Emissions and Energy Consumption from Inland Navigation in Germany – A New Inventory Model with High Resolution of Input Data and Results

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Abstract

A relevant part of freight transport in Europe, in Germany currently approximately 10% of the transport performance (ton-km), is covered by inland navigation. In the context of emission reporting for greenhouse gases (Kyoto protocol) and air pollutants (NEC directive), the sector has been considered in the German emission inventory since the 90s.

However, in the past, the level of detail in emission calculation for inland navigation was far below that for road transport. Thus, in recent research projects for the German Federal Environment Agency (UBA) the emission calculation of inland navigation was updated and improved. A broad research for typical input data was carried out and integrated in a detailed emission calculation model for inland navigation. The new data and results were integrated in the German emission inventory model for the transport sector TREMOD (Transport Emission Model).

For the volume of freight transport on inland waterways a dataset of high resolution was obtained by the German Federal Statistic Bureau. The statistics provide detailed information about the mileage by ship characteristics and freight types for individual regions and waterways in Germany. Most vessels on German inland waterways run under Dutch flag and about 80% of the transport take place on free flowing river sections of the Rhine River.

The fuel demand is calculated with a bottom-up approach. It bases on a regression function which considers the ship type and size, the capacity load factor, the type of waterway and flow direction. The specific fuel consumption factors were crosschecked and validated with values from literature and measurements. A comparison with international bunker statistics (for Western Europe) in 2011 proved a good correlation between the top-down fuel consumption of 9.3 g Diesel per ton-km and 9.1 g/ton-km in the bottom-up model.

Specific emission factors for regulated pollutants (NOx, PM, CO, HC) were derived from a broad basis of engine measurements and literature data. The emission data was evaluated for the main engines by their year of construction. Through a research of the inland ship fleet and its engines in use, the emission factors could by assigned to the transport and energy consumption data. Thus, specific emissions of the current fleet - which are lower for large vessels because of their lower engine age - as well as future emissions can be plausibly modelled.

The new emission model offers additional opportunities compared to the previous aggregated approach in TREMOD:

- Better database for national emission inventory reporting.
- Illustration of the influence of transport activity data on “average” specific fuel consumption and emission factors
- Supply of regional and local data for state or municipal emission cadastres.
- Detailed assessment of trend and policy scenarios regarding shifts in fleet or freight composition, introduction of new emission limits and alternative technology or fuel choices

Background

Inland navigation has a significant role in freight transport in several European countries, in Germany, currently accounting for approximately 10% of the freight volume (in ton-km). In the context of emission reporting for greenhouse gases (Kyoto protocol) and air pollutants (NEC directive), the sector has been considered in the German emission inventory since the 90s.

However, contrary to other transport modes and especially road transport the data and methodology for inland navigation was not updated and improved appreciably in the past years. Thus, the German emission inventory model for the transport sector TREMOD (Transport Emission Model) used aggregated data based on global emission factors (mass per ton-km) and the transport performance of the total fleet. This approach would not allow an adequate temporal and spatial differentiation of the freight and vessel fleet structure.

Thus, in recent research projects for the German Federal Environment Agency (UBA) the emission calculation of inland navigation was updated and improved. A broad research for typical input data was carried out and data, methodology and trends were discussed in an expert workshop with important stakeholders. The results of the study are processed in a new detailed emission calculation model for inland navigation named TREMOD-NA (navigation) and integrated in TREMOD.

This paper focuses only on the main elements of the emission model TREMOD-NA. Comprehensive information about the research project is available in a report for the German Federal Environment Agency (UBA) in German (IFEU and INFRAS, 2013).

General approach of the model

The general approach for the emission inventory model is based on a bottom-up calculation. The emissions are calculated as a product of transport activity, specific energy consumption and specific emission factors for very individual layers of vessel, freight and waterway characteristics in a reference year[1] (Figure 1). The result of the calculation is the energy consumption and the emissions of a reference year for different pollutants (NO_x, PM, CO, HC, CH_4, N_2O, NH_3, N_2O, NO_2 and SO_2 and NMHC fractions).

As Figure 1 demonstrates, the highest data resolution is given for transport activity, whereas specific energy consumption and emission factors are used on more aggregated levels according to the data quality and relevance of each characteristic. The different sources and the processing of the data for these parameters are explained in the following sections.

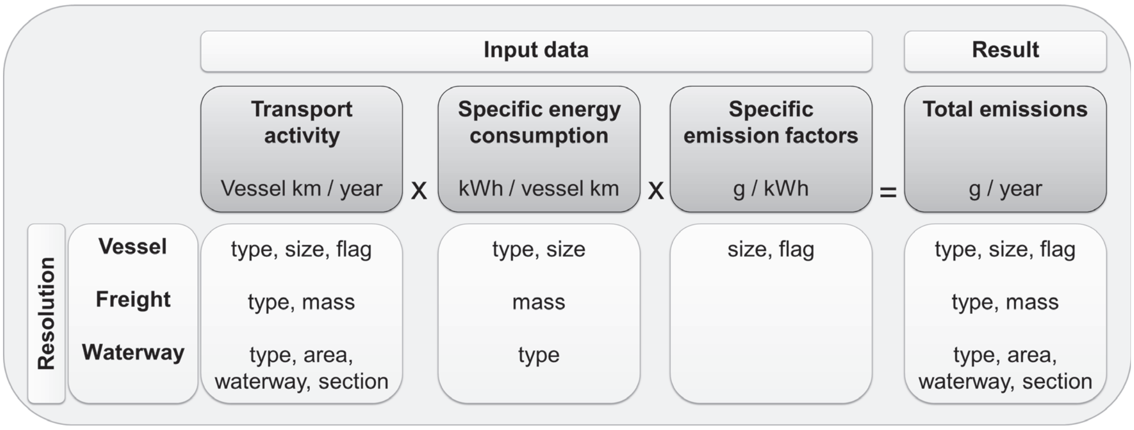

Figure 1: General approach for emission calculation and resolution of input data in TREMOD-NA

Transport activity data

Transport activity data of freight transport on inland waterways is available in official statistics of the German Federal Statistic Bureau (DESTATIS, 2013). Since 2009, the statistics provide very detailed information about the transport performance (ton-km) and mileage (km) by ship characteristics and freight types for individual regions and waterways in Germany. The data is compiled in a comprehensive survey based on obligatory questionnaires for ship owners in inland ports and selected watergates. An overview of the transport performance share in 2010 is given in **Figure 3**. In general, transport performance of inland navigation in Germany is dominated by the following characteristics:

- Ship/Freight type: Freight motor vessels transporting dry bulk goods
- Ship size: Vessels with a dead weight tonnage > 1,000 tonnes, mostly 2,001-3,000 tonnes
- Waterways: Free flowing rivers (especially the Rhine river)
- Ship flag: Vessels with a Dutch or German flag
- Transport relation: International transports (export, import and through transport)

[1] Due to the data quality of activity statistics, the shown resolution is only convenient since the year 2009. A more aggregated approach is used for past years and future scenarios (until 2030) so far.

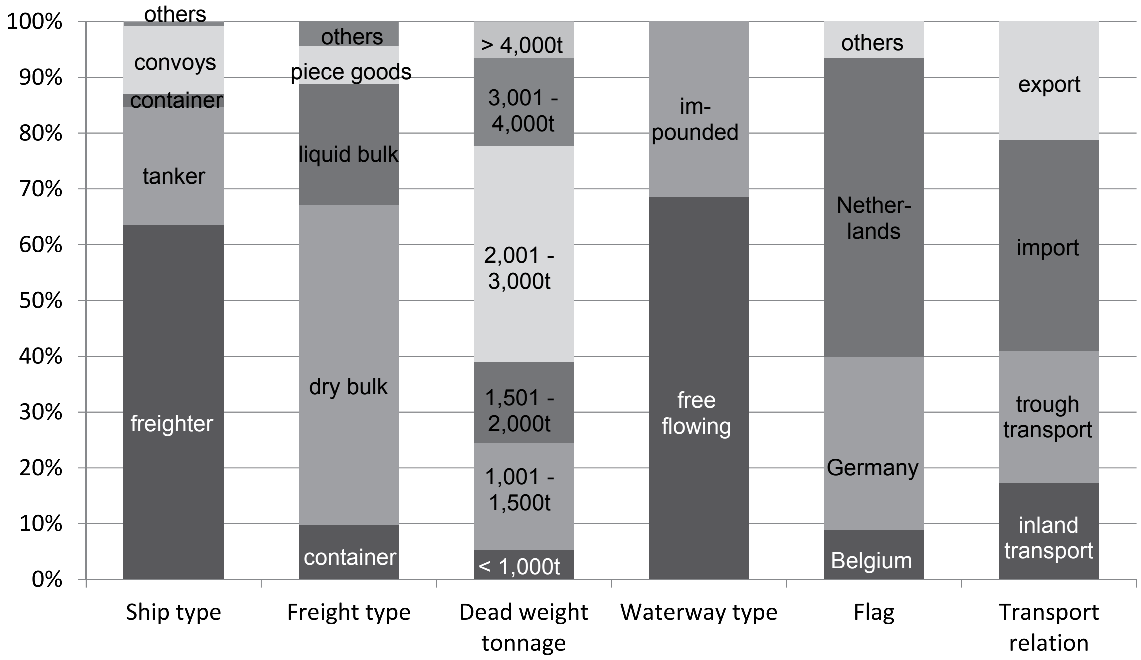

Figure 2: Share of transport performance (ton-km) in inland navigation by different characteristics in Germany, 2010

Though, the level of detail of the transport activity statistics is very high, the data could not be used unprocessed for emission calculation. This is mainly due to the fact that the statistics focus rather on the freight and not on the vessels. As a consequence a) empty trips are not included; b) the distance covered by freight may be higher than the mileage of the vessel if freight is transported in several consignments (e.g. for different recipients) and c) transport with convoys is registered only for lighters (unmotorized freight vessels), so the mileage is overestimated if more than one lighter is part of a convoy[2].

Thus, to derive a complete and realistic mileage for the emission model, the following additional assumptions had to be taken:

a) Additional empty trips were derived from Watergate reports counting the number of empty and loaded vessels: they indicate that dry bulk transports have about 35% additional empty trip km and liquid bulk transports 80% (especially downriver trips occur without freight) additional empty trip km

b) Bulk transports (dry and liquid) which have the major part in transport performance mostly occur in one consignment, so the mileage of the freight is similar to the mileage of the vessel. Container transports mostly consist of several consignments. The freight mass and mileage of container transports is, therefore, bundled to receive a typical load factor of 60% of the dead weight tonnage of a vessel.

c) Convoys are generated following the limitations due to the waterway quality (CEMT class). Thus, big convoys with six lighters occur only on large waterways, e.g. Rhine River. In this case the mileage for such a convoy would be reduced by factor six.

The most significant changes in the activity data due to the assumptions are listed in Table 1. For freighters and container ships the mileage decreases due to the bundling of container transports[3]. For these ship types, also the load factor of the average dead weight tonnage increases. Additional empty trips lead to increased mileages and lower load factors for tankers, for freighters the effect is overcompensated due to adjustment for container transports, since freighter also carry containers. Last, for convoys the mileage decreases compared to the original data for individual lighters. However, tanker convoys are also strongly affected by the high share of empty trips while for freighter convoys fewer empty trips are assumed.

[2] Convoys with one or several lighters are usually moved by motorized push or tug boats
[3] though the main freight type of freighter ships is dry bulk, they have also a relevant share in container transport

Table 1: Changes in transport activity data after adjustment by ship type in 2010

Ship type	Distance passed/ mileage in 1000 km		Mio. ton-km	Ø DWT in tonnes		Capacity load factor (freight mass/DWT)	
	ori.	adj.	ori. / adj.	ori.	adj.	ori.	adj.
freighter	43,787	36,653	39,557	2,310	1,904	39%	57%
tanker	7,984	14,369	13,180	2,140	2,142	77%	43%
container ship	7,004	753	1,432	3,855	3,169	5%	60%
freighter convoy	8,583	3,969	7,644	1,911	3,194	47%	60%
tanker convoy	203	192	384	1,975	3,816	96%	52%
other	58	64	82	1,657	1,655	85%	77%

ori: original statistical data, ajd: adjusted data

Calculation of fuel consumption

The adjusted activity data is combined with differentiated specific energy consumption factors**.** To ensure an adequate level of differentiation, a simplified bottom-up approach was chosen basing on the following formula for the energy consumption of the main propulsion engines of inland vessels[4] (Planco, 2007):

$$EC = D\ x\ \frac{P_{engine}\ x\ LF_{engine}\ x\ EC_{engine}}{v_{water} \pm v_{current}}$$

With:

- EC = Energy consumption of an inland vessel for a distance D (kg)
- D = Distance covered by an inland vessel (km)
- P_{engine} = Average engine power for a ship size class (kW)
- LF_{engine} = Average load factor for defined draught, water depth and vessel velocity against water
- EC_{engine} = Energy consumption of the engine = BSFC (kg/kWh)
- v_{water} = Velocity against water (km/h)
- $v_{current}$ = Velocity of the current

The formula indicates that total energy consumption is the product of the mileage of a ship, and a number of other parameters which influence specific energy consumption (installed power, load factor and break specific fuel consumption of the engine; velocity of the current and of the ship against water).

Parameters such as the average engine power (P_{engine}), the break specific fuel consumption of the engine (EC_{engine}) and the velocity of the current ($v_{current}$) can be rather easily defined. The engine power depends on the ship type and the ship size (dead weight tonnage) and can be given by a linear function. The specific fuel consumption of inland vessel engines is often stated as a constant value of approximately 0.2 kg Diesel per kWh engine power (TNO, 2010; Planco, 2007; VBD, 2004). The current velocity can be given as average values for a river section, e.g. 6 km/h for the Rhine river (VBD, 2001 und 2004).

More difficult is the definition of the engine load factor (LF_{engine}) and the ship velocity against water (v_{water}). The engine load factor depends on the ship type, the draught[5], the water depth and the ship velocity. The ship velocity depends on the ship type, the level of load and type of waterway. On free flowing rivers the flow direction (up- or downriver) has an influence on the engine load factor. In general, the load factor of an engine and specific fuel consumption decrease as ship velocity decreases.

[4] The energy consumption of auxiliary engines in freight transport is estimated to be comparably low. Basing on different literature data a constant share of 5% of the main propulsion engines fuel consumption was assumed.

[5] Depth between water surface and the bottom edge of the ship depending on the load level

Due to these influences and in combination with the activity data, the specific fuel consumption factors were derived as values in kg Diesel per km differentiated by

- the type of ship (motor vessels vs. pushed convoys),
- the ship size given as dead weight tonnage,
- the waterway type (free flow, impounded or canal) and except for canals,
- the flow direction (up or downriver)

All the needed factors for the above given formula were derived from different literature source. Thus, from a pool of consistently calculated specific fuel consumption factors regression functions were generated to enable a calculation for each layer of the transport activity data set. As an example, two of these functions are given in **Figure 3** and **Figure 4**. Both figures indicate that specific fuel consumption decreases relatively to the vessel's dead weight tonnage. Thus, larger ships have lower energy consumption per tonne of freight if the capacity load factor (in this case only full or empty) is similar.

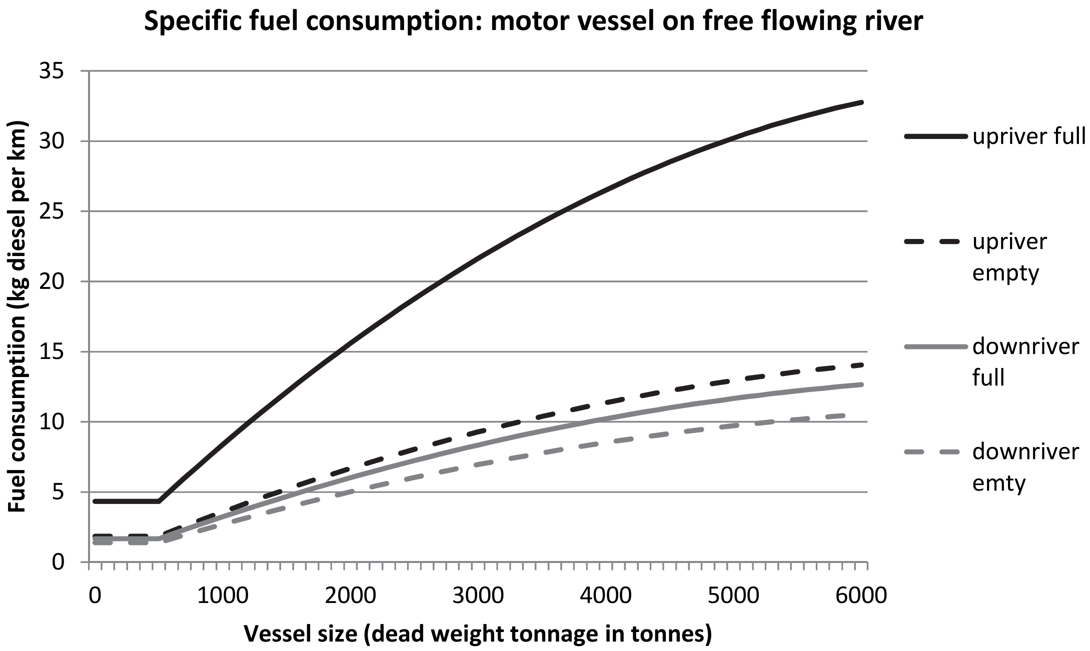

Figure 3: Specific fuel consumption functions for motor vessels on free flowing rivers

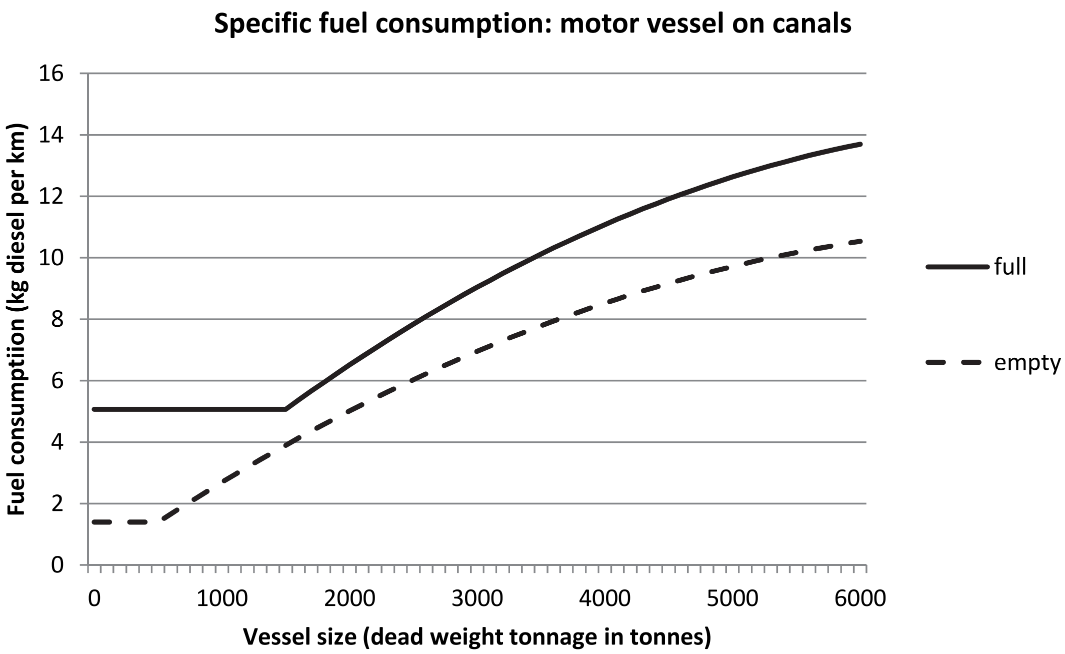

Figure 4: Specific fuel consumption functions for motor vessels on canals

As a crosscheck, the average specific fuel consumption per ton-km by the simplified bottom up approach was compared with bunker statistics for inland navigation. For this purpose instead of national energy balance data from the Federal Office of Economics and Export Control (BAFA)[6] an investigation by the Central Commission for the Navigation on the Rhine (CCNR) was used. The CCNR derived fuel consumption balances based on CDNI[7] data. A comparison which was only possible for the reference year 2011 proved a very good correlation between the top-down fuel consumption of 9.3 g Diesel per ton-km and 9.1 g/ton-km in the bottom-up model. The comparison indicates that despite the insecurities of the parameters in the bottom-up calculation, it is possible to give plausible specific energy consumption factors for a differentiated and detailed emission inventory model.

Calculation of pollutant emissions

The energy consumption, given as used power (kWh), also provides a link to the specific emission factor which can be expressed – according to the engine emission regulations – as mass of pollutant per kWh.

The emissions inland vessels engines (NOx, PM, CO and HC) are regulated in the context of the Rhine Vessel Inspection Regulations (RVIR) by the CCNR and EU directive 97/68/EC. The stages I and II by CCNR were introduced in 2002 and 2007, respectively, and EU stage IIIA between 2006 and 2008 depending on the engine size. Beside the regulation limits, especially for older engines, the specific emissions depend on technical parameters such as the rated speed and power, engine pressure and the engine settings. Due to limited data, it is assumed that the influence of technical parameters and engine settings can be expressed by the year of engine manufacture. Thus, specific parameters such as rated speed and power or swept volume are considered as average characteristic for a manufacture year.

Operation characteristics e.g. the engine load profile are relevant for “real world” emission factors, too. Since only little information was available on the emissions for different operation points, it is assumed that the type approval values (measured in E2, E3 cycle) are representative for the average operation profiles of inland vessels.

Input data for the specific emission factors were obtained by engine test measurements from different sources (Table 2). Additional data from literature was used to supplement the emission factors for older engines (TNO, 2010; Oonk et al, 2007).

Table 2: Overview of data sources for emission measurements from engine tests

Source	WTZ 2011	BfG 2001	ZSUK
Number of engines/tests	38	13*	363
Year of manufacture	1987 - 2011	1966 - 2000	2001 - 2013
Rated power in kW	450 - 3880	132 - 5400	25 - 3000
Rated speed in min-1	375 - 1800	375 - 1800	750 - 4300
* not for all pollutands			

The average emission factors of regulated pollutants for engine manufacture years since 1965 are demonstrated in **Figure 5**. While CO and PM emissions continuously decrease for newer engines, NOx emissions temporarily increased until the introduction of emission CCNR I in 2002 and later emission limits. This can be explained by technical measures for an increased engine pressure and temperature since the 1970s (BfG, 2001).

[6] In previous evaluations it was found that national data for BAFA have very strong annual fluctuations which cannot be explained with fluctuating transport performances. It is assumed that so called tank tourism (fuel supply and consumption at different countries) may be a main reason for this fluctuation.
[7] International convention on the collection, deposit and reception of waste produced during navigation on the Rhine and other inland waterways which contains a fixed fee per litre diesel.

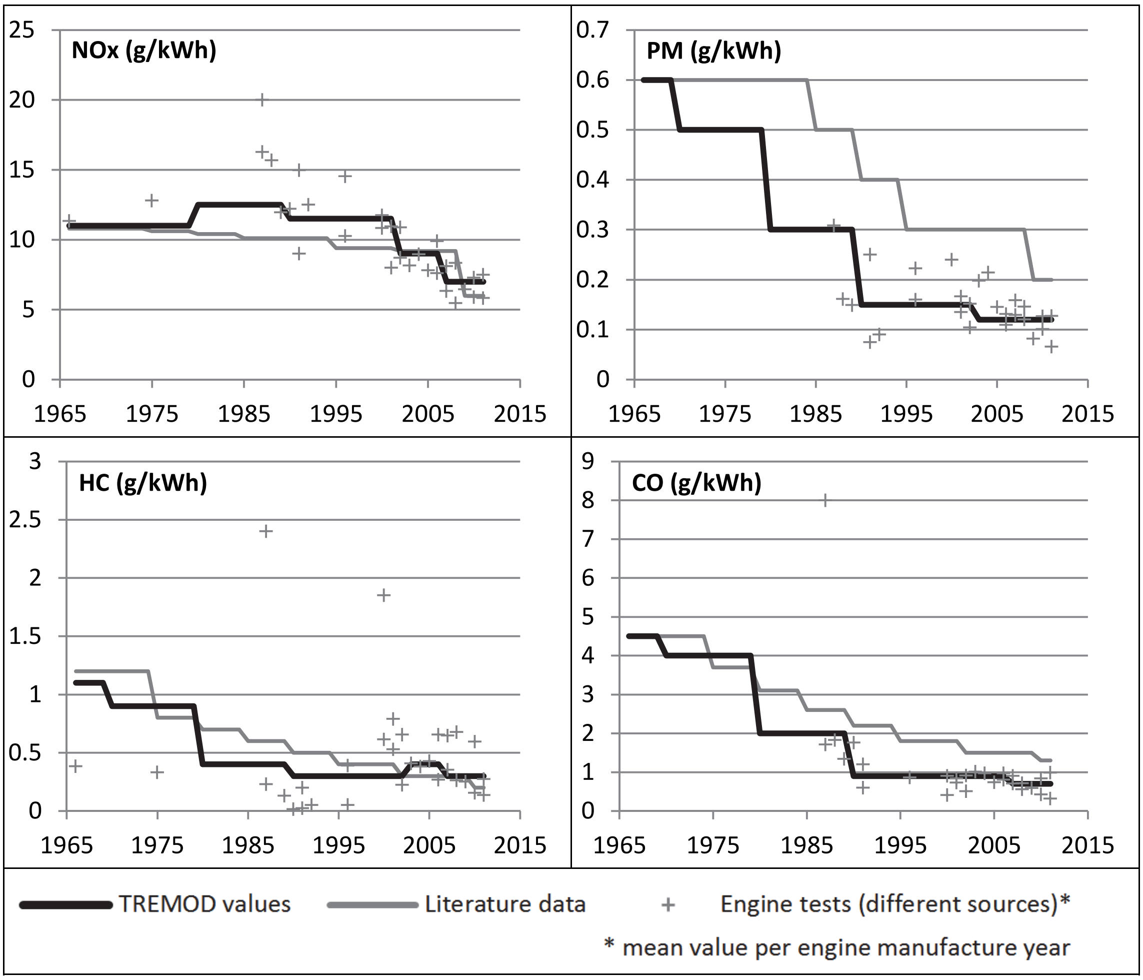

Figure 5: Emission factors for inland vessels binned by year if engine manufacture

While on the one hand, emission factors strongly depend on technical characteristics of and the manufacture year of the engines, on the other hand, this information is not given in the transport activity data. Therefore, for applying the emission factors in g/kWh to the emission model additional research was necessary.

The age distribution of inland vessel engines is partly recorded in national ship registers. However, in most cases this only applies for type approved engines which came into market after 2003. Some additional information for older engines was obtained from literature (BfG 2001). To generate a complete dataset for the age distribution of the engines in the inland vessel fleet in 2010 and later, the available engine data was supplemented with an engine scrapping modeling approach.

This approach bases on the ship registers of Germany and the Netherlands which contain the manufacture year of the vessels. It is assumed that the first engine in a vessel is scrapped with a likelihood function based on the engine age and a median lifetime: 100% of new ships have their first engine, after the median life time 50% of the engines remain and when the engine age reaches the double of median life all engines are scrapped. Median life times were determined according to literature (Planco 2007, CCNR 1999) and assume a longer life for old engines:

- Engine manufacture before 1990: 38 years
- Engine manufacture in 1990-1999: 20 years
- Engine manufacture since 2000: 12 years

While the scrapping approach is a rough estimation for the engine composition of the present fleet, this approach further enables an estimation of engine compositions in scenarios as well.

Analyzes of the engine age distribution in comparison with fleet characteristics show that ship nationality (flag) on the one hand, and ship size (DWT) on the other hand are critical parameters for a differentiation of emission factors in the ship fleet. The result for the distribution of engines by age classes/emission standard is demonstrated in **Figure 6**. In general small vessels have older engines than large vessels. Also, ships running under Dutch flag are supposed to have newer engines. This may be primarily attributed to higher construction rates of new ships in the Netherlands, but federal engine renewal programs may also have an impact.

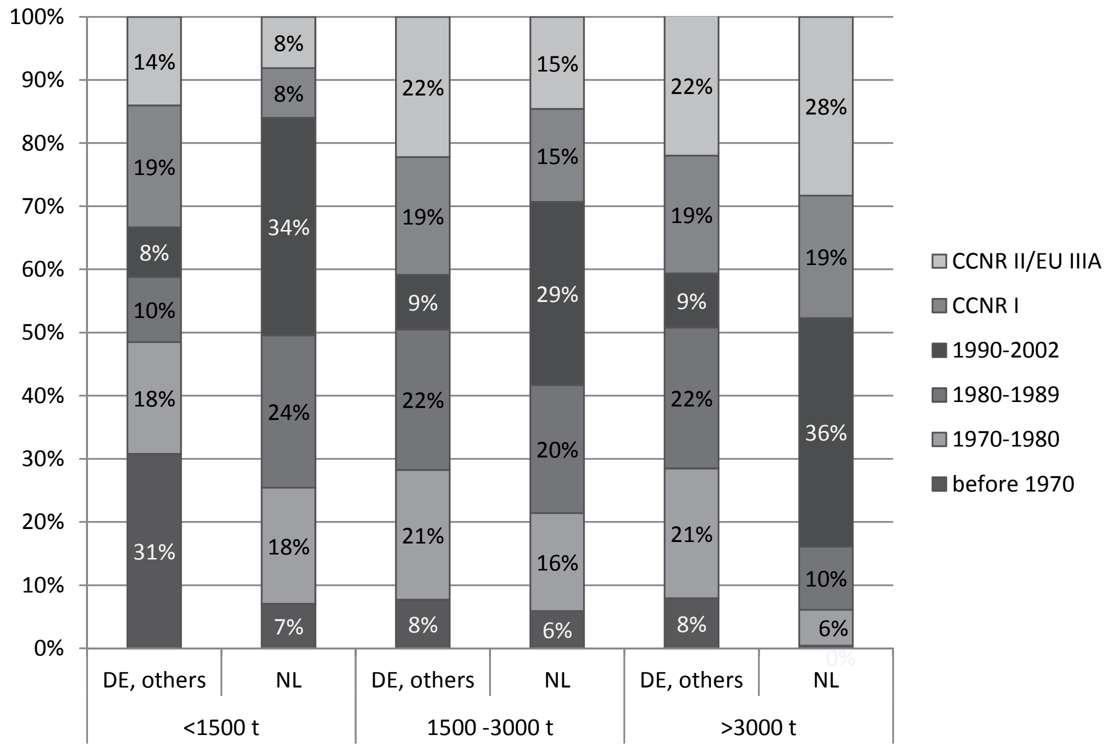

Figure 6: Fleet composition by engine age/emission standards differentiated by vessels size and flag

Results and conclusions

The following chapter only presents some results for the emissions from inland navigation, for the development of the model itself was the major task within the presented research project. However, important aspects regarding a) national emission inventory reporting, b) average specific fuel consumption factors c) availability of regional data and d) future trend or policy scenarios shall be discussed.

For **national emission inventory** reporting, the detailed model gives more accurate and topical data compared to the previous approach in TREMOD (until version 5.3). The main differences, listed in Table 3, are:

- The total diesel consumption is about 5-13% lower than in TREMOD 5.3. The differences between the reference years indicate that not only the total transport performance in ton-km (only basis of the old approach) but also fleet characteristics have an influence on the energy consumption. With the detailed approach, relatively higher diesel consumption is found for 2011 due to lower capacity loads of large vessels (see next section).
- Due to differentiated emission factors and fleet composition, the pollutant emissions are lower than in the previous calculations: A high decrease is found for HC (up to -49 %), followed by PM (-37 %), CO (-21 %) and NOx (-19 %). This decrease in the pollutant emissions seems plausible by a comparison with more recent sources for average national emission factors e.g. from (Planco, 2007) and (TNO, 2010) (see IFEU/INFRAS, 2013).

Table 3: Changes in national emissions of inland navigation due to the new model

Component	Version	2010	2011	2012
	Values in tonnes per year			
	TREMOD 5.3	597,384	527,720	560,487
	Detailed model	519,955	499,006	485,155
Diesel consumption	Difference	-13%	-5%	-13%
	TREMOD 5.3	1,899,085	1,677,621	1,781,788
	Detailed model	1,652,938	1,586,339	1,542,309
CO2	Difference	-13%	-5%	-13%
	TREMOD 5.3	6,037	5,332	5,653
	Detailed model	5,042	4,438	4,438
CO	Difference	-16%	-17%	-21%
	TREMOD 5.3	2,515	2,222	2,355
	Detailed model	1,338	1,260	1,197
HC	Difference	-47%	-43%	-49%
	TREMOD 5.3	33,380	29,107	30,459
	Detailed model	27,046	25,724	24,691
NOx	Difference	-19%	-12%	-19%
	TREMOD 5.3	1,067	938	991
	Detailed model	702	659	623
PM	Difference	-34%	-30%	-37%

Annual differences of the **specific energy consumption** also illustrate the coherence between activity data and the average specific fuel consumption. While larger ships in profit from lower fuel consumption per ton-km for similar capacity load factors, this effect does only partly apply in the current fleet. Temporal influences such as lower water levels in 2011 can additionaly limit the capacity load factor of large ships and thus increase their specific fuel consumption (**Figure 7**).

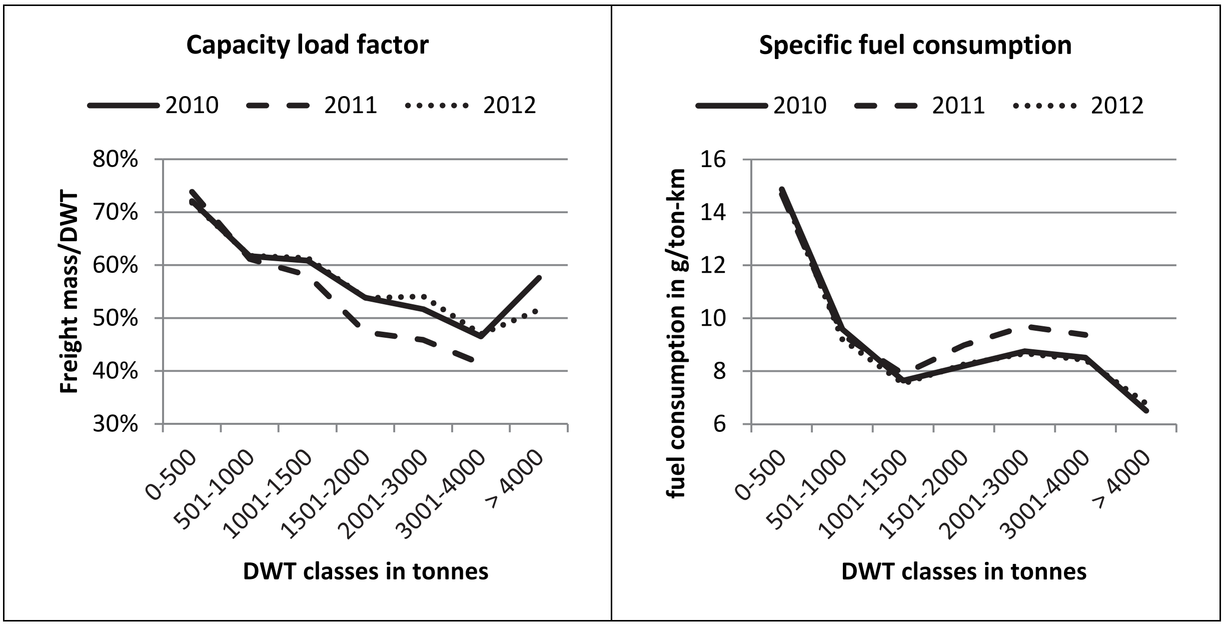

Figure 7: Average capacity load factor and specific fuel consumption by ship size (DWT) in 2010-2012

Due to the high resolution of the transport activity data, it is possible to provide **regional data** differentiated by individual waterway sections. Such emission data can be used for state or municipal emission cadastres as a basis of air quality plans since municipalities not always have the data and resources for a detailed calculation of inland navigation emissions. An extract of the results for transport activity and fuel consumption for the Rhine are is given in Table 4.

Table 4: Activity data and fuel consumption for waterway section in the Rhine area

Waterway section	Type	CEMT class	Length	Transport performance	Diesel consumption	
			in km	in Mio ton-km	tonnes	g/ton-km
Rhine, Rhinefelden to Straßburg	impounded	VIb	52	75	600	8.0
Rhine, Straßburg to Neuburgweier	impounded	VIb	59	1,337	11,512	8.6
Rhine, Neuburgweier to Mannheim	free flow	VIb	83	2,794	21,423	7.7
Rhine, Mannheim to Bingen	free flow	VIb	92	4,657	38,037	8.2
Rhine, Bingen to Lülsdorf	free flow	VIb	137	8,985	75,173	8.4
Mosel	impounded	Vb	242	2,799	24,556	8.8
Saar, Völklingen to Güdingen (border)	impounded	I	40	10	82	8.5
Saar, Mosel to Völklingen	impounded	Vb	60	255	2,068	8.1
Rhine, Lülsdorf to Orsoy	free flow	VIc	128	11,214	93,745	8.4
Rhine, Orsoy to Dutch border	free flow	VIc	72	10,596	92,127	8.7
Schiffahrtsweg Rhine-Kleve	impounded	VIc	10.0	0.01	0.1	13.3
Main, estuary of Main-Danube-Kanals to Würzburg	Canal	Va	141	843	5,975	7.1
Main, Würzburg to Aschaffenburg	impounded	Va	167	1,189	12,977	10.9
Main, Aschaffenburg to Offenbach	impounded	Vb	41	365	3,976	10.9
Main, Offenbach to Rhine	impounded	Vb	39	513	5,429	10.6
Neckar, Heilbronn to Rhine	impounded	Va	109	733	6,352	8.7
Neckar, Stuttgart to Heilbronn	impounded	Va	77	170	1,626	9.5
Neckar, Plochingen to Stuttgart	impounded	Va	15	12	115	9.9
Rhine are, Lahn, Main, Mosel, Neckar, Saar			*1,564*	*46,548*	*395,774*	*8.5*
All waterways in Germany			*6,312*	*58,491*	*485,155*	*8.3*

In **trend or policy scenarios** a detailed inventory model gives the opportunity to estimate the effects of different influencing factors. The current trend scenario in TREMOD considers basic developments until 2030 such as a further shift from smaller to larger vessels; faster engine renewal rates and the introduction of new emission limits (see IFEU/INFRAS 2013). Additional trends will be considered in following updates (after 2016) to enable a more detailed trend scenario (e.g. shift in freight types or detailed assessment of fuel efficiency potentials from technical and operational measures).

Other aspects such as technology or fuel choices are currently also discussed on a European level and could be the focus of policy scenarios, e.g.:

- Alignment of the European emission legislation for inland vessel engines with stricter stage Tier III standards for maritime vessels or even Euro VI for heavy duty vehicles, see (COM, 2013b)
- Development of an alternative fuel infrastructure for inland navigation, especially for liquefied natural gas (LNG), see (COM, 2013a)

A closer understanding of the waterway, freight, vessel and engine composition in inland navigation will improve to modelling of impacts from such aspects in future scenarios.

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