EMISSSION FACTORS IN INLAND NAVIGATION

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Rezumat: *Lucrarea prezintă câteva rezultate obținute de IPA CIFATT în cadrul proiectului CREATING, derulat în FP6/STREP - Priority 1.6.2 Sustainable Surface Transport. De asemenea, sunt identificați factorii de emisie şi contribuția acestora la poluarea atmosferei.*

Cuvinte cheie: *factori de emisie, poluare, concentrație de poluant.*

Abstract: *The paper presents some results obtained by IPA CIFATT within the project CREATING under FP6/STREP - Priority 1.6.2 Sustainable Surface Transport. The emission factors are also identified and their contribution to the atmosphere pollution is quantified.*

Key words: *emission factors, pollution, concentration of pollutant.*

1. INTRODUCTION

CREATING is a R&D project under FP6/STREP - Priority 1.6.2 Sustainable Surface Transport and has two general objectives:

- *to minimize emissions impact of vessels engines on human health, environment and atmosphere;*
- *to attain optimal transport performances in inland navigation.*

CREATING brings together 27 partners from Europe and IPA CIFATT is one of them.

Emissions factors is a fundamental tool in developing national, regional, and local emissions inventories for air quality management decisions and in developing emissions control strategies.

Emissions factors are representative values that attempt to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant.

These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (e.g., kilograms of pollutant emitted per ton of fuel).

For many systems (processes) emission factor represents an average of pollutant measurements in a time period and can be an emissions parameter for whole process. In the navigation process, on sea or on rivers, this is not possible.

We have in navigation process a complex system where the emission factor depends on many parameters.

These are numerous studies and research works that follow to find a methodology to establish emission factors, so that they mirror better the whole navigation process. Although there are many studies in the field, there is not a unitary methodology yet. Every work treats the navigation process from certain points of view, every study use own assumptions and approximations and the results are various.

Generally, these studies follow to estimate emission level from navigation activities on emission factors base and not to establish a methodology for emission factors determination.

From our analysis on many of such studies, the emission factors used in different equations is taken over from different databases. The main source for databases used in emission factors analyzing are Lloyds Register, Marintek, Germanisher Lloyd, IVL, Swedish Environmental Research Institute, EPA. The Lloyd's Register of Ships is considered to be the authoritative resource for information about ship details, including owner, operator, ship name, registry number, cargo handling equipment, flag of registry and, significantly, ship origin details, such as maximum horsepower and number of auxiliary engines.

2. NAVIGATION PROCESS SHORT DESCRIPTION

Like any combustion system, engines used in inland navigation burn a fuel to release heat and produce power.

This process involves the oxidation of hydrocarbons from fuel to produce water and carbon dioxide.

However, the fuel and air used in combustion typically contain more elements than hydrogen and carbon and oxygen.

During combustion additional elements implied in process, form new molecules under the intense heat and pressure.

In general, these unnecessary products of combustion include the pollutants that affect our health and environment.

Fuel combustion for navigation activities, like other fuel combustion processes, produces CO_2, CH_4, N_2O, CO, NOx, NMVOCs, and SO_2.

Engines combustion process is presented in Figure 1 in a simplified scheme:

Three main fuel types are used in inland navigation:

● Residual Oil (RO) – heavy fuel oil (the common fuel used on ships today) with a content of 2.7% sulfur.

● Marine Diesel Oil (MDO) – slightly lighter blend of distillate with a content of 1.0%

● Marine Gas Oil (MGO) – the “lightest” fuel with a content of 0.5%

Chemical composition for some fuel is presented in table 1.

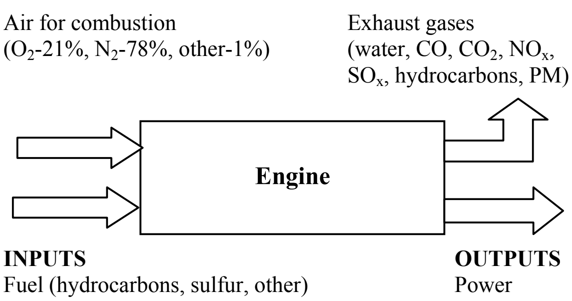

Fig. 1. Engines combustion process.

3. EMISSION FACTORS

The quantity of pollutant release from engines combustion process is a direct function of quantity of consumed fuel.

Table 1. **Typical chemical composition for different fuels**

Fuel	C %	H %	S %	O %	Exhaust gases density
Diesel	86.2	13.6	0.17	0	1.292 – 1.294
RME	77.2	12.0	0	10.8	1.292 – 1.296
Methanol	37.5	12.6	0	50.0	1.233 – 1.272
Ethanol	52.1	13.1	0	34.7	1.26 – 1.281
Natural gases	60.6	19.3	0	1.9	1.28 – 1-257
Propane	81.7	18.3	0	0	1.268 – 1-284
Butane	82.7	17.3	0	0	1.273 – 1.285

*Volumetric composition: CO_2 1.10%; N_2 12.10%; CH_4 84.20%; C_2H_6 3.42%; C_3H_8 0.66%; C_4H_{10} 0.22%; C_5H_{12} 0.05%; C_6H_{14} 0.05%.

Starting from this judgement we can define a basic emission factor like the quantity of pollutant produced by a weight unit of fuel at a moment or the quantity of pollutant produced when the consumed fuel produces a power unit.

Basic emission factors are necessary to shape emissions from each navigation process activities: engines activities and ships activities.

By compilation of these emission factors, using equations and different information from databases regarding engines types, fuel types, ships operation modes, time for every operational mode, number of ships, etc., one can estimate the emissions level specific for a source (in our case the source is non-road engines for inland navigation).

The elements necessary to calculate basic emission factors for a steady working state (Figure 2), are:

• pollutant concentration in exhaust gases: *c* expressed in weight units/weight units or volume %, (ppm, %);

• fuel mass flow registered in the measurement moment: *q* expressed in kg/h;

• engine power in the measurement moment: *P* expressed in kW.

The relation between BEFQ and BEFP is:

$$BEFP = BEFQ \times sfc \times 10^{-3} \text{ (g/kW-h)} \qquad (1)$$

where *sfc* is the specific fuel consumption (g/kW-h); generally this is an engine parameter given by manufacturer in performances diagrams and differs function engine power.

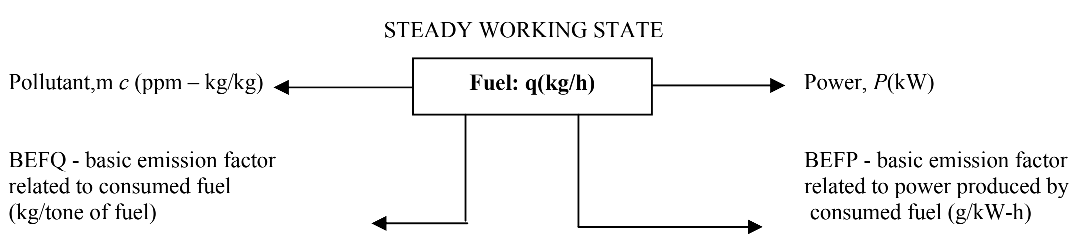

Fig. 2. Necessary elements to calculate basis emission factors.

Basic emission factors characterise an engine under constant working conditions. For every steady working condition must be established a basic emission factor.

Emission factors can be obtained using some methods:

3.1. Direct measurements

Measurements need to be collected over a period of time, to be representative for operations followed and to respect existent requirements and standards in the field. The European standard in exhaust emissions measurements is ISO 8178, "Reciprocating Internal Combustion Engines – Exhaust Emission Measurement," that contains 9 parts:

- Part 1: Test-bed measurement of gaseous and particulate exhausts emissions;
- Part 2: Measurement of gaseous and particulate exhausts emissions at site;
- Part 3: Definitions and methods of measurement of exhaust gas smoke under steady-state conditions;
- Part 4: Test cycles for different engine applications;
- Part 5: Test fuels;
- Part 6: Test report;
- Part 7: Engine family determination;
- Part 8: Engine group determination; and
- Part 9: Test-bed measurement of exhaust gas smoke emissions from engines used in non-road mobile machinery.

For in-service waterway engine testing, the most important parts of ISO 8178 are Parts 2 and 4.These parts specify theoretical conditions and test cycles to in-service engine testing. Although exists this standard, it is difficult to respect its conditions for on-board measurements. These measurements are generally adapted to real conditions so that the ship can execute its activities without changes. For such measurements were published different work manuals and guides based on ISO 8178 but with modifications for on-board (in-service) conditions.

Following such guides a protocol for pollutant measurement on-board was outlined and basic emission factor was determined.

3.2. Mass balance

A mass balance identifies the quantity of substance going in and out of the process.

Emission factors can be calculated as the difference between input and output of each substance present in this process.

These techniques are best applied to systems with prescribed inputs, defined internal conditions, and known outputs.

This method is recommended to be used in calculation of exhaust gas flow and/or combustion air consumption: "Carbon balance method" and "Carbon/oxygen balance".

Both methods are based on exhaust gas concentration measurements and on knowledge of fuel consumption and composition.

The both methods are described in Technical Code on Control of Emission of Nitrogen Oxides from Marine Diesel Engines**,** MP/CONF. 3/35, adopted on September 1997 by the Conference of Parties to the International Convention for the Prevention of Pollution from Ships.[5]

3.3. Engineering calculation

An engineering calculation is an estimation method based on physical/chemical properties of the substances and mathematical relationships.

Theoretical and complex equations or models can be used for estimating emission factor from a variety of waterway activities and processes.

3.4. Associated method for estimation of emission factors

This method is a combination of the first three methods and is based on developing a correlation between pollutant emission rates and process parameters through measurements, information from databases or statistic and calculation.

This method allows facilities to develop specific emission factors, or emission factors more relevant for particular process stages. Based on test data and using various parameters, a mathematical correlation can be developed to establish emission factors relevant for the process.

In this case it is necessary to outline the techniques to determine emission factors of pollutant substances from the principal operational activities considered at major in navigation process, to establish the data inputs required, and sources of this data. These calculations are based on standard assumptions about vessel operations, engine load profiles, and emissions characteristics.

It is widely acknowledged that in-service engines perform differently than the new engines tested and certified by manufacturers.

We mention here reference 2, Vessel Operator Engine Emissions Measurement Guide, Final Report, Submitted by James J. Corbett, P.E., Ph.D., Principal Investigator University of Delaware (may 2003).

This document provides general guidelines and information to an operator who wants to monitor the emissions from one or more of the engines in a fleet of vessels.

These guidelines are a result of a partnership between MARAD, the University of Delaware, and industry to research, develop, and disseminate information on energy and emissions technology and technology applications.

4. INVENTORY OF EMISSION FACTORS RELEVANT FOR NAVIGATION PROCESS

At present the data that underlie emission factors is limited and is an aggregation of engine tests on a variety of engine types and sizes, fuel types, operational mode, etc.

Emission factors are still derived from limited data.

We proposed in this research work to make a collection of emission factors used in analyzed materials and to calculate emission factors from kg/ton of fuel in g/kWh to have a unitary image of these elements. To perform this calculation we used break specific fuel consumption – bsfc (g/kW-h)

Table 2 provides information about Brake Specific Fuel Consumption (bsfc).

For diesel engine, information was taken from the EEA/EMEP CORINAIR 1999 and for steam and gas turbine data information was taken from IMO 2000.

Table 2. **Breake specific fuel consumption**

Engine type	Bsfc (g/kW-hr)
Slow-speed diesel	207
Medium-speed diesel	227
High-speed diesel	227
Steam turbine	290
Gas turbine	290

In inland navigation it were identified some categories of ships presented in Table 3.

In Table 4 are presented engines types and abbreviations used for each type.

Table 3. **Categories of ships**

Category	Code
Solid bulk	SB
Liquid bulk	LB
General cargo	GC
Container	CO
Passenger/RoRo/Cargo	PC
Passenger	PA
High speed ferries	HS
Inland Cargo	IC
Sail ships	SS
Tugs	TU
Fishing	FI
Other	OT

Table 4. **Engine types**

Engine type	Code
Slow speed diesel, residual oil	SSD-RO
Medium speed diesel, residual oil	MSD-RO
High speed diesel, marine diesel oil	HSD-MDO
Steam turbine, residual oil	ST-RO
Steam turbine, marine diesel oil	ST-MDO
Steam turbine, marine gas oil	ST-MGO
Gas turbine	GT

Using these classification and information from other studies, Starcrest Consulting Group, LLC established a "basic emission rate" by pollutant for each type of vessels, as illustrated in table 5.

From other sources – "Proposed emission factors MEET RF98" [1], we selected the values from "emission factors" corresponding to engines types presented in Table 4. Values are in kg/ton of fuel.

Using bsfc values from table 2 we calculated emission factors in g/kW-h with the relation (2).

$$\textit{Emission factor}\ (\text{g/kW-h}) = \textit{Emission factor}\ (\text{kg/ton of fuel}) \times 10^{-3} \times \textit{bsfc}\ (\text{g/kW-h}) \qquad (2)$$

Calculated values are presented in Table 6.

Another important source for our emission factors review is ENTEC study prepared for use by European Commission and covering a large European navigation area.

Table 5. **Basic emission rate**

Pollutant	SSD-RO	MSD-RO	HSD-MDO	ST-RO	ST-MDO	ST-MGO	GT
CO_2	682.44	748.37	719.59	956.07	919.30	919.30	919.30
CO	1.59	1.75	1.68	0.12	0.17	0.17	0.15
SO_2	11.63	12.75	2.27	16.29	5.80	2.90	2.90
NO_x	19.67	14.13	12.94	2.11	1.81	1.81	4.64
HC	0.58	0.64	0.61	0.03	0.15	0.15	0.06
PM	1.64	1.79	0.27	0.75	0.61	0.61	0.32

Table 6. **Emission factors (g/kW-h) and specific fuel consumption for engines and fuel types**

Engine type-fuel type	**MSD/MGO**	**MSD/MDO**	**MSD/RO**	**HSD/MGO**	**HSD/MDO**	**HSD/RO**
U.M.	**g/kW-h**	**g/kW-h**	**g/kW-h**	**g/kW-h**	**g/kW-h**	**g/kW-h**
sfc (g/kW-h)	217	217	227	217	217	227
Pollutant						
CO_2	690	690	722	690	690	722
SO_2	1.1	4.3	12.3	1.1	4.3	12.3
NO_x	13.9	13.9	14.7	10.9	10.9	11.6
HC	0.4	0.4	0.4	0.4	0.4	0.4
PM	0.3	0.3	0.8	0.3	0.3	0.8

ENTEC study develops a detailed analyze for emission factors based on different operational modes and fuel types.Using data from LMIS (Lloyd's Marine Intelligence Services) ENTEC presented the emission factors. There are no data for slow speed engines, steam turbine and gas turbine engines and nor for CO.

From ENTEC [6] we take over emission factors and specific fuel consumption regarding engine/fuel types for every operating mode

We applied specific fuel consumption–*sfc* (g/kW-h) (equation 2) to proposed emission factors from MEET [1] to have emission factors in g/kW-h corresponding to every operation mode as described in table 7.

Table 7. **Emission factors in g/kWh regarding engine / fuel type for cruising mode (on sea)**

Engine type / Fuel type \ **Pollutant**	NO_x	SO_2	CO_2	**HC**	**Specific fuel consumption**
SSD / MGO	17.0	0.9	588	0.6	185
SSD / MDO	17.0	3.7	588	0.6	185
SSD / RO	18.1	10.5	620	0.6	195
MSD / MGO	13.2	1.0	645	0.5	203
MSD / MDO	13.2	4.1	645	0.5	203
MSD / RO	14.0	11.5	677	0.5	213
HSD / MGO	12.0	1.0	645	0.2	203
HSD / MDO	12.0	4.1	645	0.2	203
HSD / RO	12.7	11.5	677	0.2	213
GT / MGO	5.7	1.5	922	0.1	290
GT / MDO	5.7	5.8	922	0.1	290
GT / RO	6.1	16.5	970	0.1	305
ST / MGO	2.0	1.5	922	0.1	290
ST / MDO	2.0	5.8	922	0.1	290
ST / RO	2.1	16.5	970	0.1	305

[Source 6]

In the recent study of EEA- **CORINAIR** Emission inventory Guidebook, September 2004 [7], inland navigation is included in the category SNAP 0803 a sub-sector of group "Other mobile sources and machinery" Inland navigation in accordance with this study have the next groups:

01. Sailing Boats with auxiliary engines

One can distinguish small sailing boats with a length of up to about 6 meters which are partly equipped with outboard engines and larger sailing ships which, in general, have inboard engines.

The small engines used for small sailing boats have a power output between about 2 and 8 kW and are all 2 stroke petrol engines.

For larger sailing boats mainly diesel engines are used having a power output between 5 and about 500 kW. Four-stroke petrol engines with a power output between about 100 and 200 kW are also on offer but rarely used.

The average 8 to 10 meter sailing boat is equipped with an engine of 10 to 40 kW power output.

02. Motorboats / Workboats

A large number of 2-stroke petrol engines is on offer for recreational motor boats with a length of about 3 to 15 meters. They have a power output between 1 and 200 kW. There are also 4-stroke engines on offer having a power output between 5 to 400 kW.

For larger motor boats generally diesel engines are used which are identical to those used for large sailing boats.

There is a large number of different workboats in use, e.g., for inland passenger transport, in harbors for ship towing and other commercial purposes (e.g., swimming cranes and excavators), for police and custom purposes.

These boats have a power output of about 20 to 400 kW and are all diesel engine equipped.

03. Personal Watercraft

These are 'moped' type crafts, all equipped with two-stroke engines.

04. Inland Goods Carrying Vessels

They are all equipped with slow diesel engines having a power output between 200 and 800 kW with an average of about 500 kW.

Table 8. **Bulk emission factors for 'Other Mobile Sources and Machinery'. Bulk emission factors for 'Other Mobile Sources and Machinery - Diesel engines' (g/kg fuel)**

	NO_x	NM-VOC	CH_4	CO	NH_3	N2O	PM
Inland waterways	42.5	4.72	0.18	10.9	0.007	1.29	4.48

Table 9. **Degradation factors of engines (% per year)**

Engine type	CH_4/NMVOC	CO	NOx	FC/SO_2/CO_2	N_2O/NH_3	PM
Diesel engines (generally)	1.5	1.5	0	1	0	3
2-stroke gasoline engines	1.4	1.5	2.2	1	0	-
4-stroke gasoline and 4-stroke LPG engines	1.4	1.5	2.2	1	0	-

Since not all vehicles/machinery listed above make use of all types of engines, the methodology can be concentrated on those engines mainly used.

In the same guidebook [7] we find a bulk emission factors for group "**Other Mobile Sources and Machinery** – diesel engines" without any information about engines parameters or ships activities and general data about engines degradation.

Emission factors are presented in table 8 and degradation factors in table 9.

Emission factors for auxiliary engines

The source of emission factors used for auxiliary engines is the ENTEC 2000 Report.8

This report directly estimates emission factors for NO_X, HC and SO_2; it also includes other data sources for CO and PM.

While the ENTEC study was geared towards estimating emissions for the European Union, it provides the latest and most insightful analysis of the worldwide commercial marine vessel fleet, even including a statistical analysis of variance in emission factors.

It should be noted, as was recognized by ENTEC, that the data used for auxiliary engines was limited by a relatively small number of emission tests, and the fact that Lloyd's data only provides information of diesel-powered auxiliaries [11].

Table 10 reports the emission factors, along with an average value that can be used if fuel and engine type is not known.

Note that CO factors were not estimated by ENTEC and were taken from the EPA 1997 *Regulatory Impact Analysis.*

Table 10. Emission factors for auxiliary engines

Engine type/fuel type	NO_X	CO *	HC	PM
MSD / MDO	13.9	1.5	0.4	0.3
MSD/RO	14.7	1.5	0.4	0.3
HSD/MDO	13.9	1.5	0.4	0.3
HSD/RO	11.6	1.5	0.4	0.8
Average	***13.53***	***1.50***	***0.40***	***0.43***

* EPA Estimate

5. CONCLUSIONS

Emission factors are a fundamental tool in developing national, regional, and local emissions inventories for air quality management decisions and in developing emissions control strategies.

Emissions factors from inland shipping are representative values that attempt to relate the quantity of a pollutant released to the atmosphere from these activities.

Emission factors are associated with a set of conditions and parameters of the inland shipping process.

Emission factors presented in this paper were compared with those that we obtained from experimental measurements performed on ships' board.

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