Emission estimates for diffuse sources
Netherlands Emission Inventory

Exhaust from recreational boats

Version dated June 2008

NETHERLANDS NATIONAL WATER BOARD - WATER UNIT
in cooperation with DELTARES and TNO

Exhaust from recreational boats

1 Description of emission source

Conventional outboard motors discharge their exhaust gases under water, in the propeller eddy. Inboard motors generally utilize wet exhaust to cool the exhaust gases [1]. The STOWA report "Watervervuiling door motoren van pleziervaartuigen" [2] assumes that a fraction of the exhaust gases ends up in the water.
The emission to the water phase relates only to the portion of the contaminants in the exhaust gas that comes directly from the exhaust and remains in the water phase. This fact sheet does not cover indirect contamination through atmospheric deposition.

2 Explanation of calculation method

The emissions are calculated by multiplying an activity rate (AR), the number of recreational boats subdivided into open and cabin motorboats and open and cabin sailboats, by the average fuel consumption per boat type times the emission factor (EF) per substance, expressed in emission per engine type per quantity of fuel. A specific distribution of motor types that determines the values of the emission factors is assigned to the various types of boats.

The emission factors are measured in quantity of emission per quantity of kinetic energy generated. Dividing by the specific fuel use (quantity of fuel required per quantity of kinetic energy generated) produces an emission factor per quantity of fuel.

Water emissions occur with engines equipped with underwater exhaust gas systems and with wet exhaust systems. The distribution of types of engines per boat type changes over time.

$$E_s = \Sigma_t \left(N_t \times B_t \times U_t \times F_{t,,m} \times EF_{m,s} / S_m \right)$$

Where:

E_s = emission of substance (s), kg

N_t = number of boats of type (t), units

B_t = average fuel consumption of boat type (t) per hour, kg/hour

U_t = average number of sailing hours of boat type (t), hours/year

$F_{t,,m}$= fraction of boats of type (t) equipped with motor type (m), fraction

$EF_{m,s}$= emission factor of substance (s) by engine type (m) per amount of power, (kg/kwh)

S_m = specific fuel consumption of engine type (m), kg/kwh

3 Activity rates

The activity rate is the number of recreational boats. The number of boats is subdivided into cabin motorboats, cabin sailboats, open motorboats and open sailboats. This inventory is based in part on statistics from the Statistics Netherlands [5] and based in part on ICOMIA figures [13]. The Statistics Netherlands has no data in this area more recent than from 1996. The 1997 figures are based on data collected by the “Stichting Recreatie” [6], and the 2004 figures are based on figures from a study by a consultancy company “Waterrecreatie Advies” [18]. The figures for the years between 1997 and 2004 are extrapolations, and the figures for 2005 and 2006 were kept constant.
Additionally, it is assumed that 35% of motorboats are speedboats. This estimate of the number of speedboats is based on the statistical material reported in [7]. The results of the estimate are confirmed by a notice by the Road Transport Directorate (RDW) [8]. Here, the term "speedboats" is used to include not only high-speed motorboats but also jet-skis, or "Personal Watercraft" (PWC). The number of speedboats is necessary for accurate estimation of fuel consumption.

Table 1: Time series of the number of boats, by type, units

Year	Open sailboat	Cabin sailboat	Cabin motorboat	Open motorboat	Open speedboat
1985	61,660	30,830	46,245	16,032	8,633
1990	59,623	29,811	44,717	15,502	8,347
1995	94,340	47,170	70,755	24,528	13,207
1997	100,000	50,000	75,000	40,000	14,000
2000	76,283	63,517	68,854	40,870	22,007
2005	44,660	81,540	60,660	60,697	32,683
2006	44,660	81,540	60,660	60,697	32,683

The fuel consumption per boat was investigated by the “Watersportberaad”, a consultative body for water sports [7]. The results of this study are shown in the table below.

Table 2: Fuel consumption per boat per type

Boat type	Engine hours (hours/year)	Consumption (kg/hour)
Open sailboat	20	1.95
Open motorboat	70	1.52
Open speedboat	56	5.09
Cabin sailboat	60	2.40
Cabin motorboat	126	3.74

4 Emission factors

Emission factors for carbon monoxide, non-methane volatile organic carbon and nitrogen oxides, as well as several other specific organic components of a variety of engine types, are provided by Samaras [9]. The Netherlands Emission Inventory [10] gives specific emission factors for two-stroke engines. The distribution of gaseous components over water/atmosphere by outboard motors is adopted from Rijkeboer [4]. Additionally, it is assumed that half of all inboard engines have a wet exhaust system and that the distribution of the emissions over water and atmosphere for wet exhaust systems are the same as with outboard motors.
These assumptions result in table 3, below.

Table 3: Percentage of water emissions per component group (%)

	Outboard motors	Inboard motors
VOCs (hydrocarbons and PAH)	40	20

Emission profiles for polycyclic aromatic hydrocarbons (PAH) and various other hydrocarbons from two-stroke motors directly into the water phase are also given by Kelly [11]. Kelly provides analysis of data measured at different loads and with different lubricants. Because there does not appear to be a direct relationship between PAH emissions and load or lubricant, all Kelly measurements are averaged. For a number of PAH components, no measurement value was available. The concentrations of these components are further estimated, relying on the assumption that the concentrations of PAH components with the same molecular weight are often in the same order of magnitude. Table 4 shows these components in italics.

The PAH emissions of low emission (LE) two-stroke and four-stroke engines are derived from the Kelly data by correlating them with the average NMVOC emission of these engines in accordance with the data from Corinair or the emission inventory.

Finally, for each specific component in the exhaust gases, a distribution of the component over the water phase and gas phase is estimated [4]. This is only done for emissions estimated using Samaras and Veldt [9, 10]. The emission factors for PAH from diesel fuels are derived by multiplying the VOC emission factor from Samaras by the "conversion factors" from the emission inventory [12] for VOC components and PAH components. It is assumed that 20% of total emission goes directly into water, because all diesel engines are installed as inboard motors.

Table 4: Emission factors into water for different engine types in recreational boats (g/Kwh)

Component	2-stroke	2-stroke (LE)	4-stroke#	Reference	D	Reference
PM	0.28	0.16	0.04	9	0.10	6
VOC	90	30	3.6	9	0.46	6
Benzene	0.90	0.45	0.16	9	8.7E-03	10
Toluene	2.7	0.9	0.49	10	6.4E-03	10
1.3-butadiene	0.15	0.075	0.027	10	1.5E-03	7
Formaldehyde	0.99	0.33	0.04	10	2.6E-02	12
Naphthalene	1.7E-04	5.7E-05	7.0E-06	11	3.1E-03	12
Phenanthrene	2.3E-04	7.6E-05	9.3E-06	11	2.2E-04	12
Acenaphthylene	2.8E-06	9.4E-07	1.1E-07	11	5.5E-05	12
Anthracene	5.1E-06	1.7E-06	2.0E-07	11	5.7E-05	12
Fluoranthene	9.7E-06	3.2E-06	3.9E-07	11	3.1E-05	12
Benzo[a]anthracene	*3.3E-05*	*1.1E-05*	*1.3E-06*	*11**	9.6E-06	*12*
Benzo[b]fluoranthene	*3.3E-05*	*1.1E-05*	*1.3E-06*	*11**	7.7E-06	*12*
Benzo(k)fluoranthene	3.3E-05	1.1E-05	1.3E-06	11	2.9E-06	12
Indeno(1,2,3-c,d)pyrene	2.8E-06	1.0E-06	1.2E-07	11	4.6E-10	12
Benzo[g,h,i]perylene	*2.8E-06*	*1.0E-06*	*1.2E-07*	*11**	1.2E-06	*12*
Benzo(a)pyrene	3.3E-05	1.1E-05	1.3E-06	11	7.7E-06	12
PAH (VROM-10)	**5.22E-04**	**1.74E-04**	**2.11E-05**		**3.5E-03**	
PAH (Borneff 6)	**1.10E-04**	**3.67E-05**	**4.34E-06**		**7.7E-05**	

* The concentrations of these components are estimated, relying on the rule that the concentrations of PAH components with the same molecular weight are often of the same order

For the 4-stroke inboard motors, these emission factors are further divided by two (see table 3).

Specific fuel consumption of the engines

To convert the emission factors by emission per quantity of fuel, a specific efficiency (fuel consumption per unit of drive energy generated) of the various engine types has to be assumed. This conversion uses the values shown in the table below.

Table 5: Specific fuel consumption and fuel for individual engine types, (kg/Kwh)

Engine type	Specific consumption	Fuel
2-stroke	0.4	Petrol
2-stroke LE	0.35	Petrol
4-stroke	0.35	Petrol
D	0.25	Diesel
PWC	0.4	Petrol

Technical composition of the fleet of recreational boats

Rijkeboer estimates the distribution of engines, by engine type, for the Netherlands [4]. This distribution is based on data from the Royal Dutch Touring Club (ANWB) up to the early 1990s, and the quantities and types of outboard motors purchased since then. This assumes that motorboats with cabin are primarily equipped with inboard diesel engines, and most boats of the other types are equipped with outboard motors. The shift from 2-stroke engines to LE 2-stroke engines and 4-stroke engines in the period from 1995-2015 is based on interpretation of/extrapolation from the ICOMIA statistics [13] by Van der Wal [3].

Table 6: Technology mix in 1995, (% of total fleet)

	2-stroke	2-stroke LE	4-stroke	D
Outboard	60	1	4	0
Inboard	0	0	5	29
PWC	0.2	0.2	0.2	0

Table 7: Technology mix in 2005, (% of total fleet)

	2-stroke	2-stroke LE	4-stroke	D
Outboard	27	6.4	32	0
Inboard	0	0	5	29
PWC	0.2	0.2	0.2	0

Table 8: Technology mix in 2015, (% of total fleet)

	2-stroke	2-stroke LE	4-stroke	D
Outboard	1	15	38.4	0
Inboard	0	0	5	40
PWC	0.2	0.2	0.2	0

Based on table 6, a fraction table is produced listing the distribution by boat type, subdivided by engine type. The supplemental assumption on which the table below is based is that open boats generally have outboard motors, which expel their exhaust gases underwater. This fraction table is shown below with a number of reference years. In this fraction table, the sum of the fractions for each boat type is always equal to 1.

Table 9: Fraction table of engine type over boat type

Boat type	Drive	Underwater exhaust	Engine type	1985	1990	1995	2000	2005	2006
Cabin motorboat	Inboard/Stern	no	4-stroke	14.7%	14.7%	14.7%	14.7%	14.7%	14.2%
Cabin motorboat	Inboard/Stern	no	D	85.3%	85.3%	85.3%	85.3%	85.3%	85.8%
Cabin sailboat	Inboard/Stern	no	4-stroke	14.7%	14.7%	14.7%	14.7%	14.7%	14.2%
Cabin sailboat	Inboard/Stern	no	D	85.3%	85.3%	85.3%	85.3%	85.3%	85.8%
Open motorboat	Outboard	yes	2-stroke	92.4%	92.4%	92.4%	66.8%	41.3%	37.9%
Open motorboat	Outboard	yes	2-stroke LE	1.5%	1.5%	1.5%	5.7%	9.8%	11.3%
Open motorboat	Outboard	yes	4-stroke	6.1%	6.1%	6.1%	27.5%	48.9%	50.8%
Open sailboat	Outboard	yes	2-stroke	92.4%	92.4%	92.4%	66.8%	41.3%	37.9%
Open sailboat	Outboard	yes	2-stroke LE	1.5%	1.5%	1.5%	5.7%	9.8%	11.3%
Open sailboat	Outboard	yes	4-stroke	6.1%	6.1%	6.1%	27.5%	48.9%	50.8%
Open speedboat	Outboard	yes	2-stroke	91.5%	91.5%	91.5%	66.2%	40.9%	37.6%
Open speedboat	Outboard	yes	2-stroke LE	1.5%	1.5%	1.5%	5.6%	9.7%	11.2%
Open speedboat	Outboard	yes	4-stroke	6.1%	6.1%	6.1%	27.3%	48.5%	50.3%
Open speedboat	PWC	yes	2-stroke	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
Open speedboat	PWC	yes	2-stroke LE	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
Open speedboat	PWC	yes	4-stroke	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%

5 Effects of policy measures

The most important emission-reducing measure is the gradual shift from 2-stroke to LE 2-stroke and 4-stroke engines for the individual boat types. As a result of this shift, the average emission factors gradually decrease over time.

6 Emission factors

At present, there is no time series of emission factors available. As soon as new type standard requirements for engines are introduced, these requirements will have to be expressed in the emission factors. The engine type 2-stroke LE, for example, is the result of previously introduced EU-regulation of engine type approval. This regulation causes the increase of such cleaner engines over time.

7 Emissions calculated

The table below shows annual emissions for the various substances expressed in kg/year.

Table 10: Direct emissions into water from recreational boats, (kg/year)

Substance\Year	1985	1990	1995	2000	2005	2006
Particulates	19,140	18,895	20,665	21,671	20,920	20,733
VOC	1,958,540	1,973,542	2,207,685	2,250,685	1,962,320	1,856,131
Benzene	21,398	21,515	24,011	25,902	25,122	24,258
Toluene	61,464	61,872	69,136	73,913	70,440	67,496
1.3-butadiene	3,576	3,595	4,012	4,328	4,197	4,053
Formaldehyde	24,320	24,423	27,220	27,799	24,534	23,382
Naphthalene	418	409	443	461	449	451
Phenanthrene	32.9	32.3	35.1	36.3	34.7	34.5
Anthracene	7.24	7.08	7.67	7.94	7.69	7.72
Fluoranthene	7.64	7.48	8.09	8.38	8.10	8.13
Chrysene	4.17	4.08	4.42	4.58	4.42	4.43
Benzo(a)anthracene	1.93	1.91	2.09	2.16	2.01	1.98
Benzo(b)fluoranthene	1.69	1.68	1.84	1.89	1.75	1.72
Benzo(k)fluoranthene	1.07	1.07	1.18	1.21	1.10	1.06
Indeno(1,2,3-c,d)pyrene	0.06	0.06	0.07	0.07	0.06	0.06
Benzo(g,h,i)perylene	0.21	0.21	0.23	0.23	0.22	0.22
Benzo(a)pyrene	1.70	1.68	1.85	1.90	1.76	1.73
PAH (VROM-10)	474	465	503	524	509	511
PAH (Borneff 6)	12.4	12.2	13.3	13.7	13.0	12.9

The emissions were calculated by multiplying the emission factors from chapter 6 by the activity rate from chapter 3. The effects of the measures are taken into account in the emission factors.

8 Release into environmental compartments

At present, the calculation method is focused only on the calculation of the emissions directly into surface water.

9 Description of emission pathways to water

The full amount of the emissions is discharged directly into the surface water. There are no emissions of this type into the sewer system.

10 Spatial allocation

The spatial allocation of emissions is assigned on the basis of a set of digital maps held by the Netherlands Environmental Assessment Agency (PBL) drawn up using emission records. These maps present the spatial distribution of all kinds of parameters throughout the Netherlands, such as population density, traffic intensity, area of agricultural crops, etc. For the purposes of emission registration these maps are used as 'locators' to determine the spatial distribution of emissions. The range of possible locators is limited (see [19] for a list of available locators), as not every conceivable parameter can be used as a locator. In practice the locator judged to be the best proxy of the activity rate of the emission in question is applied for the distribution of emissions.
It is assumed that the distribution of emissions throughout the country is proportional to the national distribution of the locator.

The table below shows the locator used for the spatial allocation of the various emission sources.

Table 8: Summary of spatial allocation method

Element	Locators
Engine emissions recreational boats	Kilometres recreational boats

The method used to determine the locators is described in [19]:

Kilometres recreational boats
The allocation is determined by multiplying the number of vessels per shipping lane segment by the length of that segment (in kilometres). Here, a distinction is made between sailboats and motorboats, the latter category naturally having significantly more emissions from fuel consumption. Data on the location and length of shipping lane segments were drawn from the shipping lane portion from the database “Nationaal Wegenbestand” (NWB).
The NWB is a file administered by the Traffic and Transport Advisory Service (AVV), an agency of Public Works & Water Management. It is updated annually and contains the position of roads, railways and shipping lanes in the Netherlands, and includes a large number of attributes.
The spatial allocation of emissions is based on the number of sailings per shipping route, as shown in [14].

11 Comments and changes in regard to previous version

Changes were made in the 2007 inventory. The table below compares the results for certain significant substances under the old method [17] and the results from this fact sheet.

Table 11: Results of emission calculation, old and new methods

Substance	Emission old method	Emission this fact sheet	Unit
VOC	2197	1678	tonne
Benzene	90	21	tonne
Toluene	233	59	tonne
PAH (VROM-10)	2046	529	kg
PAH (Borneff 6)	101	13	kg

The most significant difference in results between the old and new methods can be traced back to the use of lower emission factors. On the one hand, the emission factors are lower because a percentage of 40 or 20 percent emissions to water (instead of 60%) was assumed. Additionally, for the petrol engines (in terms of PAHs) the primary source was literature based on direct measurements of PAH emission from outboard motors in water.

The AR was adjusted in the 2008 inventory, using data from a study by the consultancy company “Waterrecreatie Advies” [18]. From 1998 on, the AR has been adjusted by interpolation of the intervening years.

12 Accuracy and indicated subjects for improvement

The method used in Emission Inventory publications has been followed as far as possible in classifying the quality of information [16]. It is based on the CORINAIR (CORe emission INventories AIR) methodology, which applies the following quality classifications:

A: a value based on a large number of measurements from representative sources;
B: a value based on a number of measurements from some of the sources that are representative of the sector;
C: a value based on a limited number of measurements, together with estimates based on technical knowledge of the process;
D: a value based on a small number of measurements, together with estimates based on assumptions;
E: a value based on a technical calculation on the basis of a number of assumptions.

Element of emission calculation	Reliability class
Activity rates	C
Emission factors	C
Distribution among compartments	D
Emission pathways to water	A
Spatial allocation	C

The main subjects where improvements could be made are:
- Better understanding of the contact of the waste gases with the surface water and the distribution of the pollutants over the water or atmosphere compartment;
- The introduction of emission factors for new certified engines;
- Re-evaluation whether the assumption that 35% of the total number of motorboats are speedboats is still fitting with current boat numbers.

13 Request for reactions

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