MASTHER THESIS

"Sustainable Reduction of CO_2 Emissions and Pollutants using LNG for the Danube Inland Navigation"

Implemented for the purpose of the acquisition of the academic degree
of an engineering graduate

Advisor

ao. Univ. Prof. Dipl.-Ing.Dr.-tech. ERNST PUCHER

Co. Advisor

Dipl.-Ing. LUIS CACHÓN

E 700

Vienna University of Technology

Faculty of Mechanical Engineering

Institute for Internal Combustion Engines and Automotive Engineering

by

FERRAN CORZO

1027319

Kandlgasse 30,
1070 Vienna

Vienna, April 2011 ....

Abstract

The aim of this work is feasibility study on the sustainable reduction of CO_2 emissions as well as particle and NO_2 emissions by using LNG (liquefied methane and bio methane) for the Danube inland navigation.
The study serves as preliminary planning for an experimental development project for a retrofit solution, contributing to short-and medium-term achievement of the Austrian climate targets.

The transportation by barge in comparison to other kinds of transport shows considerably specific lower energy requirements. Additional benefits are shown concerning the noise impact of residents near traffic roads as well as a discharge of the road system. However, CO_2 emissions resulted of diesel combustion could be reduced significantly by using low-carbon fuels such as methane and bio methane once again. Due to the high age of marine propulsion systems up to 30 years, these ones show nowadays unusual high local emissions of particulate matters (PM) and nitrogen oxides (NO_X). For this reason a trend towards climate and environmentally friendly drive systems applied the inland waterway transportation sector can be simply recognized conditionally. In 2005 uniform emission standards for all member states of the EU regarding new barges were introduced. The specific emission limits contained therein do not conform to the standard, which is applied to comparable categories of engines for other modes. By use of "clean fuels", a sustainable reduction of climate-altering emissions as well as local emissions directly harmful to humans and the nature could be achieved especially in environmentally sensitive areas such as the Austrian Danube valley.

Kurzfassung

Acknowledgements

This thesis was accomplished at Institute for Internal Combustion Engines and Automotive Engineering of the Vienna University of Technology under the direction of Prof. Dr. Ernst Pucher.

I would like to acknowledge Prof. Dr. Ernst Pucher and his research group for their professional and personal support to the success of this study, in particular DI. Luis Cachón for placing his trust in me, his continued assistance, his understanding and comprehension throughout the whole study.

Besides, special thanks to my family, who made me possible to study in Vienna, for their constant patience, understanding, encouragement and support from Barcelona.

Danksagung

Contents

Abbreviations

BAR_SP	Self-propelled barge
BAR_NSP	Barge not self-propelled
BAR_TK_SP	Self-propelled tanker barge
BAR_TK_NSP	Tanker barge not self-propelled
b_e	Specific Fuel Factor
BFO	Bunker Fuel Oil
CH_4	Methane
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon dioxide
DDF	Diesel Dual Fuel
DEF	Diesel Exhaust Fluid
DF	Dual Fuel
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
DPM	Diesel Particulate Matter
E	Fuel Consumption
ECU	Electronic Control Unit
EF	Emission Factor
EGR	Exhaust Gas Recirculation
EU	European Union
GD	Gas Diesel
HC	Hydrocarbons
HCNG	Hydrogen Enriched Natural Gas

HD	Heavy Duty
HFO	Heavy Fuel Oil
HPDI	High Pressure Direct Injection
H_20	Water
IMO	International Maritime Organisation
IWT	Inland Waterway Transport
IWW	Inland Waterway
LBM	Liquefied Biomethane
LFO	Light Fuel Oil
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
MDO	Marine Diesel Oil
MCR	Engine Load
MGO	Marine Gas Oil
NECA	NO_X Emission Control Areas
NG	Natural Gas
NMVOCs	Non-Methane Volatile Organic Compounds
NO	Nitrogen Oxide
NO_2	Nitrogen Dioxide
NO_X	Nitrogen Oxides
N_2	Nitrogen
OIGI	Oil Ignition Gas Injection
OTH_GDVES	Other Goods Carrying Vessel
O_2	Oxygen
PAHs	Polycyclic Aromatic Hydrocarbons
PINE	Prospects for Inland Navigation within the Enlarged Europe
PM	Particulate Matter

RoPax	Rolling goods and passengers
RoRo	Roll on Roll off vessel
SCR	Selective Catalytic Reduction
SECA	Sulphur Dioxide Emission Control Area
SI	Spark Ignited
SNCR	Selective Non Catalytic Reduction
SOF	Soluble Organic Fraction
SO_2	Sulphur dioxide
SO_4	Sulfate
TDC	Top Dead Center
TEU	Twenty-foot Equivalent Unit
UN	United Nations
VESS_SEA	Seagoing Vessel
VSV	Vacuum Switching Valve

1. Introduction

The aim of this work is to study the feasibility on the sustainable reduction of exhaust emissions for using Liquefied Natural Gas (LNG) or Compressed Natural Gas (CNG) as fuel for ship propulsion.

Moreover, the performance of dual-fuel engines will be studied in depth as well as the different bunkering systems for these types of ships (Chapter 4). In Chapter 5 the different exhaust after-treatment systems are analyzed.

In chapter 6 and 7 the Austrian and Danube fleet as well as the transport volume and type of commodities transported throughout the Danube will be explained.

The main emissions from ship engines that will be analyzed are: nitrogen oxides (NO_X), sulphur dioxide (SO_2), particulate matter (PM) and carbon dioxide (CO_2) – Chapter 9. Two models have been used in order to calculate these emissions as well as the fuel consumption (Chapter 8).

Natural gas is a feasible substitute for current marine fuels with low emissions to air. When the shipping sector considers its options to comply with current and planned restrictions on environmental grounds natural gas, in particular as Liquefied Natural Gas (LNG), promises solutions with few technical obstacles, but with a number of logistical and economical challenges to overcome.

Natural gas is a reliable fuel for both private and commercial vehicles and builds on a proven technology already implemented in many European countries. In other European cities natural gas powered vehicles for urban services, e.g. public transport and garbage collecting services, have proven successful. However, this success has been the result of a political will to support the use of natural gas fuel with subsidies or reduced tax. It is a commonly shared belief that lower taxes on natural gas are important for a successful implementation of natural gas driven vehicles both in land and inland waterway transport.

2. Objectives

The aim of this study is to evaluate exhaust gas emissions from the Danube waterway vessels as well as to analyze the potential of inland vessels which run on LNG.

Therefore, the following objectives, methods and partial results are intended:

- Modelling and calculation of the potential of improvement of the climate-relevant CO_2 emissions and trace substances (NO_X and particulate matter) of the Danube- inland navigation.

- Investigation for a sustainable retrofitting of diesel engines of typical Danube barges on a methane pilot ignition engine.

- Valuation of the expected emission levels.

- Design and installation concept of an LNG tank technology for inland vessels (natural gas and bio methane).

- Development of a concept for LNG refuelling infrastructure for the Danube waterway vessels and for the supply on their typical routes.

3. Methodology

As it has been mentioned previously, the aim of this work is to calculate the exhaust emissions from current inland shipping at the Danube as well as the exhaust emissions that would be emitted if the vessels ran on LNG.

First of all, a large amount of information was collected regarding natural gas and dual-fuel technologies used in the naval sector.

Secondly, exhaust emission systems have been studied in order to know its performance and its potential to reduce the different pollutants.

As well, the Danube and Austrian fleet were analyzed in detail: number of vessels, power, load… in order to ensure the calculations were as accurate as possible.

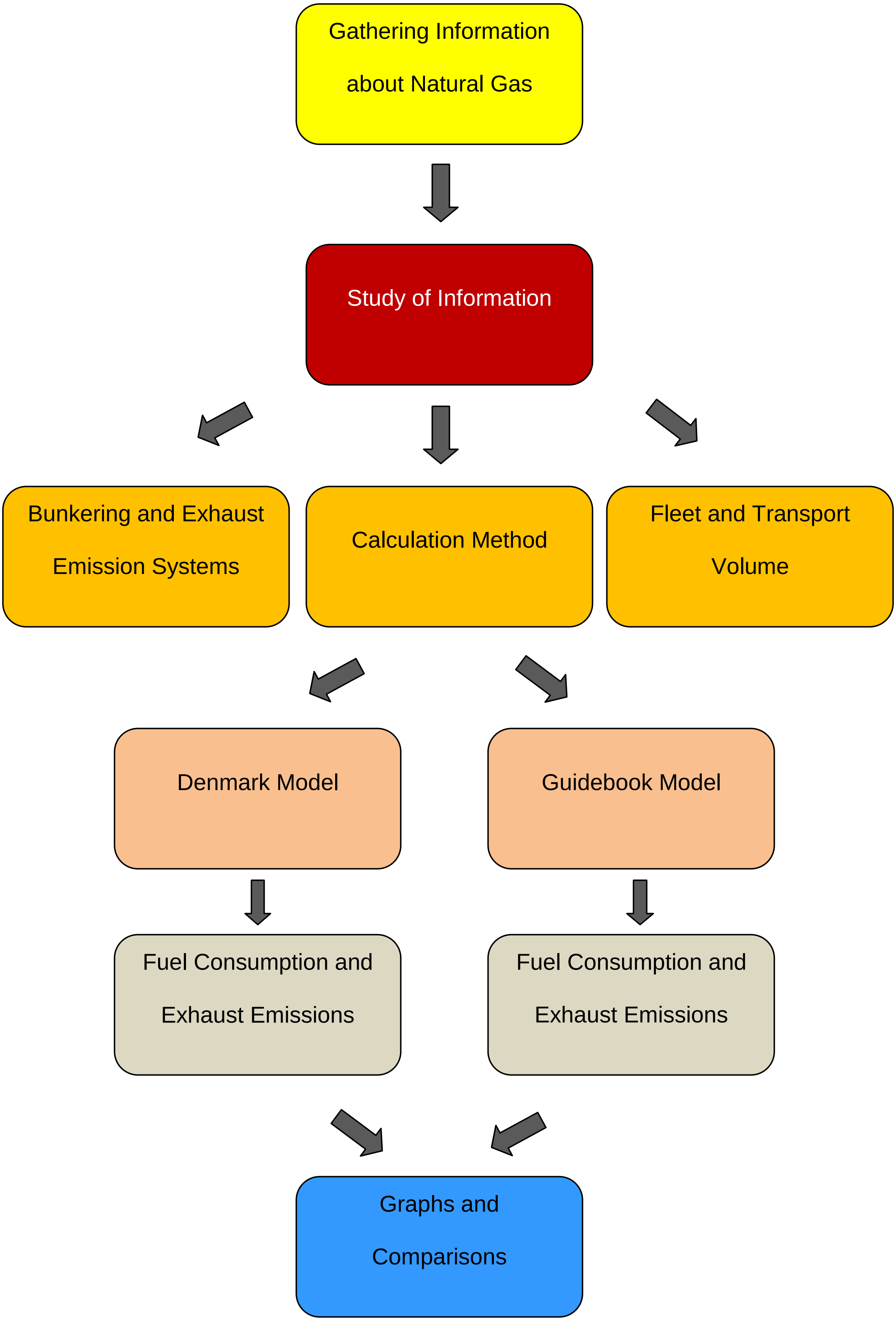
Thus, with respect to calculation, all data have been gathered in an Excel-file.

On the one hand, transport volume in recent years has been collected from *Eurostat* and *Statistik Austria.* After some calculations, the fuel consumption and exhaust emissions are found.

On the other hand, powers per country and type of vessel were gathered from *PINE*. Thus, making some calculations, fuel consumption was calculated. Then, the exhaust emissions were calculated through two models: Guidebook model and Danish model. Moreover, both models are analyzed in depth through tables and graphs.

All kinds of data have been extrapolated in graph form to look them clearer and more understandable.

The following flowchart summarizes the whole process developed:


Gathering Information about Natural Gas
Study of Information
Bunkering and Exhaust Emission Systems
Calculation Method
Fleet and Transport Volume
Denmark Model
Guidebook Model
Fuel Consumption and Exhaust Emissions
Fuel Consumption and Exhaust Emissions
Graphs and Comparisons

4. Dual-Fuel Propulsion Technology for Inland Navigation

The use of natural gas (NG) as a marine fuel has taken on added significance as a result of the IMO's stringent requirements concerning emissions from ships.

In October 2008, the IMO (International Maritime Organization) finalized its revision of the Marpol Annex VI – the Prevention of Air Pollution from Ships. The stringent requirements thus introduced concern mostly the sulphur oxide (SO_X) and nitrogen oxide (NO_X) emissions from the exhaust gases. However, the IMO is also working on other measures intended to reduce greenhouse gases from shipping.

Global relevance of mobility will keep growing and even more with the exponential growth of China, India and Brazil. Therefore it is very important to have fuels which are available on a long-term. Natural gas (NG) offers this security. The known reserves today are twice as large as those of crude oil. Besides, biogas adds even more potential.

Technology for CNG engines is fully developed and field-tested. Dual-fuel engines in gas mode produce roughly 80% less NO_X compared to IMO Tier I levels and practically zero SO_X and particulates, and are, therefore, compliant with the most stringent regulations. Moreover, when gas is used in a dual-fuel engine, CO_2 emissions are reduced by about 20% compared to liquid fuels.

In addition to the environmental issues, the use of natural gas as a marine fuel has positive effects on a ship's operating costs. Depending on the initial purchase price, the LNG used to power ship engines can be expected to have a similar, or slightly higher, price per energy content than heavy fuel oil.

Expenses for engine management and exhaust gas treatment are about the same as with classical drivetrains, while fuel costs less. This makes NG drivetrains a cost-effective contribution to cleaner mobility, which will become ever more important nowadays in the growing number of large cities.

4.1 Introduction Dual-Fuel Engines

When adapting a Heavy Duty (HD) Diesel engine to run on methane there are two options, either to change the combustion system from the Diesel-cycle to the Otto-cycle or to use the Diesel Dual Fuel (DDF) cycle which uses a Diesel-like cycle. The first option, the Otto-cycle (spark ignited, SI) is the most common option when rebuilding a diesel engine to operate on methane. However, the Diesel dual fuel cycle can offer some advantages since it uses Diesel injection for ignition of the methane/air mixture (“like a liquid” spark plug). Moreover, DDF systems can either use the original Diesel injectors together with injection of methane into the air intake, allowing thus the use of methane and/or diesel for greater flexibility, or employ a specially designed gas/Diesel injector, incorporating only a small range of Diesel injection which disable operating the engine on 100 % Diesel, but allows for more Diesel substitution by methane over the full operating range of the engine.
The fuel used in methane fuelled engines can be biomethane, compressed natural gas (CNG), liquefied natural gas (LNG) or liquefied biomethane (LBM). Outside the marine field, on the one hand LNG/LBM is the preferred fuel for long haul trucks since it has significantly higher energy density implying smaller, but different gas cylinders on-board the vehicle. On the other hand, for vehicles operated in a local area, compressed methane gas might be the most suitable alternative. Other combinations of methane fuels could also be used as fuel within the transportation sector such as blends of fuels from fossil and renewable origin and hydrogen enriched natural gas, hythane (HCNG).
Compared to a spark ignited methane fuelled engine a Diesel Dual Fuel concept could end up with better fuel efficiency using current engine technology. However, the potential for substitution of diesel with methane would be lower over the full operating range of the vehicle, and emissions performance may impair the ability to fully use the fuel consumption benefits offered by the Diesel cycle.

The name Dual Fuel is wide spread when two fuels are used simultaneously where one is used mainly for ignition (Diesel) and the other mainly used for energy supply (methane). Dual Fuel should not be confused with the name Bi-fuel which is commonly used for passenger cars that runs either on gasoline or on gas (methane or LPG).

4.1.1 Gas-Diesel Engines

The Gas-Diesel engine utilizes the diesel combustion process in all operational modes so can virtually burn any possible mixture of gas and liquid fuel. In gas mode, a measured quantity of natural gas is mixed with the air just before it enters into the cylinder and compressed to the same levels as the diesel engine to maintain efficiency (the gas is injected at high pressure -for four-stroke around 350 bar and for two-stroke around 250 bar-). The natural gas mixture does not ignite spontaneously under compression, so is used a small injection of diesel fuel (pilot fuel), equivalent to approximately 5-10% of the fuel energy input at full engine load, to ignite the main charge of gas and air. Natural gas burns cleaner than diesel due to its inherently low carbon content.

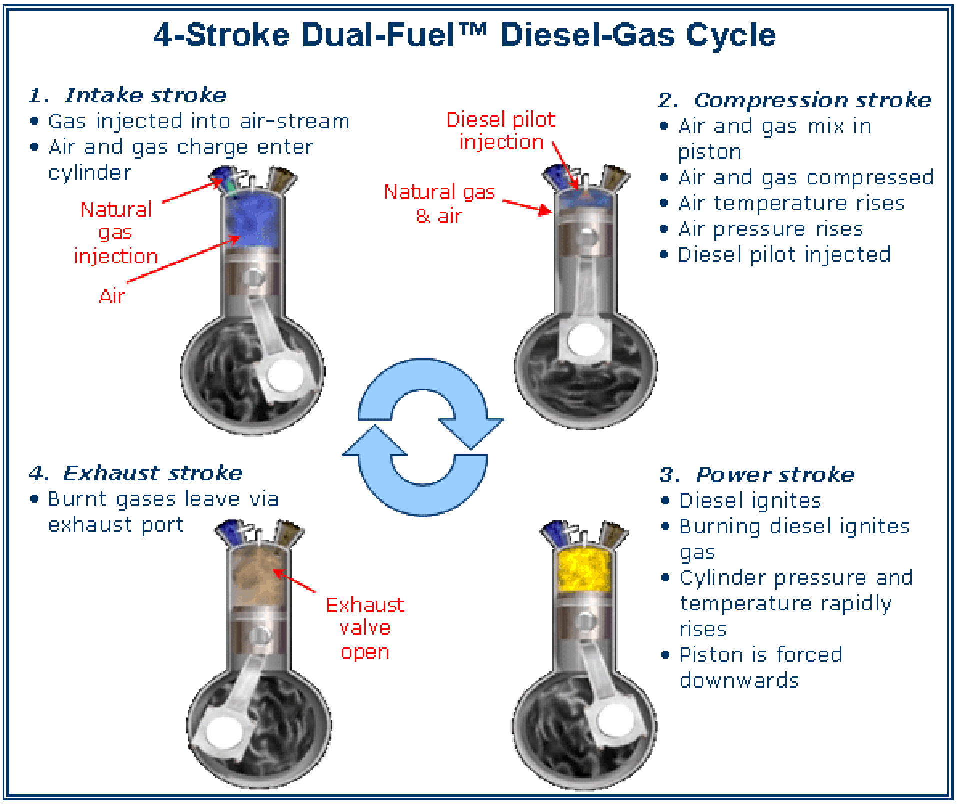


Figure 1. 4-Stroke Diesel-Gas Cycle (Clean Air Power)

The diesel engine itself is virtually unchanged, except for the addition of the gas injection system and the ECU, fitted externally to the engine. The temperatures and pressures into the cylinder are within those of pure diesel operations, so the converted engine operates within the designed limits of the original engine.

The gas-diesel engine can be switched over instantly to liquid fuel mode operation. The liquid fuel can be light fuel oil, heavy fuel oil or crude oil. In this case, the process is the same as the conventional diesel process.

In fuel sharing mode, the ratio between liquid and gas fuel amounts can be controlled and varied during operation. The GD engine can run in either 95% gas / 5% liquid fuel mode or in 100% liquid fuel mode, as well as any other gas-to-liquid fuel ratio in between according to the fuel sharing window.

The gas-diesel process can tolerate big variations in the gas quality and is especially suitable for "non-pipeline quality gas", such as associated gas in oil fields. Dual-Fuel injectors are controlled by pulse-width modulated signals from the ECU. The signals are based on manifold pressure, charge air temperature, gas pressure, gas temperature and fuel mapping, providing the best combination of emissions and efficiency.

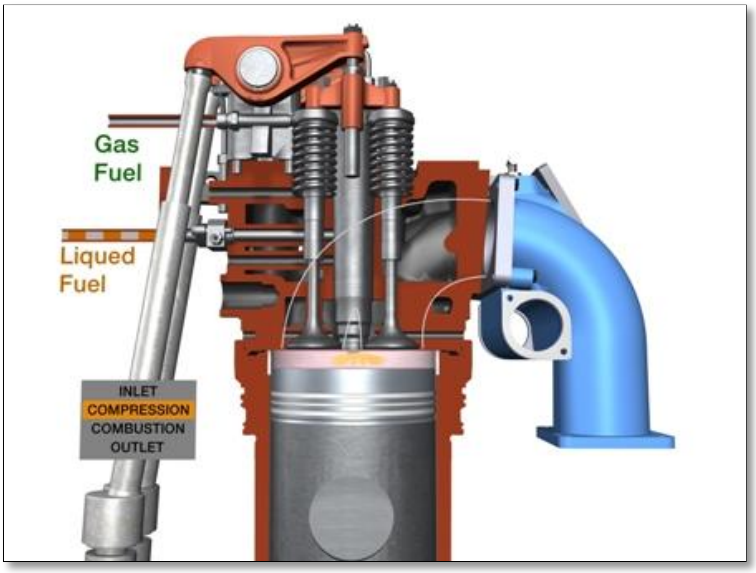


Figure 2. Gas-Diesel Engine (Wärtsilä)

All Dual-Fuel engines run on either Compressed Natural Gas or Liquefied Natural Gas. Super-cooled LNG requires vacuum-insulated low-pressure fuel tanks and requires less on-board space than compressed CNG gas tanks.

As boil-off gas is generated at atmospheric pressure, large gas compressors are required to boost the gas pressure to the appropriate level. These compressors require a substantial amount of electric power to operate and are costly and heavy. Besides, the presence of high-pressure gas in the engine room is a major safety concern, especially on LNG carriers.

PUMP DRIVES

Wärtsilä 32GD

Technical data	750 rpm	6L32GD	8L32GD	9L32GD
Shaft power	kW	2520	3360	3780
Shaft power	hp	3378	4504	5067
Heat rate	kJ/kWh	7912 (7580)*	7912 (7580)*	7912 (7580)*
Shaft efficiency	%	45.5 (47.5)*	45.5 (47.5)*	45.5 (47.5)*

*Technical data is based on mechanical output at shaft, including engine-driven pumps, ISO conditions and LHV > 36 HJ/m^3. Tolerance 5%. Gas pressure at engine inlet 350 bar. * In liquid mode.*

Wärtsilä 32GD

Technical data	750 rpm	12V32GD	16V32GD	18V32GD	20V32GD
Shaft power	kW	5040	6720	7560	8400
Shaft power	hp	6757	9009	10135	11261
Heat rate	kJ/kWh	7912 (7580)*	7912 (7580)*	7912 (7580)*	7912 (7580)*
Shaft efficiency	%	45.5 (47.5)*	45.5 (47.5)*	45.5 (47.5)*	45.5 (47.5)*

*Technical data is based on mechanical output at shaft, including engine-driven pumps, ISO conditions and LHV > 36 HJ/m^3. Tolerance 5%. Gas pressure at engine inlet 350 bar. * In liquid mode.*

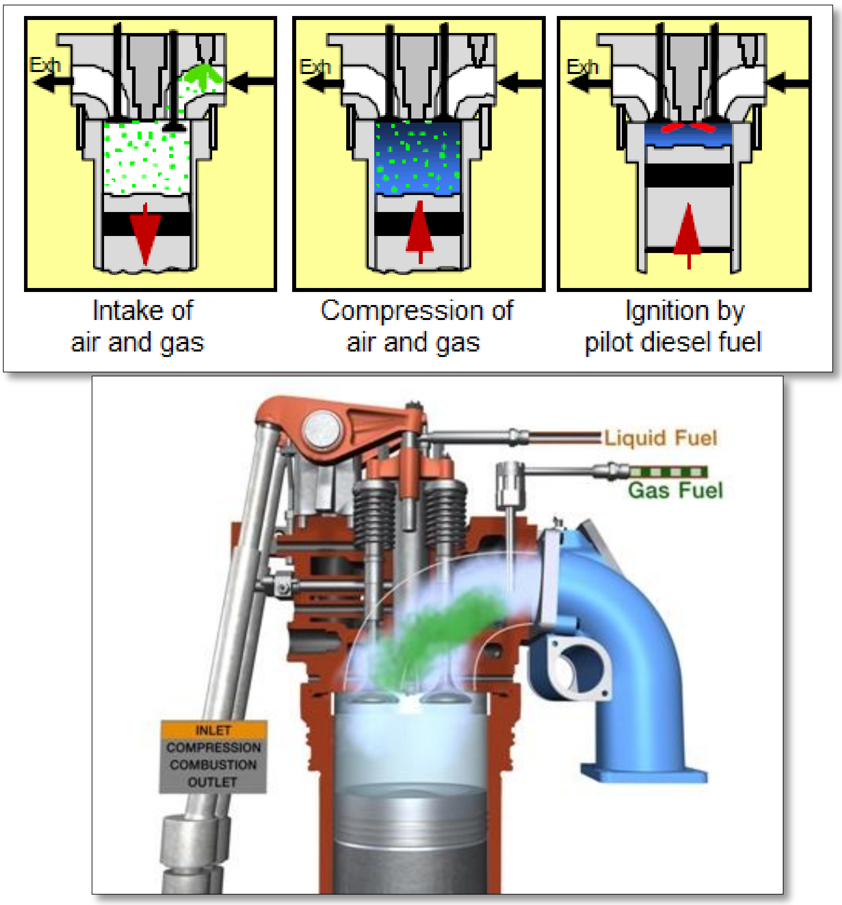
Figure 3. Gas-Diesel engine properties (Wärtsilä)

4.1.2 Dual-fuel Engines

The dual-fuel engine utilizes a “lean-burn” Otto combustion process when operating on gas. Here, the gaseous fuel is mixed with air before it enters the combustion chamber. After the compression phase, the gas/air mixture is ignited by a small amount of liquid pilot fuel (LFO). After the working phase the exhaust gas valves open and the cylinder is emptied of exhaust gases. The inlet air valves open when the exhaust gas valves close, and the process starts again.

The DF engine can operate in both 100% fuel oil mode and in 99% gas / ~1% fuel oil mode with optimum performance. The DF concept is mainly used in applications where pipeline quality gas with a high methane number is available.

The dual-fuel engine is also equipped with a backup fuel system. In the event of a gas supply interruption, the engine transfers from gas to fuel oil operation (LFO, HFO) at any load instantaneously and automatically without loss of engine power or speed. Furthermore, the separate backup fuel system makes it possible to switch over from LFO to HFO without load reduction. During fuel oil operation the DF engine utilizes the conventional diesel process.



Gas mode:

·Otto principle

·Low-pressure gas admission

·Pilot diesel injection

Figure 4. Dual-fuel engine working principle (Wärtsila-PU Machinery Systems)

The transfer from diesel to gas mode is carried out fully-automatic on demand.

This engine (*Figure 5*) is available in six-, eight- and nine-cylinder inline and twelve-, sixteen- and eighteen-cylinder Vee-form configurations. With an output of 950 kilowatt per cylinder, it delivers between 6 to 17 megawatt at full load.

Figure 5. Six-cylinder Wärtsilä 50DF (Wärtsilä)

As a result of higher efficiency and cleaner fuel, emissions of dual-fuel installations are lower than those of steam turbine, diesel and gas-diesel installations.
In combination with an electric propulsion system, dual-fuel installations achieve optimum performance and high efficiency at virtually any load.

Wärtsilä 34DF

Technical data	750 rpm	9L34DF	16V34DF	20V34DF
Shaft power	kW	4050	7200	9000
Shaft power	hp	5431	9655	12069
Heat rate	kJ/kWh	7790 (7877)*	7790 (7877)*	7790 (7877)*
Shaft efficiency	%	46.2 (45.7)*	46.2 (45.7)*	46.2 (45.7)*

*Technical data is based on mechanical output at shaft, including engine-driven pumps, ISO conditions and LHV. Heat rates and shaft efficiencies with a tolerance of 5% in gas mode. Methane number > 80. * In liquid mode.*

Figure 6. Gas-Diesel engine properties (Wärtsilä)

In the Figure 7 below, the engine performance achieved is very similar both Diesel and Dual-Fuel Engine.

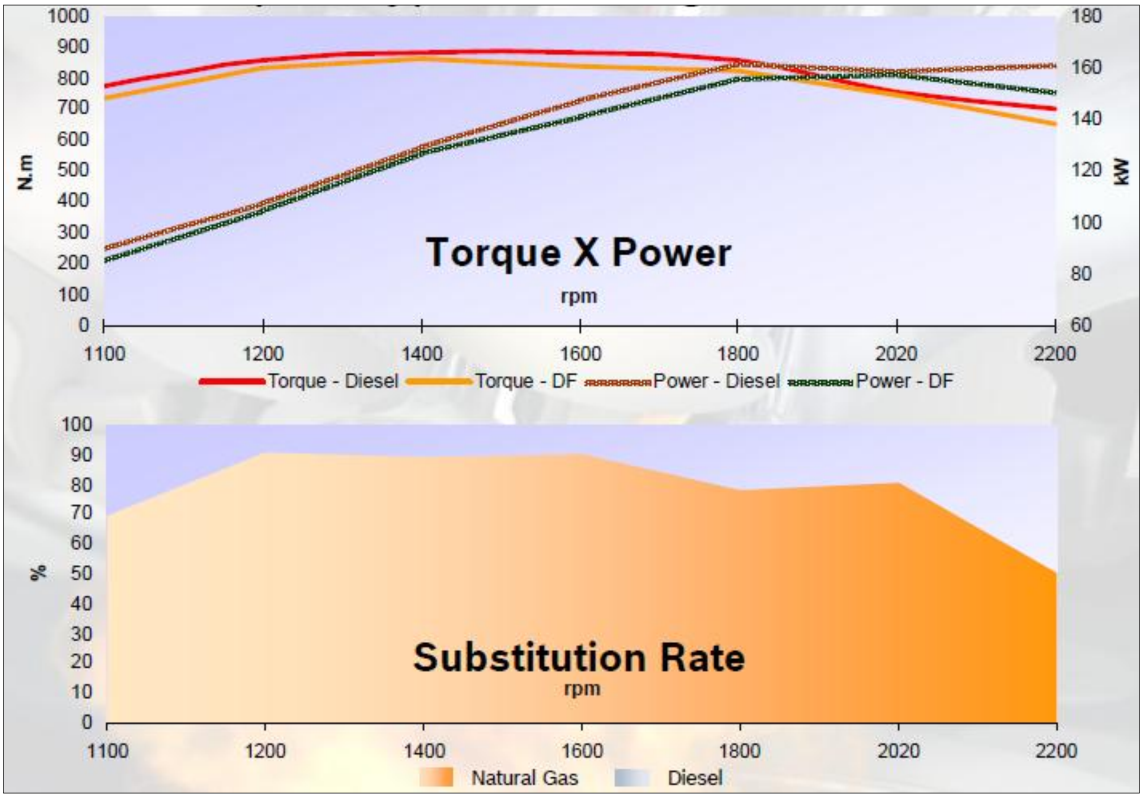


Figure 7. Engine performance depending on the fuel type (Bösch)

Figure 8 shows the fuel Consumption (g/kWh) depending on the type fuel. The Dual-Fuel mode consumption is slightly lower than Diesel Fuel.

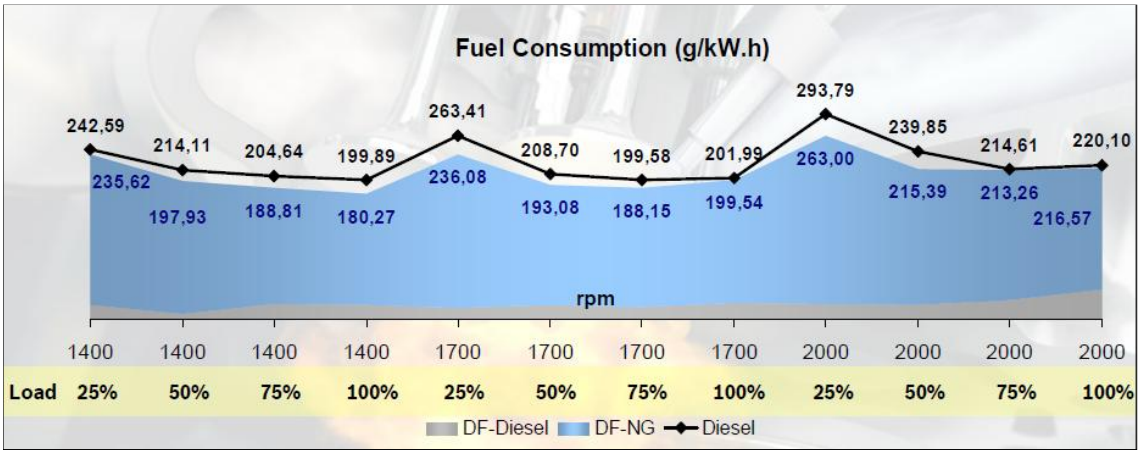


Figure 8. Specific fuel consumption depending on rpm and %Load (Bösch)

4.2 Bunkering System for Dual-Fuels Ships

Bunkering operations refer to the transfer of LNG into the fuel tank of a vessel, i.e. the final stage of the supply process. *Table 1* provides indications of the amount of LNG required per week for different types of vessels.

Ship type	kW engine	m^3 LNG per week
RoRo	12000	400
RoPax (regular)	20000	700
Superfast	25000	900

Table 1. Indications of LNG fuel requirements per ship per week (Magaloc)

The bunkering operation consists of a number of steps, and it shall last less than 50 minutes and consists of the following steps (fuel oil):

Before bunkering	During bunkering	After bunkering
• **Checklist to receiving ship** • **Connection link** • **Connection hose** • **Return of signed checklist** • **Open manual valves** • **Ready signal ship/sender**	• Pump start sequence • Transfer sequence • Pump stop sequence ↔ Transfer rate: 150 t/hr30 minutes	• Shut manual valves • Purging cargo lines • Disconnecting hose • Inerting of cargo lines (receiver) • Disconnection link • Delivery cargo document • Inerting cargo lines (sender)

Table 2. Bunkering operation (Natural gas for ship propulsion in Denmark – Danish Ministry of the environment)

LNG bunkering facilities

Pressurized above ground LNG vessels is preferred since these allow pump free transfer of LNG. Furthermore there are three more ways to transfer the LNG to the ships:

- **Permanents piping and loading arms**

Good option if ships can be bunkered predominantly at one location, and there is available space to install permanent LNG tanks within short distance (250 meters maximum).

.

Figure 9. Bunkering from fixed filling lines (Magaloc)

- **Truck to ship bunkering**

  Truck bunkering is convenient since the LNG storage does not have to be in the port. A tanker truck can deliver 55 m^3 of LNG and the loading operation from one tanker usually lasts 1 ½ hours.

  Bunkering from a tanker truck is normally slower than other alternatives, but has the advantage of flexibility.

Figure 10. LNG bunkering from tanker truck (Magaloc)

- **Ship to ship (tanker or barge)**

  This concept is not in utilization yet, but some companies have shown proof of concept of the transfer of LNG from one vessel to another.
  LNG bunkering from a barge may provide for efficient bunkering of vessels at different locations around a harbor area.

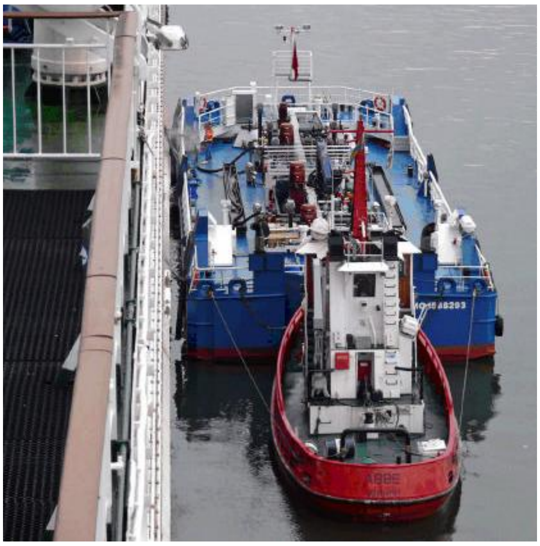


Figure 11. Bunkering barge for conventional bunker fuel assisted by tugboat (Magaloc)

LNG terminal at bunkering port

The LNG terminal concept at a bunkering port is the local facility from which LNG can be supplied for delivery to ships by permanent filling lines, truck or barge.

An LNG terminal has to provide the following functions:

- Receipt of LNG mainly by ship delivery but also by truck delivery
- Enough storage for quantity of LNG for the required bunkering operations
- Supply of LNG for the required bunkering operations (bunkering by truck, barge or permanent filling line)
- The terminal must comply with all applicable regulations and to ensure a high level of safety

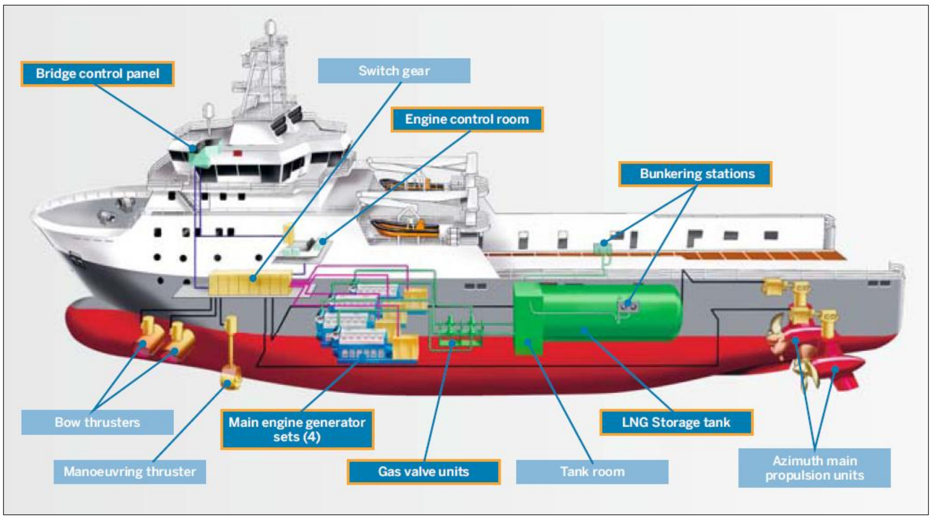


Figure 12. The LNGPac system layout from Wärtsilä (Wärtsilä)

Bunkering station(s)

This is the ships connection with the LNG terminal on shore or with the LNG bunkering barge through an insulated pipeline, usually accompanied by a vapor return line and a nitrogen purging line with respective control/thermal relief valves (pressure safety valves) and flanges. Due to the large temperature differential between the LNG (-162 ºC) and ambient temperature the pipeline should be as short as possible in order to minimize heating of the LNG.

LNG vacuum insulated pipes

From the bunkering station, LNG is led to the tank via insulated pipes. Vacuum insulation is selected for its excellent insulation properties, and to minimize LNG evaporation during bunkering. The connection between the transfer line and the ship can be accomplished by flexible hoses.

LNG storage tanks

Storage tanks for LNG tend to be the predominant feature of LNG terminals in terms of physical size and construction cost. Storage tanks have high costs due to the high requirements for temperature insulation.

Two alternative tank concepts exist depending on the tank volume required: Pressurized tanks and atmospheric tanks.

On the one hand, pressurized tanks are designed to hold pressure of a few bars. They are cylindrically shaped with dished ends mounted either horizontally or vertically.

On the other hand, atmospheric tanks are designed to hold the LNG at below boiling point and ambient pressure. In contrast to pressurized tanks, atmospheric tanks cannot be removed from their location for re-installation elsewhere. They are generally larger than the pressurized tanks, and preferred for larger required storage volumes.

In both tanks the tank volume of LNG that can be filled and emptied in the course of normal operations, is less than the gross volume.

LNG tanks are insulated with perlite/vacuum. The tank consists of a stainless steel inner vessel, which is designed for an internal pressure, and an outer vessel that acts as a secondary barrier. The outer vessel can be made of either stainless steel or carbon steel.

According to the current IMO Guidelines, the LNG fuel tanks have to be selected from among the “Independent Types A, B, or C”.

A summary of the main characteristics of the independent tank types is shown in *Table 3*. The pressure vessel allows easy handling of the evaporated gas (boil-off), since the tank is designed to withstand a significant pressure increase and the pressure relief valves are set at 9 bar(g).

Tank type	Description	Pressure	Pros	Cons
A	Prismatic tank adjustable to hull shapes. Full secondary barrier	< 0,7 bar (g)	Space efficient	·Boil-off gas handling ·More complex fuel system (compressor required)
B	Prismatic tank adjustable to hull shapes. Partial secondary barrier	< 0,7 bar (g)	Space efficient	·Boil-off gas handling ·More complex fuel system (compressor required)
	Spherical (Moss type). Full secondary barrier	< 0,7 bar (g)	Reliable/proven system	·Boil-off gas handling ·More complex fuel system (compressor required)
C	Pressure vessel (cylindrical shape with dished ends)	> 2 bar	·Allows pressure increase (easy boil-off gas handling) ·Very simple fuel system ·Little maintenance ·Easy installation	·Space demand on board the ship

Table 3. Comparison of IMO IGC independent tanks (Wärtislä Technical Journal)

In practice, vessels can operate for a long time in liquid fuel mode (HFO or MDO) before having to take care of the pressure increase in the tank. The handling of the boil-off is done very simply by a temporary switch over of the engines to gas mode, and the gas is taken from the vapor phase in the upper part of the tank. As an indication, a 200 m^3 pressurized type C tank, filled at 50% could hold LNG for about 25 days, even without any gas consumption from the tank.

A (Type C) dual-fuel engine requires approximately 4 – 5 bar(g) at the inlet of the gas valve unit. In case LNG is stored at atmospheric pressure (Type A and Type B tanks), the fuel system should include either compressors or cryogenic pumps to deliver the fuel at the correct pressure.

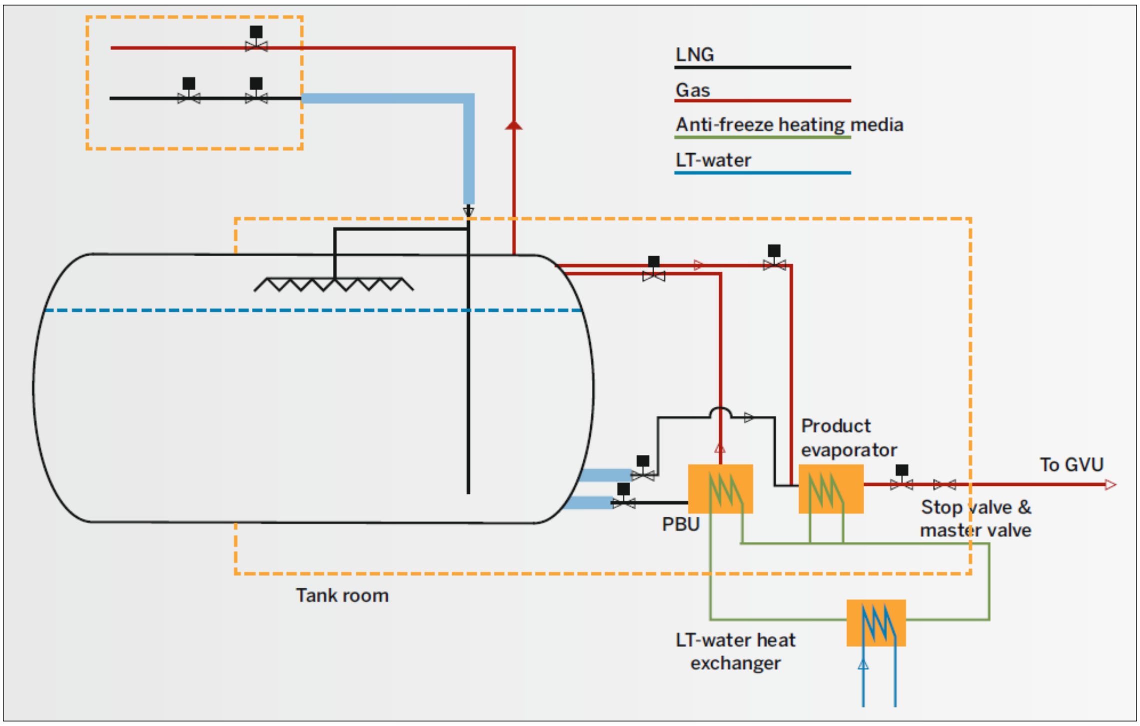


Figure 13. LNGPac simplified P&ID (Wärtsilä)

The tank room is a stainless steel barrier welded to the outer vessel of the tank. The structure contains the process skid and all the pipe penetrations to the tank. In the unlikely event of an LNG leakage, the tank room acts as a barrier that avoids damage to the external compartments, and facilitates the quick ventilation of the evaporated gas.

The handling of gas in a safe way is, of course, of great importance. It requires the adequate integration of the entire chain, from the bunkering stations at shipside to the engine inlet, until the stored hydrocarbon energy is finally converted into power.

4.3 Market

- **Westport Innovations**

Westport Innovations has a patented DDF system working with the principle of high pressure direct injection (HPDI).

HPDI injectors provide a small diesel pilot spray (5% of the total energy input) and a larger gas spray. HPDI injectors are common-rail, diesel actuated and electronically controlled. The mixture is directly injected at the end of the compression stroke from the same injector which reduces methane slip and the risk of knocking (No premixed fuel). *Figure 14* shows the principal lay-out of the injector.

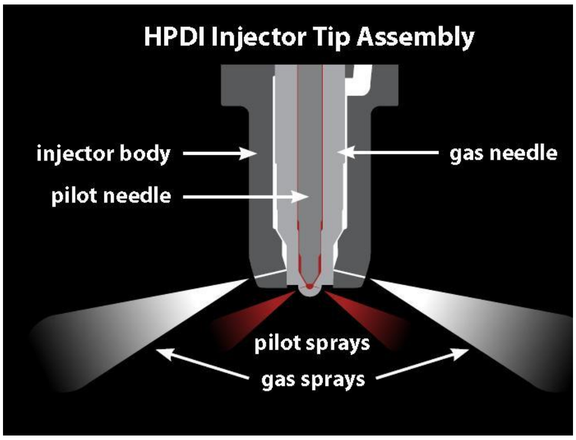


Figure 14. Westport Innovation HPDI injector (Westport)

- **Bosch Heavy-Duty Natural Gas Dual-Fuel Conversion Kit**

Bosch has developed a methane dual-fuel conversion kit for heavy duty Diesel vehicles. The system is called GD Flex. The Diesel fuel is estimated to be substituted by gas up to 90% depending upon engine operation. Currently the system is suitable for a small number of engines but more engines is planned to be added in the near future.

The basic lay-out of the system is shown in *Figure 15*

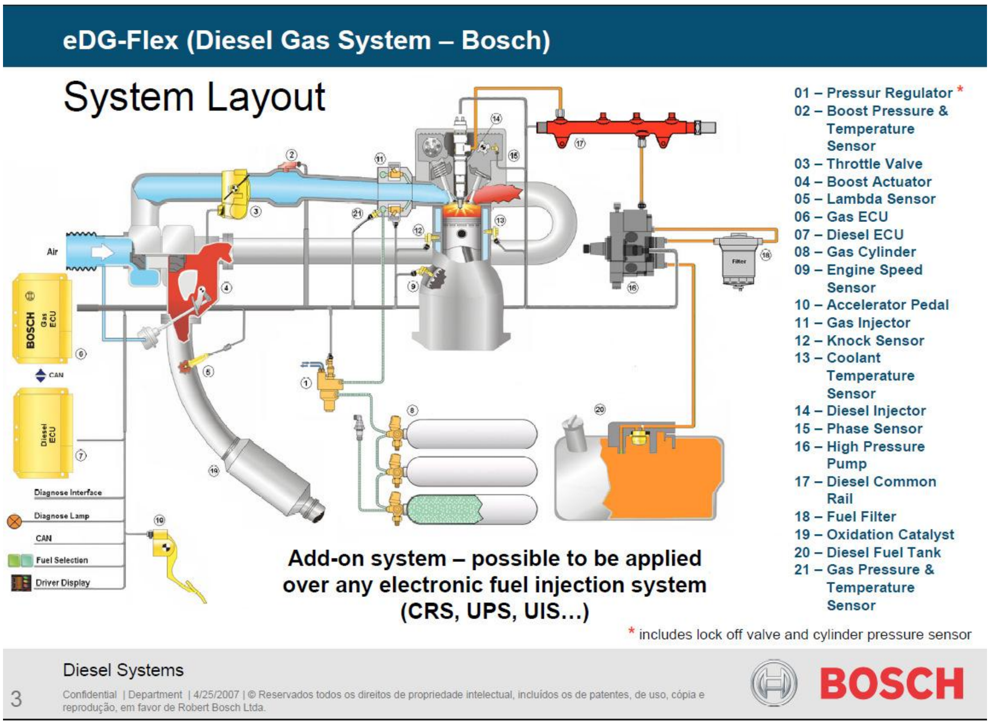


Figure 15. Bosch Dual Fuel system eDG-Flex (Source: Bosch Brazil)

In the dual fuel mode, the engines used approximately 86 % methane gas and 14 % Diesel.

The Hardstaff Group

The Hardstaff Group presented in 2006 the second generation of a retrofit Diesel dual fuel system called Oil Ignition Gas Injection (OIGI). Hardstaff has also a patented catalytic temperature control system.

- **Hardstaff OIGI**

The Hardstaff OIGI® is a dual fuel system developed to substitute natural gas for Diesel in light and heavy duty engines.

A separate electronic control unit (ECU) controls the gas injection in all the moment. Diesel is required as the ignition source in dual fuel engines. With the system the engine will use 100 % Diesel at idle; gas injection and Diesel reduction commences when engine speed increases from idle. A principal lay-out of the system is presented in *Figure 16*.

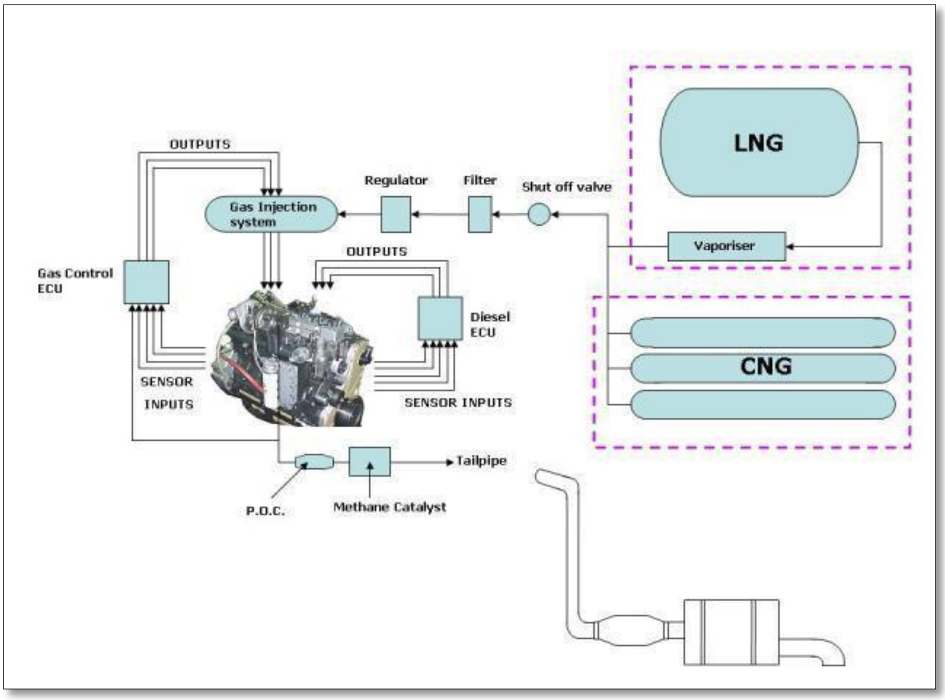


Figure 16. Hardstaff OIGI Diesel dual fuel system (Hardstaff)

European Commission (EU)

However, today, it is not possible to approve Diesel dual fuel concepts according to the European emission requirements. For the time being there is no plan from the Commission to implement dual fuel concepts in the emission requirements for Euro VI. However, if there is an increasing demand it might be possible to reconsider the situation, but today this is not the main priority of the Commission. Since emission limit values are defined based on the working principle of an engine, the limit values for engines operating according to DDF principle should be the same as for Diesel engines since the same working principle is used. The detailed regulations and requirements must however be designed accordingly. The Commission also expressed an interest to follow the future development of DDF concepts.

5 Emission treatment systems

Pollutant emissions can be controlled by two mechanisms: control of the combustion technology combined with exhaust gas treatment, and control of the fuel quality. Both these measures are used.

The principal legislative instrument Marpol Annex VI controls:

- NO_X limits
- ozone depleting substances
- sulphur oxides, through sulphur in fuel
- sulphur oxides further through the designation of Sulphur Dioxide Emission Control Area (SECA)
- Volatile organic compounds from tankers

The measures in Marpol Annex VI describe the outcomes; they do not stipulate how they are to be achieved.

Diesel emissions are controlled from their origin due to engine design and modifications or to exhaust gas aftertreatment. The two approaches are in fact complementary and are followed simultaneously in reality.

There are two groups of diesel exhaust aftertreatment devices: diesel traps and diesel catalysts. Diesel traps, which are primarily diesel filters, control diesel particulate matter emissions by physically trapping the particulates. The major challenge in the design of diesel filter system is to regenerate the trap from collected particulate matter in a safe and cost-effective manner.

Oxidation Catalyst

Modern catalytic converters consist of a monolith honeycomb substrate coated with platinum group metal catalyst, packaged in a stainless steel container. The honeycomb structure with many small parallel channels presents a high catalytic contact area to exhaust gasses. As the hot gases contact the catalyst, several exhaust pollutants are converted into harmless substances: carbon dioxide and water.

The diesel oxidation catalyst is designed to oxidize carbon monoxide, gas phase hydrocarbons, and the SOF fraction of diesel particulate matter to CO_2 and H_2O:

$$CO + \frac{1}{2}O_2 \rightarrow CO_2$$

$$[Hydrocarbons] + O_2 \rightarrow CO_2 + H_2O$$

$$[SOF] + O_2 \rightarrow CO_2 + H_2O$$

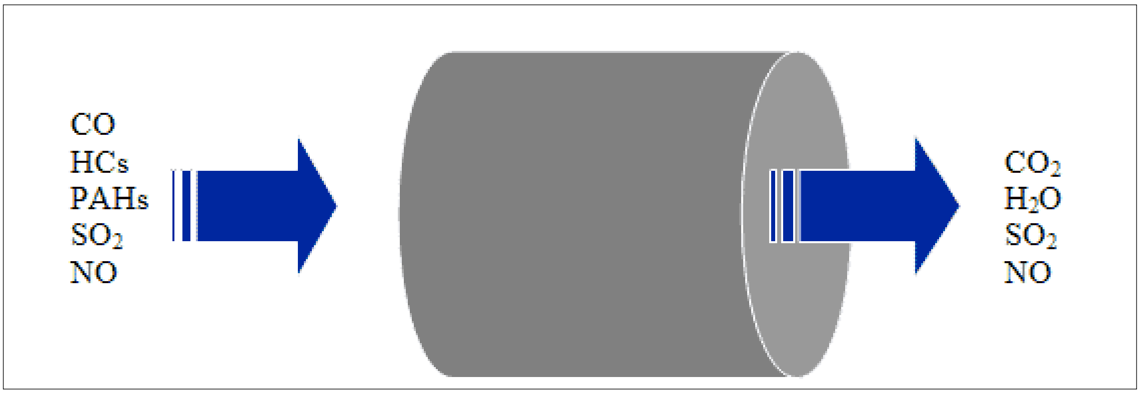
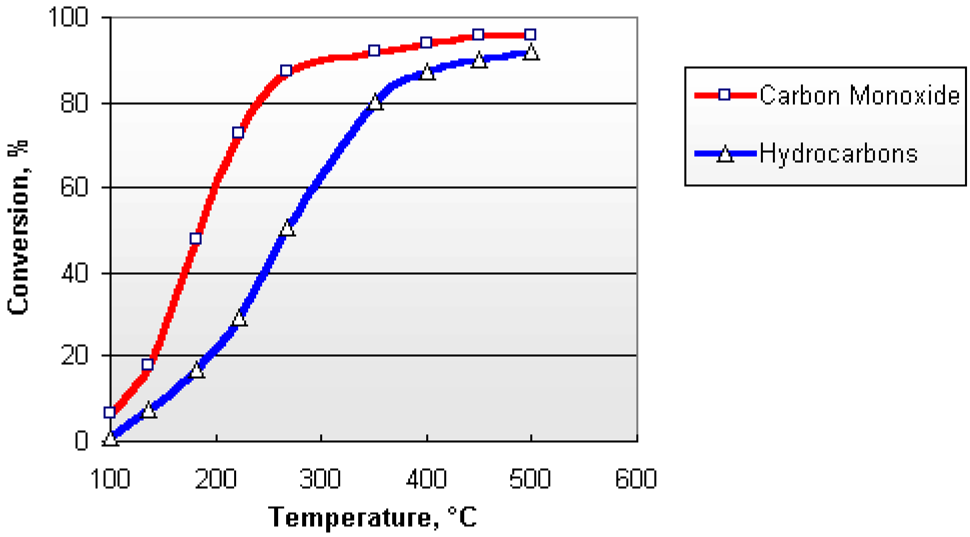


Figure 17. Diesel Oxidation Catalyst (MECA)

Diesel exhaust contains sufficient amounts of oxygen, necessary for the above reactions. The concentration of O_2 in the exhaust gases from diesel engine varies between 3 and 17%, depending on the engine load. Typical conversion efficiencies for CO and HC in diesel catalyst are given in *Graph 1*. The catalyst activity increases with temperature. A minimum exhaust temperature of about 200°C is necessary for the catalyst to start functioning well. At elevated temperatures, conversions depend on the catalyst size and design and can be higher than 90%.



Graph 1. Catalytic Conversion of Carbon Monoxide and Hydrocarbons (Net)

Conversion of diesel particulate matter is an important function of the modern diesel oxidation catalyst. The catalyst exhibits a very high activity in the oxidation of the organic fraction (SOF) of diesel particulates. Conversion of SOF may reach and exceed 80%. At lower temperatures, around 300°C, the total DPM conversion is usually between 30 and 50% (*Figure 18*). At high temperatures, above 400°C, a counterproductive process may occur in the catalyst. It is the oxidation of sulfur dioxide to sulfur trioxide, which combines with water forming sulfuric acid:

$$SO_2 + \frac{1}{2}O_2 \rightarrow SO_3 \xrightarrow{H_2O} H_2SO_4$$

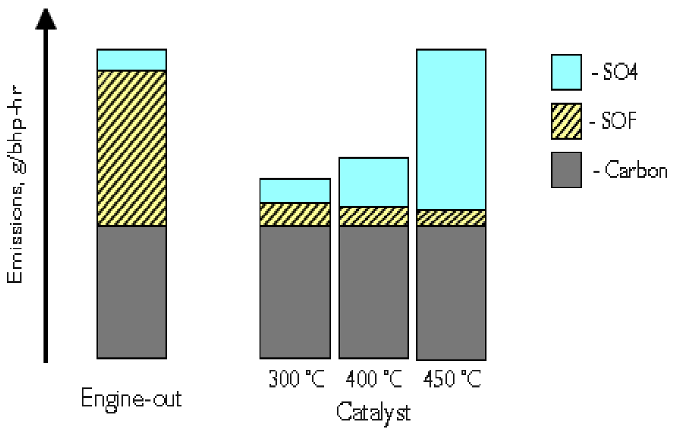


Figure 18. Catalyst Conversion of DPM depending on temperature (Net)

A formation of the sulfate (SO_4) particulates occurs, outweighing the benefit of the SOF reduction. *Figure 18* shows an example situation; where at 450°C and the engine-out the catalyst total DPM emissions are equal. In reality the generation of sulfates strongly depends on the sulfur content of the fuel as well as on the catalyst formulation. It is possible to decrease DPM emissions with a catalyst even at high temperatures, provided suitable catalyst formulation and good quality fuels of low sulfur contents. On the other hand, diesel oxidation catalyst used with high sulfur fuel will increase the total DPM output at higher temperatures. This is why diesel catalysts become more widespread only after the commercial introduction of low sulfur diesel fuel.

The diesel oxidation catalyst, depending on its formulation, may also exhibit some limited activity towards the reduction of nitrogen oxides in diesel exhaust. NO_X conversions of 10-20% are usually observed. The NO_X conversion exhibits a maximum at medium temperatures of about 300°C.

System EGR

The Exhaust Gas Recirculation (EGR) system is designed to reduce the amount of Oxides of Nitrogen (NO_X) created by the engine during operating periods that usually result in high combustion temperatures. NO_X is formed in high concentrations whenever combustion temperatures exceed about 1370 ºC (2500 ºF).

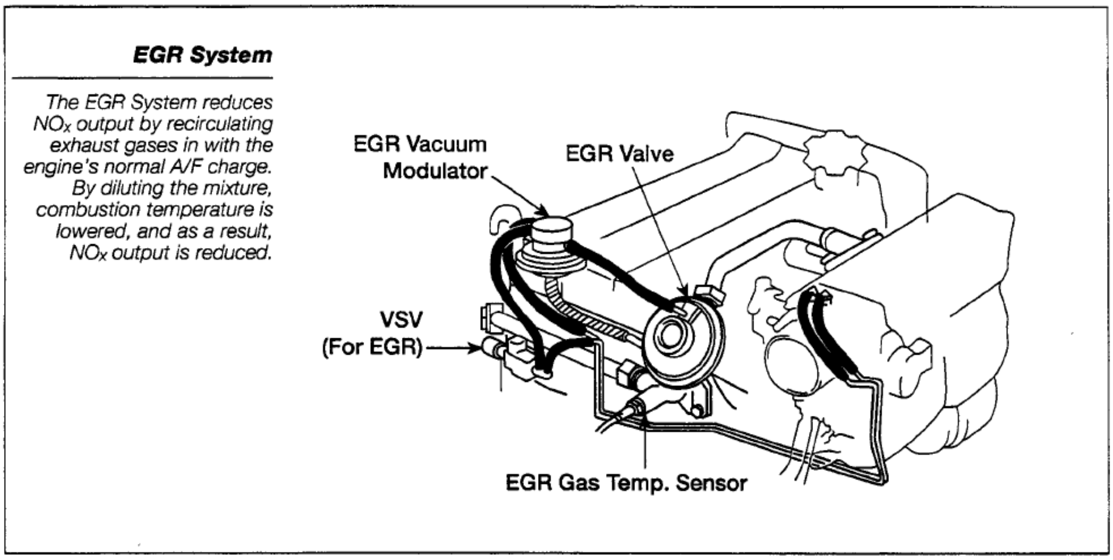


Figure 19. EGR System

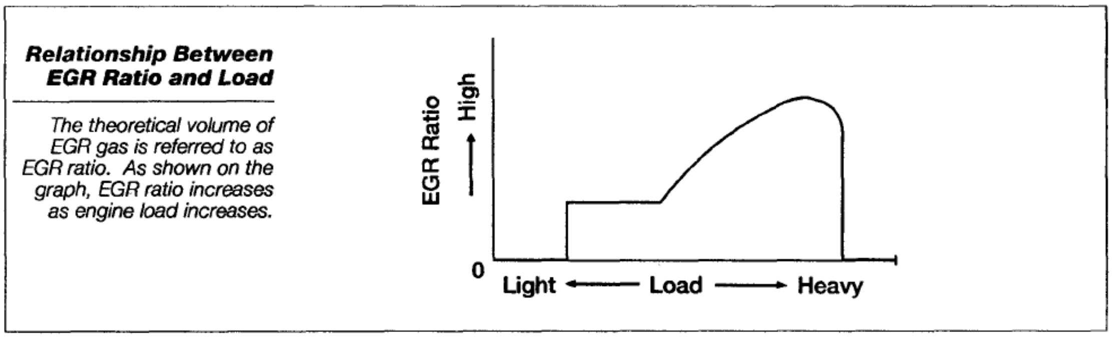
The EGR system reduces NO_X production by recirculating small amounts of exhaust gases into the intake manifold where it mixes with the incoming air/fuel charge. By diluting the air/fuel mixture under these conditions, peak combustion temperatures and pressures are reduced, resulting in an overall reduction of NO_X output. By and large, EGR Flow should match the following operating conditions:

- **High EGR flow** is necessary during cruising and mid-range acceleration, when combustion temperatures are typically very high.
- **Low EGR** flow is needed during low speed and light load conditions.
- **NO EGR** flow should occur during conditions when EGR operation could adversely affect engine operating efficiency or vehicle driveability (engine warm up, idle, wide open throttle, etc.)

EGR Theory of Operation

The purpose of the EGR system is to precisely regulate EGR flow under different operating and conditions, and to override flow under conditions which would compromise good engine performance. The precise amount of exhaust gas which must be metered into the intake manifold varies significantly as engine load changes. This results in the EGR system operating on a very fine line between good NO_X control and good engine performance.

If too much exhaust gas is metered, engine performance will suffer. If too little EGR flows, the engine may knock and will not meet strict emissions standards. The theoretical volume of recirculated exhaust gas is referred to as EGR ratio. As the accompanying graph shows, the EGR ratio increases as engine load increases.



Graph 2. EGR Ratio vs Load

EGR System Components

To achieve this designed control of exhaust gas recirculation, the system uses the following components:

- Vacuum Actuated EGR Control Valve
- EGR Vacuum Modulator Assembly
- ECM Controlled Vacuum Switching Valve (VSV)

EGR Control Valve

The EGR control valve is used to regulate exhaust gas flow to the intake system. A ported vacuum signal and calibrated spring on one side on the diaphragm are balanced against atmospheric pressure acting on the other side of the diaphragm. The key to accurate EGR metering is the EGR vacuum modulator assembly which precisely controls the strength of the applied vacuum signal.

EGR Vacuum Modulator

Because exhaust backpressure increases proportionally with engine load, the EGR vacuum modulator uses this principle to precisely control the strength of the vacuum signal to the EGR valve. The typical EGR control system uses two ported vacuum signals from the throttle body.

ECM Controlled Vacuum Switching Valve (VSV)

In addition to the EGR modulator, an ECM controlled VSV is used to inhibit EGR operation during conditions where it could adversely affect engine performance and vehicle driveability.

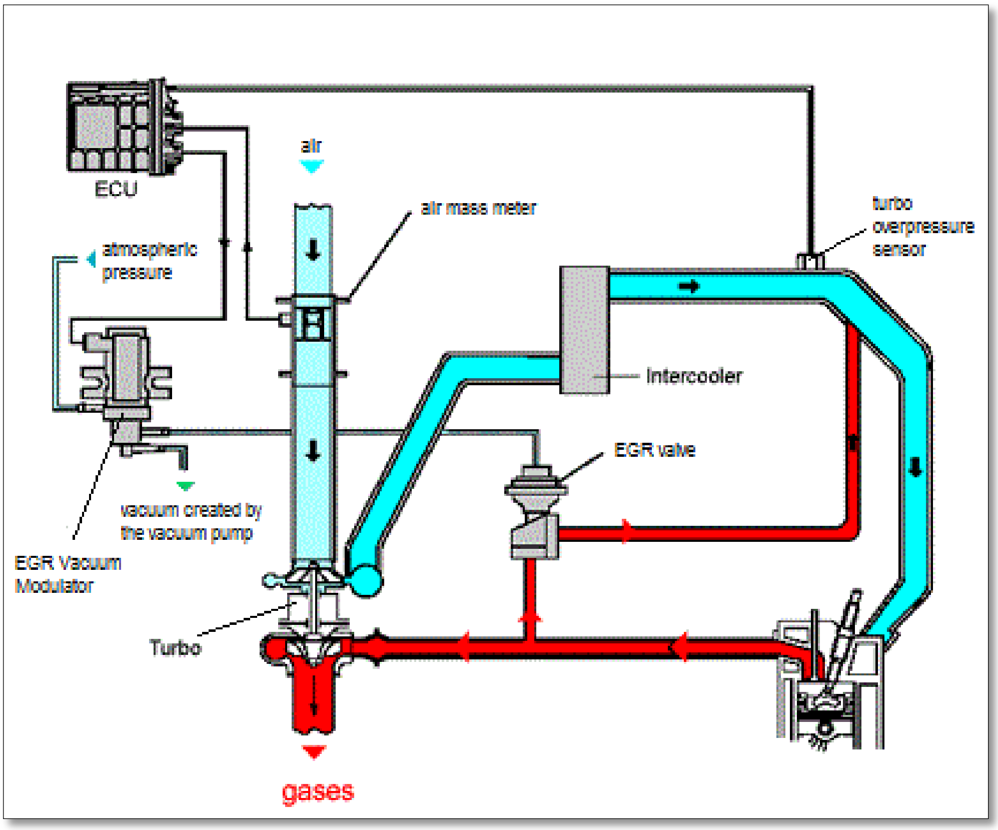
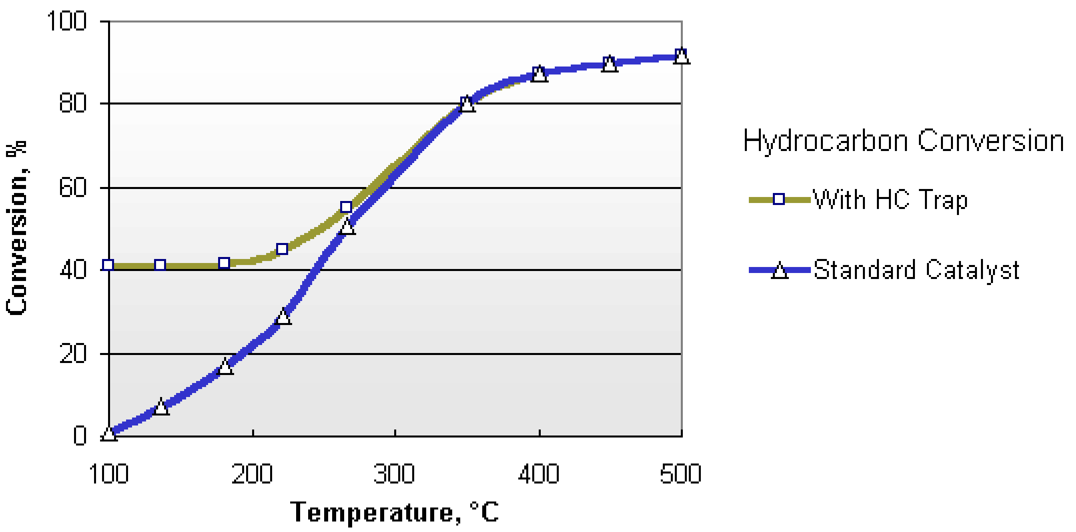


Figure 20. EGR Scheme (Mecanica Virtual)

Hydrocarbon Traps

Diesel engines are characterized by relatively low exhaust gas temperatures. When diesel engines operate at idle or with low engine load, the catalyst temperature may be lower than required for the catalytic conversion. At such conditions, the exhaust pollutants may pass untreated through the catalytic converter.

A new diesel catalyst technology has been developed to enhance the low temperature performance of the diesel oxidation catalyst. The technology incorporates hydrocarbon trapping materials into the catalyst washcoat. Zeolites, also known as molecular sieves, are most frequently used as the hydrocarbon traps. These zeolites trap and store diesel exhaust hydrocarbons during periods of low exhaust temperature, such as during engine idling. Then, when the exhaust temperature increases, the hydrocarbons are released from the washcoat and oxidized on the catalyst. Due to this hydrocarbon trapping mechanism, the catalyst exhibits low HC light-off temperatures (*Graph 3*) and excellent diesel odor control.



Graph 3. Hydrocarbon Conversion in Catalyst with HC Trap (Net)

The HC trapping catalysts are designed to work at transient engine conditions. Since the low temperature performance occurs through adsorption rather than through catalytic conversion, periods of hot exhaust temperature are needed for hydrocarbons desorption and regeneration of the catalyst. Otherwise, the adsorption capacity will become saturated and increasing HC emissions will break through the catalyst.

Particulate traps

In a diesel, fuel is injected late in the cycle and the air is not as well mixed as in a gasoline engine. As a result of this less homogeneously mixed fuel and air, there are fuel-dense pockets in the combustion chamber. The consequence is that diesel engine exhaust contains incompletely burned fuel (soot) known as particulate matter (PM).

In order to minimize the amount of unburned fuel, modern diesels use high-pressure fuel injection for better fuel atomization and turbochargers to more aggressively mix and force the air-fuel mixture into the combustion chamber. The result is a reduction in the formation of particulates, although some PM is still produced. Particulate filters are a proven technology for PM reduction on both light-duty and heavy-duty diesels. Particulate filter technology has been proven over and over to be able to reduce PM by 95 percent or more. However, the key to the successful application of particulate filters on diesel engines was the ability to reliably regenerate the filter, or in other words, burn the PM that the particulate filter "traps" or collects.

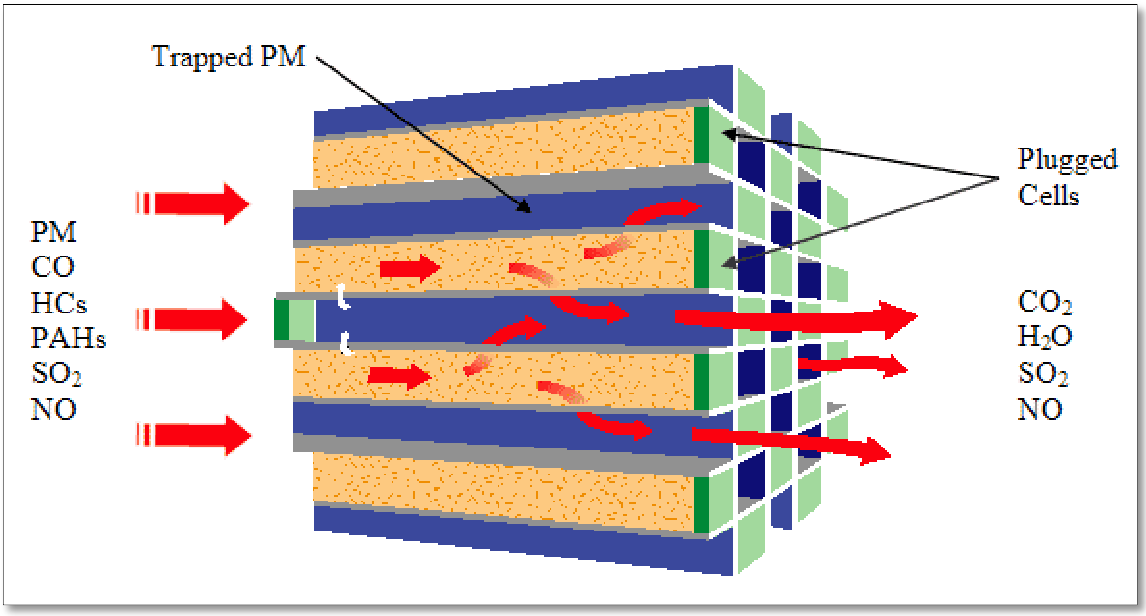


Figure 21. Diesel filter traps (MECA)

To understand how a filter regenerates, one must understand how soot or PM burns. Traditionally, combustion of soot is done in an oxygen atmosphere (air). In air, soot will burn at about 450 ºC to 500 ºC. However, this is not a typical operating temperature for diesel engine exhaust. As a result, in order to burn soot in air, an active system, one that increase the temperature of the exhaust using some external heat source, is required. But if an active system is not carefully controlled, it can often experience an "uncontrolled burn" where the temperature increases to 600 ºC or more. This would damage the filter element and it would also be a potential risk to the vehicle.

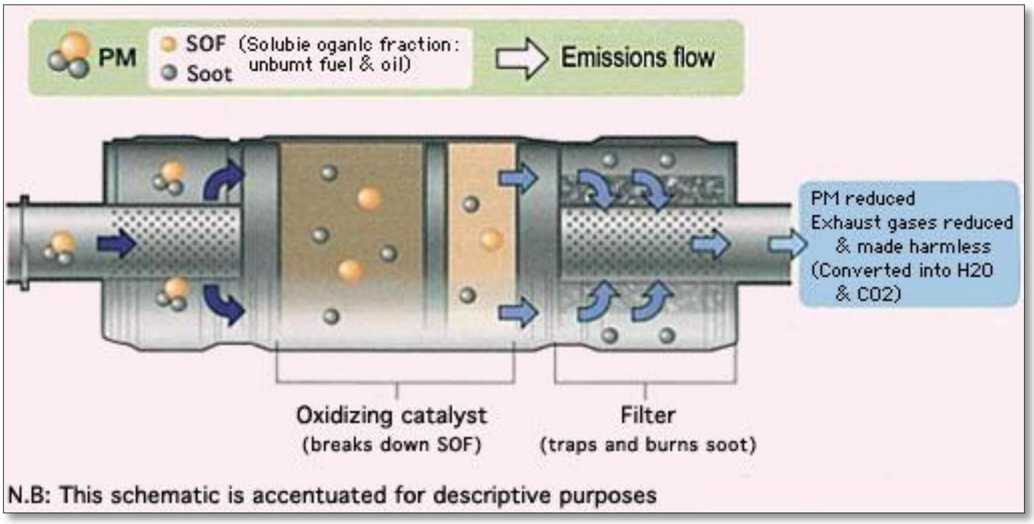


Figure 22. Process (Mitsubishi)

Regeneration. Many techniques can be used to regenerate a diesel particulate filter. Some of these techniques are used together in the same filter system to achieve efficient regeneration. Both on- and off-board regeneration systems exist. The major regeneration techniques are listed below.

- Catalyst- based regeneration using a catalyst applied to the surfaces of the filter. A base metal or precious metal coating applied to the surface of the filter reduces the ignition temperature necessary to oxidize accumulated particulate matter.
- Catalyst- based regeneration using an upstream oxidation catalyst. In this technique, an oxidation catalyst is placed upstream of the filter to facilitate oxidation of nitric oxide (NO) to nitrogen dioxide (NO_2). The nitrogen dioxide reacts with the collected particulate, substantially reducing the temperature required to regenerate the filter.
- Fuel-borne catalysts. Fuel-borne catalysts reduce the temperature required for ignition of trapped particulate matter. These can be used in conjunction with both passive and active filter systems.

- Air-intake throttling. Throttling the air intake to one or more of the engine cylinders can increase the exhaust temperature and facilitate filter regeneration.
- Post top-dead-center (TDC) fuel injection. Injecting small amounts of fuel in the cylinders of a diesel engine after pistons have reached TDC introduces a small amount of unburned fuel in the engine's exhaust gases. Fuel can also be injected into the exhaust pipe. This unburned fuel can then be oxidized in the particulate filter to combust accumulated particulate matter.
- On-board fuel burners or electrical heaters. Fuel burners or electrical heaters upstream of the filter can provide sufficient exhaust temperatures to ignite the accumulated particulate matter and regenerate the filter.
- Off-board electrical heaters. Off-board regeneration stations combust trapped particulate matter by blowing hot air through the filter system.

Selective Catalytic Reduction (SCR)

SCR has been used to control NO_X emissions from stationary sources for over 15 years. More recently, it has been applied to select mobile sources including trucks, marine vessels, and locomotives. Applying SCR to diesel-powered vehicles provides simultaneous reductions of NO_X, PM, and HC emissions.

An SCR system uses a metallic or ceramic washcoat catalyzed substrate, or a homogeneously extruded catalyst and a chemical reductant to convert nitrogen oxides to molecular nitrogen and oxygen in oxygen-rich exhaust streams like those encountered with diesel engines. In mobile source applications, an aqueous urea solution is usually the preferred reductant. In some cases ammonia has been used as the reductant in mobile source retrofit applications. The reductant is added at a

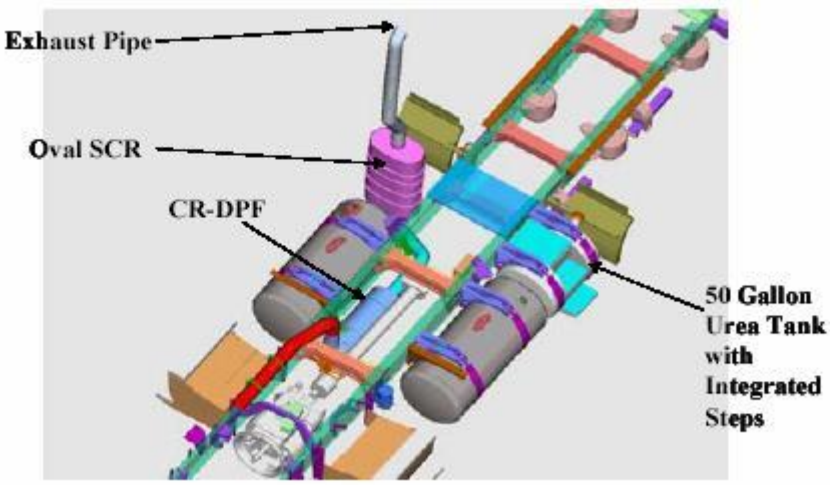


Figure 23. Layout SCR (MECA)

rate calculated by an algorithm that estimates the amount of NO_X present in the exhaust stream. The algorithm relates NO_X emissions to engine parameters such as engine revolutions per minute (rpm), exhaust temperature, backpressure and load. As exhaust and reductant pass over the SCR catalyst, chemical reactions occur that reduce NO_X emissions. A typical layout for a retrofit SCR system for highway vehicle is shown in *Figure 23*. In this system a DPF is followed by an SCR catalyst for combined reductions of both diesel PM and NO_X.

Opened loop SCR systems can reduce NO_X emissions from 75 to 90 percent. Closed loop systems on stationary engines can achieve NO_X reductions of greater than 95 percent. SCR systems reduce HC emissions up to 80 percent and PM emissions 20 to 30 percent. They also reduce the characteristic odor produced by a diesel engine and diesel smoke. Like all catalyst based emission control technologies, SCR performance is enhanced by the use of low sulfur fuel. However, low sulfur fuel is not a requirement. SCR catalysts may also be combined with DOCs or DPFs for additional reductions of PM emissions. Combinations of DPFs and SCR generally require the use of ultra-low sulfur diesel to achieve the highest combined reductions of both PM and NO_X. Application of SCR to vehicles and equipment with transient operating conditions offers special challenges and it may not be appropriate for all vehicle applications. Care must be taken to design a SCR system for the specific vehicle or equipment application involved.

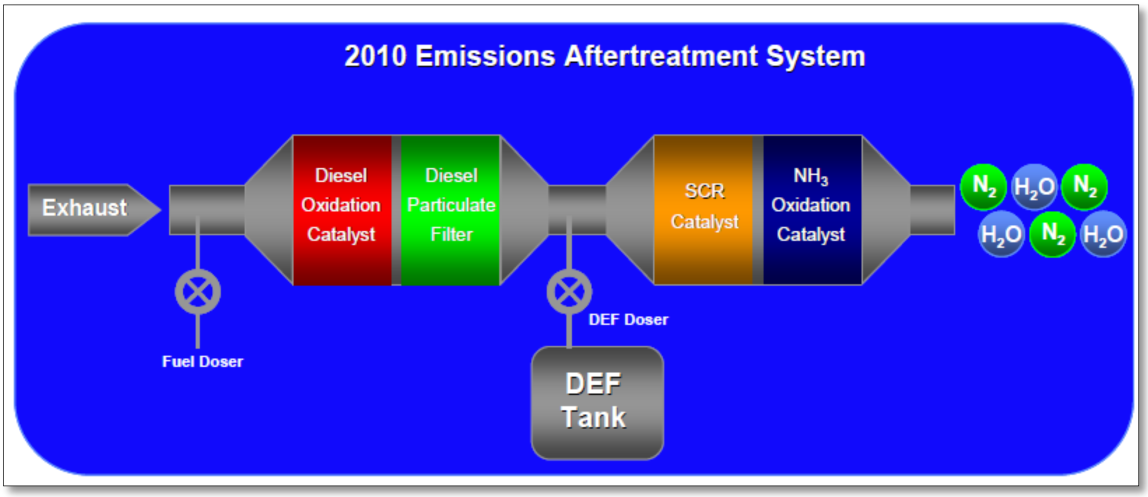


Figure 24. Aftertreatment System (Kenworth)

DEF is a non-toxic solution of purified water (67%) and Urea (33%). Urea is a natural compound which is produced from natural gas and commonly used in everyday products such as fertilizer. It is not dangerous. DEF can be stored, dispensed and handled in bulk and smaller quantities.

NO_X Adsorber

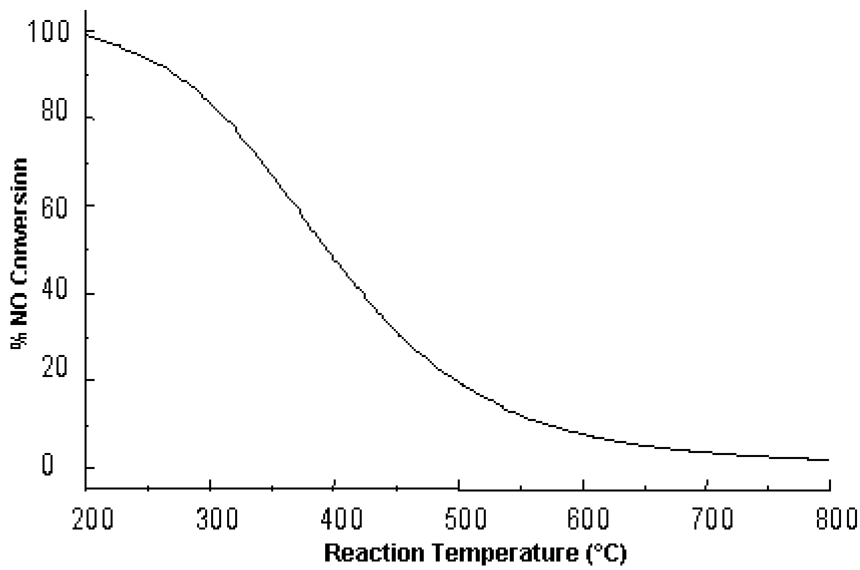
A NO_X adsorber is designed to reduce oxides of nitrogen emitted in the exhaust gas of a lean burn internal combustion engine. Lean burn engines, particularly diesels, present a special challenge for emission control system designers because of the relatively high levels of O_2 (atmospheric oxygen) in the exhaust gas stream. Because of the increasing need to limit NO_X emissions from diesel engines technologies such as exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) have been used, however EGR is limited in its effectiveness and SCR requires a reductant, and if the reductant tank runs dry the SCR system ceases to function.

The majority of NO_X emitted from the engine is in the form of NO. NO_2 is more easily adsorbed than NO. The following are the chemical reactions representing the oxidation and adsorption of NO:

Oxidation: $2NO + O_2 = 2NO_2$

Adsorption: $2NO + 1.5O_2 + MO = M(NO_3)_2$

However, the oxidation of NO to NO_2 is equilibrium limited. The equilibrium conversion of NO is shown in *Graph 4* as a function of temperature.



Graph 4. % NO Conversion depending on Temperature (Net)

The NO_X adsorber was designed to avoid the problems that EGR and SCR experienced as NO_X reduction technologies. The theory is that the zeolite will trap the NO and NO_2 molecules -in effect acting as a molecular sponge. Once the trap is full (like a sponge full of water) no more NO_X can be absorbed, and it is passed out of the exhaust system. Various schemes have been designed to "purge" or "regenerate" the adsorber. Injection of diesel fuel (or other reactant) before the adsorber can purge it-the NO_2 in particular is unstable and will join with hydrocarbons to produce H_2O and N_2. Use of hydrogen has also been tried, with the same results, however hydrogen is difficult to store. Some experimental engines have mounted hydrogen reformers for on-board hydrogen generation; however fuel reformers are not mature technology.

6 Austrian Maritime Fleet

First of all, the *table 4* below shows a brief description of the different types of transport.

Characteristics	Inland Waterway	Rail All	Rail combined	Road	Air 1)
Network size	EU_{15}: 30,000km EU_{25}: 37,200km	EU_{15}: 156.000 km EU_{25}: 207.000 km		EU_{15}:51'000km Motorway+ 270'000 km nat.highways; CC13: 4'800 km motorway	
Commodity type; mode of appearance	dry bulk, liquid bulk, container; specially bulky shipments; dangerous goods	all except perishables	container, swap bodies	all	all except dangerous goods
Shipment size	large, depending on waterway class and ship configuration	train loads, wagon loads	depending on train length	up to ca. 28 t	small
Commercial speed	Slowest mode ex. Basel-Rotterdam (860km, 72h): 12kmh (see foot note 1)	Scheduled (complete) trains: 50-60 kmh	ex. Brindisi-Gothenborg (3186km, 109h): 29kmh	ex. Basel-Rotterdam (788km,21,65h) 36,4kmh; Barcelona-Warsaw (2726km, 88h): 31km/h	Overnight for most relations
Punctuality (jit)	Sporadic congestion problems only	Predominant-ly night traffic	scheduled services	guaranteed delivery time	overnight transport, guaranteed delivery time
Reliability (problems)	Climate: high, low water levels; ice	meteorological problems, labour conflicts		Major congestion, accidents, snow & ice, labour conflict problems	minor meteorologi cal problems, labour conflicts
Safety	high	medium		major problem	limited
Energy consumption/ emissions	lowest/lowest (difference between downstream and upstream)	medium/emissions depending on type of traction		high/high	high/high
Costs	lowest costs of all modes	medium/significant level of subsidies		high/prices to large extent below cost	Premium

1) Within Europe, over 80% of airfreight is transported by truck

Table 4. *Goods Transport Characteristics – comparison by mode. Sources: DG TREN, RECORDIT, PINE Consortium*

Inland network size

Nowadays, total length of inland waterway (IWW) in the European Union is 29’500 km of classified rivers and canals, increasing to 36’500 km in the enlarged Union. In comparison with the existing railway lines in the same areas, inland waterways are less than one fifth.

On the one hand, Inland Waterway Transport (IWT) has the advantage that is particularly suitable for both dry and liquid bulk commodities.

On the other hand, small size ships carry generally up 500 tonnes of bulk commodities, whereas large size ships up to 2’000 tons of dry bulk and up to 3’000 tons of liquid bulk. A pusher convoy with two barges can carry over 5’000 tonnes of dry bulk. This equals approximately 125 railway wagons of 40 tons each, or 250 road trucks of 20 tons payload each. The largest container ships can today load over 400 TEUs[1].

<u>Ship types</u>

There exist a large variety of classification methods for floating objects used in inland navigation. Among others the most distinctive are:

1) According to the area of navigation: • River (canal) ships; • River-sea vessels (sea-going vessels properly equipped also for the operation in inland waterways); • Lakers (vessels designed and built to cope with specific conditions on the lake where they operate).

2) According to the dedicated purpose:
• Commercial vessels including:
    o Cargo ships
    o Passenger ships for daily excursions or for cruising (equipped with cabins)
    o Technical floating objects (push boats, tugs, dredgers, floating cranes, floating docks, workboats etc.);
• Pleasure crafts (motor or sailing yachts and boats, water bikes, wind surfing-boards etc.);
• Special ships (police, customs, survey, fire-fighting ships, icebreakers, military vessels, supply ships etc.).

3) According to the installed machinery (self-propelled and non-self-propelled vessels)
4) According to the kind of propulsion
5) According to the floating regime when running
6) According to the hull configuration (conventional monohulls, twin-hulls, trimarans)

Table 5. Fleet classification (PINE)

The majority of inland navigation ship types are standardized in their main dimensions (although within certain tolerances).

The wide variety of vessel sizes is mainly caused by both the market requirements and the area of navigation. On the one side, larger shipment sizes, stable markets and favorable nautical conditions along the route (that means wide and deep rivers and canals with high bridges) are the main prerequisites for the operation of larger ships. But on the other side, larger ships cannot operate on smaller waterways if draught, width or air draft restrictions are too big. That allows smaller vessels also have a place in the fleet.

About the utilization of carrying capacity of the fleet, the shipment size might not always be equal to the maximal carrying capacity of the ship at her draught allowed. Eventually, in recent times the carrying capacity expressed in tons is not always and not the only decisive measure of ship’s size class.

The vessels operating on isolated lakes have not been included here due the relatively small number of such units and moreover commercial cargo transports on lakes are not usual.

The following classification of ship types is adopted for the purpose of data presentation and analysis for European inland navigation:

- self-propelled dry cargo vessels
- dry cargo towed barges
- dry cargo push barges
- self-propelled liquid cargo vessels (including gas and chemical tankers)
- liquid cargo towed barges
- liquid cargo push barges
- river tugs
- pusher-tugs (tugs with pushing equipment)
- river passenger vessels (daily excursion vessels and river cabin cruisers)

Another possible classification would be which Magaloc uses:

- RoRo: Roll on roll off, i.e. vessels taking cargo on board as truck trailers or other rolling items.
- RoPax: Rolling goods and passengers.
- Super fast vessels: high speed RoPax vessels, usually travelling at more than 30 knots.

But in the Austrian case, the fleet is a little bit more reduced. There are three ship types: dry cargo self-propelled, liquid cargo self-propelled and pushed convoys (includes river tugs and push boats)

Dry cargo self-propelled

Dry cargo carriers can transport an enormous variety of goods, such as round timber, steel coils, cereal and ore. It is used mainly in pushed convoys or coupled formations. There are about 100 motor cargo vessels navigating the Danube region in cross-border operations. This category of vessels has a deadweight tonnage of 1,000 to 2,000 tonnes. The following figure 5 shows the main properties of a dry cargo self-propelled.

Figure 25. Dry cargo self-propelled (Via Donau)

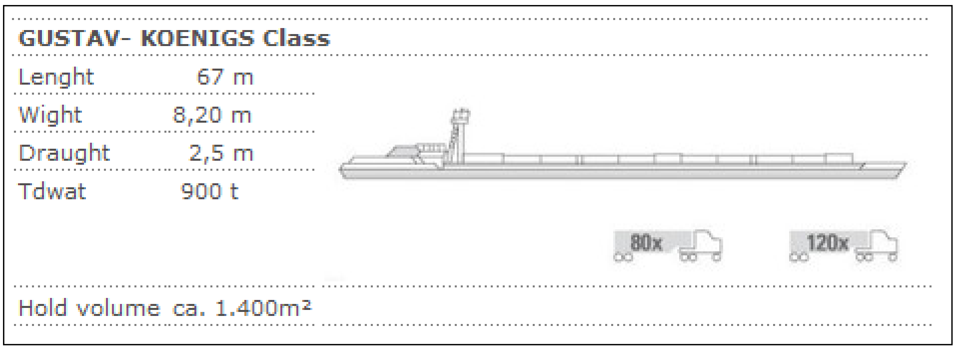


Figure 26. Dry cargo self-propelled properties (Via Donau)

Liquid cargo self-propelled (TANKERS)

Liquid cargo self-propelled also known as tankers transport the following liquid goods:

- Mineral oil and its derivatives – petrol, diesel, heavy and light fuel oil, etc.
- Chemicals – acids, alkalis, benzene, styrene, methanol, etc.
- Liquid gases

Most of these goods are classified as dangerous material. So to ship them, the tanker industry has to use special vessels in order to meet the corresponding safety requirements. The European regulations and recommendations as described in ADN, ADN-R and ADN-D, as well as the national legislation on hazardous material are particularly relevant for this industry.

Figure 27. Liquid cargo self-propelled properties (Via Donau)

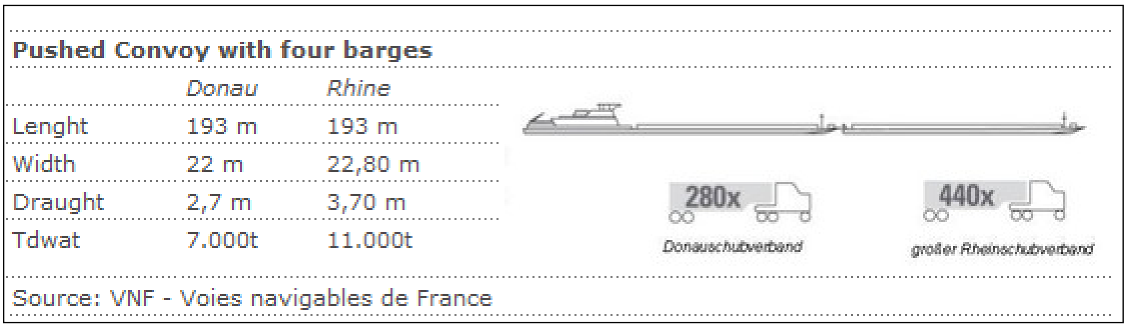
Modern vessels are double-hulled in order to prevent the dangerous cargo from leaking in the event of a rupture. The goal is to have the maximum number of systems completely separated. This means that the lading and the extinguishing equipment, the residues and gas displacement pipes, as well as the residues tanks are exhaustively separated. These systems and equipment are necessary to prevent contact of toxic steam and liquids with the environment. In order to prevent chemical reactions between the surface of the tanks and these goods, tanks and cargo holds are covered with special coating. By heating the tanks and by means of valves, goods with a low freezing point can also be shipped in winter. On the other hand, sprinkler systems on deck protect the tanks from rises in pressure caused by solar heat. Shipping liquid goods demands an advanced technology.

Liquid gas is transported under pressure and refrigerated in special canisters. However, this type of cargo is not common on the Danube. Most tankers have pumps on board, so that loading and unloading liquid cargo is also possible at ports where lack special transshipment equipment. Tankers on the Danube which doesn't have pumps yet available on board are being equipped with it. A vessel has mostly two pumps since, basically, each pump may be used only for one particular liquid good. The Danube tankers have an average deadweight of about 2,000 tonnes. Tankers are also used almost exclusively in pushed convoys or coupled formations.

Figure 28. Liquid cargo self-propelled (Dimension Guide)

PUSHED CONVOYS

Convoys are the predominant category of vessels navigating on the Danube. About 90% of all shipments are carried out this kind of vessel. Only 10% of them are performed by individual motor cargo vessels. A convoy comprises either one motor cargo vessel (a ship with its own cargo hold) or a pusher and one or more barges rigidly coupled to the freighter or pusher.



Pushed Convoy with four barges

	Donau	Rhine
Lenght	193 m	193 m
Width	22 m	22,80 m
Draught	2,7 m	3,70 m
Tdwat	7.000t	11.000t

Source: VNF - Voies navigables de France

Figure 29. Pushed convoys properties (Via Donau)

The ships that make up these formations must be grouped in a way that reduces water resistance to a minimum. Moreover, the barges have to be distributed of line towards the rear in order to minimize the resistance exerted by the bow wave. If the required technical equipment is available, the units of the convoy are coupled through flexible joints rather than rigidly, which permits a guided articulation of the convoy to better pass tight-radius curves. The bow-thrusters system can further improve the barge's maneuverability. Besides, passive rudders are used to increase the directional stability of the entire convoy. The arrangement of the barges within the convoy depends on the moving direction, either upstream or downstream. When travelling upstream, the convoy's cross-section with the current must be as small as possible in order to minimize fuel consumption. For this purpose, the barges are arranged one after the other in the shape of a tube. Downstream the barges navigate side by side to improve maneuverability and, specifically, to facilitate stopping. The maximum number of barges allowed in a convoy depends on the different sections of the Danube (from 4 up 16 barges).

Figure 30. Pushed convoy (Via Donau)

Danube fleet

The Danube navigation extends along ten countries and a few more not directly located on the river banks but geographically gravitating and therefore likely concerned for the Danube transport corridor and waterway potential. The Danube is divided in first of all two countries in the upper river course – Germany[1] and Austria –, two in the middle course (Slovakia and Hungary) and further two in the lower part of the Danube (Romania and Bulgaria). The Danube is the second biggest European river (after the Volga) and by far the biggest within the enlarged EU, therefore the Danube together with its several large navigable tributaries and canals provides good preconditions for the development of a large, potential and peculiar river fleet.

Size

About 10 years ago, the share of cargo space on non-self-propelled units was even higher than 90% and however, since 2000 seems to be reduced to about 75%.
Accounting both towed and pushed units there were more than 2650 dry cargo and some 330 tank barges at the end of 2000. A considerable number of towed barges (several hundred) have been re-equipped for pushing technology and have not decommissioned yet.

Pushed barges differ in size and capacity and the last ones built in the last 30 years tend to comply with the recommended standard ‘Danube-Europe IIb’ type with an average capacity of between 1350 and 1500 t at a draught span between 2.3 and 2.5 m. This fleet of barges is classified according to size: fleet of push boats, tugs and pusher-tugs.
It is difficult to define a cargo vessel prototype of the Danube due to the relatively small sample, the large diversity of sizes, purposes and navigational areas (upper, middle and lower course of the river, as well as navigable tributaries and canals). On the other side the typical push boat is a twin-screw unit totaling some 1500 to 1800 kW output which usually operates 4-6 barges in a train.

[1] Due to the geographic location of Germany in the central Europe and the fact that three of the identified four waterway corridors lead through the country it is not possible to strictly distinguish parts of the national fleet assigned to the particular corridor. This relates to the German ‘Danube’ fleet since 1992 as well as to the fleet operating on the eastern part of the West-East Corridor since the unification of Germany (e.g. Elbe and Oder). It is especially difficult to define the German ‘Danube’ fleet since the single units operating on the Rhine and on the Danube are technically pretty similar. (PINE)

Performances

According to the recommendations of the Danube Commission about the minimal speed and maneuvering abilities, the ships and pushed convoys have to be able to achieve a speed of 12 km/h relative to the water and to stop within a distance of 200 meters if heading upstream or 600 meters if heading downstream.

Age

The average age of the dry cargo self-propelled Danube vessels varies between 18 years (Croatia, Ukraine) and 32 years (Slovakia, Moldova). Regarding Austria the average is 25 years. The total average in the Danube is also 25 years. On the other side, the average age of liquid cargo self-propelled Danube vessels is more difficult to find out because there are not data.

The pushed barge fleet is on average less than 20 years old with the exception of Serbia and Croatia (more than 25 years). Pushed barge fleets of Romania (735 units, on average 17 years old) and especially Ukraine (369 units, 12 years old) are by far the largest and youngest on the Danube. Regarding Austria dry cargo push barges has an average of 19 years.

Character

There are still a large number of obsolete towing barges (counting hundreds of units) still retained in operational status on the Danube. A large number of these vessels, especially in Hungary and Austria, have been reconstructed over recent decades. They have some technical problems but despite of all disadvantages, compared with the pushing system as e.g. higher resistance, considerably higher exploitation cost due to the presence of crew onboard, etc., towed convoys are still occasionally in operation, however, under certain circumstances.

For instance, in periods of low waters on the Danube course, when the allowed draught is less than 1.7 m on certain points, barges (pushed or towed) can be just partially loaded, e.g. to the draught of 1.3 m but long range push boats with their draughts of 1.8 to 2.2 meters are useless. However under such conditions, the old tugboats with considerably lower draughts, very often less than 1.6 m and light loaded towed barges are still applicable. For this reason these vessel types still exist on the Danube in a large number.

The extremely low share of self-propelled vessels tends to increase in recent years. The ratio of available cargo capacity between self-propelled ships and barges have changed from about 1:9 at the beginning of nineties to about 1:4 ten years later. New built river cargo ships are very rare exceptions.

The typical design draught of Danube vessels is in the range from 2.3 to 2.5 meters and corresponds to the average nautical conditions in the corridor. But, if such a ship cannot be fully loaded due to the severe draught restrictions during longer periods of time, and is still expected to operate then, an economic operation might be achieved only with splitting up the propulsion power to two propellers of smaller diameter therefore fully submerged also at much lower draughts of the ship. For this reason this twin-screw arrangement used in the Danube is more expensive than the single-screw execution habitual on the Rhine.

Standard Danube pushed barges have a breadth of 11.0 m and not 11.4 as the corresponding Rhine barges. This discrepancy results from the different width allowance by passing the locks. The West-European standard allowance is 0.60 m while the Danube allowance on the Iron Gates is 1.00 m and has officially not changed yet.

Despite of this difference, the Danube pushed barge of ‘Europe II’ size has practically the same cargo capacity as the 0.4 m wider Rhine barge at the same draught.

Fleet technologies

Dominant navigational conditions, local market demands and economy models in particular corridors influence in many cases the choice of technologies and technical characteristics of the fleet units.

The fleet typical for the certain waterway or region might be characterized by:

- Typical unit size (length, breadth, draught, carrying capacity)
- Applied technology (self-propelled vessels, pushing or towing technology)
- Specific technical solutions (design, propulsion and steering arrangements, facilities on board, accommodation)

Danube (South-East Corridor):

- Pushed trains consisting of 2, 4, 6 or even up to 9 pushed barges and pushboat of appropriate power, e.g. barge train consisting of 4 'Europe-II b' barges (2 in line, 2 abreast) with 153 x 22 m (LxB) of the train without pushboat) and having about 6000 tons cargo capacity at 2.5 m draught.
- Characteristics: Standard 'Danube-Europe II b' barges for dry cargo, no additional steering devices (bow thrusters or rudders), pushboat with twin-screw shaft propulsion, conventional main rudder blades and flanking rudders, elevating wheelhouse, large deckhouse to provide accommodation (single and double bed cabins, common living/mess and sanitary premises) for crew of 10 (or even more) necessary for long lasting voyages along the river.

European infrastructure

Four corridors are identified within the European IWW network:

- ***Rhine Corridor*** comprising the Rhine confluence and the canals in the western part of Germany, the Netherlands, Switzerland, the eastern part of France and in Luxembourg
- ***Danube (South-East) Corridor*** including the entire Danube confluence with all tributaries and navigable canals as well as the Main-Danube Canal
- ***East-West Corridor*** with the Mittelland Canal in northern Germany and the confluences of Elbe, Oder and Wisla
- ***North-South Corridor*** covering the major rivers, navigable tributaries and linking canals extending between the lower Rhine area and the Mediterranean, practically throughout France including the links to the Belgian network.

As well as there are waterways less important in:

- Scandinavia, i.e. in Finland and Sweden
- the United Kingdom
- Italy
- The Iberian peninsula, i.e. Portugal and Spain

In the Figure 31 below, it can see the mentioned corridors.

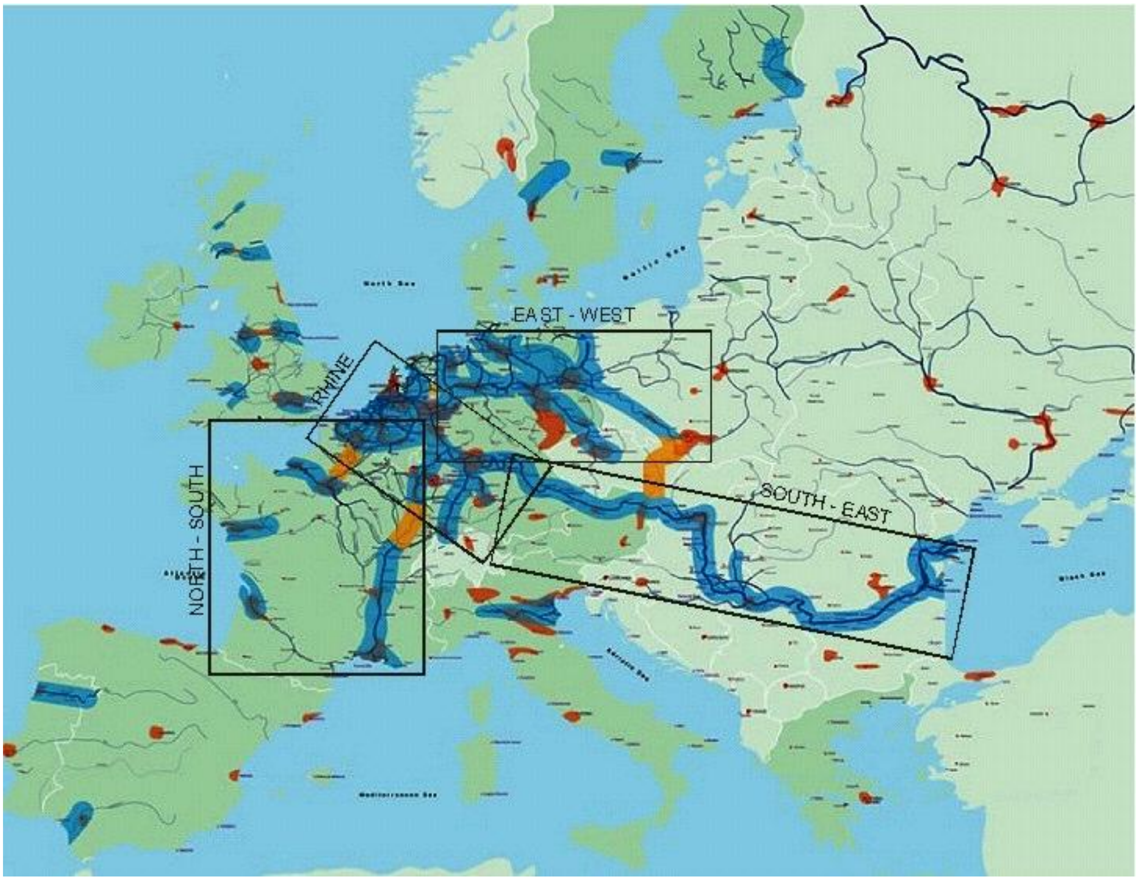


Figure 31. *Inland Waterway corridors in Europe (By courtesy of INE/Via Donau)*

The following table shows some properties of each corridor.

Corridor	Area [sq. km]	Waterways [km]	Waterway density [km/1000 sq. km]	Corridor	Population [mill]	Population density [pop. per sq. km]
Rhine	465308	13902	30	R	116272	250
South-East	1077021	13068	12	SE	150399	140
East-West	748567	11323	15	EW	131176	175
North-South	574483	7170	13	NS	68781	120
Rest (with IWT)	1922596	10257	5	Rest	185477	96

Table 6. *Corridor summary (overlapping of corridors, just IWT countries accounted)*

Danube corridor

The Main-Danube waterway represents the major axis of the South-East corridor and both rivers are mutually linked by the Main-Danube Canal. Besides there are a number of navigable tributaries and canals merging the Danube in its middle course as well as three navigable arms and two large canals in the Danube Delta. With the last unions of some countries in the EU the Danube has more IWT strengths and potential.

Country	Area [sq. km]	Waterways [km]	Waterway density [km/1000 sq. km]	Corridor	Population [mill]	Population density [pop. per sq. km]
Austria	83859	358	4	SE	8066	96
Bulgaria	110910	472	4	SE	8150	73
Croatia	56414	595	11	SE	4391	78
Germany						
Hungary	93030	953	10	SE	10198	110
Romania	238390	1166	5	SE	22431	94
Serbia	88361	1561	18	SE	9500	108
Slovakia	49035	422	9	SE	5403	110
Ukraine		174		SE		

Table 7. *Waterway network and population density within the PINE area*

The ***South-East*** corridor is practically the confluence of the Danube river, with a navigable length of 2414 km the second biggest in Europe, after the Volga.

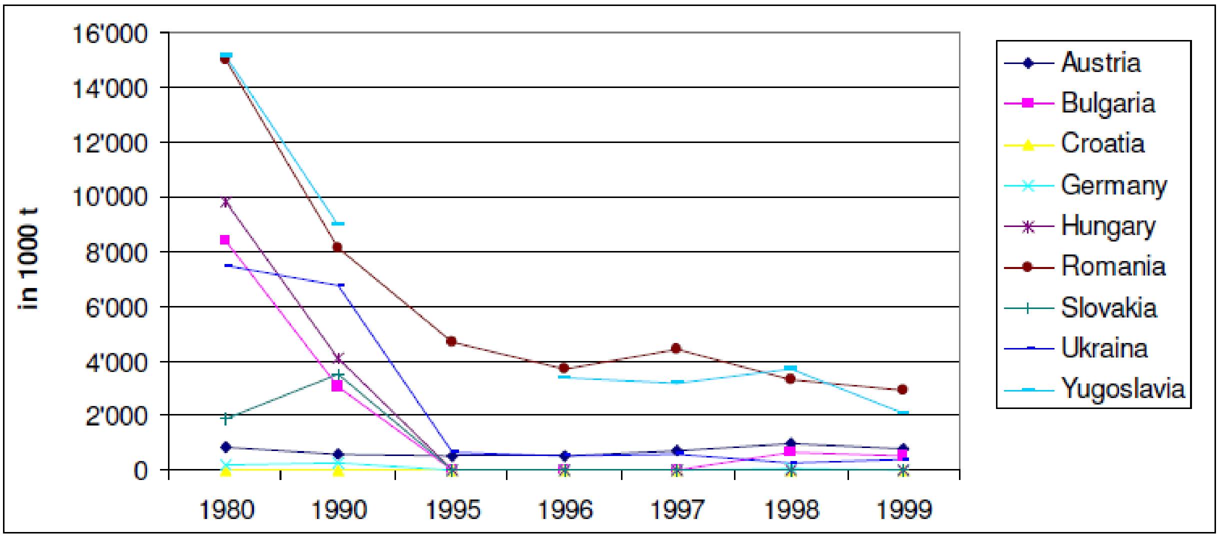
The most unfavorable facts in this corridor are the existence of critical points – bottlenecks – and the large annual fluctuations of the water level. Moreover, the level of hydro-technical measures, maintenance and nautical aids are different in the upper and the lower river range. Namely, maintenance and safety standards (e.g. markings as nautical aids) applied in the upper range, in Germany, Austria, Slovakia and Hungary are much higher than those in Romania and Bulgaria.

7 Inland Waterway Transportation at the Austrian Danube

In this point it will be analyzed the inland waterway transportation both at the Danube Corridor and in Austria. It will be also analyzed the changes over the years and their reasons as well as the transportation type and the fleet used in Austria.

7.1 Transportation at the Danube Corridor

Transport Data from recent years on the Danube comes from Statistics Austria whereas series data prior to 1999 have been taken from the United Nations.
The data from the UN Bulletin of Transport Statistics differentiates between internal and international loaded transport (see Figure 32 and Figure 33) from 1980 until 2000.

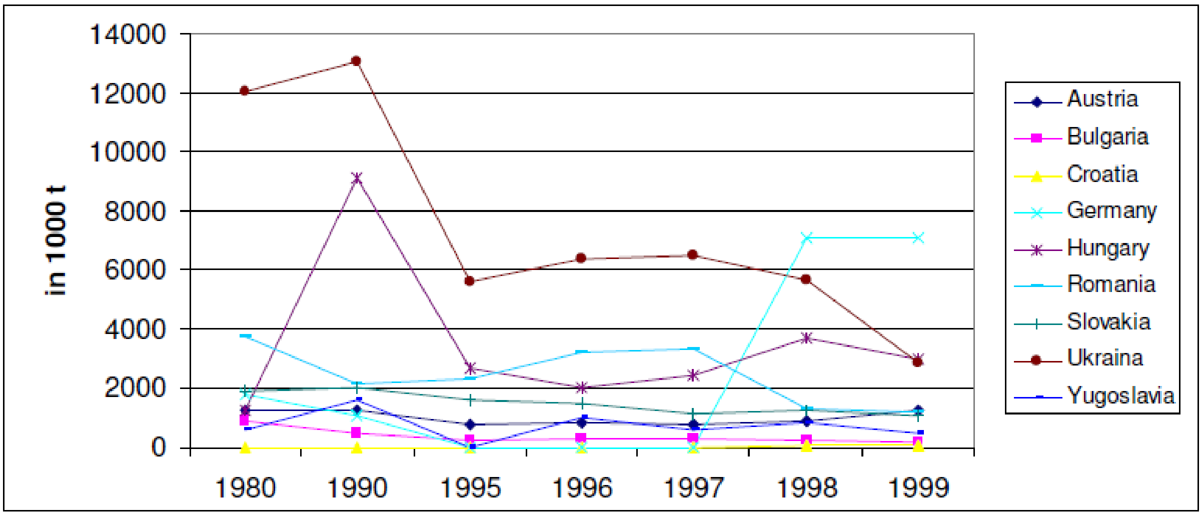


Country	1980	1990	1995	1996	1997	1998	1999
Austria	830	607	522	539	698	964	774
Bulgaria	8.389	3.060	n.a.	14	11	664	498
Croatia	n.a.	n.a.	n.a.	n.a.	n.a.	12	14
Germany	192	289	n.a.	n.a.	n.a.	55	17
Hungary	9.819	4.109	n.a.	n.a.	n.a.	n.a.	n.a.
Romania	15.003	8.144	4.715	3.686	4.423	3.304	2.934
Slovakia	1.865	3.490	n.a.	11	9	9	11
Ukraina	7.478	6.776	675	498	561	273	409
Yugoslavia	15.156	8.994	n.a.	3.405	3.203	3.705	2.102
Total	58.732	35.469	5.912	8.153	8.905	8.986	6.759
Goods entered by sea	8.080	3.345	2.688	2.350	519	572	452
Index (1980 = 100)	100	77	24	28	27	34	27

Figure 32. Danube – Internal transport; goods carried between the ports of a country, in 1000 tonnes (United Nations 2001)

As it can see in the figures, there is a clear trend towards a decline in transport volumes in this period between 1980 and 1999. In broad strokes, the development can be explained mainly by several reasons (→ consequence):

- Rearrangement of statistical collection method (since 1990) → decrease
- Change of economic system in the Eastern European countries in 1989 → decrease
- First crisis in Yugoslavia between 1992 and 1995 → decrease
- Second crisis in Yugoslavia between 1999 and 2002 → decrease
- Opening of the Main-Danube-canal in 1992 → increase



Country	1980	1990	1995	1996	1997	1998	1999
Austria	1246	1236	789	812	780	922	1263
Bulgaria	903	477	222	310	286	241	204
Croatia	n.a.	n.a.	n.a.	n.a.	n.a.	51	51
Germany	1808	1085	n.a.	n.a.	n.a.	7075	7088
Hungary	1279	9114	2674	2017	2414	3706	2968
Romania	3769	2120	2320	3200	3353	1298	1176
Slovakia	1885	2020	1583	1495	1142	1270	1087
Ukraina	12029	13071	5617	6360	6519	5632	2881
Yugoslavia	612	1634	n.a.	1028	586	814	494
Total	23531	30757	13205	15222	15080	21009	17212

Figure 33. Internation transport; good which have been loaded in the reporting country and have left with a destination, whether Danubian or not, in 1000 tonnes (United Nations 2001)

The following table shows the different types of commodities as well as their transport ship used.

NST/R	Commodities	Dry Bulk		Liquid Bulk		Inter-modal	RoRo
		normal	silo	tanker	slurry		
0,1	Food products						
2	Coal						
3	Mineral oils						
4	Ores						
4,5	Iron and steel; scrap metals						
6	Construction materials						
6	Construction wastes; contaminated soils						
7,8	Chemical products						
	Recycling products						
9	Vehicles						
9	Intermodal loading units						

Table 8. IWT potentials by market segments (PINE)

Below an analysis of transport volumes by exchanged goods categories between Western European countries and Danube riparian countries is given in the following table 9. Column numbers are the different goods according to previous numbering.

Transport volumes from Western European countries (N, B, F, CH, D) to Danube countries (A, SK, H, BG, RO)

Goods category (NST/R)

Country of loading	0	1	2	3	4	5	6	7	8	9	Total
Netherlands	96.967	490.703	6.566	55.422	841.125	40.427	89.087	72.197	23.662	7.186	1,723.342
Belgium	5.294	35.087	22.469	15.783	2.581	3.914	10.318	28.775	8.983	2.639	135.843
France	25.393	2.500	-	-	-	474	-	8.878	3.853	3.433	44.531
Switzerland	4.896	-	-	-	-	-	-	-	-	-	4.896
Germany	262.955	307.353	43.026	61.992	474	53.448	37.413	46.643	18.172	18.572	850.677
Total	395.505	835.644	72.061	133.197	844.808	98.263	136.818	156.493	54.670	31.830	2,759.289

Transport volumes from Danube countries (A, SK, H, BG, RO) to Western European countries (N, B, F, CH, D)

Goods category (NST/R)

Country of unloading	0	1	2	3	4	5	6	7	8	9	Total
Netherlands	191.912	82.523	-	48.020	12.920	51.568	3.980	13.855	16.534	85.383	506.695
Belgium	37.216	103.520	-	10.331	10.310	174.651	15.038	3.912	395	12.638	368.011
France	1.000	-	-	-	430	46.400	-	10.252	-	1.488	59.570
Switzerland	3.694	914	-	-	-	-	-	3.950	-	-	8.558
Germany	52.196	230.940	48.486	265.638	39.987	535.139	176.466	583.692	6.934	27.893	1,967.371
Total	286.018	417.897	48.486	323.989	63.647	807.758	195.484	615.661	23.863	127.402	2,910.205

Table 9. Transport volumes (in tonnes) between Danube and Western European countries by goods categories in 2000 (Statistic Austria)

Thus, table 9 shows the different kinds of goods exchanged via inland navigation between Western European countries (Netherlands, Belgium, France, Switzerland and Germany) and Danube riparian countries (Austria, Slovakia, Hungary, Bulgaria and Romania). As it can be seen, on the one hand, the main goods categories from Western European countries to Danube countries are categories 1 and 4, i.e., foodstuffs and ores). On the other hand, the dominant goods categories from Danube countries to West countries are above all the categories 5 and 7, i.e., metal products and fertilizers.

7.2 Transportation in Austria

In this section, inland waterway navigation and freight transport in Austria will be studied in greater depth. As it has been mentioned, since 2000 data for Danube navigation transport have been analyzed on the basis of the Austrian national statistics. In this statistics all inland waterway transports related to Austria are included (origin- destination-, transit transports).

Following table shows Danube navigation transport volumes from, to and via Austria including the average transport distances:

Country of unloading

Country of loading	Netherlands	Belgium	Luxembourg	France	Switzerland	Germany	Austria	Slovakia	Hungary	Bulgaria	Romania	Serbia-Mont.	Croatia	Ukraine	Total
Netherlands							1.256.251	124.486	342.605	463	0	0	0	0	1.723.805
							1.382	*1.666*	*1.816*	*2.525*	*0*	*0*	*0*	*0*	
Belgium							74.006	5.312	56.527	0	0	0	0	0	135.845
							1.544	*1.664*	*1.895*	*0*	*0*	*0*	*0*	*0*	
Luxembourg							0	0	0	0	0	0	0	0	0
							0	*0*	*0*	*0*	*0*	*0*	*0*	*0*	
France							17.916	6.303	18.589	274	0	1.500	0	0	44.582
							1.261	*1.404*	*1.525*	*2.527*	*0*	*1.771*	*0*	*0*	
Switzerland							4.896	0	0	0	0	0	0	0	4.896
							1.206	*0*	*0*	*0*	*0*	*0*	*0*	*0*	
Germany							439.772	68.969	319.423	10.443	0	67.502	16.222	877	923.208
							651	*613*	*879*	*1.584*	*0*	*1.130*	*975*	*2.156*	
Austria	229.644	109.571	0	25.472	3.950	544.002		81.387	143.598	142	34	39.424	884	13.759	1.191.867
	1.463	*1.452*	*0*	*1.145*	*1.175*	*602*		*159*	*424*	*1.556*	*1.000*	*842*	*799*	*2.047*	
Slovakia	116.163	62.671	0	27.434	0	650.823	2.008.289								2.865.380
	1.621	*1.660*	*0*	*1.318*	*0*	*593*	*229*								
Hungary	147.504	196.119	0	6.665	4.608	770.138	1.503.436								2.628.470
	1.872	*1.935*	*0*	*1.580*	*1.795*	*1.044*	*434*								
Bulgaria	0	0	0	0	0	21.276	39.781								61.057
	0	*0*	*0*	*0*	*0*	*1.608*	*1.385*								
Romania	463	650	0	0	0	9.374	6.747								17.234
	2.525	*2.569*	*0*	*0*	*0*	*1.823*	*1.627*								
Serbia-Monteneg	923	0	0	0	0	123.947	70.665								195.535
	2.281	*0*	*0*	*0*	*0*	*1.242*	*682*								
Croatia	1.229	1.708	0	0	0	3.146	0								6.083
	2.447	*2.190*	*0*	*0*	*0*	*1.838*	*0*								
Ukraine	0	0	0	0	0	9.034	28.137								37.171
	0	*0*	*0*	*0*	*0*	*2.299*	*2.033*								
Total	495.926	370.719	0	59.571	8.558	2.131.740	5.449.896	286.457	880.742	11.322	34	108.426	17.106	14.636	9.835.133

Table 10. Danube navigation from, to and via Austria in 2000 (in tons) and average transport distances (PINE)

Table 10 shows transport volumes on the Danube which are related to Austria as well as distances. Noticeable are the long transport distances between some countries, above all between Western European countries and Danube riparian countries (linked over the Main-Danube canal), but also within the Danube area (e.g. average transport distance between Austria and Romania is 1.627 km).

Utilization degree for transports from Western European countries (N,B,F,CH,D) to Danube countries (A, SK, H, BG, RO)

	tdW (loading capacity of utilized vessels in tonnes)	Transported goods (in tonnes)	Average utilization degree
Import to Austria	2728.394	1792.841	65.7%
Transit via Austria	1850.111	1038.980	56.2%
Total from West	4578.505	2831.821	61.9%

Utilization degree for transports from Danube countries (A, SK, H, BG, RO) to Western European countries (N, B, F, CH, D)

	tdW (loading capacity of utilized vessels in tonnes)	Transported goods (in tonnes)	Average utilization degree
Export from Austria	1658.730	911.641	55.0%
Transit via Austria	3703.522	2153.874	58.0%
Total to West	5362.252	3065.515	57.2%

Table 11. Utilization degrees of transport relations between Western European countries (N,B,F,CG,D) and Danube countries (A,SK,H,BG,RO) in 2000 (Statistics Austria)

Table 11 shows the average utilization degrees of loaded vessels operating between Western European countries and Danube countries. The average utilization rates are with 61,9% (transports Western European countries – Danube countries) and 57,2% (transports Danube countries - Western European countries). There rates are significantly lower than the rest of Europe. The reasons for this difference are not lacking transport volumes but above all infrastructure bottlenecks on the Upper Danube: Long average transport distances (see Table 10) lead to the problem of unpredictable water level prognoses and herewith to a higher risk for the vessel operators.

The infrastructure bottlenecks on the Upper Danube in Germany, Austria and Hungary have insufficient waterway depths and besides heavily fluctuating water levels which lead to drastically reduced utilization rates of vessels operating between Western European countries and Danube countries.

AUSTRIA

Freight transport on the Danube (including the Rhein-Main-Donau-Canal)
Transport volume and transport performance itemised by types of transport in the years 1995 and 2007 – 2009 in 1000 tonnes.

Unit	Type of transport				Total
	Inland transport	International goods receipt	International goods dispatch	Transit 1)	
Year 1995					
BAR_SP	65	1222	608	1029	**2924**
BAR_NSP	66	2383	98	1497	**4043**
BAR_TK_SP	123	449	29	293	**894**
BAR_TK_NSP	268	527	54	52	**900**
VESS_SEA					**0**
OTH_GDVES		20		9	**29**
Total	**522**	**4600**	**789**	**2879**	**8790**
…					
BAR_SP					**-**
BAR_NSP					**-**
BAR_TK_SP					**-**
BAR_TK_NSP					**-**
VESS_SEA					**-**
OTH_GDVES					**-**
Total	**…**	**…**	**…**	**…**	**…**
Year 2007					
BAR_SP	79	1.663	747	1.899	**4.388**
BAR_NSP	321	3.599	208	1.151	**5.279**
BAR_TK_SP	86	580	272	199	**1.137**
BAR_TK_NSP	486	422	320	73	**1.301**
VESS_SEA					**0**
OTH_GDVES				1	**1**
Total	**972**	**6.264**	**1.547**	**3.323**	**12.106**
Year 2008					
BAR_SP	101	1.482	1.110	1.624	**4.317**
BAR_NSP	44	3.259	410	895	**4.608**
BAR_TK_SP	34	381	229	229	**873**
BAR_TK_NSP	324	608	416	61	**1.409**
VESS_SEA					**0**
OTH_GDVES		1			**1**
Total	**503**	**5.731**	**2.165**	**2.809**	**11.208**
Year 2009					
BAR_SP	50	1.293	842	1.589	**3.774**
BAR_NSP	9	2.691	284	654	**3.638**
BAR_TK_SP	27	328	190	162	**707**
BAR_TK_NSP	243	633	266	60	**1.202**
VESS_SEA					**0**
OTH_GDVES					**0**
Total	**329**	**4.945**	**1.582**	**2.465**	**9.321**

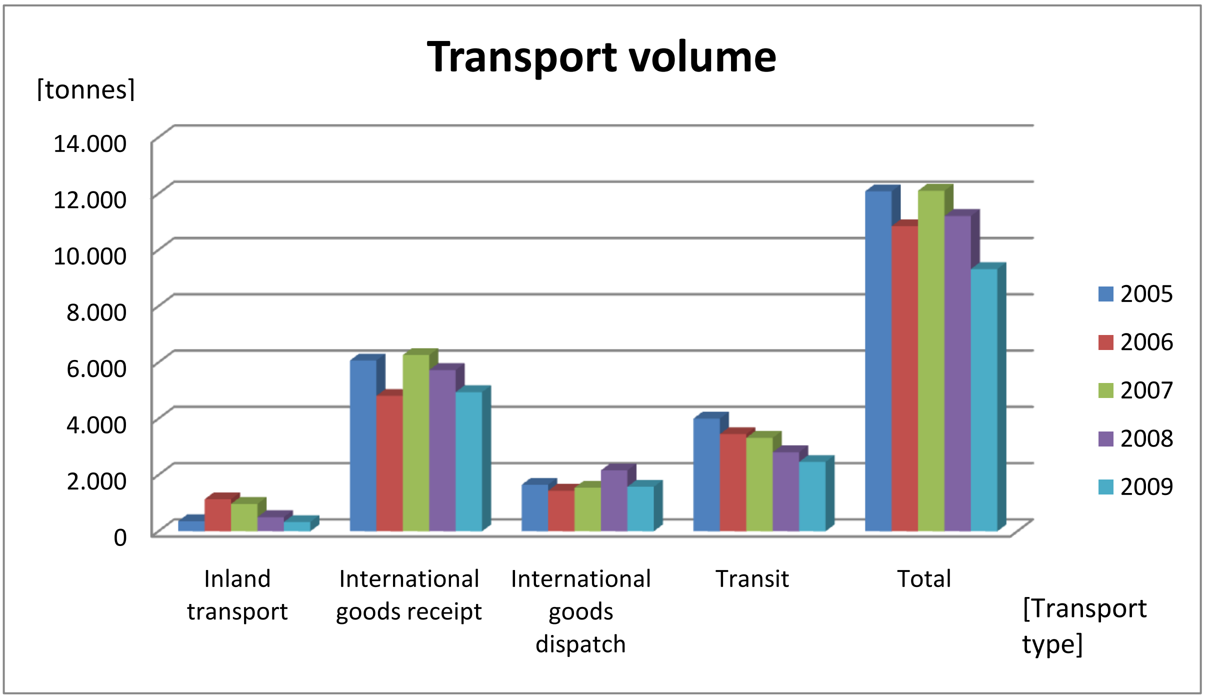
Rounding differences may occur between sums and total values.
[1)] 2005: Adjustments and imputations for the results of transit transport; 2006 until 2009: Adjusted results of transit transport.
S: STATISTICS AUSTRIA. Compiled on 07 April 2010.

Table 12. Transport volume depending on transport and ship types in Austria from 1995 to 2009 in 1000 tonnes (Statistic Austria)

BAR_SP	Self-propelled barge
BAR_NSP	Barge not self-propelled
BAR_TK_SP	Self-propelled tanker barge
BAR_TK_NSP	Tanker barge not self-propelled
VESS_SEA	Seagoing vessel
OTH_GDVES	Other goods carrying vessel

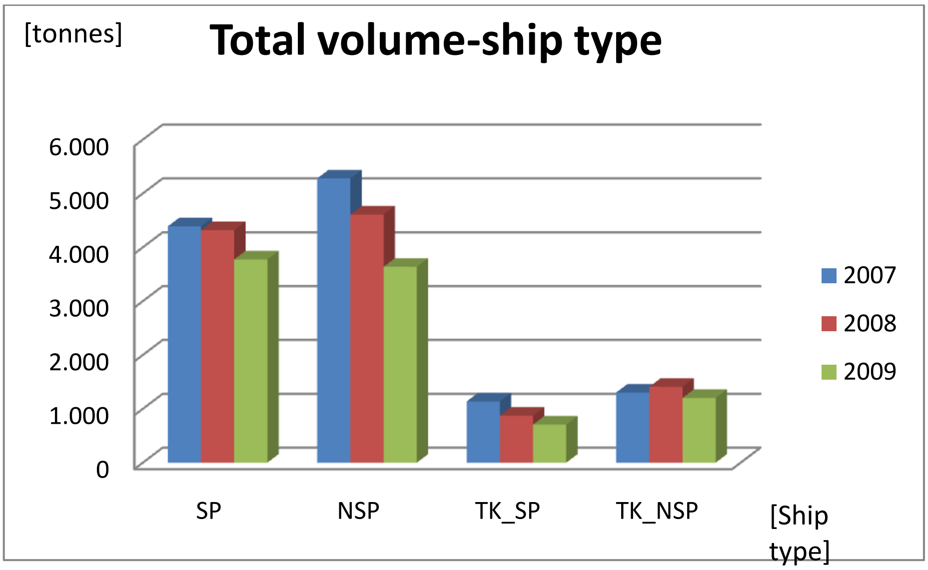
Table 13. Types of vessel

The following graphs are meant to visually represent the above data in order to see easier way.



Graph 7. Transport volume depending on transport type between 2005 and 2009

Graph 7 shows the transport volume depending on the transport type and the year. As it can be seen international goods receipt is the transport type most used. On the other hand, inland transport is the least used method. Besides, shipping on transit has decreased every year.

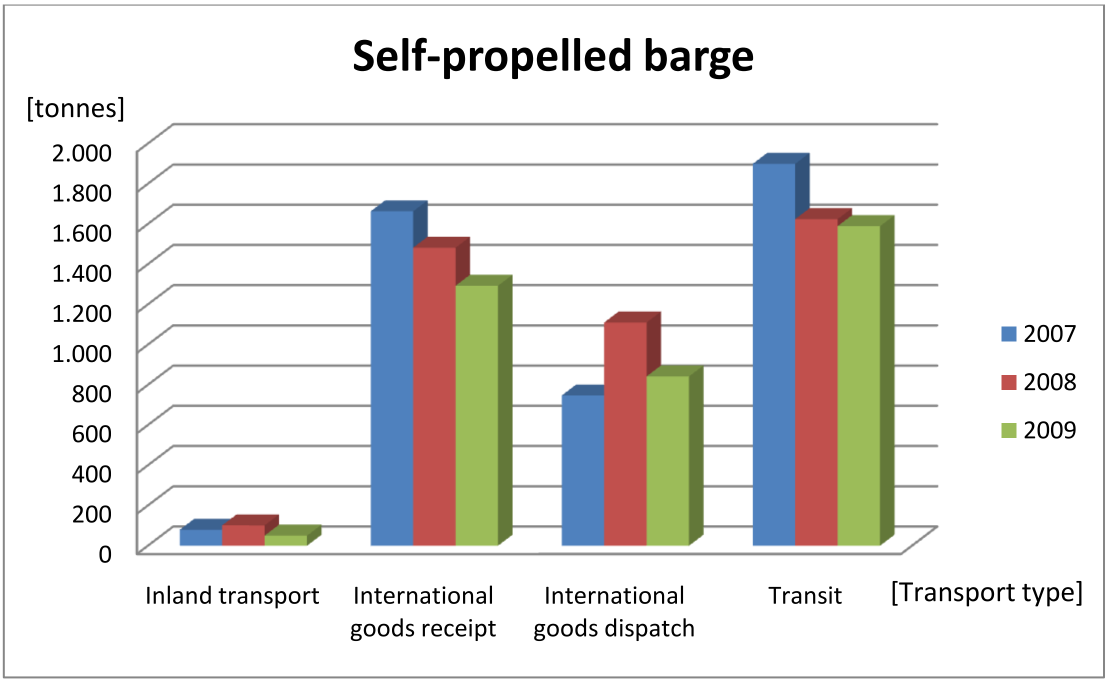


Graph 8. Total volume depending on ship type between 2007 and 2009

Graph 8 shows the total volume carried out by each ship type between 2007 and 2009. Self-propelled and not self-propelled barges are more common than tankers. Once again it can be seen that transport volume has decreased in the latest years.

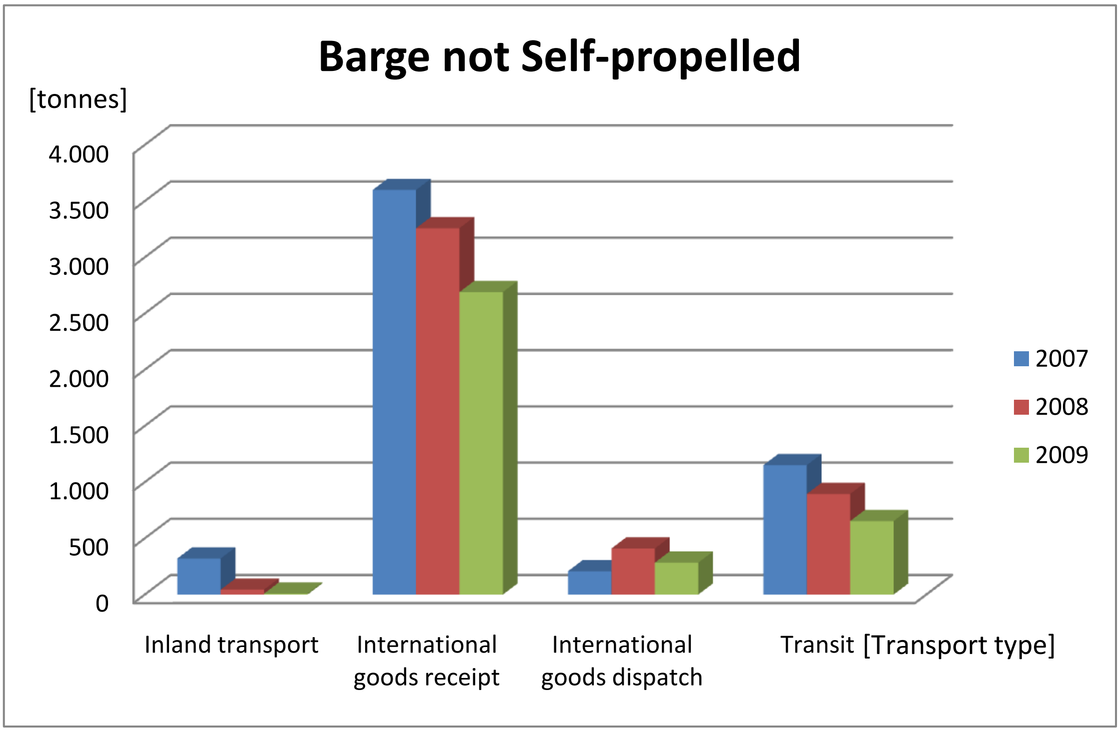
Transport volume of each ship type between 2007 and 2009

SELF-PROPELLED BARGE



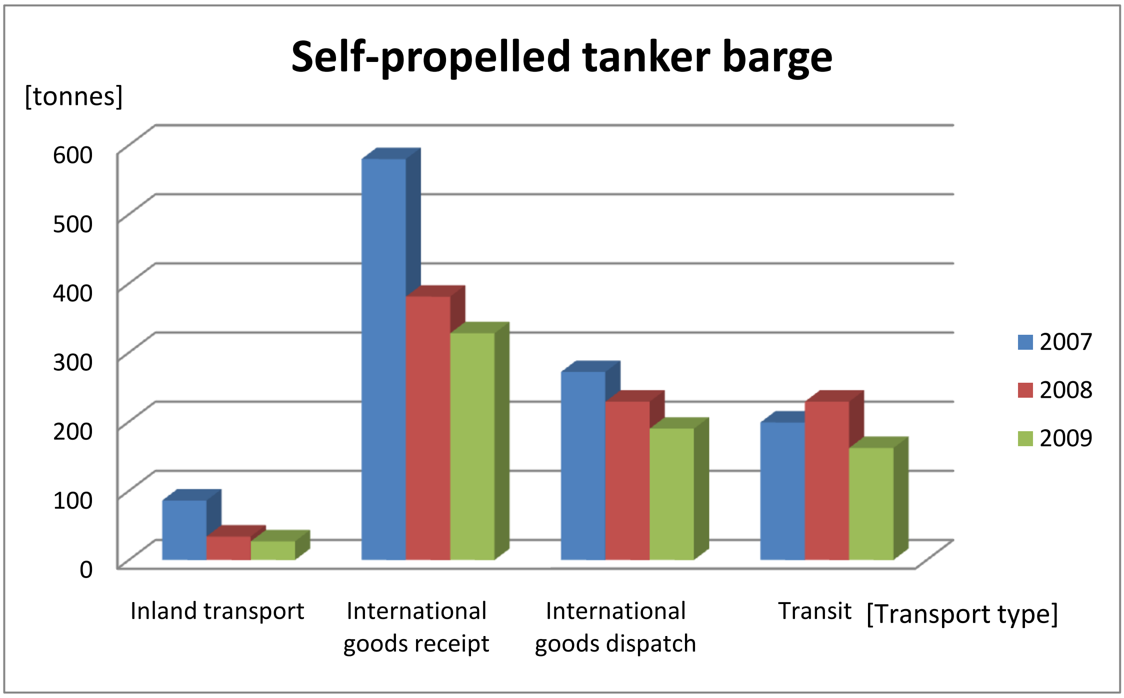
Graph 9. Transport volume depending on transport type

BARGE NOT SELF-PROPELLED



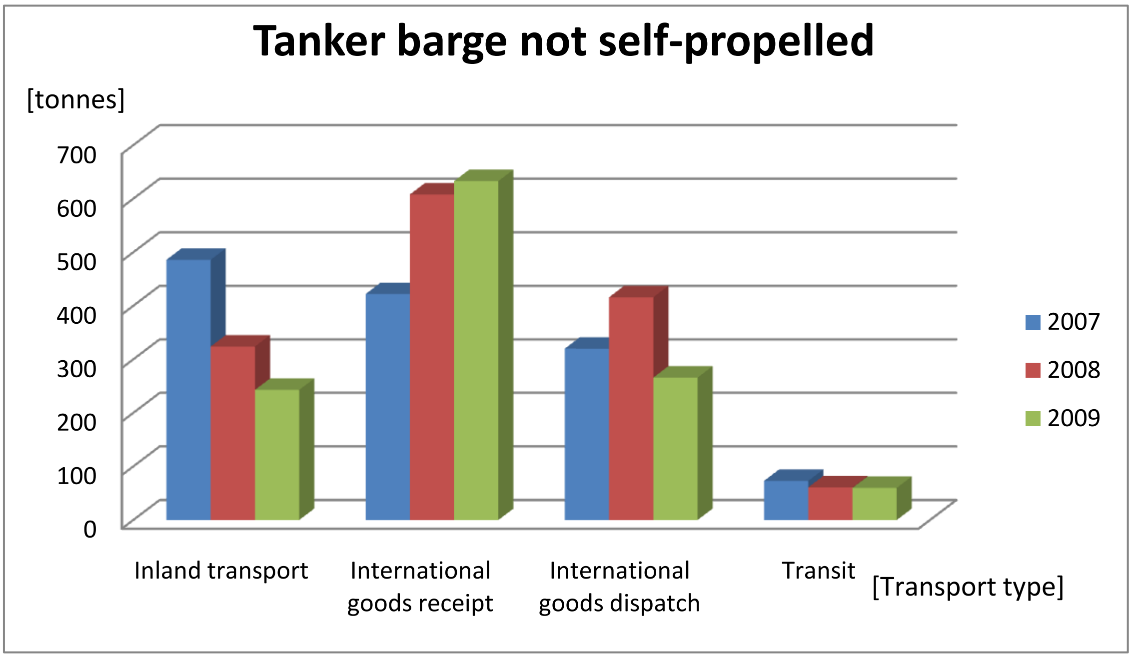
Graph 10. Transport volume depending on transport type

SELF-PROPELLED TANKER BARGE



Graph 11. Transport volume depending on transport type

TANKER BARGE NOT SELF-PROPELLED



Graph 12. Transport volume depending on transport type

As it can be seen in the previous graphs, barge self-propelled takes charge mainly of transit transport. On the other hand, the others ship types (barge not self-propelled, self-propelled tanker barge and tanker barge not self-propelled) take charge mostly of transport of international goods receipt.

Freight transport on the Danube (including the Rhein-Main-Donau-Canal) Transport volume and transport performance itemised by types of transport in the years 2005 - 2009

Unit	Type of transport				Total
	Inland transport	International goods receipt	International goods dispatch	Transit [1]	
Year 2005					
tons	355.631	6.069.543	1.652.988	4.005.412	**12.083.574**
1 000 tkm domestic	37.318	1.079.105	195.798	1.447.355	**2.759.576**
1 000 tkm abroad	-	5.496.120	908.427	3.851.686	**10.256.233**
Year 2006					
tons	1.136.577	4.813.237	1.440.795	3.453.555	**10.844.164**
1 000 tkm domestic	137.349	901.868	170.730	1.208.745	**2.418.692**
1 000 tkm abroad	-	5.002.071	771.282	3.590.020	**9.363.373**
Year 2007					
tons	972.156	6.264.069	1.547.234	3.323.081	**12.106.540**
1 000 tkm domestic	145.721	1.125.488	162.330	1.163.078	**2.596.617**
1 000 tkm abroad	-	5.753.240	838.217	3.357.475	**9.948.932**
Year 2008					
tons	502.228	5.730.621	2.166.354	2.809.508	**11.208.711**
1 000 tkm domestic	91.517	1.023.270	260.417	983.327	**2.358.531**
1 000 tkm abroad	-	5.373.515	1.396.976	2.630.466	**9.400.957**
Year 2009					
tons	329.463	4.945.292	1.581.387	2.465.668	**9.321.810**
1 000 tkm domestic	62.477	878.148	199.026	862.984	**2.002.635**
1 000 tkm abroad	-	4.190.621	940.002	2.454.660	**7.585.283**

Rounding differences may occur between sums and total values.
[1] 2005: Adjustments and imputations for the results of transit transport; 2006 until 2009: Adjusted results of transit transport.
S: STATISTICS AUSTRIA. Compiled on 07 April 2010.

Table 14. Summary of transport volume depending on transport type between 2005 and 2009 (Statistic Austria)

8 Fuel Consumption and Exhaust Emissions Calculation Model

It has been used two models in order to calculate the fuel consumption and the exhaust emissions

8.1 Guidebook

This source category, accepted and used by European Union, covers all water-borne transport from recreational craft to large ocean-going cargo ships that are powered primarily by high-, slow- and medium-speed diesel engines and occasionally by steam or gas turbines. Water-borne navigation causes emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), as well as carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), sulphur dioxide (SO_2), particulate matter (PM) and oxides of nitrogen (NO_X).
The source categories are:

- Water-borne navigation
- International water-borne navigation (International bunkers)
- Domestic water-borne navigation
- Fishing (mobile combustion)
- Mobile (water-borne navigation component)
- Multi-lateral operations (water-borne navigation component)

Techniques
Marine diesel engines are the predominant form of power unit within the marine industry for both propulsion and auxiliary power generation. Around 99% of the world's fleet is powered by marine diesel, with steam turbines powering less than 1 %. The only other type of engine highlighted was gas turbines, used virtually only on passenger vessels (around 0.1 % of vessels (Trozzi, 2010)). Diesel engines can be categorized into slow (around 18% of engines), medium (around 55%), or fast (around 27%), depending on their rated speed.

Engine Types

- **Slow speed diesel engines**: these have a maximum operating speed of up to 300rev/min, although most operate at speeds between 80–140 rev/min. They usually operate on a two-stroke cycle, and are cross head engines of 4–12 cylinders. Some current designs are capable of developing in excess of 4 000 kW/cylinder and with brake mean effective pressures of the order of 1.7 MPa.
  These engines are exclusively used for main propulsion purposes and comprise the greater proportion of installed power, and hence fuel consumption, within the industry.

- **Medium speed diesel engines**: these marine diesel engines operate at speeds between 300–900 rev/min. They generally operate on the four-stroke cycle, are normally trunk piston engines of up to 12 cylinders in line, or 20 cylinders in 'V' formation.
  Current designs develop power output in the range 100–2000 kW/cylinder and with brake mean effective pressures in the range 1.0–2.5 MPa. Engines of this type may be used for both main propulsion and auxiliary purposes in the marine industry. These engines are used in multi-engine installations and also in diesel-electric installations.

- **High speed diesel engines**: this term is used to describe marine diesel engines with a maximum operating speed greater than 900 rev/min. They are used on smaller vessels and are often the source of auxiliary power on board vessels.

Speed	%Fleet	Operating speed (rpm)	Cycles	Nº Cylinders	Power (KW/cyl)
Slow	18	80-140	2-stroke	4-12	4000
Medium	55	300-900	4-stroke	12 I – 20 V	100-2000
High	27	>900	4-stroke		

Table 15. Properties of each vessel type

- **Steam turbines**: they dominated in the early twentieth century but they have been replaced by the more efficient diesel engines which are cheaper to run. The steam turbine vessels are predominantly fuelled with fuel oil rather than lighter fuels.

- **Gas turbines**: this type of engine is more widely used in warships, although they are currently installed in only a very small proportion of the merchant fleet, often in conjunction with diesel engines.

Besides the categorization into five types of engines, the marine engines can be further stratified according to their principal fuel: bunker fuel oil (BFO), marine diesel oil (MDO) or marine gas oil (MGO). Hence emissions will depend on engine type and also on fuel type.

Controls

Thus, as a summary from point 5 Exhaust treatment systems, technology for controlling emissions includes:

- improved engine design, fuel injection systems, electronic timing, etc. to obtain optimum efficiency (optimizing CO_2 emissions) reducing PM and VOC emissions;
- Exhaust gas recirculation (EGR) where a portion of the exhaust gas is routed back to the engine charge air whereby the physical properties of the charge air are changed. For marine diesel engines, a typical NO_X emission reduction of 10–30 % can be found. This technique has not yet been in regular service for ships;
- Selective catalytic reduction (SCR) where a reducing agent is introduced to the exhaust gas across a catalyst. Hereby NO_X is reduced to N_2 and H_2O. However this technology imposes severe constraints on the ship design and operation to be efficient. A reduction of 85–95 % in NO_X can be expected applying this technology. The technology is in use in a few ships and is still being developed;
- Selective non catalytic reduction (SNCR) where the exhaust gas is treated as for the SCR exhaust gas treatment technique, except the catalyst is omitted. The process employs a reducing agent, supplied to the exhaust gas at a prescribed rate and temperature upstream of a reduction chamber. Installation is simpler than the SCR, but needs a very high temperature to be efficient. Reductions of 75–95 % can be expected. However, no installations have been applied yet on ships;

- Sea water scrubbing. Sea water scrubbing involves removal of SO_2 by sea water scrubbing (Concawe, 1994). This technique has not yet become widespread due to cost issues but also because this delivers sulphur directly to the oceans which is not considered good practice.

Moreover, existing EU directives are related to the content of sulphur in marine gas oil (EU Directive 93/12 and EU-Directive 1999/32) and the content of sulphur in heavy fuel oil used in SECA (EU-Directive 2005/33).

The current Marpol 73/78 Annex VI legislation on NO_X emissions, formulated by IMO (International Maritime Organisation) is relevant for diesel engines with a power output higher than 130 kW, which are installed on a ship constructed on or after 1 January 2000 and diesel engines with a power output higher than 130 kW which undergo major conversion on or after 1 January 2000.

The Marpol Annex VI, as amended by IMO in October 2008, considers a three tiered approach as follows:

- Tier I: diesel engines (> 130 kW) installed on a ship constructed on or after 1 January 2000 and prior to 1 January 2011;
- Tier II: diesel engines (> 130 kW) installed on a ship constructed on or after 1 January 2011;
- Tier III (1): diesel engines (> 130 kW) installed on a ship constructed on or after 1 January 2016.

The Tier I–III NOx legislation values rely on the rated engine speeds (n) given in RPM (revolutions per minute). The emission limit equations are shown in Table 16.

Regulation	NO_X	Rated engine speed (rpm)
Tier I	17 g/kWh	n < 130
	45 × n-0.2 g/kWh	130 ≤ n < 2000
	9,8 g/kWh	n ≥ 2000
Tier II	14.4 g/kWh	n < 130
	44 × n-0.23 g/kWh	130 ≤ n < 2000
	7.7 g/kWh	n ≥ 2000
Tier III	3.4 g/kWh	n < 130
	9 × n-0.2 g/kWh	130 ≤ n < 2000
	2 g/kWh	n ≥ 2000

Table 16. Tier I-III NO_X emission limits for ship engines (amendments to Marpol Annex VI)

8.1.1 Method

There are three methods to calculate the emissions: Tier I, Tier II and Tier III.

Tier I is the simplest and Tier III is the most accurate. Tier I only takes into account the fuel type while Tier III takes into account both technical information (e.g. engine size and technology, power installed or fuel use, hours in different activities,…) and ship movement data.

<u>Tier II</u>

The Tier 2 approach, uses fuel consumption by fuel type, besides requires country specific data on the proportion of fuel used by fuel type and engine type (slow, medium or high speed engines).

For this approach the algorithm used is:

$$E_i = \sum_m \left(\sum_j FC_{m,j} \times EF_{i,m,j} \right)$$

where:

- E = annual emission (tonnes),
- $FC_{m,j}$ = mass of fuel type m used by vessels with engine type j (tonnes),
- $EF_{i,m,j}$ = average emission factor for pollutant i by vessels with engine type j using fuel type m
- i = pollutant
- j = engine type (slow-, medium-, and high-speed diesel, gas turbine, and steam turbine for large ships and diesel, gasoline 2S and gasoline 4S for small vessels).
- m = fuel type (bunker fuel oil, marine diesel oil/marine gas oil (MDO/MGO) or gasoline)

Tier II engine and fuel-specific emission factors

For all pollutants except NO_X, NMVOC and PM (TSP, PM_{10} and $PM_{2,5}$), the Tier II emission factors for a specific fuel type are the same as Tier I emission factors (Table 17.1 to Table 17.3). Tier II emission factors for NO_X, NMVOC, PM and specific fuel consumption (g_{fuel}/kWh) are shown in Table 17.4.

Bunker fuel oil

Tier 1 default emission factors					
	Code	Name			
NFR Source Category	1.A.3.d.i 1.A.3.d.ii 1.A.4.c.iii 1.A.5.b	International navigation National navigation Off-road vehicles and other machineries Other, mobile (including military, land based and recreational boats)			
Fuel	Bunker Fuel Oil				
Not estimated	NH_3, Benzo(a)pyrene, Benzo(b)fluoranthene, Benzo(k) fluoranthene,Indeno(1,2,3-cd)pyrene				
Not applicable					
Pollutant	Value	Unit	95% confidence interval		Reference
			Lower	Upper	
NO_x	79.3 [2]	kg/tonne fuel	NA	NA	Entec (2007)
CO	7.4	kg/tonne fuel	NA	NA	Lloyd's Register (1995)
NMVOC	2.7 [2]	kg/tonne fuel	NA	NA	Entec (2007)
SO_x	20 * S [1]	kg/tonne fuel	NA	NA	Lloyd's Register (1995)
TSP	6.2	kg/tonne fuel	NA	NA	Entec (2007)
PM_{10}	6.2	kg/tonne fuel	NA	NA	Entec (2007)
$PM_{2.5}$	5.6	kg/tonne fuel	NA	NA	Entec (2007)
Pb	0.18	g/tonne fuel	NA	NA	average value [3]
Cd	0.02	g/tonne fuel	NA	NA	average value [3]
Hg	0.02	g/tonne fuel	NA	NA	average value [3]
As	0.68	g/tonne fuel	NA	NA	average value [3]
Cr	0.72	g/tonne fuel	NA	NA	average value [3]
Cu	1.25	g/tonne fuel	NA	NA	average value [3]
Ni	32	g/tonne fuel	NA	NA	average value [3]
Se	0.21	g/tonne fuel	NA	NA	average value [3]
Zn	1.20	g/tonne fuel	NA	NA	average value [3]
PCDD/F	0.47	TEQmg/tonne	NA	NA	Cooper (2005)
HCB	0.14	mg/tonne	NA	NA	Cooper (2005)
PCB	0.57	mg/tonne	NA	NA	Cooper (2005)

Table 17.1. Tier 1 emission factors for ships using bunker fuel oil

Notes

1. S = percentage sulphur content in fuel; pre-2006: 2.7 % wt. [source: Lloyd's Register, 1995]. For European Union as specified in the Directive 2005/33/EC:
   a. 1.5 % wt. from 11 August 2006 for Baltic sea and from 11 August 2007 for the North Sea for all ships;
   b. 1.5 % wt. from 11 August 2006 in EU territorial seas, exclusive economic zones and pollution control zones by passenger ships operating on regular services to or from any Community port at least in respect of vessels flying their flag and vessels of all flags while in their ports;
   c. 0.1 % by wt. from 1 January 2010 for inland waterway vessels and ships at berth in Community ports.
2. Emission factors for NO_X and NMVOC are the 2000 values in cruise for medium speed engines (see Tier 2).
3. Reference: 'average value' is between Lloyd's Register (1995) and Cooper and Gustafsson (2004).

Marine diesel oil/Marine gas oil

Tier 1 default emission factors					
	Code	Name			
NFR Source Category	1.A.3.d.i 1.A.3.d.ii 1.A.4.c.iii 1.A.5.b	International navigation National navigation Off-road vehicles and other machineries Other, mobile (including military, land based and recreational boats)			
Fuel	Marine diesel oil/marine gas oil (MDO/MGO)				
Not estimated	NH_3, Benzo(a)pyrene, Benzo(b)fluoranthene, Benzo(k) fluoranthene,Indeno(1,2,3-cd)pyrene				
Not applicable					
Pollutant	Value	Unit	95% confidence interval		Reference
			Lower	Upper	
NO_x	78.5 [2]	kg/tonne fuel	NA	NA	Entec (2007)
CO	7.4	kg/tonne fuel	NA	NA	Lloyd's Register (1995)
NMVOC	2.8 [2]	kg/tonne fuel	NA	NA	Entec (2007)
SO_x	20 * S [1]	kg/tonne fuel	NA	NA	Lloyd's Register (1995)
TSP	1.5	kg/tonne fuel	NA	NA	Entec (2007)
PM_{10}	1.5	kg/tonne fuel	NA	NA	Entec (2007)
$PM_{2.5}$	1.4	kg/tonne fuel	NA	NA	Entec (2007)
Pb	0.13	g/tonne fuel	NA	NA	average value [3]
Cd	0.01	g/tonne fuel	NA	NA	average value [3]
Hg	0.03	g/tonne fuel	NA	NA	average value [3]
As	0.04	g/tonne fuel	NA	NA	average value [3]
Cr	0.05	g/tonne fuel	NA	NA	average value [3]
Cu	0.88	g/tonne fuel	NA	NA	average value [3]
Ni	1	g/tonne fuel	NA	NA	average value [3]
Se	0.10	g/tonne fuel	NA	NA	average value [3]
Zn	1.2	g/tonne fuel	NA	NA	average value [3]
PCDD/F	0.13	TEQmg/tonne	NA	NA	Cooper (2005)
HCB	0.08	mg/tonne	NA	NA	Cooper (2005)
PCB	0.38	mg/tonne	NA	NA	Cooper (2005)

Table 17.2. Tier 1 emission factors for ships using marine diesel oil/marine gas oil (Guidebook)

Notes

1. S = percentage sulphur content in fuel; pre-2000 fuels: 0.5 % wt. [source: Lloyd's Register, 1995]. For European Union as specified in the Directive 2005/33/EC:
   a. 0.2 % wt. from 1 July 2000 and 0.1 % wt. from 1 January 2008 for marine diesel oil/marine gas oil used by seagoing ships (except if used by ships crossing a frontier between a third country and a Member State);
   b. 0.1% wt. from 1 January 2010 for inland waterway vessels and ships at berth in Community ports.
2. Emission factor for NO_X and NMVOC are the 2000 values in cruise for medium speed engines (see Tier 2).
3. Reference: 'average value' is between Lloyd's Register (1995) and Cooper and Gustafsson (2004)

Gasoline

Tier 1 default emission factors					
	Code	Name			
NFR Source Category	1.A.3.d.ii	National navigation			
Fuel	Gasoline				
Not applicable	Aldrin, Chlordane, Chlordecone, Dieldrin, Endrin, Heptachlor, Heptabromo-biphenyl, Mirex, Toxaphene, HCH, DDT, PCB, HCB, PCP, SCCP				
Not estimated	NH3, Pb, Cd, Hg, As, Cr, Cu, Ni, Se, Zn, PCDD/F, Benzo(a)pyrene, Benzo(b)fluoranthene, Benzo(k)fluoranthene, Indeno(1,2,3-cd)pyrene, Total 4 PAHs				
Pollutant	Value	Unit	95% confidence interval		Reference
			Lower	Upper	
NOx	9.4	kg/tonne fuel	0	0	Winther & Nielsen (2006)
CO	573.9	kg/tonne fuel	0	0	Winther & Nielsen (2006)
NMVOC	181.5	kg/tonne fuel	0	0	Winther & Nielsen (2006)
SOx	20	kg/tonne fuel	0	0	Winther & Nielsen (2006)
TSP	9.5	kg/tonne fuel	0	0	Winther & Nielsen (2006)
PM10	9.5	kg/tonne fuel	0	0	Winther & Nielsen (2006)
PM2.5	9.5	kg/tonne fuel	0	0	Winther & Nielsen (2006)

Note: The table contains averaged figures between 2-stroke and 4-stroke engines, assuming a share of 75% 2-stroke and 25% 4-stroke ones. If more detailed data are available the Tier 2 method should be used.

Table 17.3. Tier 1 emission factors for ships using gasolina (Guidebook)

In the table different NO_X emissions factors are reported for 2000 and 2005. The emission factors for 2000 (Entec, 2002) are representative of the fleet before application of IMO NO_X Technical Code (see *Controls*) while 2005 values (according to Entec, 2007) are obtained from the year 2000 NO_X emission factors with a reduction of 3.4% to account for the new engines introduced by 2005.

Tier 2 default emission factors							
Engine type	**Fuel type**	**NO_x 2000** (kg/tonne)	**NO_x 2005** (kg/tonne)	**NMVOC** (kg/tonne)	**TSP - PM_{10}** (kg/tonne)	**$PM_{2.5}$** (kg/tonne)	**Specific fuel consumption** (g fuel/kWh)
Gas turbine	BFO	20.0	19.3	0.3	0.3	0.3	305
	MDO/MGO	19.7	19.0	0.3	0.0	0.0	290
High-speed diesel	BFO	59.6	57.7	0.9	3.8	3.4	213
	MDO/MGO	59.1	57.1	1.0	1.5	1.3	203
Medium-speed diesel	BFO	65.7	63.4	2.3	3.8	3.4	213
	MDO/MGO	65.0	63.1	2.4	1.5	1.3	203
Slow-speed diesel	BFO	92.8	89.7	3.0	8.7	7.8	195
	MDO/MGO	91.9	88.6	3.2	1.6	1.5	185
Steam turbine	BFO	6.9	6.6	0.3	2.6	2.4	305
	MDO/MGO	6.9	6.6	0.3	1.0	0.9	290

Table 17.4. Tier 2 emission factors for NO_X, NMVOC, PM and specific fuel consumption for different engine types/fuel combinations (Entec (2002), Entec (2007))

- emission factors calculated in kg/tonne of fuel using specific fuel consumption.
- BFO –Bunker Fuel Oil, MDO –Marine Diesel Oil, MGO –Marine Gas Oil

8.1.2 Specific Emissions Calculation

Guidebook tables above have been followed in order to calculate specific emissions.

- **NO_X**

		NO_X			
		NO_X 2000 [kg/tonne fuel]	NO_X 2005 [kg/tonne fuel]	EF [g_{fuel}/kWh]	[g/kWh]
High-Speed Disel	BFO	59,6	57,7	213	12,5
	MDO/MGO	59,1	57,1	203	11,8
Medium-Speed Diesel	BFO	65,7	63,4	213	13,7
	MDO/MGO	65	63,1	203	13,0
Slow-Speed Diesel	BFO	92,8	89,7	195	17,8
	MDO/MGO	91,9	88,6	185	16,7

Table 18. Tier 2 emission factors for NO_X and specific fuel consumption for different engine types/fuel combinations (Entec 2002, Entec 2007)
BFO –Bunker Fuel Oil, MDO –Marine Diesel Oil, MGO –Marine Gas Oil

$$[g/kWh] = NO_X * EF / 1000$$

- **SO_2**

  SO_X only depends on %S.

	SO_2			
	%S	[kg/tonne fuel]	EF [g/kWh]	[g/kWh]
bunker	0,5	10	2,05	2,05
MDO/MGO	0,5	10	1,95	1,95
gasoline	1	20	3,9	4,4

Table 19. Tier II emission factor for SO_2 (Lloyd's Register, 1995)
S = percentage sulphur content in fuel; pre-2000 fuels: 0.5 % wt. [source: Lloyd's Register, 1995]. For European Union as specified in the Directive 2005/33/EC:

- 0.2 % wt. from 1 July 2000 and 0.1 % wt. from 1 January 2008 for marine diesel oil/marine gas oil used by seagoing ships (except if used by ships crossing a frontier between a third country and a Member State);
- 0.1% wt. from 1 January 2010 for inland waterway vessels and ships at berth in Community ports.

$$SO_2 \text{ [kg/tonne fuel]} = 20 * \%S$$

$$[g/kWh] = SO_2 \text{ [kg/tonne fuel]} * EF_{fuel} / 1000$$

- **PM**

		PM			
		PM_{10} [kg/tonne fuel]	$PM_{2,5}$ [kg/tonne fuel]	EF [g_{fuel}/kWh]	[g/kWh]
High-Speed Disel	BFO	3,8	3,4	213	0,77
	MDO/MGO	1,5	1,3	203	0,28
Medium-Speed Diesel	BFO	3,8	3,4	213	0,77
	MDO/MGO	1,5	1,3	203	0,28
Slow-Speed Diesel	BFO	8,7	7,8	195	1,61
	MDO/MGO	1,6	1,5	185	0,29

Table 20. Tier 2 emission factors for PM and specific fuel consumption for different engine types/fuel combinations (Entec 2002, Entec 2007)

$$[g/kWh] = PM_X\ [kg/tonne\ fuel] * EF_{fuel} / 1000$$

- **CO_2**

For CO_2, the emission factors in g/kWh are calculated as:

$$EF_{CO_2}(g/kWh) = \frac{LHV \cdot EF_{CO_2}(g/MJ) \cdot sfc}{1000}$$

The CO_2 emission factors (g/MJ) are country specific (heavy fuel: 78 g/MJ; gas oil: 74 g/MJ). LHV = Lower heating value in MJ/kg (heavy fuel: 40.9; diesel: 42.7). Source (Danish Energy Authority (DEA)).

		CO_2		
		[kg/tonne fuel]	EF [g_{fuel}/kWh]	[g/kWh]
High-Speed Disel	BFO	3160	213	673
	MDO/MGO	3160	203	641
Medium-Speed Diesel	BFO	3160	213	673
	MDO/MGO	3160	203	641
Slow-Speed Diesel	BFO	3160	195	616
	MDO/MGO	3160	185	585

Table 21. Tier II emission factor for SO_2 (Lloyd's Register, 1995)

8.2 Denmark Model

8.2.1 Method

The fuel consumption for each ship is estimated from the equation found below by summarizing the product of engine load (MCR%), main engine size (kW), AIS signal time interval (s) and fuel consumption factor (g/kWh):

$$E(X) = \sum_i \%MCR \cdot P_{ME} \cdot EF_{k,l,X} \cdot \Delta t_i / 3600$$

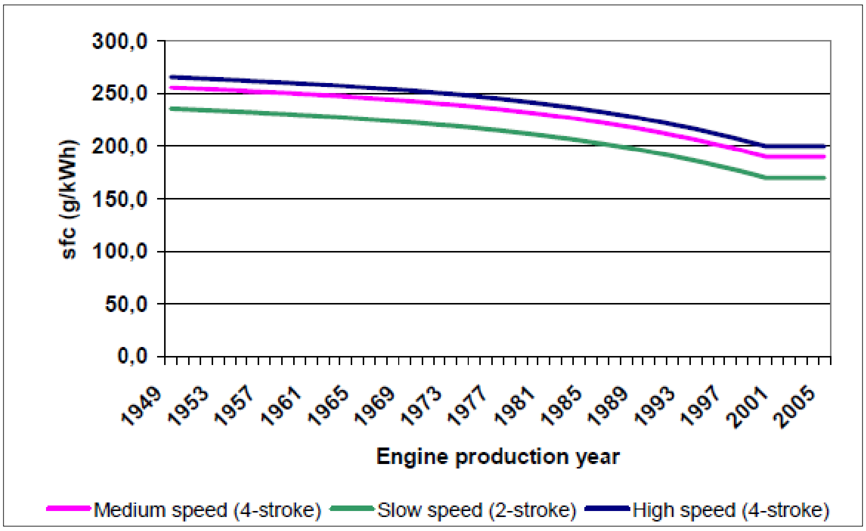
where E = fuel consumption, %MCR = engine load (%), Δt = Sailing time (s), P_{ME} = main engine power (kW), EF = specific fuel consumption factor (g/kWh), I = AIS signal interval, k = fuel type, l = engine type, X = calculation year.

Fuel consumption and emission factors

Generally, the fuel consumption and emission factors in g/kWh depend on to engine type, fuel type and engine production year.

- **Specific fuel consumption**

The standard curves for specific fuel consumption, sfc (g/kWh), are shown in *Graph 13* for slow-, medium- and high-speed engines, as a function of engine production year.



Graph 13. Specific fuel consumption for marine engines related to the engine production year (g/kWh) (Danish TEMA2000, Ministry of Transport and Hans Otto Kristensen, DTU, 2009)

For newer engines, the fuel consumption trend is established based on expert judgement. The graph is, however, still regarded as valid in relation to its use in estimating emission for engines in the situation which prevails today (pers. comm. Hans Otto Kristensen, DTU, 2006). The sfc figures for 2005 are used for engines built from 2006 onwards to provide the basis for the fuel consumption calculations for future years.

Engine type	Engine size (kW)	Engine type (estimated)	Fuel type (estimated)	Engine life time (years,estimated)
Gas turbine		Gas turbine	Diesel	30
2-stroke		Slow speed	HFO	30
4-stroke	<= 1000	High speed	Diesel	10
	1000-4000	Medium speed	Diesel	30
	>4000	Medium speed	HFO	30

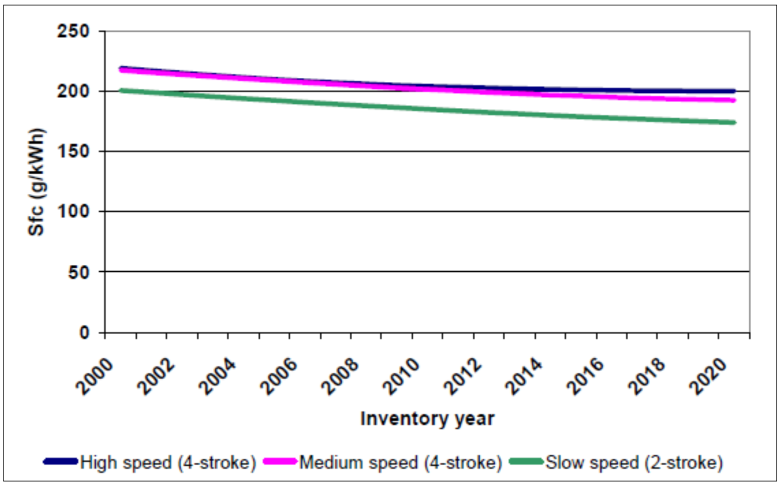
Table 22. Estimated main engine type and fuel type for ship engines in the present inventory (PU Ship Emissions and air pollution in Denmark)

Using the average engine life times, LT, listed in Table 8, the average sfc factors per inventory year, X, is calculated from:

$$sfc_{k,X} = \frac{\sum_{year=X}^{year=X-LT} sfc_{k,y}}{LT_k} \qquad (1)$$

Where sfc = specific fuel consumption (g/kWh), X = inventory year, k = engine type, y = engine production year, LT = engine life time.

The average sfc factors per inventory year are shown in *Graph 14* for the inventory years 2000-2020.



Graph 14. Average sfc factors for marine engines for the inventory years 2000-2020 (g/kWh)

- **NO_X emission factors**

As it has mentioned before, the Marpol Annex VI, as amended by IMO in October 2008, considers a three tiered approach as follows:

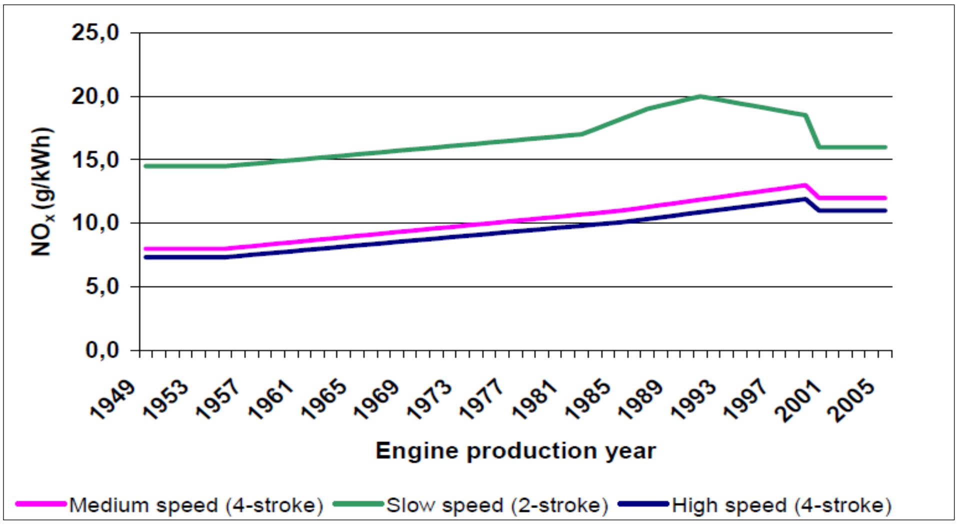
- Tier I: diesel engines (> 130 kW) installed on a ship constructed on or after 1 January 2000 and prior to 1 January 2011;
- Tier II: diesel engines (> 130 kW) installed on a ship constructed on or after 1 January 2011;
- Tier III (1): diesel engines (> 130 kW) installed on a ship constructed on or after 1 January 2016.

The NO_X emission limits for ship engines in relation to their rated engine speed (n) given in RPM (Revolutions Per Minute) are shown in Table 23.

Regulation	NO_X	Rated engine speed (rpm)
Tier I	17 g/kWh 45 × n-0.2 g/kWh 9,8 g/kWh	n < 130 130 ≤ n < 2000 n ≥ 2000
Tier II	14.4 g/kWh 44 × n-0.23 g/kWh 7.7 g/kWh	n < 130 130 ≤ n < 2000 n ≥ 2000
Tier III	3.4 g/kWh 9 × n-0.2 g/kWh 2 g/kWh	n < 130 130 ≤ n < 2000 n ≥ 2000

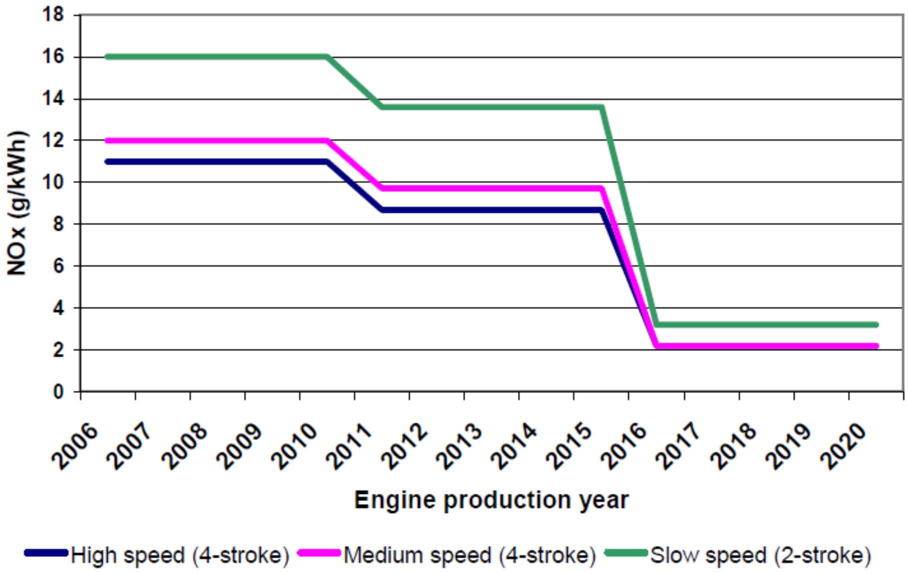
Table 23. Tier I-III NO_X emission limits for ship engines (amendments to Marpol Annex VI)

The NO_X emission factors (g/kWh) for slow- and medium-speed engines are obtained from MAN DIESEL (2006). However, for high speed engines the emission factor level is determined by Kristensen (2006).



Graph 15. NO_X emission factors for ship engines built before 2006 (g/kWh) (PU Ship Emissions and air pollution in Denmark)

The Tier III requirements for new ships built after 2016 will apply in designated *NOX Emission Control Areas* (NECA). It is assumed that the AIS inventory area is appointed a NECA. Thus, for newer engines in compliance with Tier II (2011) and Tier III (2016) emission standards, emission factors are estimated by adjusting the Tier I emission factors (2000-2005) in two steps, relative to the Tier II: Tier I and Tier III: Tier I ratios. The estimated emission factors for the engine production years 2006-2020 are shown in Graph 16.



Graph 16. NO_X emission factors for ship engines built from 2006 onwards (g/kWh) (PU Ship Emissions and air pollution in Denmark)

- **SO_2**

Fuel sulphur content of 1.5% is used for heavy fuel oil in 2007. In 2011 and 2016 the sulphur content gradually become lower, as prescribed by the IMO fuel standards.
In order to obtain emission factors in g/kWh, the sulphur percentages depending on the fuel type are inserted in the following expression:

$$EF(SO_2) = \frac{2 \cdot S\% \cdot sfc}{100} \qquad (2)$$

Where EF = emission factor in g/kWh, S% = sulphur percentage, and sfc = specific fuel consumption in g/kWh. The sfc factor is taken from equation 1.
Equation 1 uses 2.0 kg SO_2/kg S, the chemical relation between burned sulphur and generated SO_2 provided in EMEP/CORINAIR (2007).

- **PM**

For diesel fuelled ship engines the emission of particle depends on the fuel sulphur content, S%. The emission factors in g/kg fuel are calculated as:

$$EF_{PM}(g/kgfuel) = 0.854 \cdot e^{(S\% \cdot 0.745)} \quad (3)$$

The PM emission factor equation is experimentally derived from measurements made by Lloyd's (1995). taken from TEMA2000 (Trafikministeriet, 2000).
Subsequently, the PM emission factor in g/kWh is found from:

$$EF_{PM}(g/kWh) = \frac{EF_{PM}(g/kgfuel) \cdot sfc}{1000} \quad (4)$$

Based on information from MAN DIESEL (N. Kjemtrup, 2006), the PM_{10} and $PM2_{.5}$ shares of total PM (=TSP) are 99 and 98.5%, respectively.

- **CO_2**

For CO_2, the emission factors in g/kWh are calculated as:

$$EF_{CO_2}(g/kWh) = \frac{LHV \cdot EF_{CO_2}(g/MJ) \cdot sfc}{1000} \quad (5)$$

The CO_2 emission factors (g/MJ) are country specific (heavy fuel: 78 g/MJ; gas oil: 74 g/MJ) and come from the Danish Energy Authority (DEA). LHV = Lower heating value in MJ/kg (heavy fuel: 40.9; diesel: 42.7).

- **Calculation procedure**

For each ship, the fuel consumption and emissions are found by summarizing the product of engine load (%MCR), main engine size (kW), AIS signal time interval (s), and fuel consumption/emission factor (g/kWh):

$$E(X) = \sum_i \%MCR \cdot P_{ME} \cdot EF_{k,l,X} \cdot \Delta t_i / 3600 \quad (6)$$

Where E = fuel consumption/emissions (g), %MCR = engine load (%), Δt = sailing time between AIS signal (s), PME = main engine size (kW), EF = fuel consumption/emission factor in g/kWh, i = AIS signal interval, k = fuel type, l = engine type, X = calculation year.

The fuel consumption factor inserted in (6) is taken from (1), and the emission factors are taken from (2), (3) (4) and (5), for NO_X, SO_2, particulates and CO_2.

8.2.2 *Specific Emissions Calculation*

As has been seen above, in this model the factors depend on year and consequently also on specific fuel consumption. Therefore it has done the average year from Danube fleet and Austrian fleet for each vessel type.

Vessel type	Danube fleet (years)	Austrian fleet (years)
Dry cargo self-propelled	25	25
Liquid cargo self-propelled (tankers)	28	43
River tugs	35	35
River pusher-tugs	27	n.a.
River pushboats	25	36

Table 24. Average of the years from the Danube fleet and Austrian fleet (PINE)

Thus, the specific emissions according to this model are:

- **NO_X**

	NO_X		
	NO_X [kg/tonne fuel]	EF [g_{fuel}/kWh]	NO_X [g/kWh]
Dry cargo self-propelled	36	250	9
Liquid cargo self-propelled (tankers)	34	250	8,5
River tugs	31	255	8
River pusher-tugs	40	240	9,5
River pushboats	57	230	13

Table 25. NO_X emission factors corresponding to the Danube fleet

This process is the reverse of Guidebook model since here, NO_X [g/kWh] is found first through the graph 13 and 14 and then NO_X [kg/tonne fuel] is found as result of:

$$NO_X \text{ [kg/tonne fuel]} = NO_X \text{ [g/kWh]} * EF \text{ [}g_{fuel}\text{/kWh]}$$

- **SO_2**

	SO_2			
	%S	SO_2 [kg/tonne fuel]	EF [g_{fuel}/kWh]	SO_2 [g/kWh]
Dry cargo self-propelled	0,5	10	250	3
Liquid cargo self-propelled (tankers)	0,5	10	250	3
River tugs	0,5	10	255	3
River pusher-tugs	0,5	10	240	2
River pushboats	0,5	10	230	2

Table 26. SO_2 emission factors corresponding to the Danube fleet
S = percentage sulphur content in fuel; pre-2000 fuels: 0.5 % wt. [source: Lloyd's Register, 1995]

As has been seen before in the method:

$$EF(SO_2) = \frac{2 \cdot S\% \cdot sfc}{100}$$

- **PM**

	PM		
	PM [kg/tonne fuel]	EF [g_{fuel}/kWh]	PM [g/kWh]
Dry cargo self-propelled	1,2	250	0,31
Liquid cargo self-propelled (tankers)	1,2	250	0,31
River tugs	1,2	255	0,32
River pusher-tugs	1,2	240	0,30
River pushboats	1,2	230	0,29

Table 27. PM emission factors corresponding to the Danube fleet

PM [g/kWh] found from:

$$EF_{PM}(g/kgfuel) = 0.854 \cdot e^{(S\% \cdot 0.745)}$$

$$EF_{PM}(g/kWh) = \frac{EF_{PM}(g/kgfuel) \cdot sfc}{1000}$$

Or such is the same:

$$EF_{PM} = \frac{0{,}854 * e^{(S\% * 0{,}745)} * sfc}{1000}$$

Considering %S = 0,5 and sfc = EF [g_{fuel}/kWh]

- **CO_2**

	CO2		
	CO_2 [kg/tonne fuel]	EF [g_{fuel}/kWh]	CO_2 [g/kWh]
Dry cargo self-propelled	3160	250	790
Liquid cargo self-propelled (tankers)	3160	250	790
River tugs	3160	255	806
River pusher-tugs	3160	240	758
River pushboats	3160	230	727

Table 16. PM emission factors corresponding to the Danube fleet

The calculation is the same as in Guidebook but as EF [g_{fuel}/kWh] is different the results are different.

$$EF_{co_2}(g/kWh) = \frac{LHV \cdot EF_{co_2}(g/MJ) \cdot sfc}{1000}$$

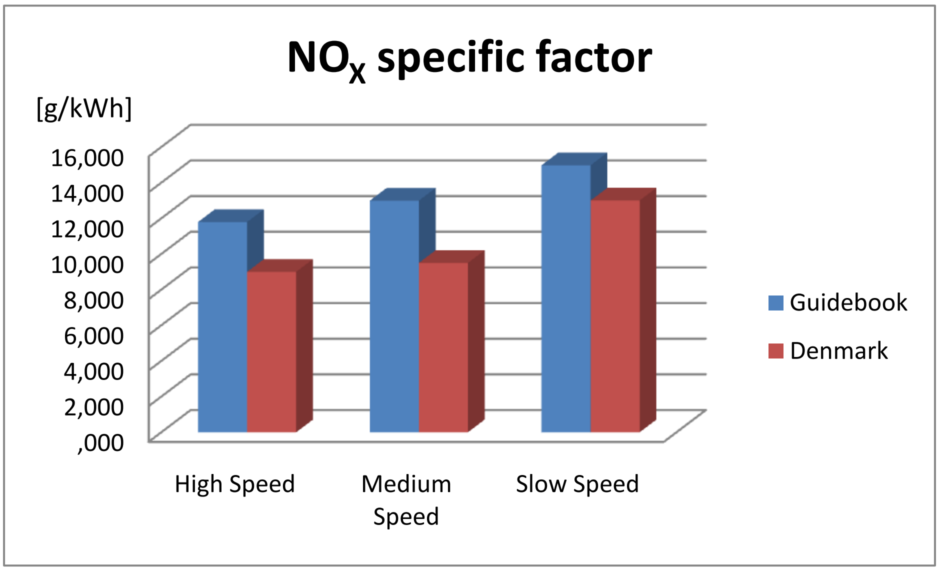
Considering:

LHV Diesel [MJ/kg]	42,7
EFCO2 [g/MJ]	74

8.3 Comparison of Guidebook-Denmark through Graphs

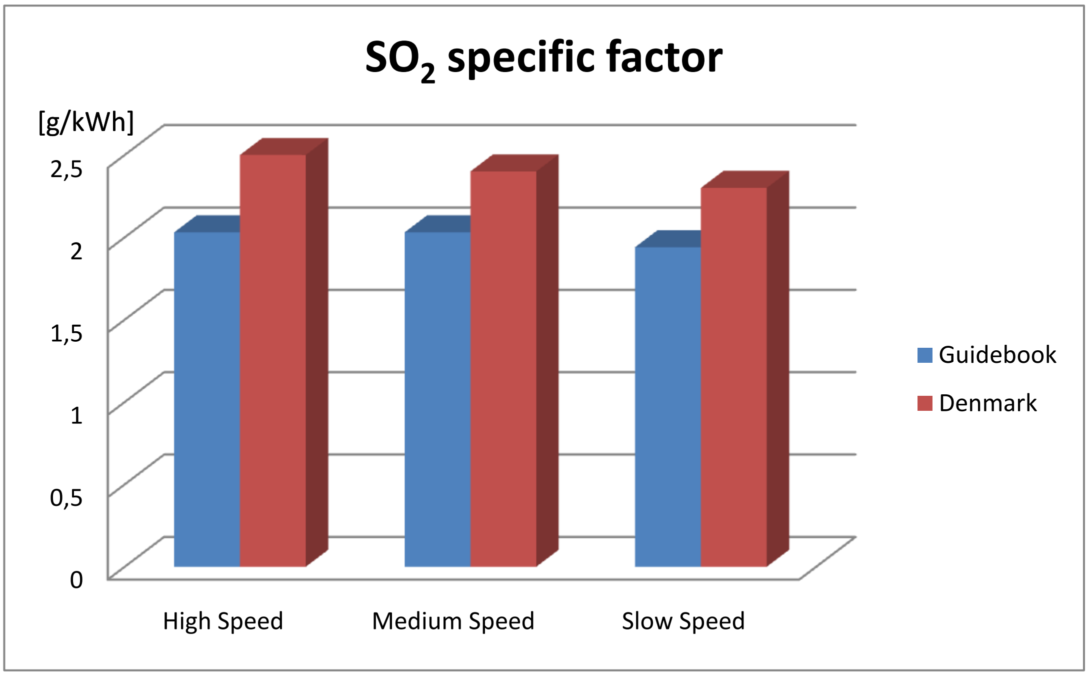
The following graphs show the differences of each specific factor between each model.

- **NO_X**



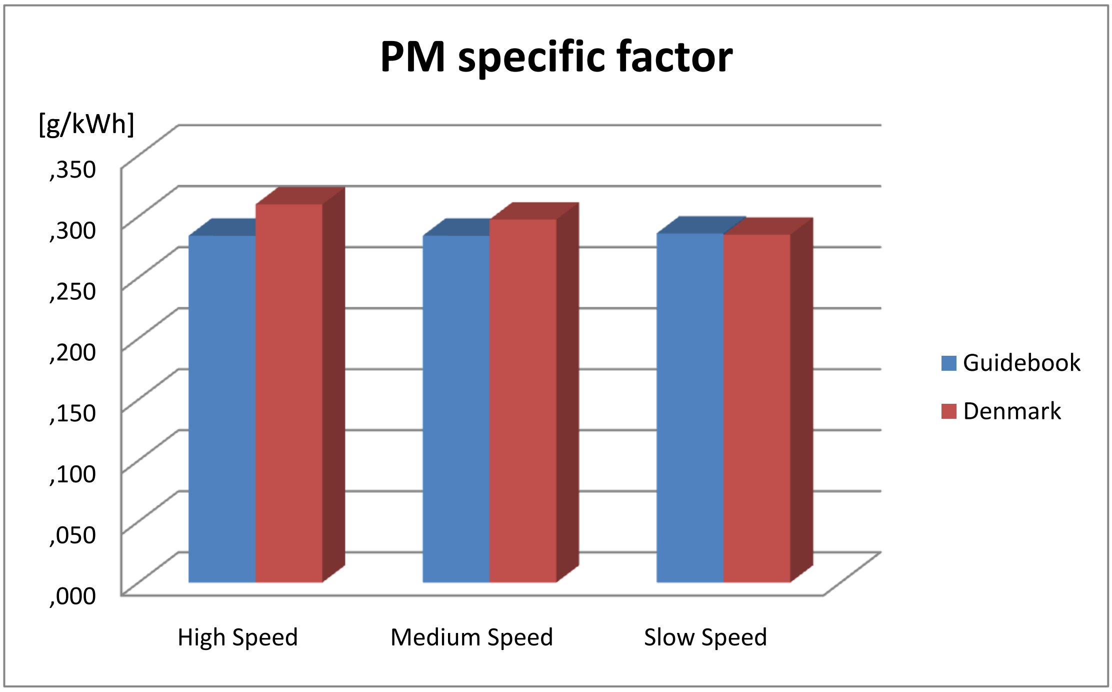
- **Graph 17**. NO_X [g/kWh] comparison depending on model

- **SO_2**



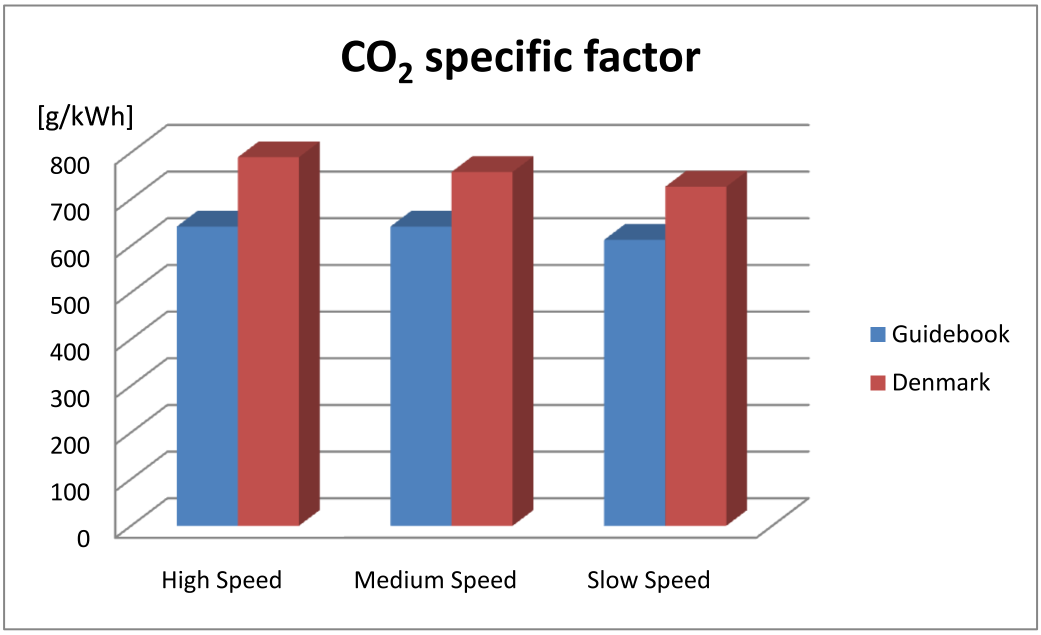
Graph 18. SO_2 [g/kWh] comparison depending on model

- **PM**



Graph 19. PM [g/kWh] comparison depending on model

- **CO_2**



Graph 20. CO_2 [g/kWh] comparison depending on model

As it can be seen, the CO_2 specific factor is the most variable since the SFC fuel of Denmark model is so high because of ship age.

9 Exhaust Emission Scenarios According to the Propulsion Technology

9.1 Current Situation- Diesel engines

First of all, a large amount of data has been gathered through Statistik Austria in an Excel-file. Secondly, data processing has been done in order to get useful data to calculate the fuel consumption and exhaust emissions.

Some changes have been done to the data table of Statistik Austria in order to have the same ship types as Via Donau.

Statistik Austria	Via Donau
Motorgüterschiff	Self-propelled barge
Schubverband = Schubleichter + Güterkahn	Barge not self-propelled
Motortankschiff	Self-propelled tanker barge
Tankschiffe = Tankschubleichter + Tankkahn	Tanker barge not self-propelled

Table 29. Relation of ship types

Besides, as the barge not self-propelled (Schubverband) can ship from 1 to 4 barges and consequently the power varies (it is not the same to carry 1 barge as 4 barges), the barge not self-propelled has been divided into two groups depending on if it carries 2 barges or 4 barges and the percentages are 88% and 12% respectively (*Statistik Austria*). Therefore each one is associated with a different power.

In regards to power, there are two models: one for engines of 1300 kW and another for engines of 2000 kW. Moreover, the path must also be taken into account since the power is different in each direction. Therefore, a cross section of the Danube has also been studied:

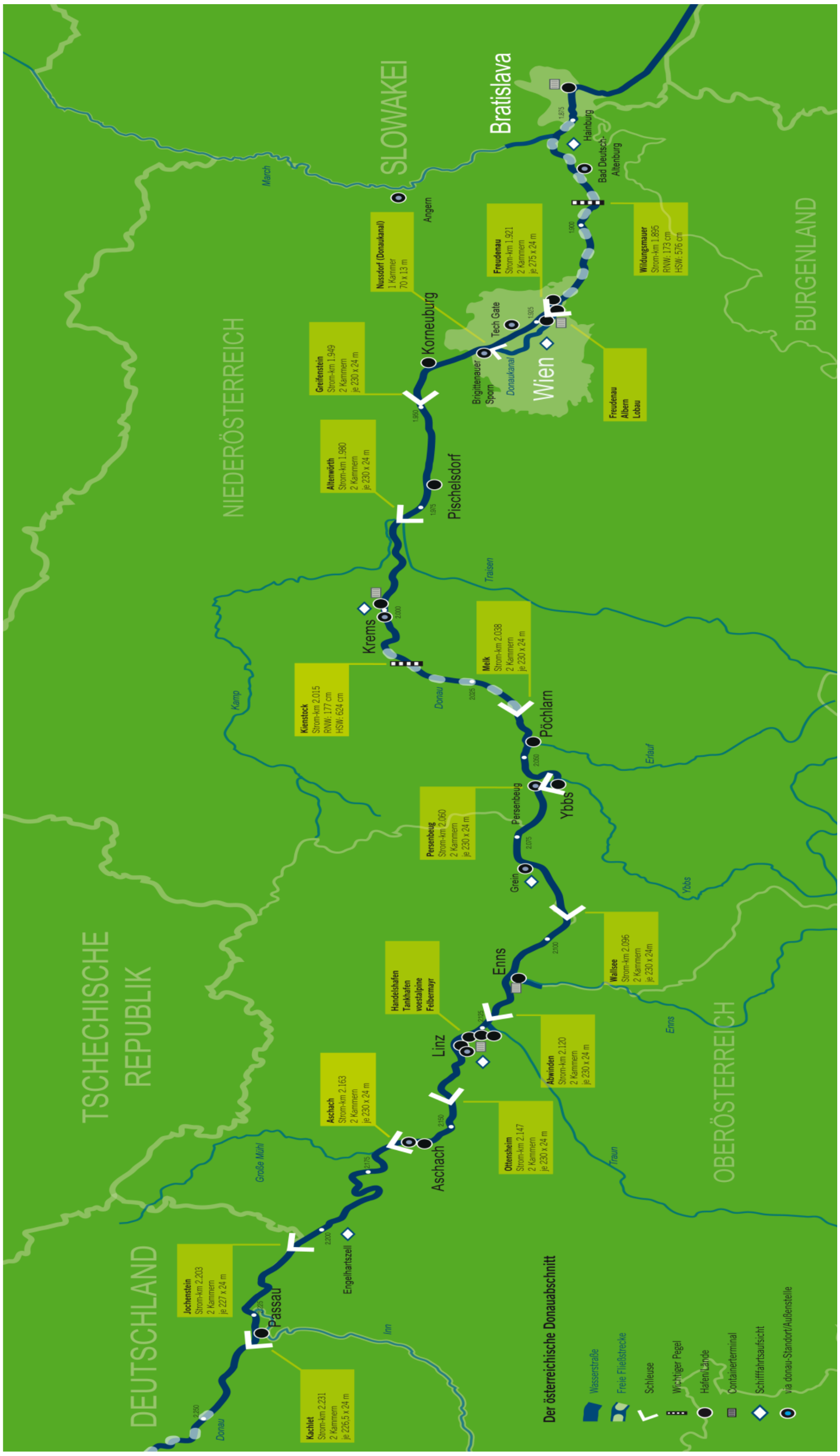


Figure 34. Cross section of Austrian Danube (Via Donau)

In total, there will be 4 powers and 4 velocities: depending on the engine power and the path. Note: the following data shows the average of the entire Austrian Danube.

Motor Class	Direction on the Danube	Velocity [km/h]	Power Requirement [kW]
1300 kW	**Up**	12,1	1133
	Down	18,5	950
2000 kW	**Up**	8,2	1700
	Down	17,4	1580

Table 30. Data depending on engine type in order to calculate the fuel consumption (Via Donau)

The data for each stretch can be found in the Annex 11.1.

In regard to cargo capacity, on the one hand each barge can carry up to 1717 tonnes. On the other hand, the cargo percent transported for each direction has to be calculated. This calculation has been done in the following way:

Year	Up % Cargo	Down % Cargo
2009	63	52,6
2008	63,7	55,3
2007	67,2	58
2006	65,6	56,9
Average	**64,9**	**55,7**

Table 31. % Cargo depending on direction and year (Statistik Austria)

Thus, the capacities and powers of each ship type are:

Ship type	Power [kW]	Capacity [t]
Motorgüterschiff + 1 Leichter = Self-propelled barge	1300	3434
Schubverband + 2 Leichter = Barge not self-propelled + 2	1300	3434
Schubverband + 4 Leichter = Barge not self-propelled + 4	2000	6868

Motortankschiff = Self-propelled tanker barge	1300	3434
Tankschiffe = Tanker barge not self-propelled	1300	3434

Table 32. Power and Capacity of each ship type

The model which has been followed is the next one:

	Ship type (Statistik Austria)		
	Ship type (Via Donau)		
Donau Model	1300/2000 kW		
	spc [g/kWh]		215
	Power up [kW]		1133/1700
	Speed Up [km/h]		12,1/8,2
	% MCR Up		64,9
	Power down [kW]		950/1580
	Speed Down [km/h]		18,5/17,4
	Capacity [t]		3434/6868
	% MCR Down		55,7
	UP [1000 tkm]	DOWN [1000 tkm]	E [tonnes/year]
Year	**X**	**Y**	**E**

Table 33. Model to calculate the fuel consumption

The X and Y values have been extracted from Statistik Austria depending on the year, the ship type and the direction (Annex 11.2.1).

The following calculation shows how to calculate the fuel consumption:

$$E = E_{Up} + E_{Down}$$

$$E_{Up} = \frac{1000 * X * Power_{Up} * spc}{Speed_{Up} * \%MCR_{Up} * Capacity * 1000000}$$

$$t/y = \frac{1000\ tkm/y * kW * g/kWh}{\frac{km}{h} * - * t * 1000000\ g/t}$$

and the same for Down:

$$E_{Down} = \frac{1000 * X * Power_{Down} * spc}{Speed_{Down} * \%MCR_{Down} * Capacity * 1000000}$$

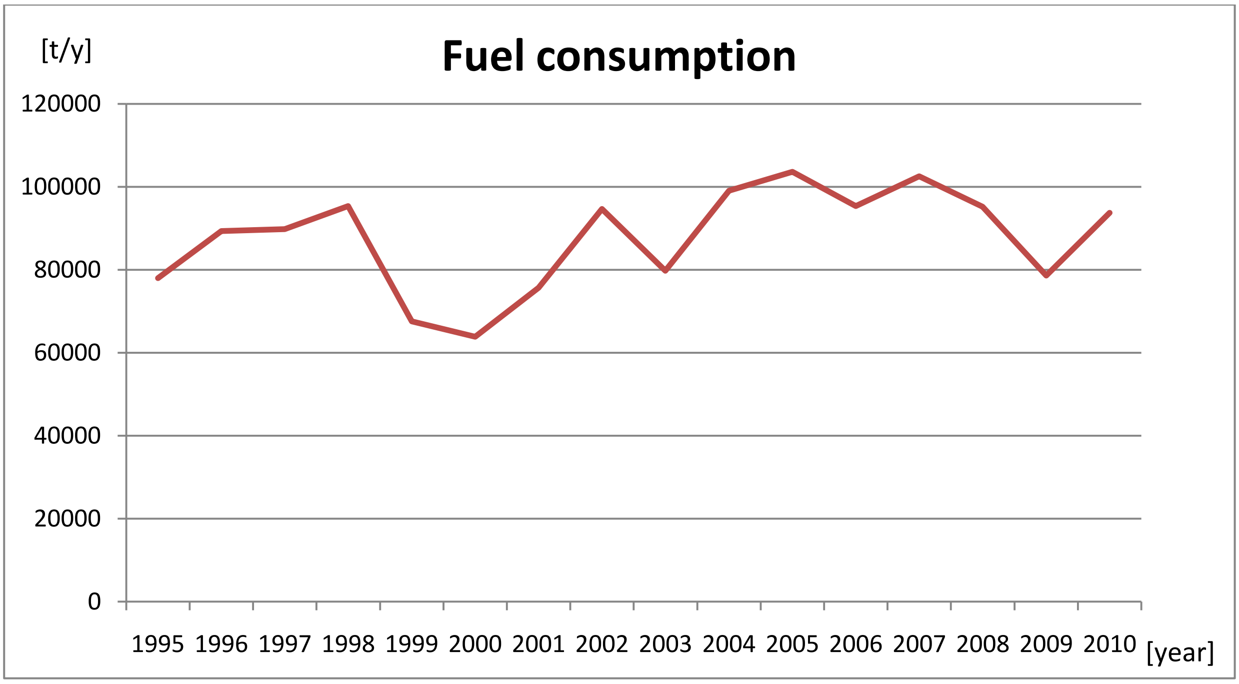
The following table shows the fuel consumption for each year:

Year	BAR_SP	BAR_NSP+2	BAR_NSP+4	BAR_TK_SP	BAR_TK_NSP	Total [t/y]
	E [t/year]	E [t/year]	E [t/year]	E [t/year]	E [t/year]	
1995	27633	39024	5794	3468	2059	**77979**
2000	31010	22850	3278	4363	2367	**63868**
2005	45526	43587	6390	4673	3435	**103611**
2010	44906	38598	5727	1652	2838	**93721**

Table 34. Total fuel consumption

In Annex 11.2.1 more detailed data can be found.

The graph below shows the fuel consumption evolution:



Graph 21. Fuel consumption evolution over the years

Therefore, the exhaust emissions can be calculated through the fuel consumption:

- **NO_X**

	NO_X					
	B_SP	B_NSP+2	B_NSP+4	T_SP	T_NSP	
NO_X [kg/t fuel]	58,1	58,1	65	58,1	58,1	
	E NO_X [t/y]	E NO_X [t/y]	E NO_X [t/y]	E NO_X [t/y]	E NO_X [t/y]	**Total [t/y]**
1995	1.605	2.267	336,7	201,5	119,6	**4530,6**
2000	1.802	1.328	190,5	253,5	137,5	**3710,7**
2005	2.645	2.532	371,3	271,5	199,6	**6019,8**
2010	2.609	2.243	332,8	96,0	164,9	**5445,2**

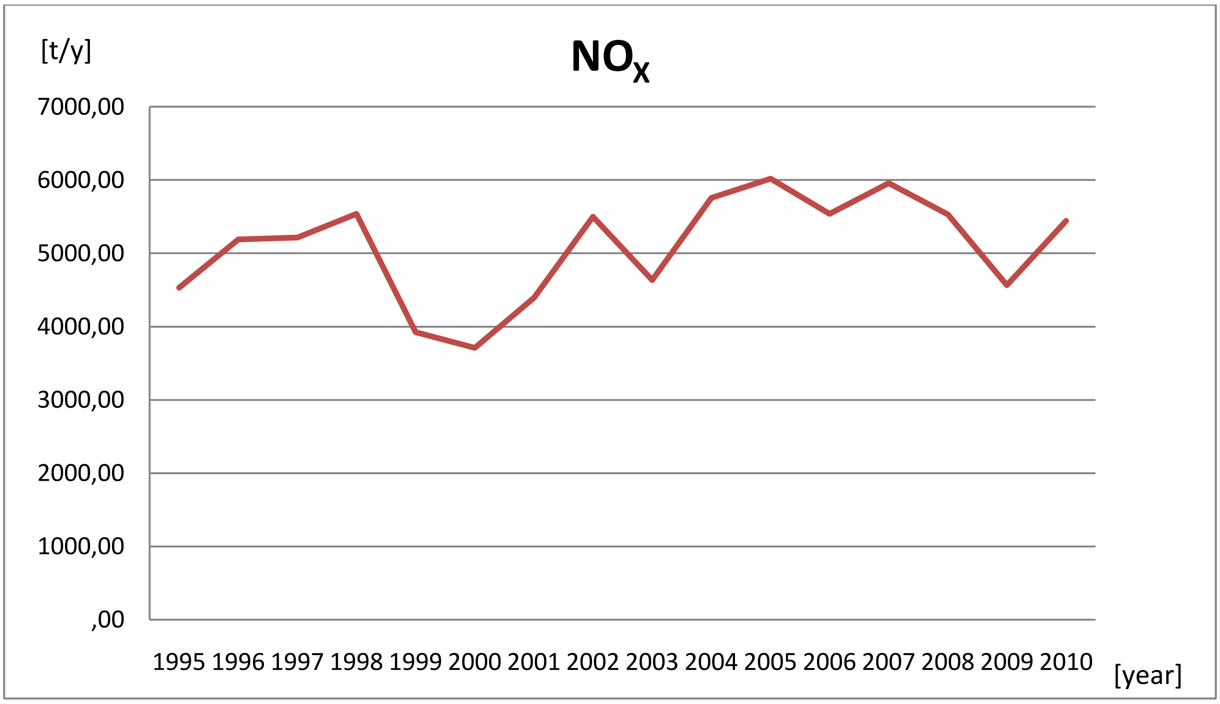
Table 17. NO_X Exhaust Emissions per year

In Annex 11.2.2 data from the rest of the years can be found.

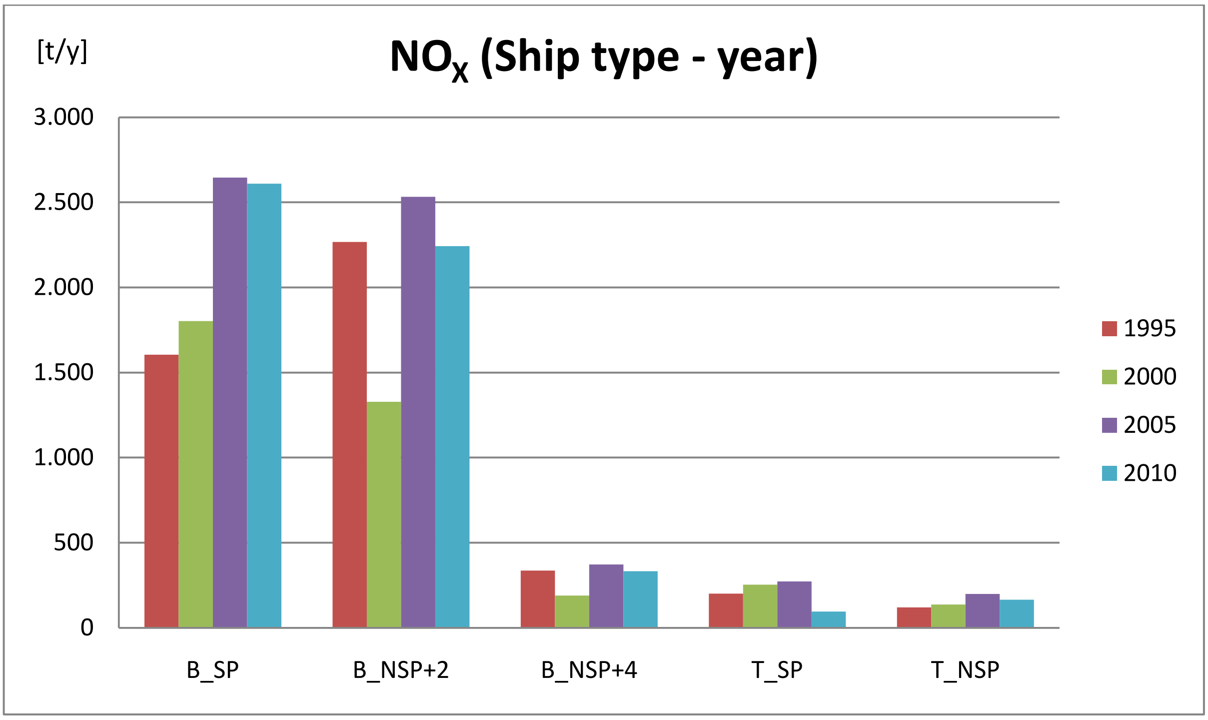
$$E_{NOx}\ \left[{}^{t\,NOx}/_{y}\right] = NOx \left[{}^{kg\,NOx}/_{t\,fuel}\right] * E \left[{}^{t\,fuel}/_{y}\right] / 1000$$

The following graphs show the evolution of NO_X exhaust emissions over the years and the NO_X exhaust emissions depending on the ship type in different years.

As can be seen in *Graph 22 below*, the NO_X curve is the same as the fuel consumption curve but logically with different values. The same will occur with the others pollutants.



Graph 22. NO_X exhaust emissions over the years



Graph 23. NO_X exhaust emissions depending on the ship type in different years

In *graph 23*, a significant growth of NO_X emissions of barge self-propelled can be seen during recent years as well as a growth in NO_X emissions of barge non self-propelled + 2 barges. On the other hand, the growth of the other ship types remains more or less stable.

- **SO_2**

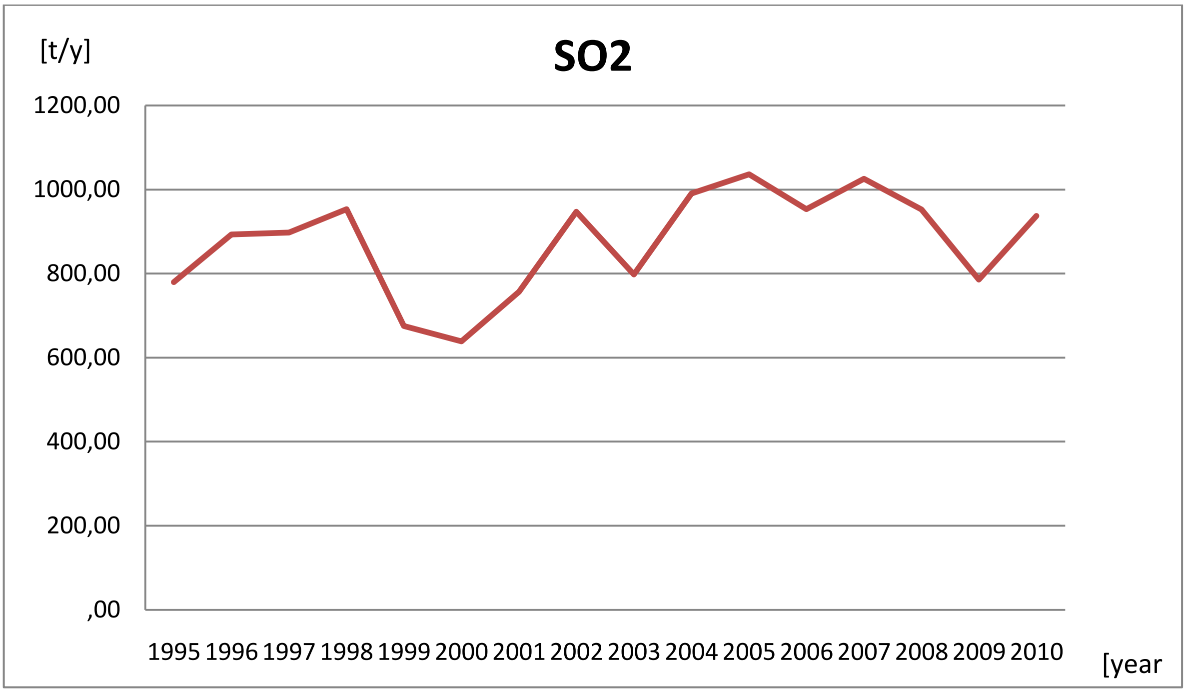
	SO2					
	B_SP	B_NSP+2	B_NSP+4	T_SP	T_NSP	
SO2 [kg/t fuel]	10	10	10	10	10	
	E SO_2 [t/y]	E SO_2 [t/y]	E SO_2 [t/y]	E SO_2 [t/y]	E SO_2 [t/y]	**Total [t/y]**
1995	276,3	390,2	57,9	34,7	20,6	**779,8**
2000	310,1	228,5	32,8	43,6	23,7	**638,7**
2005	455,3	435,9	63,9	46,7	34,4	**1036,1**
2010	449,1	386,0	57,3	16,5	28,4	**937,2**

Table 36. SO_2 Exhaust Emissions per year

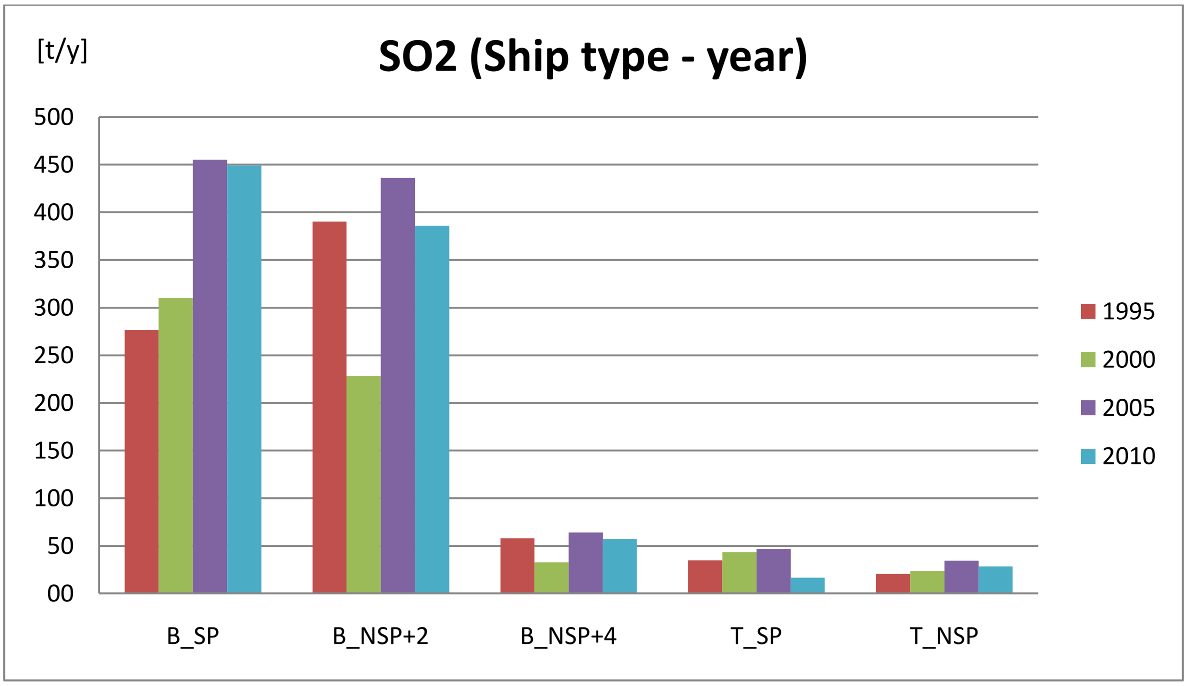
In Annex 11.2.2 data from the rest of the years can be found.

$$E_{SO2}\ [{}^{t\ SO2}/_{y}] = SO2\left[{}^{kg\ SO2}/_{t\ fuel}\right] * E\left[{}^{t\ fuel}/_{y}\right] / 1000$$

The following graphs show the evolution of SO_2 exhaust emissions over the years and the SO_2 exhaust emissions depending on both ship type and year.



Graph 24. SO_2 exhaust emissions over the years



Graph 25. SO_2 exhaust emissions depending on the ship type in different years

The same occurs in SO_2. Barge self-propelled and Barge non self-propelled + 2 barges are major contributors to pollution.

- **PM**

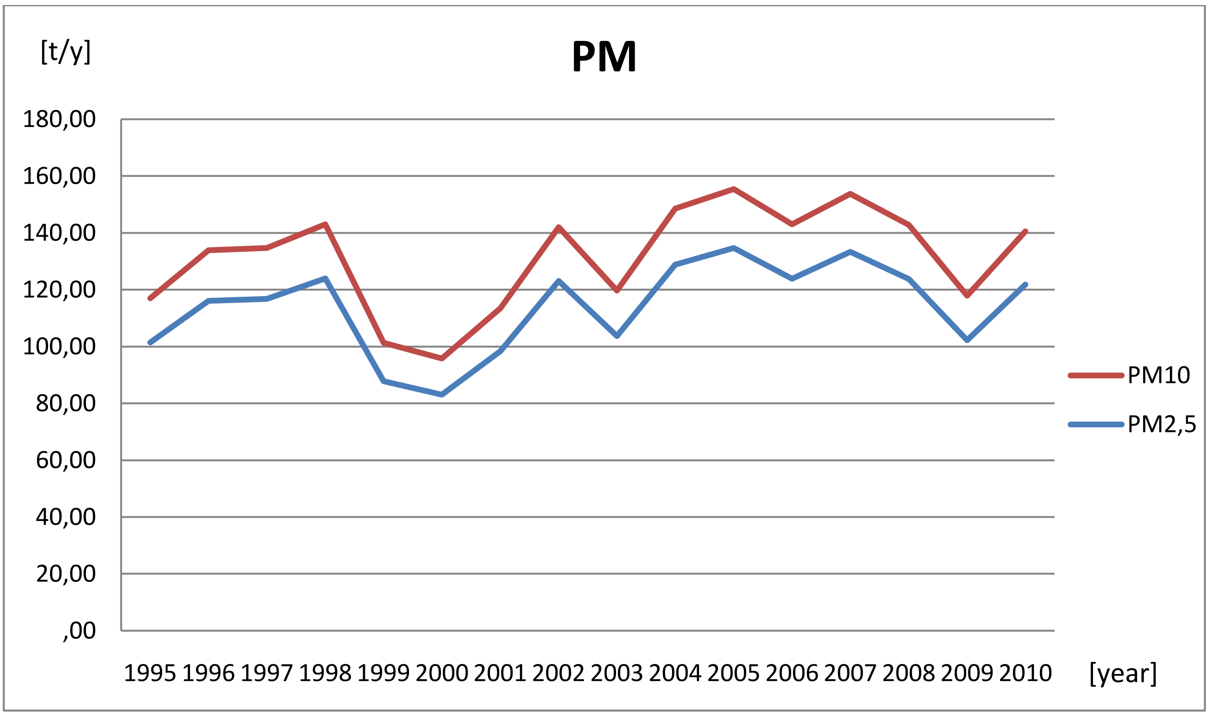
	PM											
	B_SP		B_NSP+2		B_NSP+4		T_SP		T_NSP			
PM [kg/t fuel]	PM_{10}	$PM_{2,5}$	PM_{10}	$PM_{2,5}$	PM_{10}	$PM_{2,5}$	PM_{10}	$PM_{2,5}$	PM_{10}	$PM_{2,5}$		
	1,5	1,3	1,5	1,3	1,5	1,3	1,5	1,3	1,5	1,3		
	E PM_{10} [t/y]	E $PM_{2,5}$ [t/y]	E PM_{10} [t/y]	E $PM_{2,5}$ [t/y]	E PM_{10} [t/y]	E $PM_{2,5}$ [t/y]	E PM_{10} [t/y]	E $PM_{2,5}$ [t/y]	E PM_{10} [t/y]	E $PM_{2,5}$ [t/y]	**Total PM_{10}**	**Total $PM_{2,5}$**
1995	41,45	35,92	58,54	50,73	8,69	7,53	5,20	4,51	3,09	2,68	**117,0**	**101,4**
2000	46,51	40,31	34,27	29,70	4,92	4,26	6,54	5,67	3,55	3,08	**95,8**	**83,0**
2005	68,29	59,18	65,38	56,66	9,59	8,31	7,01	6,07	5,15	4,47	**155,4**	**134,7**
2010	67,36	58,38	57,90	50,18	8,59	7,45	2,48	2,15	4,26	3,69	**140,6**	**121,8**

Table 37. PM Exhaust Emissions per year

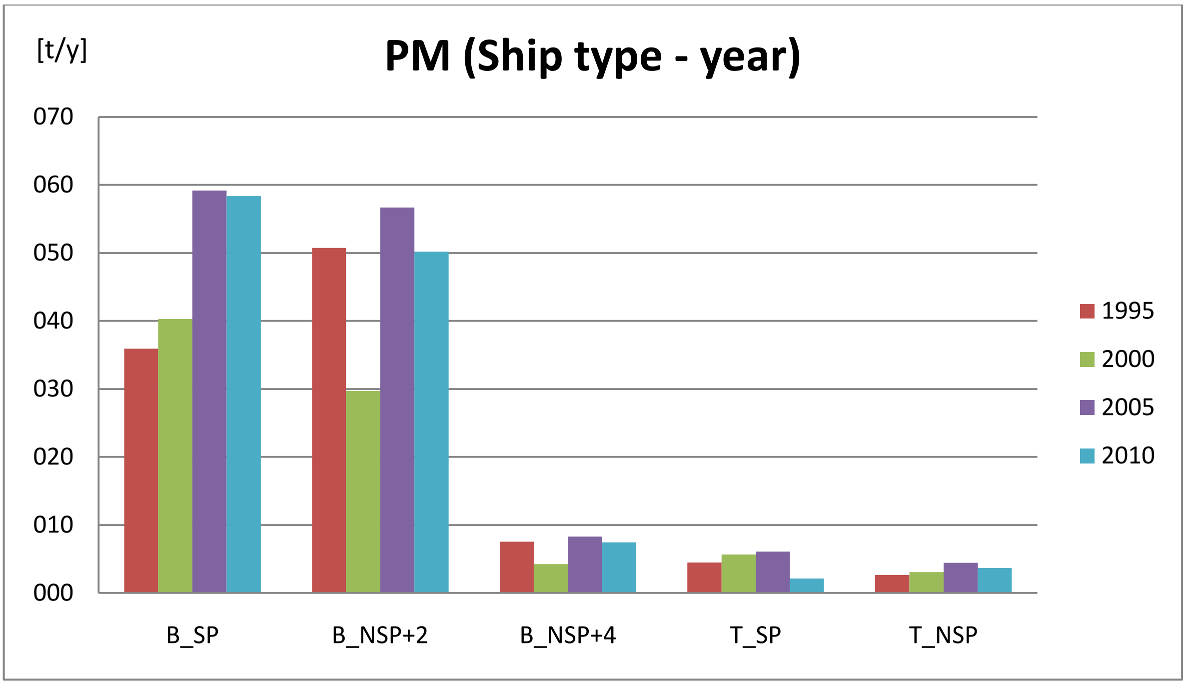
In Annex 11.2.2 data from the rest of the years can be found.

$$E_{PM}\ [{}^{t\,PM}/_{y}] = PM\left[{}^{kg\,PM}/_{t\,fuel}\right] * E\left[{}^{t\,fuel}/_{y}\right] / 1000$$

The following graphs show the evolution of PM exhaust emissions over the years and the PM exhaust emissions depending on both ship type and year.



Graph 26. PM exhaust emissions over the years



Graph 27. $PM_{2,5}$ exhaust emissions depending on the ship type in different years

The graph of PM is very similar to the previous graphs, but the values are the lowest. In 2000, the emissions from barge non self-propelled + 2 barges were lower than in any other year.

- **CO_2**

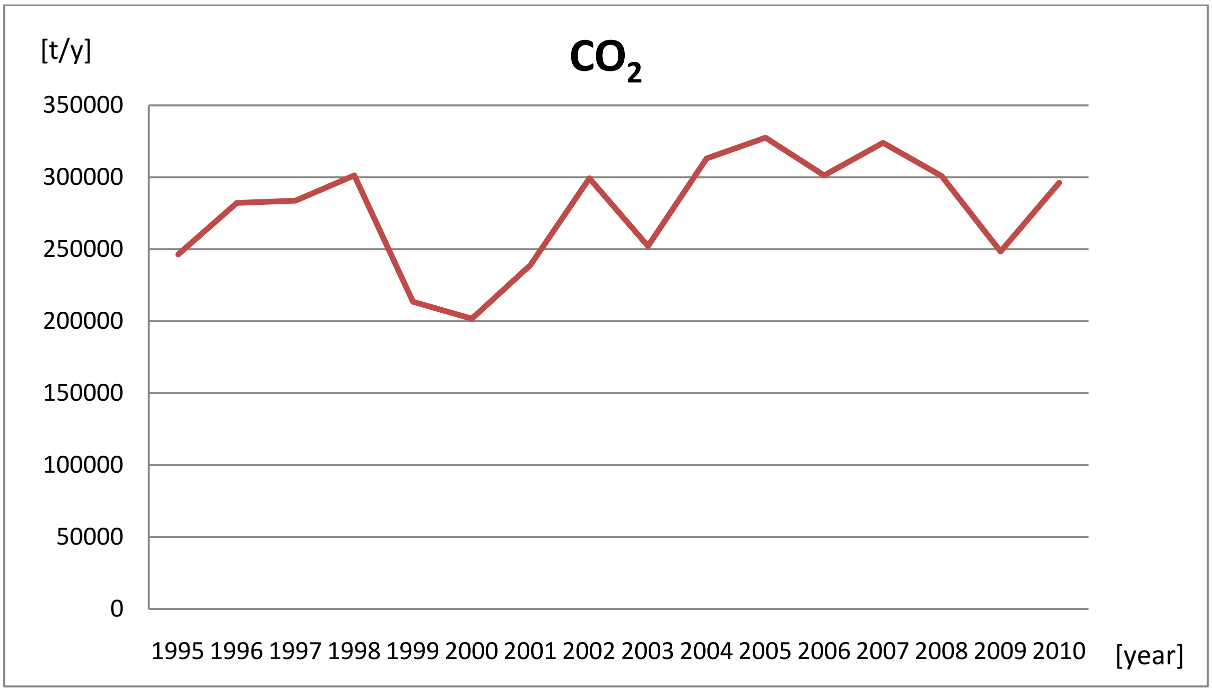
	CO_2					
	B_SP	B_NSP+2	B_NSP+4	T_SP	T_NSP	
CO_2 [kg/t fuel]	3160	3160	3160	3160	3160	
	E CO_2 [t/y]	E CO_2 [t/y]	E CO_2 [t/y]	E CO_2 [t/y]	E CO_2 [t/y]	**Total [t/y]**
1995	87.321	123.317	18.311	10958	6507	**246413**
2000	97.991	72.205	10.359	13788	7480	**201822**
2005	143.861	137.734	20.193	14765	10856	**327410**
2010	141.902	121.971	18.099	5220	8968	**296160**

Table 18. CO_2 Exhaust Emissions per year

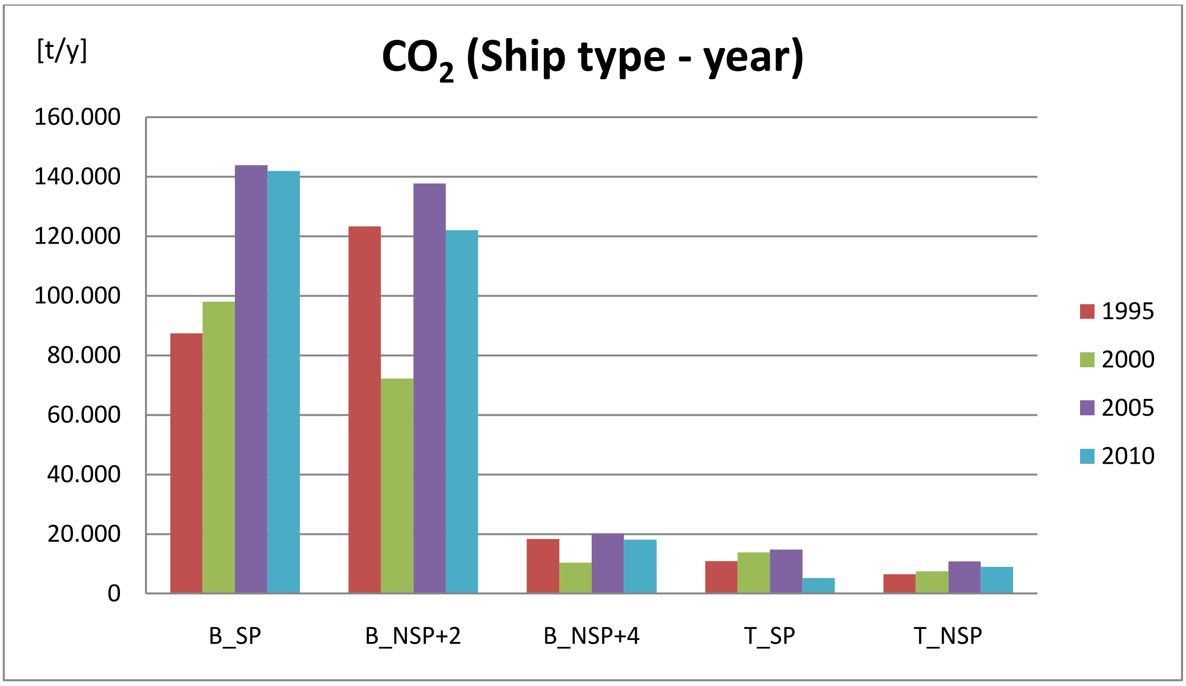
In Annex 11.2.2 data from the rest of the years can be found.

$$E_{CO2}\ [{}^{t\ CO2}/_{y}] = CO2\left[{}^{kg\ CO2}/_{t\ fuel}\right] * E\left[{}^{t\ fuel}/_{y}\right] / 1000$$

The following graphs show the evolution of CO_2 exhaust emissions over the years and the CO_2 exhaust emissions depending on both ship type and year.



Graph 28. CO_2 exhaust emissions over the years

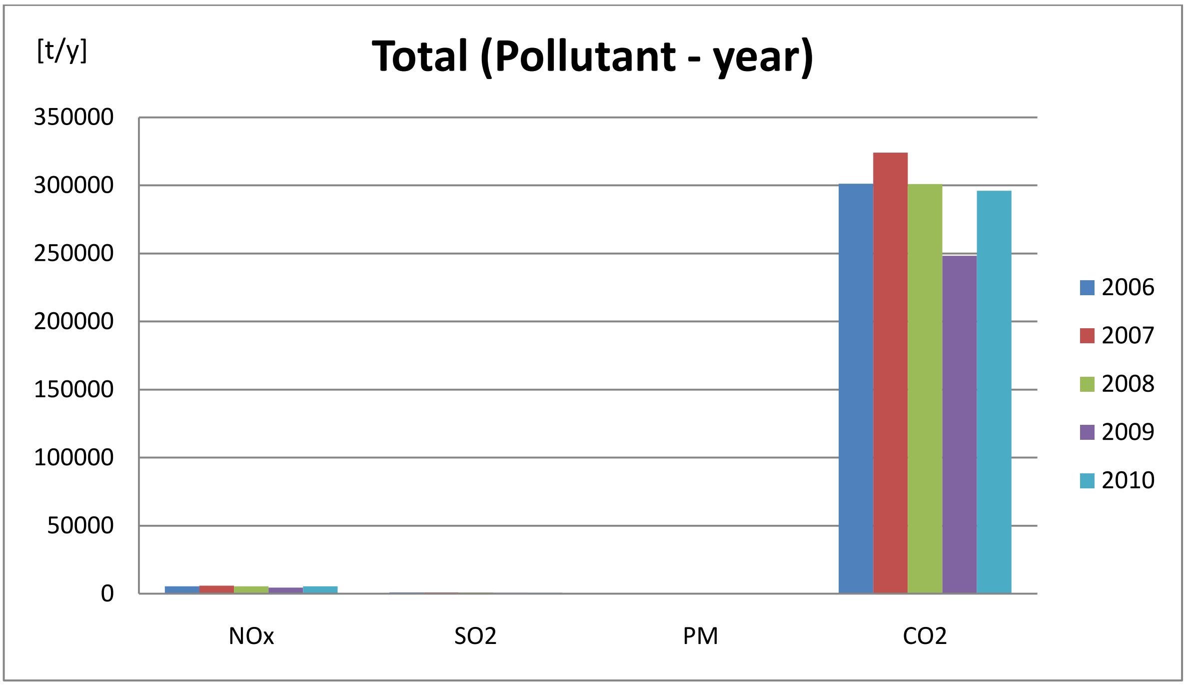


Graph 29. CO_2 exhaust emissions depending on the ship type in different years

In this event, CO_2 emissions are so high above all emissions of barge self-propelled during recent years. Although CO_2 emissions are the highest only represent less than 1% of the total CO_2 emissions of Austria (land transport, industry, air transport…).

Further within this text, an explanation of how dual-fuel engines will attempt to reduce CO_2 emissions will be provided.

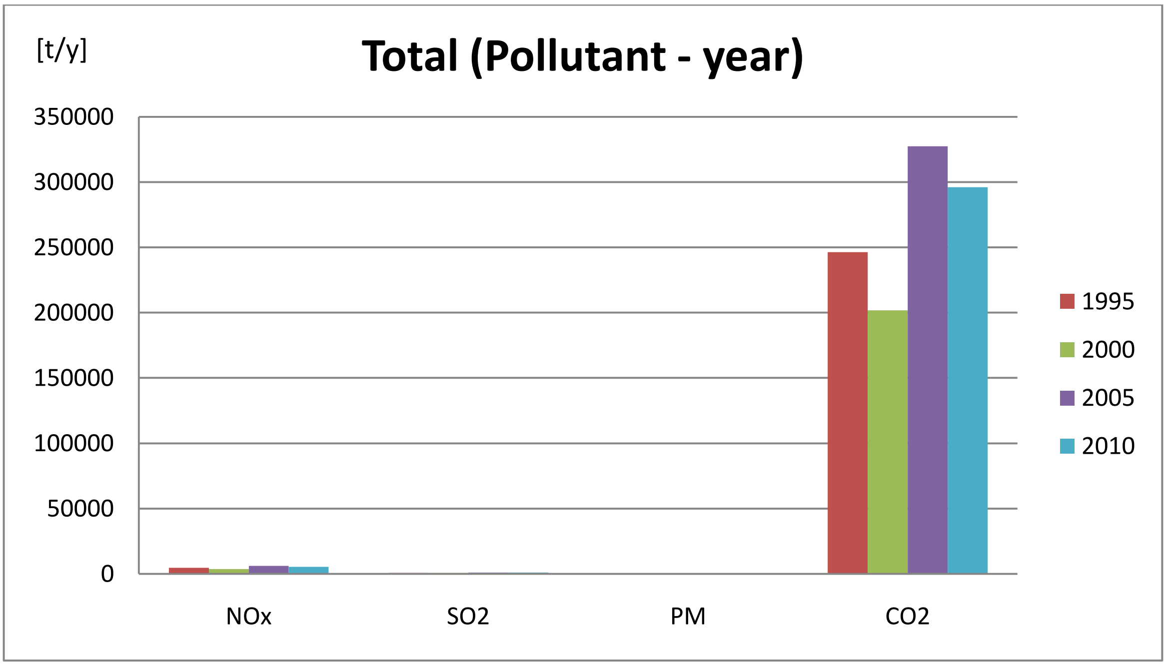
The following graph attempts to clarify and compare the magnitude of each pollutant in recent years:



Graph 30. Exhaust emissions of each pollutant in recent years

As can be seen in *Graph 30*, the CO_2 emissions had an important reduction due probably to crisis.

The graph below shows the evolution of exhaust emissions in different years.



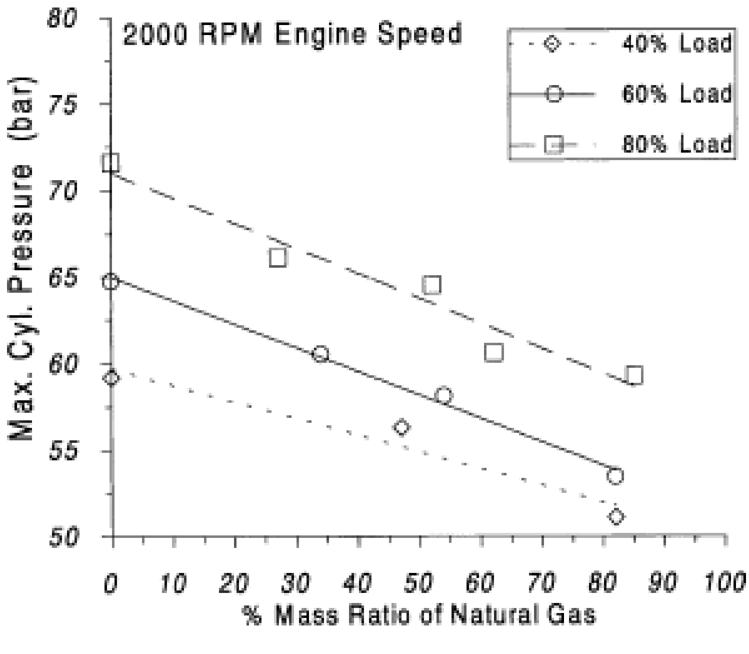
Graph 31. Emissions of each pollutant in different years

From 2000 to 2010, CO_2 emissions have grown almost 100.000 tonnes. Indeed, from 2000 to 2005 the growth of CO_2 was more than 120.000 tonnes. CO_2 emissions are 2500 times higher than PM.

9.2 Scenario – Dual-fuel engines

Below, an analysis of exhaust emissions from dual-fuel engines in order to reduce mainly CO_2 emissions will be done.

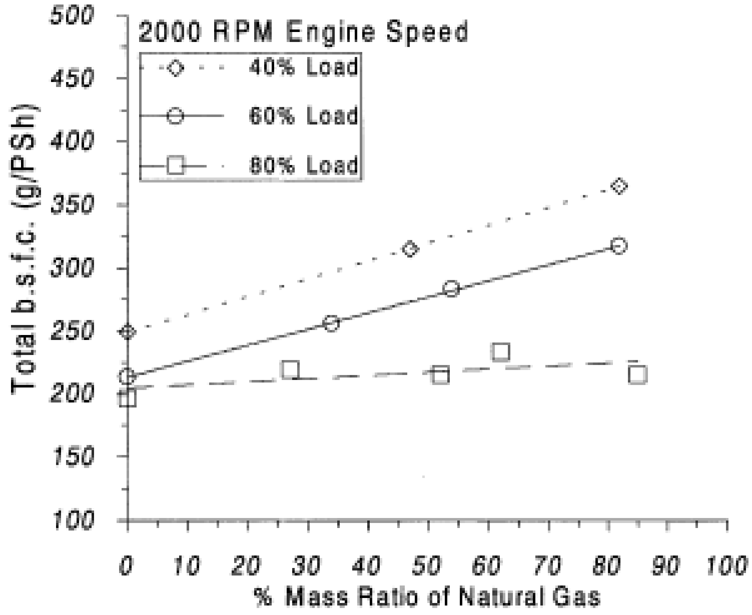
First of all, natural gas and diesel have been treated separately. LHV and b_e (specific fuel consumption) of each one have been found in order to calculate subsequently the global LHV and b_e of dual-fuel. Utilizing global LHV and sfc, the global efficiency can be calculated. A thermodynamic phenomenon occurs in dual-fuel engines; the specific fuel consumption varies due to some temperature and pressure changes. The graph below shows the variation of peak cylinder pressure versus natural gas mass ratio for 2000 rpm engine speed at 40%, 60% and 80% of full engine load respectively.



Graph 32. Maximum combustion pressure as function of natural gas mass ratio at 2000 rpm for various engine loads (*Papagiannakis-Houantalas*)

As shown, the maximum combustion pressure under dual fuel operation decreases when increasing the amount of natural gas. Therefore a higher amount of fuel is needed to reach the same kWh. The pressure decreases due to a knocking phenomenon.

The following graph provides a variation of total brake specific fuel consumption (bsfc) of natural gas mass ratio for various loads at 2000 rpm engine speed.



Graph 33. Variation of sfc as function of natural gas mass ratio at 2000 rpm for various engine loads (*Papagiannakis-Houantalas)*

Thus, considering a 5% slope, the new total specific fuel consumption will be:

$$SFC_{Dualfuel} = SFC * \left(1 + {}^{5}/_{100}\right) = 215 * 1{,}05 = 226\ g/kWh$$

So, the global efficiency of dual-fuel engine will be:

$$\eta_{Dualfuel} = \frac{1}{\%_{NG} * sfc_{NG} * LHV_{NG} + \%_{Diesel} * sfc_{Diesel} * LHV_{Diesel}}$$

Considering the mixture 50% natural gas and 50% diesel and for Lower Heating Value: LHV_{NG} = 48,6 MJ/kg and LHV_{Diesel} = 42,7 MJ/kg

$$\eta = \frac{1000 * 3{,}6}{0{,}5 * 226 * 48{,}6 + 0{,}5 * 226 * 42{,}7} * 100 = 34{,}9\%$$

Thereby, the new fuel consumption will be:

$$E_{Dualfuel} = E_{Diesel} * \left(1 + {}^{5}/_{100}\right)$$

The following table shows this important growth of fuel consumption in several years:

year	E [t/y]	Total: E' dualfuel [t/y]	Diesel	Natural Gas
1995	**77979**	**81878**	40939	40939
2000	**63868**	**67061**	33531	33531
2005	**103611**	**108791**	54396	54396
2010	**93721**	**98407**	49204	49204

Table 39. Fuel consumption by Diesel engines and Dual-fuel engines

In Annex 11.3.1 data of the rest of the years can be found.

Logically, natural gas and diesel consumption are the same since the mixture is 50% natural gas - 50% diesel.

As regards exhaust emissions, the results would be the next one:

Specific factors

	NO_X	SO_2	PM	CO_2	
	kg/t_{diesel}	kg/t_{diesel}	kg/t_{diesel}	g/kWh	kg/t_{diesel}
Diesel	59	10	1,3	721	3160
Natural Gas	-	-	-	603	2673

	Diesel Emissions				Dual Fuel Emissions			
year	NO_X	SO_2	PM	CO_2	NO_X	SO_2	PM	CO_2
1995	4531	780	101	246413	2415	409	53	238789
2000	3711	639	83	201823	1978	335	44	195578
2005	6020	1036	135	327410	2299	390	51	227272
2010	5445	937	122	296159	2903	492	64	286995

Table 4019. Exhaust emissions from Diesel engines and Dual-fuel engines

In Annex 11.3.2 data of the rest of the years can be found.

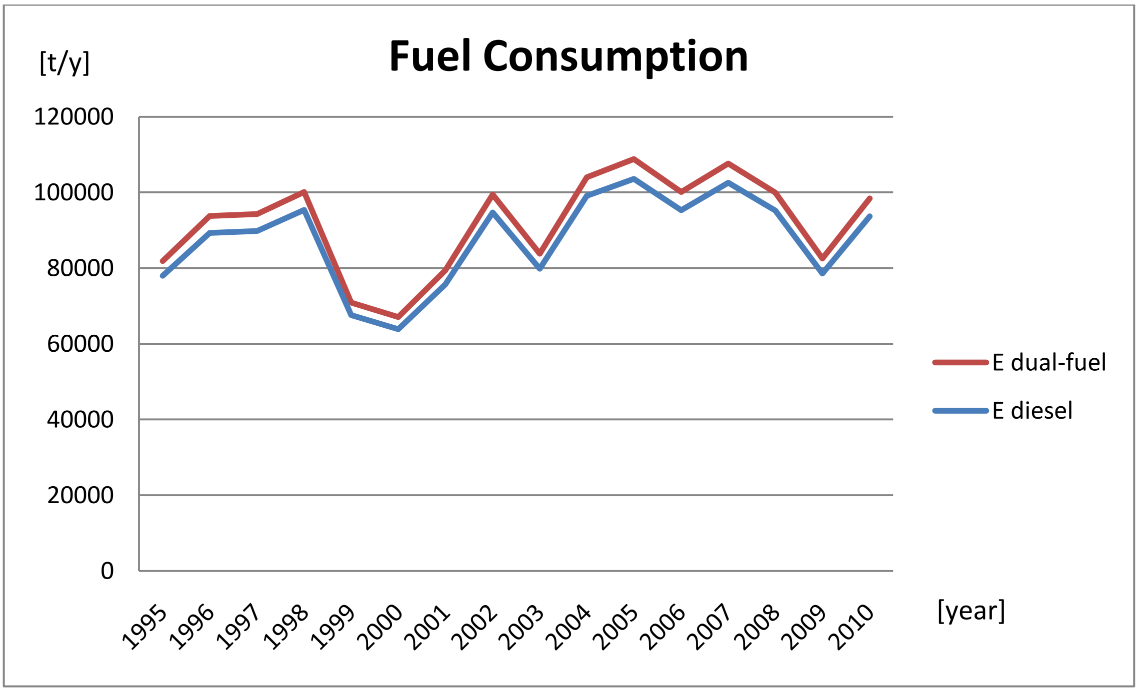
The following table shows % reduction of each pollutant:

	NO_X	SO_2	PM	CO_2
Reduction [%]	46,7	47,5	47,5	3,1

Table 41. Reduction of each pollutant

The main goal was to reduce CO_2 emissions, but only a 3.1% reduction has been achieved. This low result is mainly due to two causes: one is the raise of the specific fuel consumption in dual-fuel engines (215 g/kWh → 226 g/kWh) so fuel consumption grows 5% and the other is the percentage of the mixture (only 50%-50%). If specific fuel consumption growth was not considered and the percentage of the mixture was 100% natural gas and 0% diesel the reduction would be around 16%. Maybe in the future with new technologies this percentage can be reached.

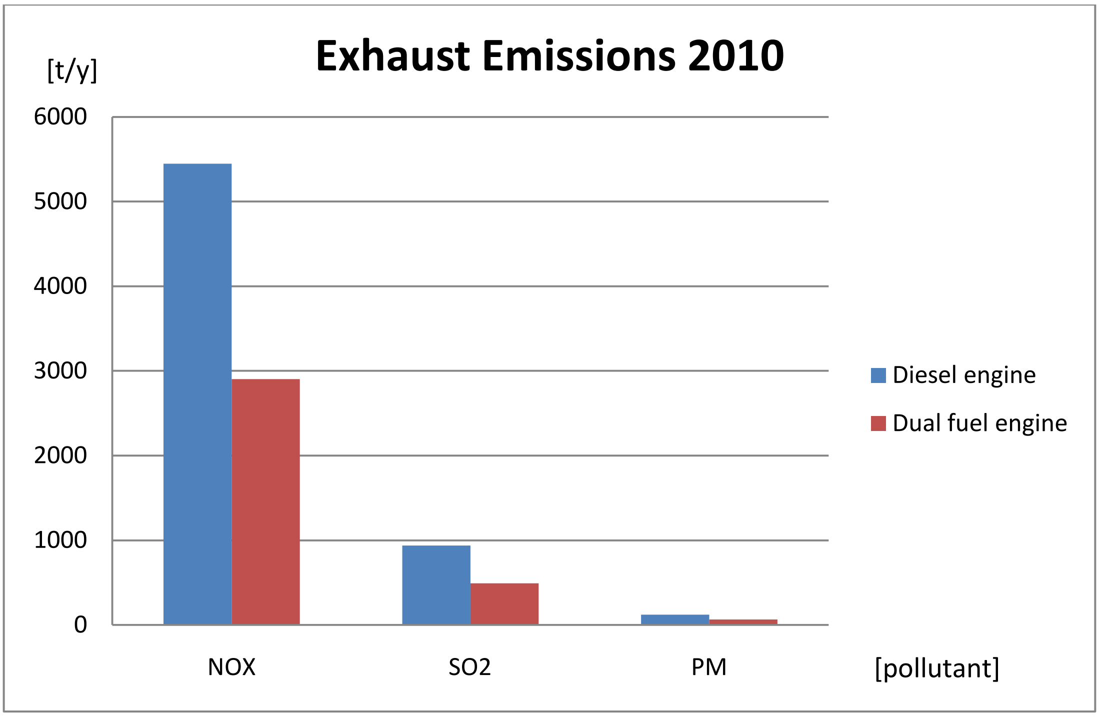
The following graphs reflect the previous results:



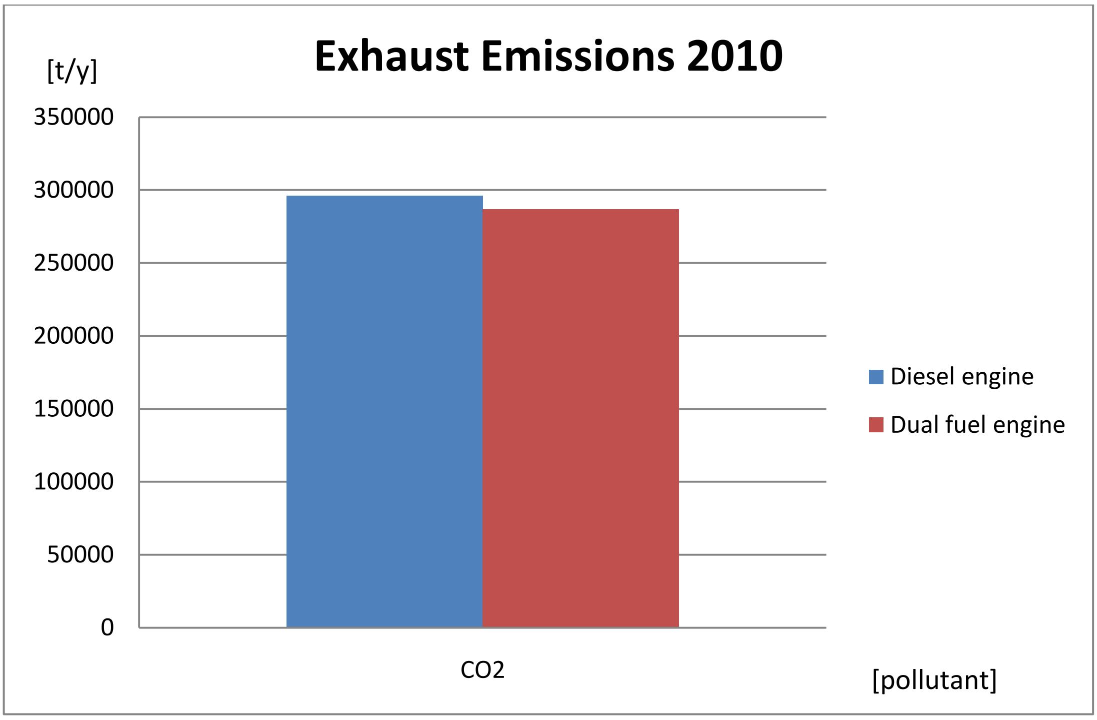
Graph 34. Fuel consumption depending on engine type

As it has been seen above, the fuel consumption is major in dual-fuel engines around 5.000 tonnes more per year.

On the other hand, although almost 50% emission reduction of NO_X, PM and SO_2 is reached only 3% reduction of CO_2 is achieved.

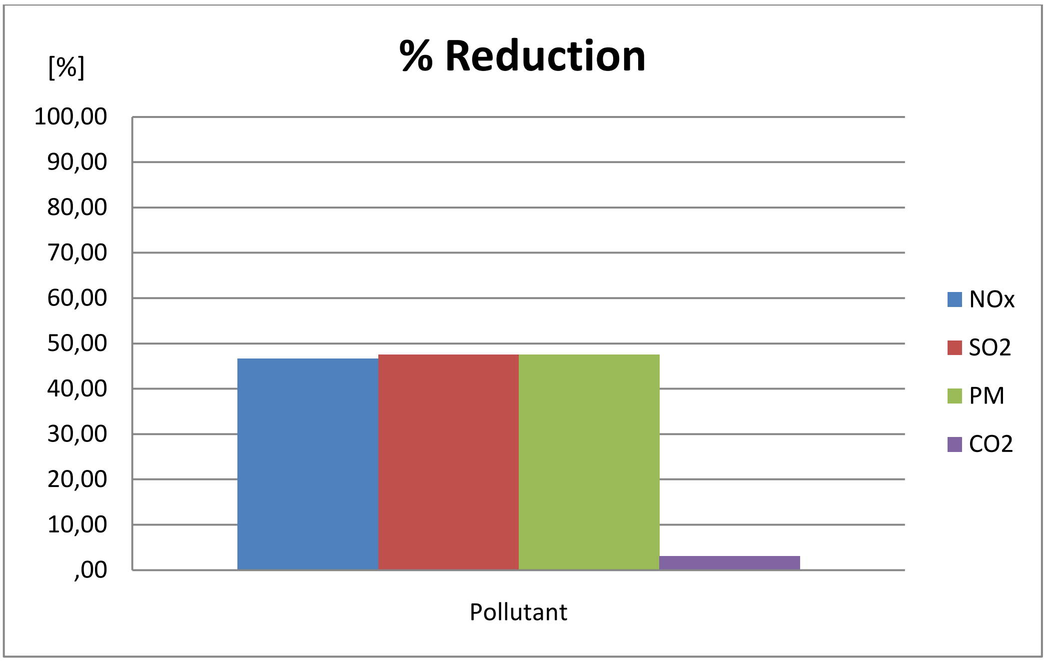


Graph 35. Exhaust emissions of NO_X, SO_2 and PM depending on engine type



Graph 36. Exhaust emissions of CO_2 depending on engine type

A slight reduction of CO_2 can be seen in Graph 25, around 10.000 tonnes. These would suppose a reduction of 3%, very low in comparison with the others pollutants.



Graph 2. %Reduction of each pollutant

Finally, the previous graph would summarize all the analysis about dual-fuel engines. On the one hand, the reduction of NO_X, SO_2 and PM emissions are quite good, around 50%. But on the other hand, the reduction of CO_2 is very slight due to the two main causes mentioned before (the growth of specific fuel consumption and the percentage of mixture).

Exhaust emissions from inland waterway on the Austrian Danube are much lower than exhaust emissions from land transport or air transport. Environmental impact would be higher if dual-fuel technology put into practice on land or air transport.

In conclusion, the use of alternative gaseous fuel in diesel engines is increasing worldwide. The use of natural gas fuel is prompted by the cleaner nature of its combustion compared to conventional liquid fuels as well as by its relatively increased availability at attractive prices.

10 References

[1] Van Basshuysen R., Schaefer F: Internal Combustion Engine Handbook. SAE International and Professional Engineering Publishing, 2004.

[2] Papagiannakis R.G., Houantalas D.T; Publication: Experimental investigation concerning the effect of natural gas percentage on performance and emissions of a DI dual fuel diesel engine, Technical University of Athens, 2002.

[3] LITEHAUZ, Incentive Partners, DNV, Ramboll Oil & Gas; Publication: Natural gas for ship propulsion in Denmark, 2010.

[4] Environmental Protection Agency, National Environmental Research Institute (Aarhus University); Publication: Ship emissions and air pollution in Denmark, 2009

[5] Buck Consultants International (Holland), ProgTrans (Switzerland), VBD European Development Centre for Inland and Coastal Navigation (Germany), via donau (Austria); Publication: Prospects of Inland navigation within the enlarged Europe, 2004

[6] Carlo Trozzi, Riccardo De Lauretis: EMEP/EEA air pollutant emission inventory guidebook 2009

[7] N.N.: http://www.statistik.at

[8] N.N.:http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/search_database

[9] N.N.: http://www.bosch.com

[10] N.N.: http://www.wärtsilä.com

[11] N.N.: http://www.via-donau.org/index.php

11 Annex

11.1 Data to calculate fuel consumption

1300 kW

1300 kW MGSS + Leichter (Europa IIB)	Fluß-kilometer	Strecken-länge	Durchschnitt						
			Geschw.	Fahrzeit	P_D	P_B	Motorenlast	Energie-bedarf	Kraftstoff-bedarf
	[km]	[km]	[km/h]	[h]	[kW]	[kW]	[%]	[kWh]	[kg]
Passau-Kachlet	2233-2231	2	10,0	0,2	1000	1042	80	208	45
Kachlet-Melk	2231-2038	193	18,6	10,4	1000	1042	80	10782	2318
Melk-Krems	2038-2008	30	17,8	1,7	650	677	52	1143	246
Krems-Freudenau	2008-1921	87	18,6	4,7	1000	1042	80	4860	1045
Freudenau-Bratislava	1921-1873	48	18,4	2,6	575	599	46	1564	336
Bratislava-	1873-1843	30	18,6	1,6	1000	1042	80	1676	360
österr. Donau		**358**	**18,5**	**19,3**		**950**	**73**	**18349**	**3945**
Bratislava-	1873-1843	30	14,6	2,1	1000	1042	80	2135,7	459
Freudenau-Bratislava	1873-1921	48	7,0	6,9	1250	1302	100	8984,4	1932
Krems-Freudenau	1921-2008	87	14,6	5,9	1000	1042	80	6193,6	1332
Melk-Krems	2008-2038	30	8,6	3,5	1250	1302	100	4557,3	980
Kachlet-Melk	2038-2231	193	14,6	13,2	1000	1042	80	13739,9	2954
Passau-Kachlet	2231-2233	2	10,0	0,2	1000	1042	80	208,3	45
österr. Donau		**358**	**12,1**	**29,5**		**1133**	**87**	**33475**	**7197**

Table 42. Data for ship engines of 1300 kW (Via Donau)

2000 kW

2000 kW Schubschiff + 4 Leichter	Fluß-kilometer	Strecken-länge	Durchschnitt				
Talfahrt			Geschw.	Fahrzeit	Motoren-leistung P_B	Energie-verbrauch	Kraftstoff-verbrauch
Abschnitt	[km]	[km]	[km/h]	[h]	[kW]	[kWh]	[kg]
Kachlet-Hafen Linz	2231-2132	99	17,4	5,7	1700	9672	2080
Hafen Linz - Schleuse Melk (4.5m/4.5m)	2132-2038	94	17,4	5,4	1700	9199	1978
Frei fließende Strecke (4.5m/3.5m)	2038-2008	30	17,4	1,7	1215	2094	450

Km 2008 - Schleuse Freudenau (4.5m/4.5m)	2008-1921	87	17,4	5,0	1700	8514	1831
Frei fließende Strecke (4.5m/3.5m)	1921-1873	48	17,4	2,8	1105	3049	655
österr. Donau Talfahrt	**2231-1873**	**358**	**17,4**	**20,6**	**1580**	**32528**	**6994**
2000 kW Schubschiff + 4 Leichter	Fluß-kilometer	Strecken-länge	Durchschnitt				
Bergfahrt			Geschw.	Fahrzeit	Motoren-leistung P_B	Energie-verbrauch	Kraftstoff-verbrauch
Abschnitt	[km]	[km]	[km/h]	[h]	[kW]	[kWh]	[kg]
Kachlet-Hafen Linz	2231-2132	99	10,3	9,6	1700	16340	3513
Hafen Linz - Schleuse Melk (4.5m/4.5m)	2132-2038	94	10,3	9,1	1700	15536	3340
Frei fließende Strecke (4.5m/3.5m)	2038-2008	30	5,2	5,8	1700	9822	2112
Km 2008 - Schleuse Freudenau (4.5m/4.5m)	2008-1921	87	10,3	8,5	1700	14379	3092
Frei fließende Strecke (4.5m/3.5m)	1921-1873	48	4,6	10,4	1700	17756	3817
österr. Donau Bergfahrt		**358**	**8,2**	**43,4**	**1700**	**73833**	**15874**

Table 43. Data for ship engines of 2000 kW (Via Donau)

11.2 Diesel engines

11.2.1 Fuel consumption

	Motorgüterschiff + 1 Leichter		
	Self-propelled barge		
	1300 kW		
Donau Model	FC [g/kWh]		215
	Power up [kW]		1133
	Speed Up [km/h]		12
	% MCR Up		64,9
	Power down [kW]		950
	Speed Down [km/h]		18,5
	Capacity [t]		3434
	% MCR Down		55,7
	UP [1000 tkm]	DOWN [1000 tkm]	**E [tonnes/year]**
1995	2.017.264	1.636.714	**27633**
1996	2.035.728	1.753.952	**28475**
1997	1.863.816	1.840.888	**27425**
1998	2.209.571	1.958.402	**31222**
1999	1.981.916	2.126.257	**30135**
2000	1.834.957	2.508.398	**31010**
2001	2.088.199	2.739.853	**34629**
2002	2.799.888	3.030.542	**42726**
2003	2.411.054	2.438.928	**35808**
2004	2.643.515	3.220.779	**42410**
2005	3.243.332	2.821.964	**45526**
2006	3.143.051	2.540.150	**42997**
2007	3.104.987	2.521.756	**42548**
2008	2.930.530	2.440.137	**40503**
2009	2.911.474	1.822.559	**36773**
2010	3.440.485	2.405.529	**44906**
Total	**37720289**	**35990441**	**547735**

Table 44. Fuel consumption of self-propelled barge

	Schubverband + 2 Leichter		
	Barge not self-propelled + 2		
Donau Model	1300 kW		
	FC [g/kWh]		215
	Power up [kW]		1133
	Speed Up [km/h]		12,1
	% MCR Up		64,9
	Power down [kW]		950
	Speed Down [km/h]		18,5
	Capacity [t]		3434
	% MCR Down		55,7
	UP [1000 tkm]	DOWN [1000 tkm]	**E [tonnes/year]**
1995	4.046.421	435.545	**39024**
1996	4.883.571	638.384	**47747**
1997	5.042.587	720.940	**49658**
1998	5.131.650	802.387	**50931**
1999	2.540.426	825.979	**27683**
2000	1.938.563	929.694	**22850**
2001	2.602.854	1.078.804	**29703**
2002	3.575.519	942.553	**37696**
2003	3.115.591	821.295	**32847**
2004	4.022.711	1.003.761	**42084**
2005	4.212.865	966.789	**43587**
2006	4.161.660	630.504	**41187**
2007	4.816.004	579.794	**46800**
2008	4.286.637	708.165	**42763**
2009	3.355.046	474.609	**33010**
2010	3.987.831	453.405	**38598**
Total	**60108736**	**11527525**	**608835**

Table 45. Fuel consumption of barge not self-propelled barge + 2

Schubverband + 4 Leichter

	Barge not self-propelled + 4		
Donau Model	2000 kW		
	FC [g/kWh]		215
	Power up [kW]		1700
	Speed Up [km/h]		8,2
	% MCR Up		64,9
	Power down [kW]		1580
	Speed Down [km/h]		17,4
	Capacity [t]		6868
	% MCR Down		55,7
	UP [1000 tkm]	DOWN [1000 tkm]	**E [tonnes/year]**
1995	551.785	59.392	**5794**
1996	665.941	87.052	**7072**
1997	687.626	98.310	**7345**
1998	699.770	109.416	**7523**
1999	346.422	112.633	**4023**
2000	264.350	126.777	**3278**
2001	354.935	147.110	**4283**
2002	487.571	128.530	**5509**
2003	424.853	111.995	**4800**
2004	548.551	136.876	**6158**
2005	574.482	131.835	**6390**
2006	567.499	85.978	**6087**
2007	656.728	79.063	**6939**
2008	584.541	96.568	**6310**
2009	457.506	64.719	**4883**
2010	543.795	61.828	**5727**
Total	**8196646**	**1571935**	**89598**

Table 20. Fuel consumption of barge not self-propelled + 4

	Motortankschiff		
	Self-propelled tanker barge		
Donau Model	1300 kW		
	FC [g/kWh]		215
	Power up [kW]		1133,4
	Speed Up [km/h]		12,1
	% MCR Up		64,9
	Power down [kW]		950
	Speed Down [km/h]		18,5
	Capacity [t]		3434
	% MCR Down		55,7
	UP [1000 tkm]	DOWN [1000 tkm]	**E [tonnes/year]**
1995	352.136	50.353	**3468**
1996	378.624	70.444	**3823**
1997	256.181	60.087	**2658**
1998	256.329	23.949	**2451**
1999	301.413	136.150	**3504**
2000	394.868	138.841	**4363**
2001	343.042	131.264	**3852**
2002	347.424	217.107	**4386**
2003	238.042	125.541	**2871**
2004	412.050	189.409	**4810**
2005	406.255	174.700	**4673**
2006	227.407	153.315	**2935**
2007	299.632	118.998	**3389**
2008	253.686	105.260	**2896**
2009	155.848	108.007	**2029**
2010	132.952	78.474	**1652**
Total	**4467010**	**1866121**	**51061**

Table 21. Fuel consumption of self-propelled tanker barge

	Tankschiffe		
	Tanker barge not self-propelled		
Donau Model	1300 kW		
	FC [g/kWh]		215
	Power up [kW]		1133
	Speed Up [km/h]		12
	% MCR Up		64,9
	Power down [kW]		950
	Speed Down [km/h]		19
	Capacity [t]		3434
	% MCR Down		55,7
	UP [1000 tkm]	DOWN [1000 tkm]	**E [tonnes/year]**
1995	208.201	31.307	**2059**
1996	214.453	42.729	**2181**
1997	277.883	32.885	**2697**
1998	346.106	15.976	**3215**
1999	226.947	26.033	**2198**
2000	239.436	35.811	**2367**
2001	315.674	59.006	**3189**
2002	415.373	108.656	**4374**
2003	307.976	119.900	**3470**
2004	287.959	173.848	**3600**
2005	199.039	284.547	**3435**
2006	166.607	105.761	**2113**
2007	226.415	139.482	**2847**
2008	217.177	136.401	**2746**
2009	163.678	74.472	**1906**
2010	258.483	87.724	**2838**
Total	**4027015**	**1474538**	**44835**

Table 22. Fuel consumption of tanker barge not self-propelled

Summary of fuel consumption

Year	BAR_SP	BAR_NSP+2	BAR_NSP+4	BAR_TK_SP	BAR_TK_NSP	**E total [t/y]**
	E [t/year]	E [t/year]	E [t/year]	E [t/year]	E [t/year]	
1995	27633	39024	5794	3468	2059	**77979**
1996	28475	47747	7072	3823	2181	**89298**
1997	27425	49658	7345	2658	2697	**89783**
1998	31222	50931	7523	2451	3215	**95342**
1999	30135	27683	4023	3504	2198	**67543**
2000	31010	22850	3278	4363	2367	**63868**
2001	34629	29703	4283	3852	3189	**75656**
2002	42726	37696	5509	4386	4374	**94690**
2003	35808	32847	4800	2871	3470	**79796**
2004	42410	42084	6158	4810	3600	**99062**
2005	45526	43587	6390	4673	3435	**103611**
2006	42997	41187	6087	2935	2113	**95319**
2007	42548	46800	6939	3389	2847	**102523**
2008	40503	42763	6310	2896	2746	**95217**
2009	36773	33010	4883	2029	1906	**78602**
2010	44906	38598	5727	1652	2838	**93721**

Table 23. Fuel consumption

11.2.2 Exhaust emissions

- **NO_X**

	NO_X					
	B_SP	B_NSP+2	B_NSP+4	T_SP	T_NSP	
NO_X [kg/t fuel]	58,1	58,1	65	58,1	58,1	
	E NO_X [t/y]	E NO_X [t/y]	E NO_X [t/y]	E NO_X [t/y]	E NO_X [t/y]	**Total [t/y]**
1995	1.605	2.267	336,7	201,5	119,6	**4530,6**
1996	1.654	2.774	410,9	222,1	126,7	**5188,2**
1997	1.593	2.885	426,7	154,4	156,7	**5216,4**
1998	1.814	2.959	437,1	142,4	186,8	**5539,4**
1999	1.751	1.608	233,7	203,6	127,7	**3924,2**
2000	1.802	1.328	190,5	253,5	137,5	**3710,7**
2001	2.012	1.726	248,9	223,8	185,3	**4395,6**
2002	2.482	2.190	320,0	254,8	254,1	**5501,5**
2003	2.080	1.908	278,9	166,8	201,6	**4636,2**
2004	2.464	2.445	357,8	279,4	209,2	**5755,5**
2005	2.645	2.532	371,3	271,5	199,6	**6019,8**
2006	2.498	2.393	353,6	170,5	122,8	**5538,1**
2007	2.472	2.719	403,2	196,9	165,4	**5956,6**
2008	2.353	2.485	366,6	168,2	159,5	**5532,1**
2009	2.137	1.918	283,7	117,9	110,7	**4566,8**
2010	2.609	2.243	332,8	96,0	164,9	**5445,2**

Table 50. NO_X exhaust emissions

- **SO_2**

	SO_2					
	B_SP	B_NSP+2	B_NSP+4	T_SP	T_NSP	
SO2 [kg/t fuel]	10	10	10	10	10	
	E SO_2 [t/y]	E SO_2 [t/y]	E SO_2 [t/y]	E SO_2 [t/y]	E SO_2 [t/y]	**Total [t/y]**
1995	276,3	390,2	57,9	34,7	20,6	**779,8**
1996	284,8	477,5	70,7	38,2	21,8	**893,0**
1997	274,2	496,6	73,5	26,6	27,0	**897,8**
1998	312,2	509,3	75,2	24,5	32,2	**953,4**
1999	301,3	276,8	40,2	35,0	22,0	**675,4**
2000	310,1	228,5	32,8	43,6	23,7	**638,7**
2001	346,3	297,0	42,8	38,5	31,9	**756,6**
2002	427,3	377,0	55,1	43,9	43,7	**946,9**
2003	358,1	328,5	48,0	28,7	34,7	**798,0**
2004	424,1	420,8	61,6	48,1	36,0	**990,6**
2005	455,3	435,9	63,9	46,7	34,4	**1036,1**
2006	430,0	411,9	60,9	29,4	21,1	**953,2**
2007	425,5	468,0	69,4	33,9	28,5	**1025,2**
2008	405,0	427,6	63,1	29,0	27,5	**952,2**
2009	367,7	330,1	48,8	20,3	19,1	**786,0**
2010	449,1	386,0	57,3	16,5	28,4	**937,2**

Table 51. SO_2 exhaust emissions

- **PM**

	PM											
	B_SP		B_NSP+2		B_NSP+4		T_SP		T_NSP			
	PM_{10}	$PM_{2,5}$	PM_{10}	$PM_{2,5}$	PM_{10}	$PM_{2,5}$	PM_{10}	$PM_{2,5}$	PM_{10}	$PM_{2,5}$		
PM [kg/t fuel]	1,5	1,3	1,5	1,3	1,5	1,3	1,5	1,3	1,5	1,3		
	E PM_{10} [t/y]	E $PM_{2,5}$ [t/y]	E PM_{10} [t/y]	E $PM_{2,5}$ [t/y]	E PM_{10} [t/y]	E $PM_{2,5}$ [t/y]	E PM_{10} [t/y]	E $PM_{2,5}$ [t/y]	E PM_{10} [t/y]	E $PM_{2,5}$ [t/y]	**Total PM_{10}**	**Total $PM_{2,5}$**
1995	41,45	35,92	58,54	50,73	8,69	7,53	5,20	4,51	3,09	2,68	**117,0**	**101,4**
1996	42,71	37,02	71,62	62,07	10,61	9,19	5,73	4,97	3,27	2,84	**133,9**	**116,1**
1997	41,14	35,65	74,49	64,56	11,02	9,55	3,99	3,46	4,05	3,51	**134,7**	**116,7**
1998	46,83	40,59	76,40	66,21	11,28	9,78	3,68	3,19	4,82	4,18	**143,0**	**123,9**
1999	45,20	39,17	41,53	35,99	6,03	5,23	5,26	4,56	3,30	2,86	**101,3**	**87,8**
2000	46,51	40,31	34,27	29,70	4,92	4,26	6,54	5,67	3,55	3,08	**95,8**	**83,0**
2001	51,94	45,02	44,56	38,61	6,43	5,57	5,78	5,01	4,78	4,15	**113,5**	**98,4**
2002	64,09	55,54	56,54	49,00	8,26	7,16	6,58	5,70	6,56	5,69	**142,0**	**123,1**
2003	53,71	46,55	49,27	42,70	7,20	6,24	4,31	3,73	5,20	4,51	**119,7**	**103,7**
2004	63,62	55,13	63,13	54,71	9,24	8,01	7,21	6,25	5,40	4,68	**148,6**	**128,8**
2005	68,29	59,18	65,38	56,66	9,59	8,31	7,01	6,07	5,15	4,47	**155,4**	**134,7**
2006	64,50	55,90	61,78	53,54	9,13	7,91	4,40	3,82	3,17	2,75	**143,0**	**123,9**
2007	63,82	55,31	70,20	60,84	10,41	9,02	5,08	4,41	4,27	3,70	**153,8**	**133,3**
2008	60,75	52,65	64,14	55,59	9,47	8,20	4,34	3,76	4,12	3,57	**142,8**	**123,8**
2009	55,16	47,81	49,52	42,91	7,33	6,35	3,04	2,64	2,86	2,48	**117,9**	**102,2**
2010	67,36	58,38	57,90	50,18	8,59	7,45	2,48	2,15	4,26	3,69	**140,6**	**121,8**

Table 52. PM exhaust emissions

- **CO_2**

	CO_2					
	B_SP	B_NSP+2	B_NSP+4	T_SP	T_NSP	
CO_2 [kg/t fuel]	3160	3160	3160	3160	3160	
	E CO_2 [t/y]	E CO_2 [t/y]	E CO_2 [t/y]	E CO_2 [t/y]	E CO_2 [t/y]	**Total [t/y]**
1995	87.321	123.317	18.311	10958	6507	**246413**
1996	89.982	150.882	22.347	12079	6893	**282183**
1997	86.662	156.919	23.210	8399	8523	**283714**
1998	98.661	160.941	23.772	7745	10160	**301280**
1999	95.225	87.480	12.712	11074	6946	**213436**
2000	97.991	72.205	10.359	13788	7480	**201822**
2001	109.426	93.863	13.536	12172	10076	**239073**
2002	135.013	119.119	17.407	13860	13823	**299221**
2003	113.155	103.796	15.168	9073	10965	**252157**
2004	134.017	132.985	19.459	15198	11376	**313036**
2005	143.861	137.734	20.193	14765	10856	**327410**
2006	135.871	130.152	19.234	9276	6676	**301209**
2007	134.451	147.888	21.928	10711	8996	**323973**
2008	127.990	135.130	19.941	9150	8676	**300887**
2009	116.203	104.313	15.432	6410	6023	**248381**
2010	141.902	121.971	18.099	5220	8968	**296160**

Table 53. CO_2 exhaust emissions

11.3 Dual-fuel engines

11.3.1 Fuel consumption

		Total	
		Diesel	Natural Gas
year	E [t/y]	E' dualfuel [t/y]	
1995	**77979**	**81878**	
		40939	40939
1996	**89298**	**93763**	
		46882	46882
1997	**89783**	**94272**	
		47136	47136
1998	**95342**	**100109**	
		50054	50054
1999	**67543**	**70920**	
		35460	35460
2000	**63868**	**67061**	
		33531	33531
2001	**75656**	**79439**	
		39719	39719
2002	**94690**	**99425**	
		49712	49712
2003	**79796**	**83786**	
		41893	41893
2004	**99062**	**104015**	
		52008	52008
2005	**103611**	**108791**	
		54396	54396
2006	**95319**	**100085**	
		50043	50043
2007	**102523**	**107649**	
		53825	53825
2008	**95217**	**99978**	
		49989	49989
2009	**78602**	**82532**	
		41266	41266
2010	**93721**	**98407**	
		49204	49204

Table 54. Fuel consumption depending on type of engine

11.3.2 Exhasut Emissions

	Diesel Emissions				Dual Fuel Emissions			
year	NO_X	SO_2	PM	CO_2	NO_X	SO2	PM	CO_2
1995	4531	780	101	246413	2415	409	53	238789
1996	5188	893	116	282183	2766	469	61	273451
1997	5216	898	117	283713	2781	471	61	274935
1998	5539	953	124	301280	2953	501	65	291957
1999	3924	675	88	213436	2092	355	46	206831
2000	3711	639	83	201823	1978	335	44	195578
2001	4396	757	98	239073	2343	397	52	231675
2002	5501	947	123	299221	2933	497	65	289962
2003	4636	798	104	252157	2472	419	54	244354
2004	5756	991	129	313036	2122	360	47	209785
2005	6020	1036	135	327410	2299	390	51	227272
2006	5538	953	124	301209	2953	500	65	291889
2007	5957	1025	133	323973	3176	538	70	313949
2008	5532	952	124	300887	2949	500	65	291577
2009	4567	786	102	248381	2435	413	54	240696
2010	5445	937	122	296159	2903	492	64	286995

Table 55. Exhaust emissions depending on type of engine