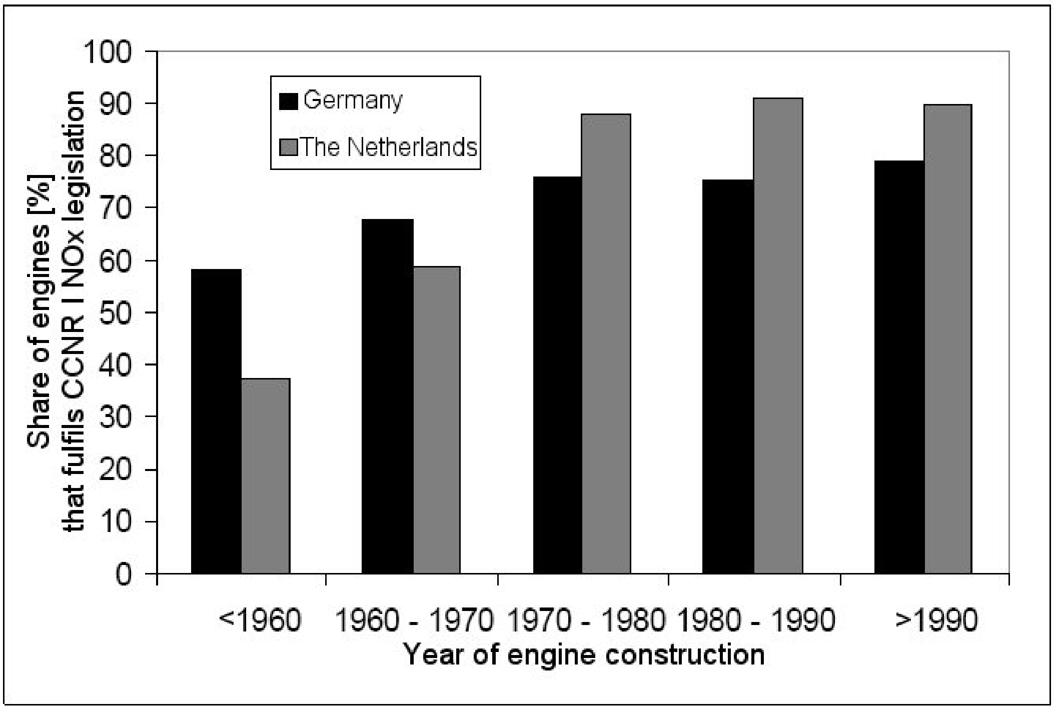

Figure 3. Share of engines that fulfils CCNR I NOx-legislation ([Kliche et al., 2001], translated)

Figure 3 shows that already ninety percent of the engines constructed after 1970 in the Dutch inland navigation fleet fulfils CCNR I legislation. This is interesting as the qualitative trend illustrated in Figure 4 (from [Kliche et al., 2001] too), seems to point to higher NOx emissions for engines from the eighties and nineties. This trend could be explained by a stronger focus on fuel efficiency and hence higher local temperatures. The only way to achieve both higher NOx emissions and fulfil CCNR I legislation is by reducing engine speed. Historical data in [Kliche et al., 2001] show that this has not been the case. More research is needed to get representative emission parameters dependant on year of engine construction and engine type. Energy research Centre of the Netherland (ECN) and the Netherlands Organisation for Applied Scientific Research (TNO) recently acquired a commission of the Dutch ministry of transport, public works and water management to measure the emission parameters. It is desirable to treat these data in such a way that an emission parameter can be coupled to engine age.

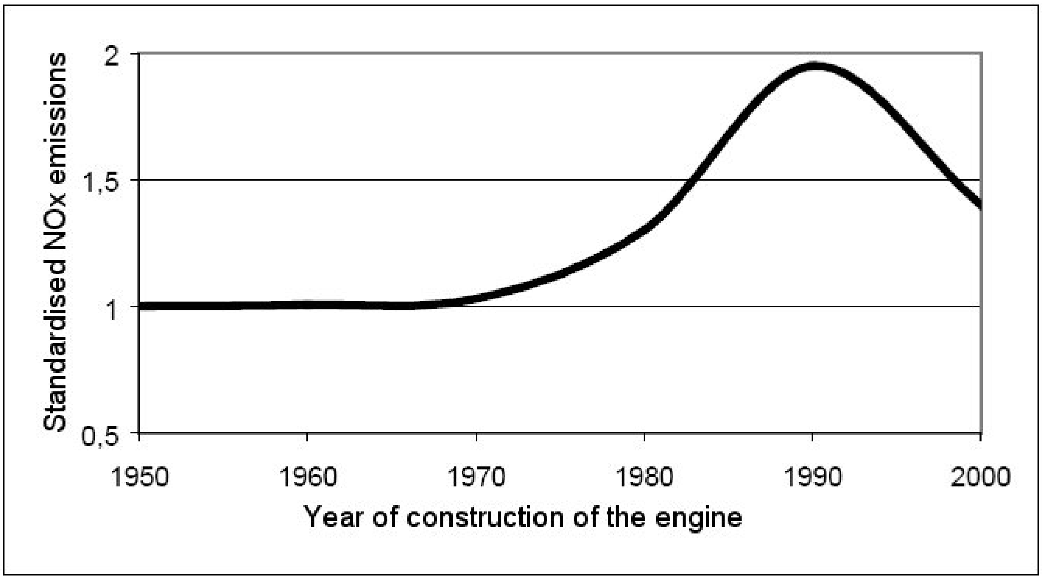

Figure 4. Influence year of construction in relation to NOx emissions, standardised to 1955 ([Kliche et al., 2001], translated)

The average lifetime of the engines of the inland shipping fleet is estimated by [Schilperoord, 2004] as 15.6 years. If however data from [Kliche et al., 2001] are used to calculate the average age of the engines, the average age is 24 years for the Dutch fleet and 31 years for the German fleet, which is significantly older than the estimation of engine lifetime in [Schilperoord, 2004]. Later, when studying the impact of emission legislation for retrofit on the total emissions, several scenarios for engine lifetime will be used.
When estimating the influence of retrofit on total emission legislation the following division will be used: older than 1950, 1950-1960, 1960-1970, 1980-1990, 1990-2001, 2002-2005 (CCNR I), 2006-2010 (EU IIIA/ CCNR II), 2011-2020 (proposed EU IV/CCNR III)

4. POSSIBLE TECHNIQUES FOR RETROFITTING PER ENGINE TYPE

4.1. Introduction

This section provides general remarks as to which emission reduction technique is suitable for which engine type. Issues that need special care, when retrofitting a certain technique behind a certain engine type, are stressed. Characteristics, relevant for retrofitting for each engine type, are dealt with in section 3.2. All technologies in the following subsections are described in [Van Rens and De Wilde, 2005] and [Kampfer et al., 2005].

4.2. Diesel oxidation catalyst

The exhaust gas temperature needs to be maintained above a certain threshold value for the diesel oxidation catalyst to function well. Use of low-sulphur fuel is recommendable from particulate matter point of view, but not necessary. Because the temperature of the exhaust gas of a 2-stroke engine is often quite low, it is necessary to fit the diesel oxidation catalyst close to the engine, possibly even in front of the turbine. For 4-stroke engines, both atmospheric and turbocharged, exhaust gas temperature is sufficiently high.

4.3. Wet scrubber

Use of a wet scrubber might result in a backpressure on the engine in excess of 3 kPa. This does not pose a problem for 2-stroke engines, as 2-stroke engines are generally older engines, which are as a rule of thumb designed for a maximum backpressure of 10 kPa. Research by Royal Netherlands Navy College (RNLNC) confirmed that increasing backpressure outside normal specifications increases cylinder and turbine inlet temperatures above design values [Dijkstra, 2005], which may lead to excessive thermal stress on the engine. Use of a wet scrubber behind a 4-stroke engine is possible when considerable care is taken to ensure that maximum backpressure is not exceeded. In the event that maximum backpressure is reached it is possible to down-tune the engine, reducing cylinder temperatures, and limiting thermal stress. This can only be done, when all important engine parameters are monitored. It is always recommended to check the manufacturers limits on maximum pressure drop in the exhaust gas pipe before application of a wet scrubber.

4.4. Diesel Particulate Filter

A diesel particulate filter also increases backpressure on the engine. In contrast to a wet scrubber the backpressure of a diesel particulate filter varies depending on the particle loading on the filter. It is strongly advised to monitor backpressure. Active regeneration seems to be mandatory for new engines due to low acceptable backpressures. Use of low-sulphur fuel is recommended and often required by manufacturers, for example by Johnson Matthey [JM, 2005] and ETG [ETG, 2005].

4.5. Selective catalytic reduction

4.5.1. Technical issues

Selective catalytic reduction can only be used in a very limited temperature window, between 250°C and 520°C according to [Argillon, 2005]. The lower boundary temperature depends on sulphur concentration, as mentioned in M06.03 Task II Retrofit potentials [Van Rens and De Wilde, 2005]. This means that for 2-stroke engines it is strongly advised to place the catalyst between engine and turbine. For 4-stroke engines with a turbocharger the catalyst can be fitted after the turbine.

4.5.2. Retrofitting inland navigation ships with selective catalytic reduction

When the discussion on the emissions of inland shipping started rising, the Shipping Projects Bureau (SPB) started two demonstration projects on the reduction of NOx on board of inland navigation ships. On behalf of SPB this project was coordinated by Dutch Logistic Development (DLD) and financially supported by SenterNovem. With financial support of the Dutch Ministry of transport, public works and water management, Energy Research Centre of the Netherlands (ECN) carried out the measurements.

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The tugboat used for retrofitting was tugboat “En Avant 4” of T.Muller Shipping Company from Dordrecht. This tugboat is equipped with a 6-cylinder 4-stroke marine turbocharged diesel engine. Other engine characteristics are displayed in Table 1.

Table 1. Engine data tugboat “En Avant 4”

Type:	M.A.N. G6 V30/45
Cyl. Volume:	31.792 cm^3
kW:	552 kW
year of production:	1962

During the tests the tug was moored tightly with its bow to the quay. In this condition measurements were carried out at engine loads of 40, 60, 80 and 100%. The NOx concentration was measured on each defined engine load several times with the SCR turned on and off. To analyse the exhaust gas a ¼-inch stainless steel tube was mounted in the exhaust gas pipe, about half a meter above the ceramic element of the SCR, while all necessary measures were taken to prevent condensation in both the sample tube and the analysers. The concentration of NOx was determined by chemo-luminescence. Two calibrated monitors were used to measure NO and NO_2.
Because the old engine is not electrically controlled and hence has no electronic control signals that could be used by the control unit of the SCR, the SCR system was controlled manually, which resulted in strong variations in NOx reduction. The broad set of measurements, however, proves that an NOx-reduction of 85% or more is possible for engine loads ranging from 40% to 100%. By adding a higher dose of urea to the exhaust further reductions are possible (up to 95%). In that case, however, the cost of urea consumption increases much more rapidly than the decrease in NOx emissions. Ammonia slip, the emission of ammonia through the exhaust due to not perfect mixing, increases with injection of a larger amount of urea-solution. Ammonia is a much stronger greenhouse gas than carbon dioxide.

Some technical difficulties were encountered, however, when retrofitting this technique. The functioning of an SCR system is dependent on the conditions of the exhaust gas. As these are likely to vary constantly during common operation of the vessel a direct link between the engine and the SCR control unit is necessary. An old engine like the one in the tugboat has no advanced control system and hence real time data suitable for input in the SCR control unit is not available. As the SCR system needs urea for operation, a urea reservoir was installed. In this project the urea tank consisted of an IBC, a medium sized container, placed on deck of the vessel. This situation is suitable to demonstrate the SCR system, but not for normal operation of the vessel. The IBC had to be removed when the tug had to go for a job. A suitable place for the urea tank could be hard to find. As it was difficult to define the needed volume of ceramic elements for reduction of NOx the ceramic elements were slightly oversized to limit ammonia slip and to make sure maximum reduction is achieved.
It proved to be difficult to fit the SCR system into the existing space with all its characteristics. On an existing vessel one has to fit the SCR system into an existing engine room. Although minor alterations of the available space may be possible it is important to be aware of the fact that the dimensions of the SCR system may need to be adjusted to fit the dimensions of the engine room.

On behalf of the Shipping Projects Bureau (SPB) a project to equip a new ship with an SCR-system was coordinated by DLD and financially supported by SenterNovem. The measurements have been carried out by Royal Netherlands Naval College (RNLNC) and were financially supported by the Dutch Ministry of transport, public works and water management. Not all elements of this demonstration will be discussed here. Only some technical and policy issues that could also be encountered when retrofitting will be discussed.

During operation of the SCR, urea crystallised in the piping and nozzle of the dosing system of the urea solution. This resulted in a non-functioning urea pump. The problem turned out to be a leaking three-way valve. After replacement of the three-way valve and the nozzle the problem did not reoccur. Another problem turned out to be the unstable power supply on board of the vessel, when switching between power sources. It might be better to design the electrical circuit of the SCR for the more stable low voltage DC than for AC. The ship in this project needed to fulfil the CCNR emission limits. An SCR-system could pay itself back, when the engine tuning is changed from low-NOx tuning to fuel economy tuning, by saving fuel. This engine was only certified by CCNR in low-NOx tuning. In order to sail with fuel economy tuning the ship needed to be officially exempted from CCNR-limits on a temporary basis, under the condition that the proper functioning of the SCR-system would be demonstrated.

4.6. Humidification of inlet air

4.6.1. Technical issues

Humidification of inlet air is possible as long as a turbocharger is present. Exhaust gas cooling, necessary for the swirl-flash technique should take place after the turbine. Injection timing and duration need to be adjusted in order to acquire optimum engine performance, due to the higher moist content of cylinder air and, if an intercooler was not present before, the cooled charge air.

As an atmospheric engine obviously has no turbocharger it is not possible to humidify and cool the charge air. It is doubtful that one of the three systems mentioned in [Van Rens and De Wilde, 2005] will work for cold inlet air. The advantages are expected to be limited anyway, as cold inlet air can contain considerably less water, than warmer inlet air.

4.6.2. Retrofitting Swirl-Flash on board of an inland navigation ship

In the same project where retrofitting SCR-technology was demonstrated (see section 4.5.2), swirl-flash technology was retrofitted as well. The engine characteristics are shown in Table 1. Unfortunately the heat exchanger in the exhaust gas pipe, that needed to create hot water, was dimensioned too small. The additional heat requirement was provided by a temporary solution. The swirl-flash technique was demonstrated with an engine load of 60% and 100%. NOx-emission was determined by chemo-luminescence. The result was a rather small 20% NOx reduction at full load and 10% NOx reduction at 60% engine load. In the light of the ill-dimensioned heat exchanger in the demonstration, it is important to mention that the temperature and pressure of the injected water need to be in a specific window to prevent engine damage by not-evaporated water.

4.7. Electrostatic precipitator

Operation of an electrostatic precipitator (ESP) is not exhaust gas temperature dependent. At low operating temperatures the material of the ESP may need to be corrosion-resistant material due to sulphuric acid formation. It is expected that the design of an ESP does not lead to backpressure problems. An ESP is voluminous however, and it is strongly dependent on the ship whether that space is available or not.

4.8. In-cylinder water injection

There are several ways to introduce water in the cylinder. This is generally water in its liquid form and is injected either as a fuel-water emulsion or as stratified layers, which means that first fuel, then water, then fuel etc. is injected during injection. This can easily be retrofitted as generally injectors have an overcapacity of approximately 20%. This may lead to maximum NOx removal of approximately 40%. Fuel injection timing and duration have to be changed. Water can be injected by a separate injector as well. This leads to the possibility of water injection timing, but this configuration is not a likely candidate for retrofitting. Injection of steam in the cylinder, called STID (see for example [Chomiak et al., 2004]), is another less likely candidate for retrofitting. STID will both enhance engine performance and reduce NOx emissions.

5. IMPACT RETROFIT LEGISLATION ON TOTAL INLAND NAVIGATION EMISSIONS

5.1. Introduction

5.1.1. Introduction to the scenarios

To investigate the reduction of harmful emissions by retrofit-legislation, several scenarios will be studied. The benefits of retrofitting old engines will be strongly influenced by the remaining lifetime of the retrofitted engines, as well as the proposed emission limit and the date of implementation. Thereto three scenarios will be investigated based on inland navigation on the river Rhine, focussed on the Dutch and German case, because most data are available for these sources.

The first case is the scenario in which the average engine age remains constant. The average engine age is based on data from [Kliche et al., 2001] and is 24 years for engines in Dutch ships and 31 years for engines in German ships.

The second case is the "Schilperoord-lifetime" scenario. This is based on the expected average lifetime, estimated in [Schilperoord, 2004], which is 15.6 years.

The third case is based on a lifetime expectancy of 45 years. This is much longer than the estimation by [Schilperoord, 2004], but has a better relation to the engine age of the existing fleet.

In each scenario only replacements of existing engines are taken into account. The introduction of new engines in new ships has been excluded in this discussion.

5.1.2. Emission limits under consideration

The focus of this section is on NOx emissions. The proposed EU IV legislation for inland navigation does include a more stringent limit for particulate matter emissions than EU IIIA and CCNR I (PM has to be reduced by 90%!!!), but as reduction of particulate matter on board of an inland navigation ship has so far not been demonstrated, it remains questionable whether this can be achieved in 2011 or not. Introduction of low-sulphur fuel (in the order of 50 ppm instead of proposed 0.1% (=1000 ppm) in 2010) is often required for particulate matter reduction with the present techniques [Van Rens and De Wilde, 2005].

To estimate the reduction of emissions CCNR I legislation is summarised as an emission of 9.2 g/kWh starting from 2002. This is at the lower end of actual emissions. A summary of all legislation can be found in [Kampfer et al., 2005]. EU IIIA and CCNR II legislation are taken together and summarised as an emission of 6 g/kWh NOx starting from 2006. This value might be on the lower end of actual emissions in 2006. EU IV and CCNR III legislation are summarised as 1.5 g/kWh NOx emissions starting from 2011, which is on the upper end of expected emissions in 2011. The emission of existing ships is estimated by multiplying the share fulfilling CCNR I by the CCNR I limit and subsequently multiplying the non-CCNR I compliant part with an emission of 14.25 g/kWh. This latter value is derived from the average value of Class III and an estimate of the average level in Class IV according to emission classes by Germanischer Lloyd [Kliche et al., 2001]. The share of existing engines complying with CCNR I is derived from Figure 3.

This leads to the NOx-emissions per decade of engine construction illustrated in Figure 5.

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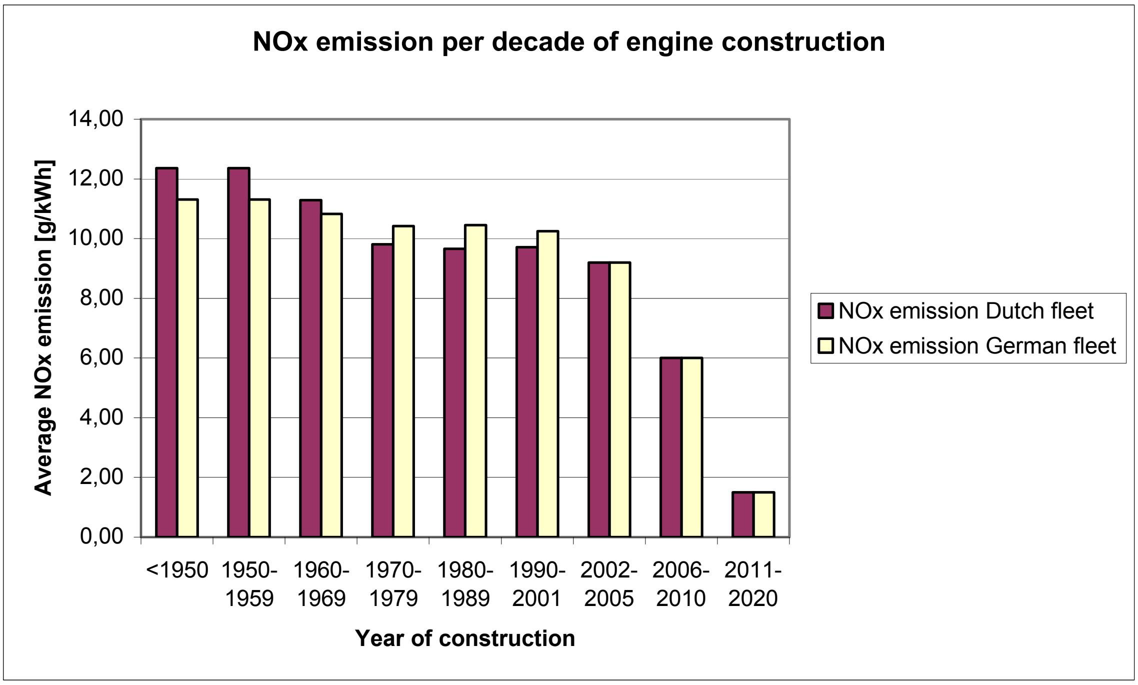

Figure 5. Average NOx-emission per decade of engine construction

The problem with tightening emission regulations by forcing retrofit is that once established these limits cannot be changed in a long time, as the investments are quite substantial. Therefore in each scenario retrofit legislation is applied only once. The emission limit under consideration is varied, however. Another problem with announcing retrofit legislation is that the moment retrofit legislation is announced shipowners will demand that the new engines they fit will fulfil the retrofit legislation. Therefore it is advisable to announce retrofit legislation a few years after the enforcement date of the same legislation for new engines. A transition period to facilitate shipyards to fit these techniques might be necessary.

For this calculation it is assumed that the retrofit legislation enters into force 5 years after the same legislation entered into force for new engines. This means either a retrofit in 2007 with CCNR I, a retrofit in 2011 with CCNR II/Euro IIIA or a retrofit in 2016 with Euro IV/CCNR III.

It is assumed that all ship engines comply with this legislation at once at these dates.

In order to assess the influence of retrofitting it is assumed that the share of engines in each decade corresponds with the share of kWh produced in a year. This assumption may not be correct, as a trend that shows that newer engines have a larger power output, is expected. Data to verify this trend was not available.

In order to compare the effects of the different retrofit legislation options with each other in a reasonable time horizon the average emission over a 2-decade period starting from 2001 is calculated. The impact of retrofit legislation (especially Euro IV/CCNR III with implementation date 2016) may continue after the 2-decade period under consideration.

5.2. Constant average engine-age scenario

5.2.1. Description average engine-age scenario

In this scenario it is assumed that the average engine-age of the fleet remains constant. This is achieved by replacing the oldest engines by new engines. These new engines have to fulfil the emission legislation at the time they are introduced. This leads to the engine age as illustrated in Figure 6 and Figure 7. Please note that these figures do not show a distribution (i.e. the surface under the curves does not equal 100%) but a share on each data point. Please note that the intervals are not equally spaced.

Retrofitting potentials

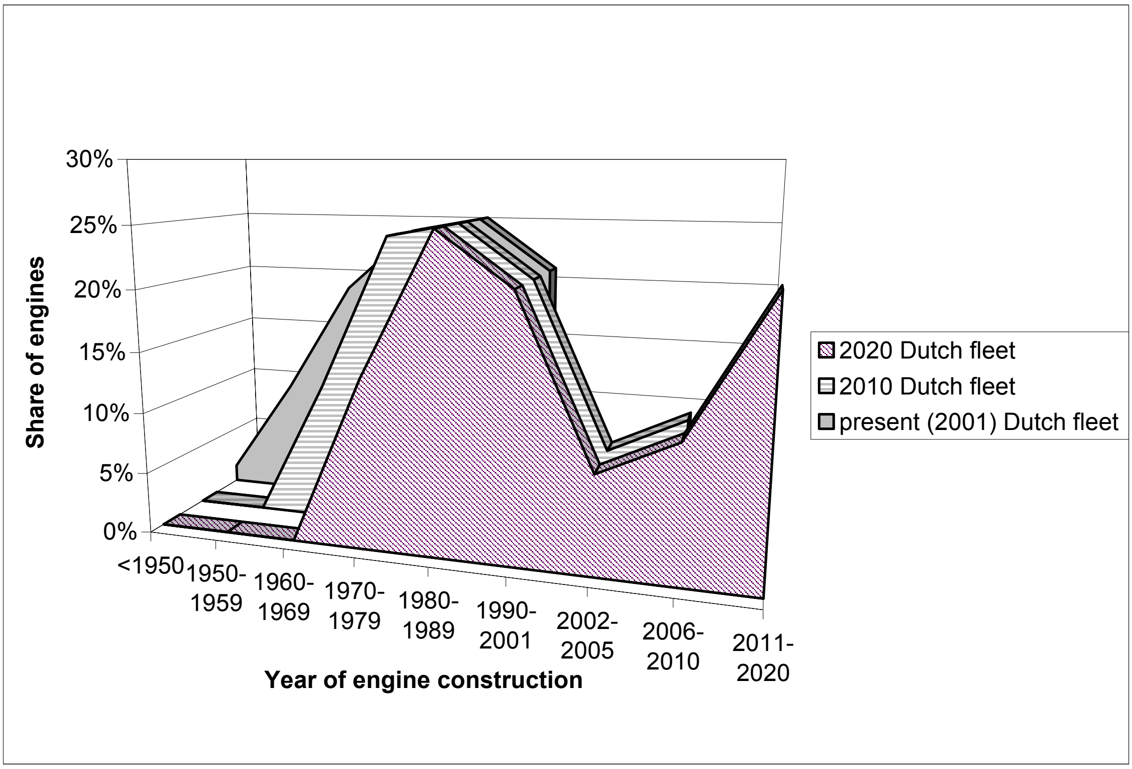

Figure 6. Prediction year of engine construction Dutch fleet according to “constant average age scenario”.

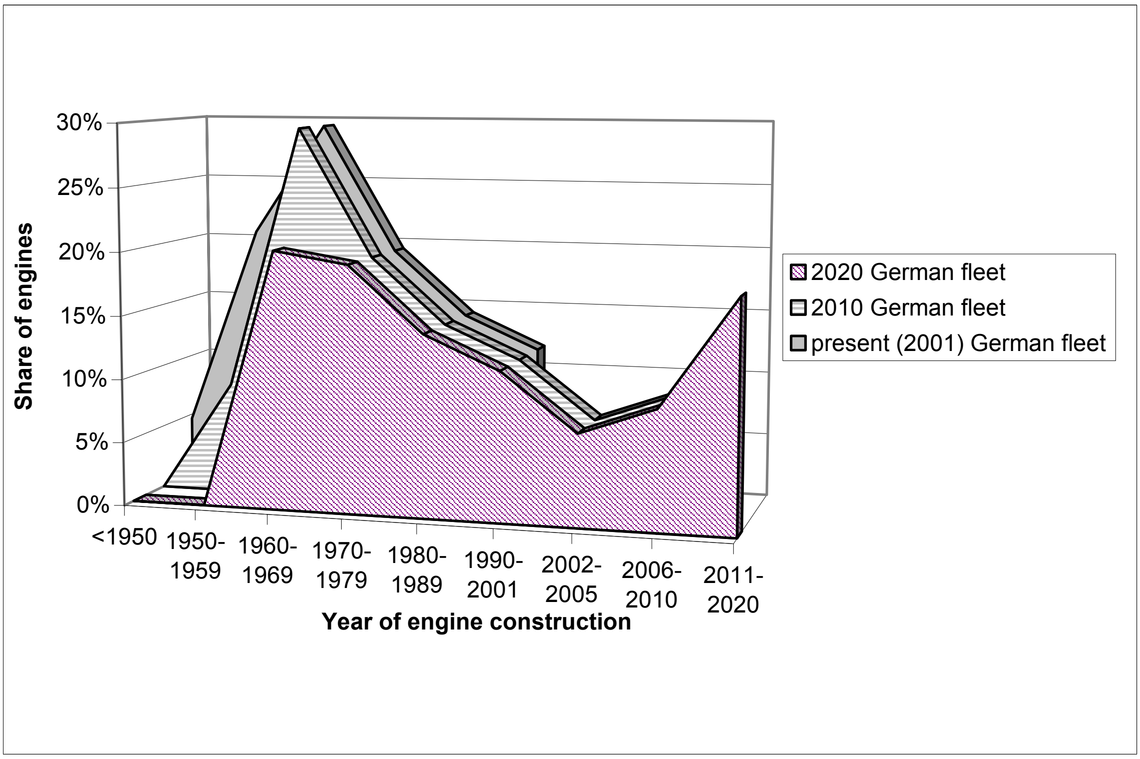

Figure 7. Prediction year of engine construction German fleet according to “constant average age scenario”

5.2.2. Results and discussion

Table 2 shows the trend of the emission of the fleet by engine substitution according to “constant average age scenario”.

Table 2. Emission fleet in a certain year by substitution according to “constant average age scenario” (no retrofit)

	2001	**2010**	**2020**
Share Dutch fleet fulfilling CCNR I [%]	78%	88%	94%
Share German fleet fulfilling CCNR I [%]	69%	76%	83%
Average NOx emission Dutch fleet [g/kWh]	10.3	9.5	7.5
Average NOx emission German fleet [g/kWh]	10.7	10.1	8.4

In order to estimate the influence of retrofit legislation, the emission in g/kWh will be averaged over 2 decades starting from 2001. This means that the influence of retrofit legislation Euro IV/CCNR III only changes the emission in the last 5 years. The influence of this legislation would be larger when extending the period under consideration. Table 3 shows the influence of the several options for retrofit legislation as mentioned in section 5.1.2 for the Dutch fleet. Table 4 does the same for the German fleet.

Table 3. Emission Dutch fleet with and without several types of retrofit legislation with substitution by “constant average age scenario”

	2007	**2011**	**2020**	**average**
NOx emission by substitution [g/kWh] (no retrofit)	9.8	9.2	7.5	9.1
NOx emission with CCNR I retrofit obligation [g/kWh]	9.1	8.7	7.2	8.8
NOx emission with Euro IIIA/CCNR II retrofit obligation [g/kWh]	9.8	5.9	5.0	7.7
NOx emission with Euro IV/CCNR III retrofit obligation [g/kWh]	9.8	9.2	1.5	7.6

Table 4. Emission German fleet with and without several types of retrofit legislation with substitution by “constant average age scenario”

	2007	**2011**	**2020**	**average**
NOx emission by substitution [g/kWh] (no retrofit)	10.4	9.9	8.4	9.8
NOx emission with CCNR I retrofit obligation [g/kWh]	9.1	8.8	7.5	9.1
NOx emission with Euro IIIA/CCNR II retrofit obligation [g/kWh]	10.4	5.9	5.2	8.0
NOx emission with Euro IV/CCNR III retrofit obligation [g/kWh]	10.4	9.9	1.5	8.0

Retrofitting potentials

From these data it can be concluded for this scenario that every one of the proposed retrofit legislations has some impact on the emission over two decades. The influence of the impact of CCNR I retrofit legislation is not very high, though (maximum 7%). The impacts of Euro IIIA/CCNR II and Euro IV/CCNR III do not differ much over a 2-decade period; this legislation will reduce the total emissions over 2 decades by 17 to 18%. Please note that the impact of Euro IV/CCNR III will become more pronounced over a longer period of time.

5.3. Schilperoord-lifetime scenario

5.3.1. Description Schilperoord-lifetime scenario

In this scenario it is assumed that the average engine remains 15 years in service. This is based on an estimation of average lifetime in [Schilperoord, 2004], hence the name. In [Schilperoord, 2004] the average lifetime equalled the rate of substitution. For convenience the 15,6 years in [Schilperoord, 2004] is rounded off to 15 years. However at this moment many engines are older than 15 years. As a consequence of this scenario many new engines are fitted between 2002 and 2005, because all engines older than 15 years are replaced at once. These new engines have to fulfil the emission legislation at the time they are introduced. This leads to the data points illustrated in Figure 8 and Figure 9.

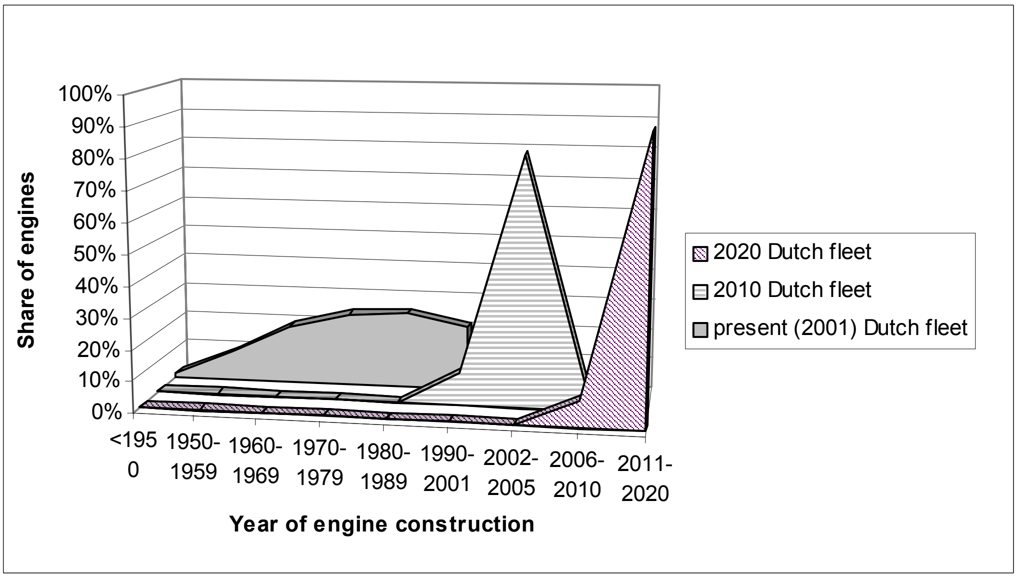

Figure 8. Prediction year of engine construction Dutch fleet according to “Schilperoord-lifetime scenario”

Retrofitting potentials

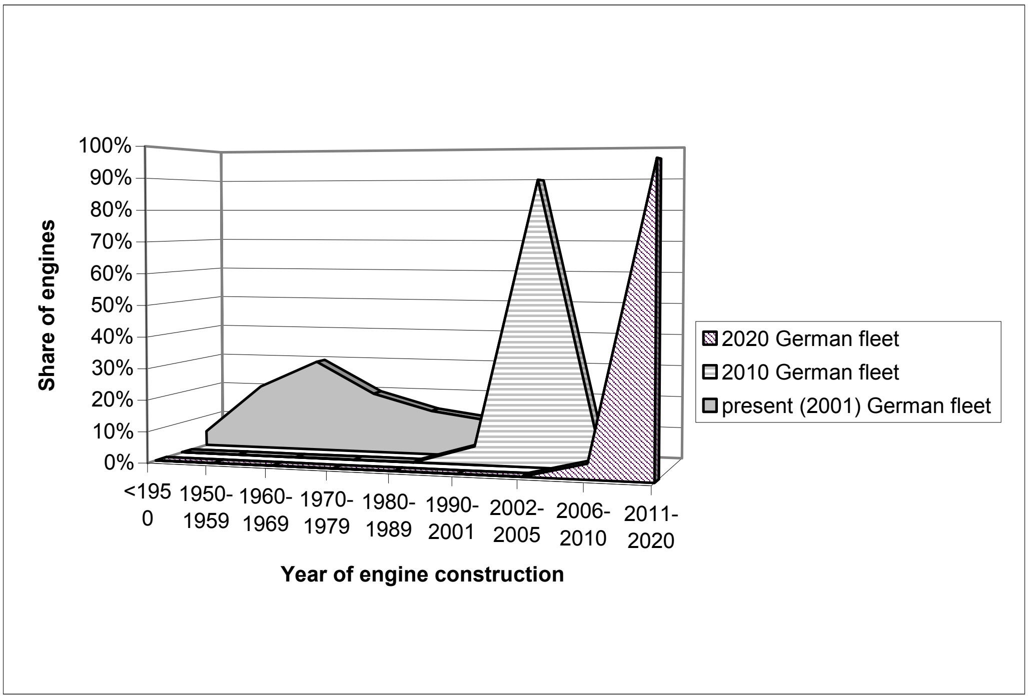

Figure 9. Prediction year of engine construction German fleet according to “Schilperoord-lifetime scenario”

It can easily be seen that the “Schilperoord lifetime scenario” results in substantially newer engines than with “constant average engine age scenario”.

5.3.2. Results and discussion

Table 5 shows the change in emissions of the fleet in a certain year by engine substitution according to “Schilperoord-lifetime scenario”. It has to be noted that virtually all engines fulfil in 2010 CCNR I according to this scenario.

Table 5. Emissions in a certain year by substitution according to “Schilperoord-lifetime scenario” (no retrofit)

	2001	2010	2020
Share Dutch fleet fulfilling CCNR I [%]	78%	99%	100%
Share German fleet fulfilling CCNR I [%]	69%	99%	100%
Average NOx emission Dutch fleet [g/kWh]	10.3	9.0	1.9
Average NOx emission German fleet [g/kWh]	10.7	9.1	1.7

Again the influence of retrofit legislation will be shown in a number of years and by calculating the average over 2 decades.

Table 6. Emission Dutch fleet with and without several types of retrofit legislation with substitution by “Schilperoord-lifetime scenario”

	2007	**2011**	**2020**	**average**

NOx emission by substitution [g/kWh] (no retrofit)	9.2	8.8	1.9	8.0
NOx emission with CCNR I retrofit obligation [g/kWh]	9.1	8.8	1.9	8.0
NOx emission with Euro IIIA/CCNR II retrofit obligation [g/kWh]	9.2	5.9	1.9	7.0
NOx emission with Euro IV/CCNR III retrofit obligation [g/kWh]	9.2	8.8	1.5	7.1

Table 7. Emission German fleet with and without several types of retrofit legislation with substitution by "Schilperoord-lifetime scenario"

	2007	**2011**	**2020**	**average**
NOx emission by substitution [g/kWh] (no retrofit)	9.2	9.0	1.7	8.2
NOx emission with CCNR I retrofit obligation [g/kWh]	9.1	9.0	1.7	8.2
NOx emission with Euro IIIA/CCNR II retrofit obligation [g/kWh]	9.2	6.0	1.7	7.1
NOx emission with Euro IV/CCNR III retrofit obligation [g/kWh]	9.2	9.0	1.5	7.3

Due to the high rate of engine substitution the influence of CCNR I retrofit legislation is barely visible. In fact 75% of the Dutch fleet and 85% of the German fleet is substituted at once by an engine from 2002 in this scenario. This is in fact not the reality but is induced by the fact that assumed lifetime and the age of the existing fleet do not correspond. The result is that in 2002 already 97% fulfils CCNR I. Euro IIIA/CCNR II and Euro IV/CCNR III still have got an influence of 13% on the emissions in the two decades under consideration, with Euro IIIA having a slightly higher influence.

5.4. 45 years lifetime scenario

5.4.1. 45 years lifetime scenario

When looking at the scenarios it strikes that with "constant average engine age scenario" many engines from the sixties (only German fleet) and seventies remain into service to 2020. "Schilperoord lifetime scenario" on the other hand is rather optimistic about the rate of substitution. Therefore an intermediate scenario is developed that is in reasonable agreement with the present situation, but instead of keeping the average age of the fleet constant an estimation of the maximum engine lifetime is used. A lifetime of 45 years is chosen. This is not based on any technical data, but only on the composition of the existing fleet. The big advantage of this scenario over the "constant average engine age scenario" is the increased rate of substitution of the relatively old German fleet. The resulting distribution is illustrated in Figure 10 and Figure 11. This scenario seems like a more natural scenario than the "Schilperoord lifetime scenario". It leads in fact to a younger German fleet than Dutch fleet in 2010 and 2020, with average engine age of 20 versus 22 and 19 versus 23. This also illustrates that this scenario is for the Dutch fleet not so different from the "constant average engine age scenario".

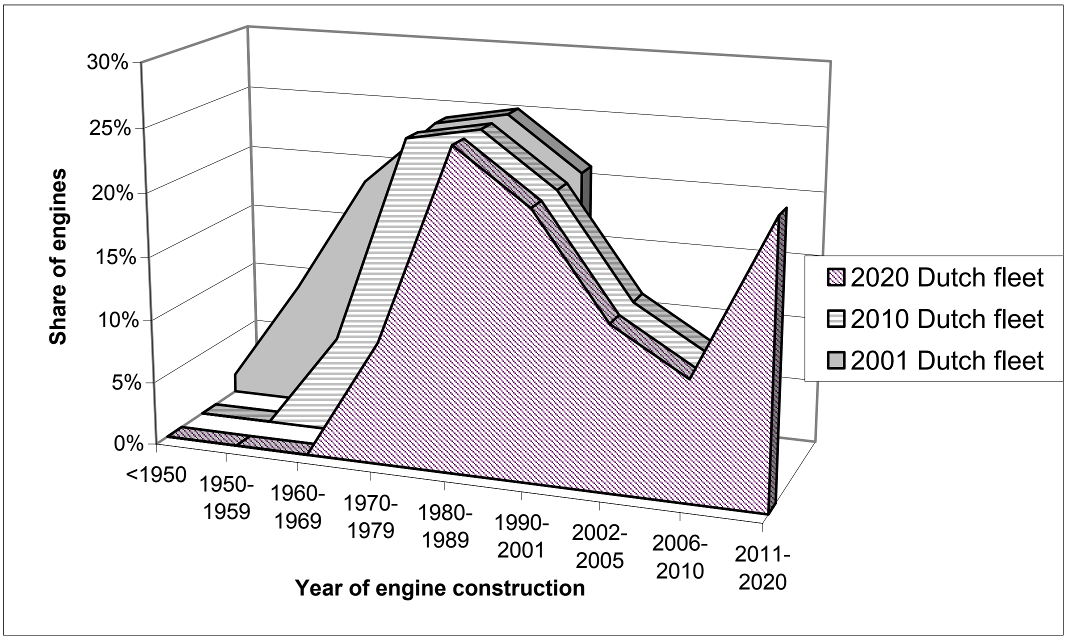

Figure 10. Prediction year of engine construction Dutch fleet according to "45 years lifetime scenario"

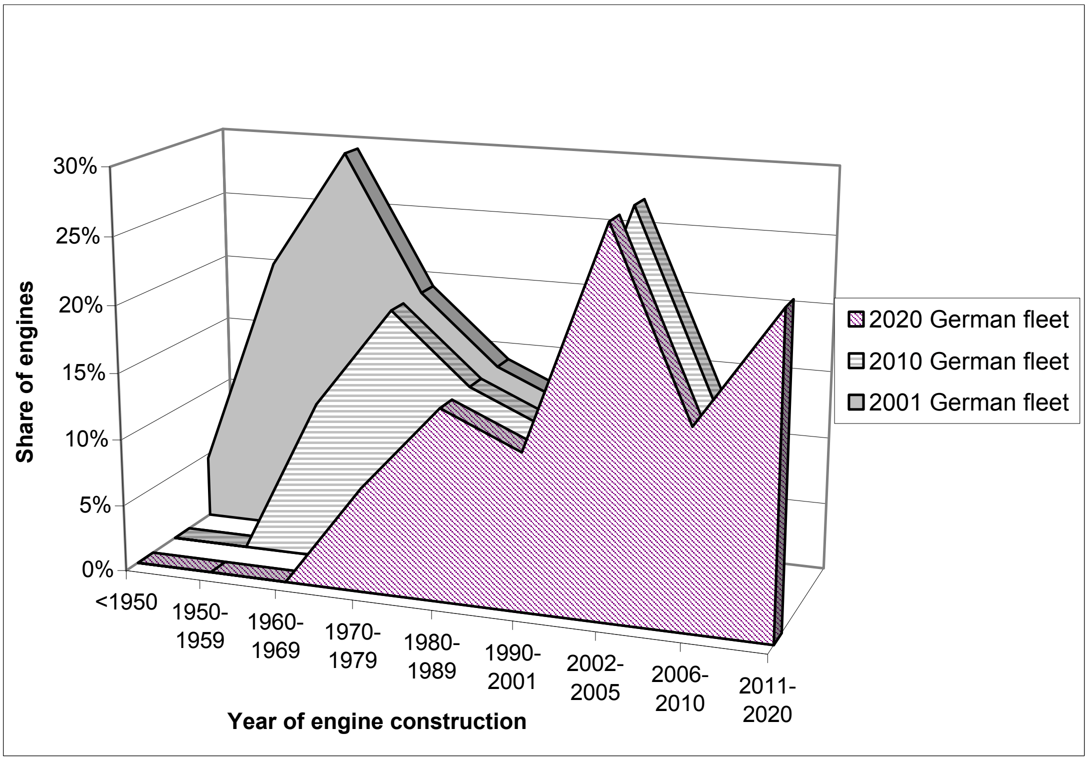

Figure 11. Prediction year of engine construction German fleet according to "45 years lifetime scenario"

5.4.2. *Results and discussion*

The share of engines fulfilling at least CCNR I is higher for the Dutch fleet than the German fleet, as illustrated in Table 8. The average NOx emission of the German fleet in 2010 and 2020 is lower however, due to the higher share of new engines.

Table 8. Emissions in a certain year by substitution according to “45 years lifetime scenario” (no retrofit)

	2001	2010	2020
Share Dutch fleet fulfilling CCNR I [%]	78%	90%	94%
Share German fleet fulfilling CCNR I [%]	69%	86%	92%
Average NOx emission Dutch fleet [g/kWh]	10.3	8.9	7.2
Average NOx emission German fleet [g/kWh]	10.7	8.7	6.9

The influence of retrofit legislation with a lifetime of 45 year is shown in Table 9 and Table 10.

Retrofitting potentials

Table 9. Emission Dutch fleet with and without several types of retrofit legislation with substitution by “45 years lifetime scenario”

	2007	**2011**	**2020**	**average**
NOx emission by substitution [g/kWh] (no retrofit)	9.7	9.2	7.5	9.1
NOx emission with CCNR I retrofit obligation [g/kWh]	9.1	8.8	7.2	8.8
NOx emission with Euro IIIA/CCNR II retrofit obligation [g/kWh]	9.7	5.9	5.0	7.7
NOx emission with Euro IV/CCNR III retrofit obligation [g/kWh]	9.7	9.2	1.5	7.5

Table 10. Emission German fleet with and without several types of retrofit legislation with substitution by “45 years lifetime scenario”

	2007	**2011**	**2020**	**average**
NOx emission by substitution [g/kWh] (no retrofit)	9.9	9.2	7.3	9.1
NOx emission with CCNR I retrofit obligation [g/kWh]	9.0	8.5	6.9	8.7
NOx emission with Euro IIIA/CCNR II retrofit obligation [g/kWh]	9.9	5.9	4.9	7.7
NOx emission with Euro IV/CCNR III retrofit obligation [g/kWh]	9.9	9.2	1.5	7.6

This scenario shows a sudden increase in engine substitution of the German fleet in the period 2002-2005 just as the “Schilperoord-lifetime scenario” but to a far lesser extent. CCNR I retrofit legislation only shows a 4% reduction in emissions over 2 decades, while Euro IV/CCNR III legislation shows up to 16% reduction over 2 decades starting from 2001, although retrofit legislation for Euro IV/CCNR III legislation in this calculation does not enter into force until 2016.

5.5. Conclusion

The available data on emissions by ship engines are limited. More detailed knowledge on emission parameters as a function of engine age and type would be welcomed. Three different scenarios are studied for engine lifetime. For this calculation it is assumed that the retrofit legislation enters into force 5 years after the same legislation entered into force for new engines. Interestingly the effect of retrofitting legislation is rather similar for the scenarios. Enforcing retrofit with CCNR I legislation only marginally influences total engine emissions over 2 decades starting from 2001 with a maximum emission reduction for all scenarios of 7% in comparison to no retrofit legislation. With the introduction of retrofit legislation according to Euro IIIA/CCNR II or Euro IV/CCNR III NOx emissions can be reduced by 12 to 18% over these 2 decades, depending on the chosen scenario. In most scenarios retrofit legislation according to Euro IV/CCNR III is most effective, even though it only has an effect in the last 5 years of the 2-decade period under consideration. Extending this period would show a larger decrease in emissions. It is recommended not to use CCNR I limits for retrofit legislation. This corresponds with the conclusion of [Schilperoord, 2004] and [Kliche et al., 2004]. Euro IIIA/CCNR II limits or Euro IV/CCNR III, when the latter indeed enters into force for new engines, are more suitable for retrofit legislation, with Euro IV/CCNR III level having the greatest impact. Advised dates for implementation of retrofit legislation are 2011 for Euro IIIA/CCNR II limits and 2016 for Euro IV/CCNR III.

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