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Exhaust emissions from in-service inland waterways vessels

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Abstract

Since the early 1990s, significant reductions of the NOx (Nitrogen Oxides) and PM (Particulate Matter) emissions from road transport have been observed, whereas current in-service freight vessels are still often equipped with diesel engines free of emission control. Despite the need for real-world emission data, very few measurements on board freight waterways vessels have been carried out so far, due to both test difficulties and the poor accessibility and availability of commercial vessels. Indeed, only a few hours of emission monitoring could be performed from measurements conducted on-board two freight vessels and a passenger boat, in the frame of a recent project. However, steady-state operating conditions were observed most of the time and reliable functions could be set up to simply derive pollutant emissions from engine speed, respectively for each pollutant (CO_2, NOx, PM and CO) and for each boat. Results in g/kWh are analyzed and confronted with standards. Significant differences are observed between tested vessels, in terms of emissions factors rated per transport unit (g/tonne.km). These factors from current waterways freighters are set against those from heavy-duty trucks.

Keywords: exhaust emissions, on-board measurement, inland waterway vessels, diesel engine

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1 Introduction

As a result of their huge load capacities, inland waterways vessels (IWV) are usually described as an environmentally friendly transport mode, especially when considering CO_2. Indeed, one pusher with 2 fully loaded barges on the river can have the same goods capacity of 150 articulated trucks on the road. Transporting goods in bulk is a significant source of savings, in terms of energy consumption per ton of goods and for many others aspects (manpower, logistical costs…). It is also true that cargo concentration is not adapted to any type of goods or transport, especially when "door-to-door" services or "just in time delivery" is required.

Despite these favourable specific energy consumption and CO_2 emissions, the introduction of exhaust emission limits for inland and marine vessels came late after the first legislation standards imposed to road transport; in addition, the current certification levels remain lenient for marine engines. Consequently, since the early 1990s, significant reductions of NOx (Nitrogen Oxides) and PM (Particulate Matter) emissions from heavy-good road vehicles have been observed, especially with Euro VI requirements, whereas current in-service freight vessels are often equipped with diesel engines free of emission control. Moreover, the long working life of marine engines does not play in favour of a quick renewal towards cleaner engines. It is then suspected that most current IWV have significant emissions of NOx and particulates, and perhaps higher specific emissions than those from heavy-duty trucks (in g/ton.km). Even if the vessels traffic is small compared to the trucks one, it seemed relevant to estimate the levels of air pollutants coming from IWV and to compare them with those given for the heaviest truck class.

The interest of a more environmentally friendly transport mode cannot be only based on fuel consumption and CO_2 reductions; it is also necessary to have cleaner ships in terms of particulate matter, nitrogen oxides and unburned hydrocarbons which are typical of diesel engines and have been pointed out for long as harmful components of the air. The aim is therefore to reduce the impact of the ship traffic on the local air quality, keeping in mind that the traffic of heavy-duty vessels is constantly increasing and that rivers and waterways often pass through or near conurbations.

In this context, one of the objectives of the research program PROMOVAN launched by "Voies Navigables de France" (VNF) was to assess the real exhaust emissions of typical freight vessels during normal operation. One pusher tug with barges and one self-propelled barge could be monitored during usual navigation on the Rhône River. In addition, a passenger boat was tested and emissions from its propulsion engines could be investigated more thoroughly: both port and starboard engines could be measured and most important, the effect of the navigation direction (upstream and downstream) was investigated. The experimental process is described, with emphasis on sampling and exhaust flow determination.

Very few measurements on board freight waterways vessels have been carried out so far, due to both test difficulties and the poor accessibility and availability of commercial vessels. Indeed, only a few hours of emission monitoring could be obtained and analyzed on both freight vessels in the frame of the PROMOVAN project. However, due to the fact that propulsion engines operate mainly in steady-state conditions, reliable functions could be set up to derive simply pollutant emissions from engine speed, respectively for each pollutant (CO_2, NOx, PM and CO) and for each vessel at various engine cruising speeds.

2 Regulatory context

European guidelines to limit pollutant emissions from IVW were introduced only recently (2007 and 2009 for larger engines), hence after the registration of most of the ships in operation today, including the three river vessels we have monitored.

The first environmental regulations for marine engines had previously been set up at a worldwide scale in the frame of the International Maritime Organization (IMO), an agency of the United Nations. In 1958, the first international convention against marine pollution (MARPOL) tackled the oils slicks to prevent environmental disasters on coasts. The “1997 Protocol” added “Regulations for the Prevention of Air Pollution from Ships” (Annex VI) with limits on NOx emissions and through sulfur abatement in marine fuels, which induced SO_2 emission reduction (and PM reduction in a lesser extent). Even if it became effective only in 2005, marine engine manufacturers have been building engines (> 130 kW) compliant with the above NOx standards from 2000. Accordingly, this regulation has also benefited to waterways vessels as they are equipped with the same marine technology engines. Annex VI amendments adopted in 2008 introduced new fuel quality requirements and the so-called “Tier II” and “Tier III” NOx emission standards for new engines, depending on the rated engine speed, as shown in Table 1.

Table 1: MARPOL Annex VI, NOx Emission Limits

Tier	**Date**	**NOx Limit (g/kWh)** (n in rpm)		
		n < 130	**130 ≤ n < 2000**	**n ≥ 2000**
Tier I	2000	17.0	$45.n^{-0.2}$	9.80
Tier II	2011	14.4	$44.n^{-0.23}$	7.70
Tier III	2016*	3.4	$9.n^{-0.2}$	1.96

* In NOx Emission Control Areas (ECA, i.e. North American area and the US Caribbean Sea, so far). Tier II standards still apply outside ECAs

The MARPOL NOx standards were imposed by the US-EPA in 2003 (Tier 1) as mandatory for the largest marine engines (category 3, more than 2 500 kW) installed on ships sailing in US waters (rivers and seas). A series of US standards was then published, broken down into stages, i.e. Tier 2 (2004-2007) and Tier 3 (2009-2014) for the least powered engines (from 37 kW). The limits of CO, HC and particulate matter were then set for the 3 engine categories. A "Tier 4" was launched for category-1 and -2 engines, applying from 2014 to 2017, respectively for larger engines first to less powerful, the latter being in the range 600-1 400 kW.

At the European scale, the first emission limits for inland waterways were introduced by the countries bordering the Rhine River through the so-called "CCNR[3] regulations", from 2002 and specifically for the Rhine navigation. The 4 major pollutants, CO, HC, NOx and PM have been targeted. The CCNR-1 limit for NOx was defined identically to the first MARPOL limit (Table 2).

Table 2: Pollutant emission limits fixed by CCNR for navigation on the Rhine

CCNR Regulations	**Power** (kW)	**CO** (g/kWh)	**HC** (g/kWh)	**NOx** (g/kWh)	**PM10** (g/kWh)
Stage I 2002	37 ≤ PN < 75	6.5	1.3	9.2	0.85
	75 ≤ PN < 130	5.0	1.3	9.2	0.70
	PN ≥ 130	5.0	1.3	n ≥ 2800 rpm : 9.2 500 ≤ n < 2800 rpm : $45.n^{-0.2}$	0.54
Stage II 2007	19 ≤ PN < 37	5.5	1.5	8.0	0.8
	37 ≤ PN < 75	5.0	1.3	7.0	0.4
	75 ≤ PN < 130	5.0	1.0	6.0	0.3
	130 ≤ PN < 560	3.5	1.0	6.0	0.2
	PN ≥ 560	3.5	1.0	n ≥ 3150 rpm : 6.0 343 ≤ n < 3150 : $45.n^{-0.2} - 3$ n < 343 rpm : 11.0	0.2

Limits given for CCNR "Stage II" since 2007 are logically close to –if not the same as– the European ones, the latter just apply to a larger scale (Directive 2004/26/EC). With Stage II, it is intended to tackle emissions from any engine power, even the smallest ones. However, comparisons between CCNR limits (Stage II) and EC ones (Stage III A) are not straightforward because engines are not differentiated by the same features: maximum power (PN) and rated engine speed (n) are used by CCNR whereas EC considers the unit cylinder displacement (D) of the engine, and maximum power (P) in addition for some cases (Table 3).

References to next steps of the CCNR regulation can be found in the literature because stage III proposal for 2012 and stage IV for 2016 were long discussed and finally not adopted by the Central Commission (RVBR-CCNR, 2016): the

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[3] CCNR : Central Commission for the Navigation of the Rhine

European regulations have been in force since 2007 or 2009 and the proposed European limits appear to be consistent with the trend drafted by CCNR.

Table 3: European emission standards for Inland Waterway Vessels – Stage III A

Category	**Displacement (D)**	**Date**	**CO**	**HC+NOx**	**PM**
	dm^3 per cylinder			g/kWh	
V1:1	D ≤ 0.9, P > 37 kW	2007	5.0	7.5	0.40
V1:2	0.9 < D ≤ 1.2		5.0	7.2	0.30
V1:3	1.2 < D ≤ 2.5		5.0	7.2	0.20
V1:4	2.5 < D ≤ 5	2009	5.0	7.2	0.20
V2:1	5 < D ≤ 15		5.0	7.8	0.27
V2:2	15 < D ≤ 20, P ≤ 3300 kW		5.0	8.7	0.50
V2:3	15 < D ≤ 20, P > 3300 kW		5.0	9.8	0.50
V2:4	20 < D ≤ 25		5.0	9.8	0.50
V2:5	25 < D ≤ 30		5.0	11.0	0.50

EC emission limits for inland waterway vessels are significantly tightened under the Stage V proposal for 2019. (Stage IV was abandoned). The Stage V standards would be applicable to propulsion engines (IWP) above 37 kW and to auxiliary engines (IWA) above 560 kW, with NOx and PM limits for the biggest engines (P ≥ 1000) in line with current standards for heavy-duty trucks.

A limit in number of particles (PN) is added for large engines (>300 kW), as it is applying already to road vehicles. The limits set for 2021 for vessel engines above 1000 kW are those of the Euro VI values for trucks, which are in force since 2013. The very low levels of particle emission, in mass and number expected for 2020 for engines above 300 kW will require a particulate filter. Similarly, the proposed low levels of NOx cannot be achieved without NOx trap or SCR devices. This proposal from the Council of Europe dated 2014 encountered opposition of the shipping industry who asked to adopt less stringent emission limits in line with the American values (NOx, 1.8 g/kWh and PM, 0.04 g/kWh), with a phased implementation from 2014 to 2017, from engines above 2000 kW to engines between 600 and 1400 kW (EBU, 2014).

The IWP limits proposed by the EC to apply around 2020 are consistent with the most restrictive values imposed on trucks, in terms of emissions of nitrogen oxides and particulates. However, the fleet renewal delay is much longer for the vessels, so that cleaner diesel engines will make up the majority of the river units not before 2040 / 2050.

3 Monitoring methodology

Two methods of measurement were carried out on board the selected vessels:

- An automated and long-term monitoring (several weeks or months):
  energy consumption (electricity and fuel) and engine parameters (speed and torque on the propeller axle) were continuously recorded for each vessel. Combined with the GPS parameters, these data were used to thoroughly describe the distances traveled by the ships and to propose patterns of use and consumption of the different machines on board (propulsion engines, generators, pumps, air conditioning and domestic use). It has then been possible to set up a 1000-second operating cycles for each propulsion engine to represent their average energy consumption over the weeks. Moreover, the 1-Hz records of fuel consumption of the engines were needed to derive subsequently the exhaust gas flow rates and by extension, the amount of pollutants emitted by those engines.
- An intermittent monitoring:
  time-limited and non-automated measurements of pollutant concentrations were performed on exhaust gas by the IFSTTAR team. The sampling and analyzing equipment was heavy and difficult to board and to install at the funnels and it required constant presence of operators during recordings. Several days of measurement were planned to encounter the widest possible variety of engine operations. The emission features of the main pollutants (CO, CO2, HC, NOx and particulates) can be displayed in g/h, g/kWh, g/km or g/t.km according to specific periods, routes or operations. Pollutant emissions are given as well along the average operating cycles which were set up for each vessel from the continuous energy and power recordings (first monitoring results).

The main difficulties to plan and realize on-board measurements were linked to the ship features them-selves and to their commercial activity:

- To get on-board (personnel and equipment) is often difficult on such industrial ships (narrow catwalk, steep staircases and small passageways before reaching the dock of the funnels). The worst case was "en route" boarding near a lock.
- The loading and unloading of barges during daytime at customers’ dock is the priority of the vessel operators and for one of the selected vessels, it means that long trips were mainly made at night or during weekends; that could not match with our work schedules.
- Business activity and the vagaries of travel (locks) result in very changing and challenging timetables to follow, as far as the 2 cargo vessels are concerned.

As a result, very few days of measurement could be carried out and even less records were usable due to some holes in the fuel use or engine data we needed.

Two sets of analysers were used, a PEMS Horiba OBS 2100 (Portable Emission Measurement System) for the gases (CO, CO_2, NOx and THC), and an AVL "Micro Soot Sensor" (MSS) for the particle mass, both being suitable to give concentrations in exhaust through continuous sampling (3.0 l/min).
No battery packs were necessary to supply the analysers because the on-board electrical network on each of the 3 boats could easily be used and thus there was no power constraint for the measurement campaigns, nor battery to transport.

The gas analysers operate on the same principles as the laboratory analysers; they are more compact and were installed on a narrow carriage (Figure 2). The in-line measurement (1Hz) of the 4 gas concentrations in the exhaust operates according to the following principles:

- CO / CO_2: absorption in the non-dispersive infrared band (NDIR); 0-10% range
- THC (total hydrocarbons): flame ionization detector (FID); works with hydrogen supplied by a hydrogen / helium stable blend (0.15 l/min); 0-1000 ppm range
- NOx: chemiluminescence detection (CLD); 0-3000 ppm range

The zero point of each analyser was set on board by using purified air (bottle of synthetic air). Calibration from reference blends was prior done in laboratory. An accuracy of 2% is expected for the OBS 2100 analysers.

Figure 1: Gas analysers on-board a cargo vessel; sampling (heated line) and concentration measurement

Figure 2: Pitot tube and exhaust gas sampling adapted to the propulsion engine funnel (passenger vessel)

To derive amounts of emitted pollutants when the analysers measure concentration in a small sampled flow, the PEMS includes a Pitot tube to continuously monitor the total flow gas in the exhaust. The Pitot tube is prior calibrated for a specific pipe diameter. The diameter (120 mm) of the exhaust pipe on the tested passenger vessel and the maximum speed of the propulsion engine are in line with the standard heavy-duty engines. Thus, the calibrated 100 mm probe we had for trucks was used for this ship, by means of adaptation on the funnel (Figure 3). Nevertheless, flow measurement of exhaust gas is often subject to inaccuracy, due to side effects in the exhaust pipe and to the pulsed nature and highly variable velocity of the outlet gas. Accuracy of Pitot tube is usually given about ± 5 % but can easily exceed it during transient engine operations; however, cargo vessels run mainly on stable cruising speeds between the locks.

The AVL Micro Soot Sensor was managed by the CRMT Company who provided the particulate measurement on behalf of IFSTTAR during this project. Both devices, PEMS and MSS, were used simultaneously on board and time-synchronised. AVL 483 (MSS) measures the concentration of soot directly in the raw exhaust and without cross-sensitivity to other components. It is based on the photoacoustic method which offers a low detection limit (5 $\mu g/m^3$) and a high data rate (10 Hz). A high sensitivity is however not necessary in the case of marine engines with expected significant amounts of PM emissions.

With the photoacoustic technique, volatile compounds are not detected (as with the filter weighing technique) and could lead to underestimation if the proportion of volatile compounds (SOF) is significant. Without estimation of this proportion in the case of marine engines, no correction factor can be applied. However, the loss of particles by thermophoresis (particle deposition on the cold walls) seems significant when sampling is done in the raw exhaust: an AVL document (Schindler, 2012) and a publication from Cao (2014) describe independent comparative measurements with different particle analysers and both indicate an underestimation with the MSS in the range of 30 – 38% compared to the standard gravimetric filter method (CVS). Therefore, particulates concentrations given by the MSS were multiplied by a factor 1.3 to account for this measurement artefact.

The gas sampling probes for the PEMS and the MSS could not be attached the same way on the 3 types of ship funnel. The sleeve for trucks which was provided initially by Horiba (calibrated with the Pitot tube and bearing temperature probes and sampling line) was used on the passenger vessel (Figure 3). Instead, we had to adapt specific sleeves for the cargo ships with their extra-large funnels (up to 300 mm). Calibration of a pitot tube on such pipe was not possible and moreover, no change in the funnel profile was feasible to avoid any bend upstream the pressure sensors. Indeed, an accurate measurement speed requires that the tube is straight upstream the probe over a length that is, at least, 10 times the diameter to ensure good homogeneity of the flow speed at any point of the pipe section.

Consequently, no gas flow monitoring was possible at the engine outlets for both cargo ships. The PEMS could solely measure the pollutant concentrations in the exhaust gases of these two vessels and subsequent calculation was needed to derive the exhaust gas flow rates from fuel consumption and emission concentrations.

Fuel consumption and mass emissions of carbon compounds are linked as follows using the carbon balance method:

$$(1)\quad \mathrm{F_{cons}} = (12.011 + 1.008 \times \mathrm{r_{H:C}} + 16 \times \mathrm{r_{O:C}}) \times \left[\frac{E_{CO2}}{M_{CO2}} + \frac{E_{CO}}{M_{CO}} + \frac{E_{THC}}{M_{THC}} + \frac{E_{EC}}{M_{EC}} + \frac{E_{OM}}{M_{OM}} \right]$$

with:

- $\mathrm{F_{cons}}$: fuel consumption in g/s (from the flowmeter in the long-term monitoring)
- $\mathrm{r_{H:C}}$: atomic ratio H/C of the fuel ($\mathrm{r_{H:C}}$ = 1,855 for the current fuel used, GNR)
- $\mathrm{r_{O:C}}$: atomic ratio O/C ($\mathrm{r_{O:C}}$ = 0,004)
- E_{CO2}, E_{CO}, E_{THC}, E_{EC} et E_{OM} are the emissions of CO2, CO, Total HC, elemental carbon (soot) and organic mass respectively in g/s. These last 2 terms are neglected.
- M_{CO2}, M_{CO}, *etc..* are the molar masses of the respective elements in g/mol

The mass emission of a given compound ("E" which is unknown) is the product of the exhaust gas flow and the concentration of this compound. For example, the equation for CO2 is:

$$(2)\quad E_{CO2} = C_{CO2} \times M_{CO2} \times Q \times \frac{1}{60} \times \frac{1}{100} \times \frac{1}{22.415} \times \frac{273.15}{293.15} \qquad \text{with:}$$

Q : gas flow in l/min (unknown value)

M_{CO2} : molar mass of CO2 in g/mol

E_{CO2} : emissions of CO2 in g/s

C_{CO2} : CO2 concentration in %

The equations are the same for the other compounds, allowing to identifying *Q*, the gas flow, as a common factor and ultimately to deduct it every second from consumption and concentrations of major carbon compounds by replacing each E_{XX} in equation (1). Numerical terms of equations (2) can also be put into common factors and it is possible to simplify the equation (1) by applying all numerical values and to give the flow rate *Q* as :

$$(3)\quad Q = \frac{F_{cons} \times 2.415}{C_{CO2} + C_{CO} + \frac{C_{THC}}{10^4}} \qquad \text{with:}$$

Q : gas flow in l/min

C_{CO2} and C_{CO} : concentrations in %

F_{cons} : fuel consumption in l/h with a fuel density of 840 g/l

C_{THC} : concentration of THC in ppm

As far as the passenger vessel is concerned, both methods of determination of the exhaust gas flow were possible: measurement by pitot tube and calculation with equation (3). Comparisons give rather consistent results, except at idle (Fig. 4).

The average gap is -11.5 % for *Q* (green line) relatively to measured values by pitot tube (blue line). Considering that our reference is usually the PEMS emissions with its Pitot tube, in order to minimize a possible underestimation of *Q* and consequently of the pollutant emissions rates, we adopted a simplified equation (3) by using only the CO2 concentration. In that case, the discrepancy is reduced to -6 %. As pollutants from idling phases are less significant, the calculation method is acceptable and is adopted to derive exhaust flow, and hence, pollutant emissions from the 2 cargo ships.

The high variability of the calculated flow (green line) is due to instability in the fuel consumption data given by the flowmeter. Moreover, despite time synchronization between data loggers, a time offset can occur between fuel and gas concentrations data due to line delays. These offsets are difficult to estimate and can distort calculation only during periods of transient running.

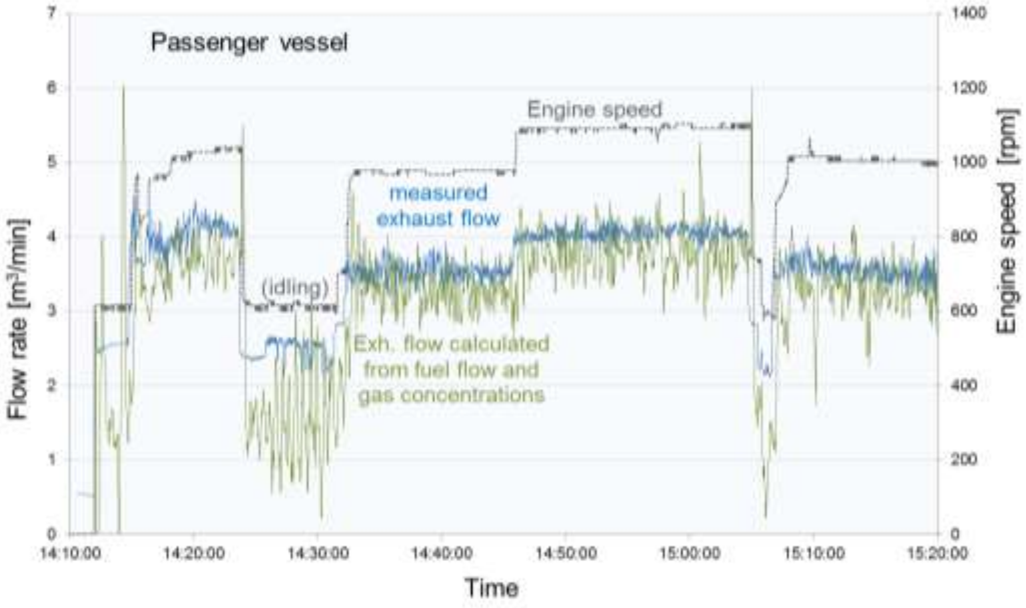

Figure 3: Exhaust flow determination and comparisons of both methods

4 Results Analysis

Pollutant emissions are analysed for each of the 3 vessels according to various criteria.

The first step was to quantify the pollutant emissions rates relatively to time, distance, energy used –for comparison with the European standard limits and between them– and finally per tonne.km. This unit enables comparisons with the road mode for freight transport. The emission rates or factors are presented both as means of the whole recorded data, and calculated along the representative operation cycle which was set up for each vessel.

4.1 Emissions profile along trips

Graphs of ship operating parameters along the route (speed, engine speed, engine torque versus time) enable to clearly distinguish the two navigation directions (upstream / downstream) and provide interesting information (Figure 5):

- Torque and engine speed are directly linked together in steady-state running according to the features of the propeller, with a simple function: Torque = a.Speed^2 with coefficient “a” being specific to each vessel (Vinot and Derollepot, 2016).
- Torque and engine speed (or propeller speed) are stable most of the time and are kept in the same range for both stream directions, unlike vessel speed; this is especially true in the case of heavy cargo ships. Pilots try to stay on the same cruising engine speeds, the ones which are known to give the best compromise between vessel speed and fuel use.
- The engine steady phases are long and easily identified whereas periods with constant vessel speed are rather brief, showing that resisting forces vary permanently under the influence of currents (depending on the section and longitudinal profile of the canal or river), of the bottoming effect (suction) or canal edge effect (waves), and secondarily, the effect of the wind. Heavy units are of course less sensitive to these speed variations due to their inertia.

CO2 varies simultaneously with engine speed, while being more in line with torque: a sharp CO2 emission increase occurs (130%) for the high speed phase (2100 rpm) when engine speed increases by about 30% and torque by 70%. CO2 is also subject to more variability during steady-state phases (especially when going upstream), due also to very high values (maximum of 38 g/s) which remain unexplained as fuel consumption is stable in the same time.

NOx emissions strictly reproduce the engine speed fluctuations, with the same magnitude.

Particulate emissions are relatively constant around 2 mg/s except at the beginning of the trip; these higher values could be related to a cold engine. However, particulate emissions decrease sharply when engine speed drops below 1500 rpm, and it looks like a threshold effect. Conversely, they become very high when engine speed reaches 2100 rpm, precisely 5 times greater (10 mg/sec) while speed is 30% higher.

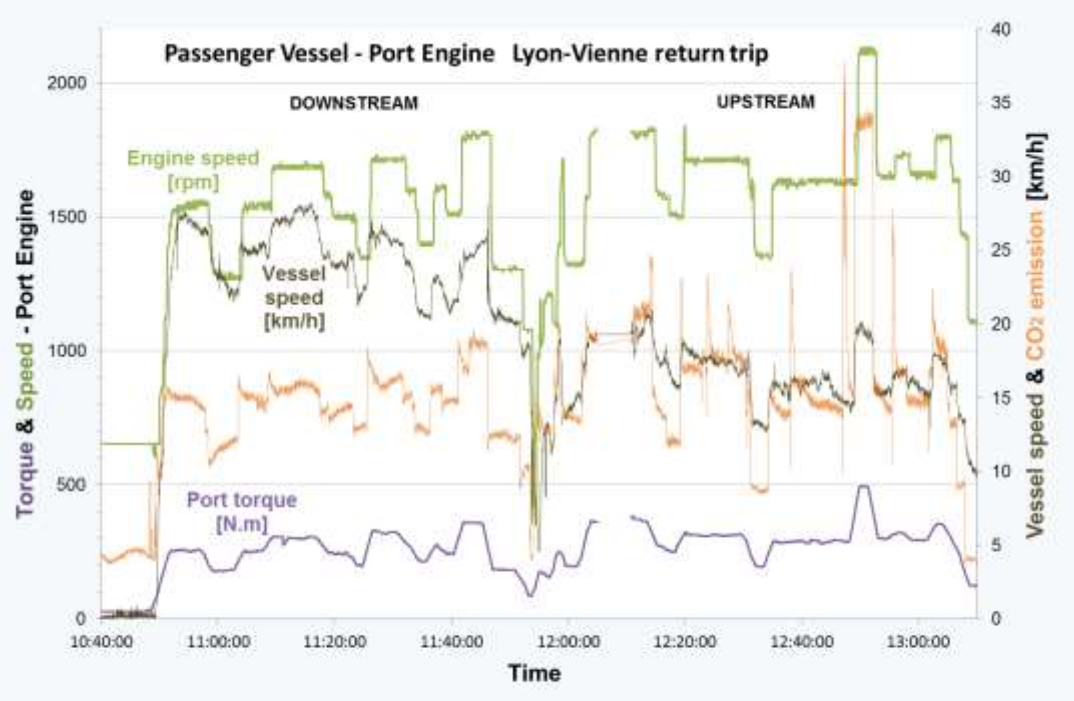

Figure 4: Tracing of engine speed and torque plus vessel speed and CO2 emission along a return trip on the Rhône River (port side engine)

CO emissions show a high variability and are therefore difficult to relate to any parameter. Besides, the THC analyser produced sometimes abnormal values during the third trip of the passenger boat (Table 5). Therefore, the THC emission of 4.9 g/km is not reliable and is not included in the global average.

The passenger boat emissions were monitored under various navigation conditions and for each of the two propulsion engines successively. It is easy to see the effect of the navigation direction on emissions (up or down-stream) but no engine comparison can be made at this stage due to non-repeatable conditions of running. However, comparison is made further from the emission modelling which has been set up specifically for each engine.

Emissions are consistent within each type of travel: pollutant rates are similar when comparing the same trips (even if speeds and distances are not quite the same). We also note the significant increase of emissions with higher cruising speed and more changing running conditions: CO_2 emissions and other gases are multiplied by about 2 while the speed average goes from 11 or 12 km/h to 14 km/h (16.8 km/h without stops) and PM emissions are multiplied by 10 on average between the "urban" trips (smooth cruising) and the "extra-urban" ones (lock and test of various engine speeds)

Table 5: Average emission of pollutants from the passenger boat (g/km) for both engines and both trip types

Passenger Vessel (45 t)		**Distance**	**Average ship speed**	**CO_2**	**NOx**	**PM** x 1,3	**CO**	**THC**
Round trip	Engine	133 km	13.3 km/h	kg/km	g/km	g/km	g/km	g/km
Urban, w/o lock	starboard	12.3	10.84	1.32	31.8	0.04	33.5	10.5
Urban, w/o lock	port	18.5	11.95	1.43	32.2	0.05	23.2	8.3
Extra-urban, 1 lock in each dir.	starboard	54.6	14.28 16.8 w/o stop	2.31	42.4	0.50	78.0	4.9
Extra-urban, 1 lock in each dir.	port	47.3	13.80 16.7 w/o stop	2.99	52.9	0.48	64.2	10.0
Average (1 engine)		(distance-weighted averages)		2.34	43.8	0.39	61.0	9.7
Vessel average (2 engines)				**4.68**	**87.6**	**0.77**	**122.0**	**19.4**

PM emissions are measured by the MicroSoot Sensor and data is increased by 30% to compensate for the thermophoresis effect.

4.2 Emissions from the pusher tug and the self-propelled barge

Compared to the passenger boat, pollutants are naturally emitted in larger quantities by the freight vessels, due to the higher involved energy and their more powerful engines. Logically, the heaviest vessel produces the highest rates of pollutants. Emissions rate per kWh is a more appropriate indicator to compare the emission characteristics of engines and their impact on air quality.

The pusher tug uses less diesel fuel and emits less CO_2 and NOx than the self-propelled barge, whereas its larger freight is less favourable. Accordingly the gaps are widening in favour of the pusher when the emission factors are given per tonne of cargo. Conversely CO and THC from the pusher tug are higher than those from the self-propelled barge ; but many problems have occurred in the measuring of these two pollutants and make them unreliable when all the records are taken into account. The selection of steady-state running points with valid measurements offers more valuable comparisons (modelling chapter).

Similar tests on freight IWV were carried out in 2011 on the Seine River, under the initiative of “Port de Paris” and VNF (TL&A and CERTAM, 2011). One difference in the conditions of monitoring is that pollutants have been recorded only for one cruising speed. Three pusher tugs with similar weight and engine power were part of this previous study and are compared to our cargo vessels. So-called “Freycinet” vessels in the range 250 - 400 t are part of the database of TL&A and they have engines with power of the same range as our passenger boat, but not the same usage and load. One of them has the same engine and operated empty when monitored and it has nevertheless been added into the comparison (Table 6).

Although in 2011 the pollutants were measured on a unique cruising speed, ultimately, the narrow range of engine speeds encountered with our pusher tug shows that the outlined difference in measurement conditions is not prohibitive to compare vessels emissions from both programmes.

Table 6: Average pollutants emissions from the tested vessels of the PROMOVAN programme and from the 2011 study along various trips (g/km)

Vessel	**Cargo**	**Power** kW	**Fuel** kg/km	**CO_2** kg/km	**NOx** g/km	**PM** g/km	**CO** g/km	**THC** g/km
Passenger boat	-	2x 160	1.4	4.7	88	0.8	122	19.4
Freyssinet barge *	0 t	2x 160	-	4.7	79	1.1	12	-
Self-prop. barge	670 t	2x 970	13.6	42.6	873	6.1	205	11.2
Pusher tug	2715 t	2x 920	9.8	30.1	726	7.0	396	56.1
Pusher 1 *	3090 t	2x 660	*8.4*	32.3	322	3.3	35	-
Pusher 2 *	4000 t	2x 735	*11.8*	53.8	458	12.5	257	-
Pusher 3 *	2800 t	2x 750	*15.1*	57.7	427	3.2	77	-

* Vessels of "Port de Paris - VNF" study in 2011. The figures for fuel are the usual consumption given by the pilots and not data from test measurements

Pusher tugs n°2 and 3 (2011 study) had particularly high CO_2 rates, which are not consistent either with their usual fuel uses, or with engine power and total weight relatively to the other vessels data. Only adverse running conditions (upstream?) can explain these high CO_2 levels, as it was the case for our self-propelled barge during test.

NOx rates from the three 2011-study pushers are consistent among each other but about 2 times lower than those we measured on the 2 freight vessels. A more recent technology to reduce NOx in line with the CCNR standards could be part of the explanation for these better results; the other reason could be the lower cylinder capacity of the engines. NOx emissions from the passenger vessel and the Freyssinet barge are very close, and their CO_2 emissions perfectly aligned, which confirms the suitability of this comparison.

Pusher tugs n°1 and 3 have particulate emissions 2 times lower than our freight vessels and no further explanation than those given for NOx discrepancies can be given. It is indeed difficult to find the reasons for such differences when results from the three 2011-study vessels exhibit such inconsistency for PM emissions.

As far as cargo vessels are concerned, it is interesting to produce the rates of pollutants per ton transported and per km for comparison with the road transport mode. It is clear that the very heavy loads carried by vessels (up to 3700 t deadweight for the pushed barges), play in favour of low emission and fuel rates versus the 25-t payload of the heavy-duty trucks ; on the heavy-duty vehicles (HDV) side, NOx and PM emissions are drastically reduced on the latest Euro VI trucks.

Two categories of trucks were chosen, the Euro II ones certified in the 1996-2000 period because their engine had a technology similar to that of the current in-use vessels, and Euro V models which account for a large share of to-day HGV fleet. The emission values given for trucks (Figure 6) are either obtained from measurements at the UTAC test bench for the Euro II trucks (Pillot et al., 2000), or from realistic models (based on measurements and actual usage) for Euro V trucks (Rexeis et al., 2014).

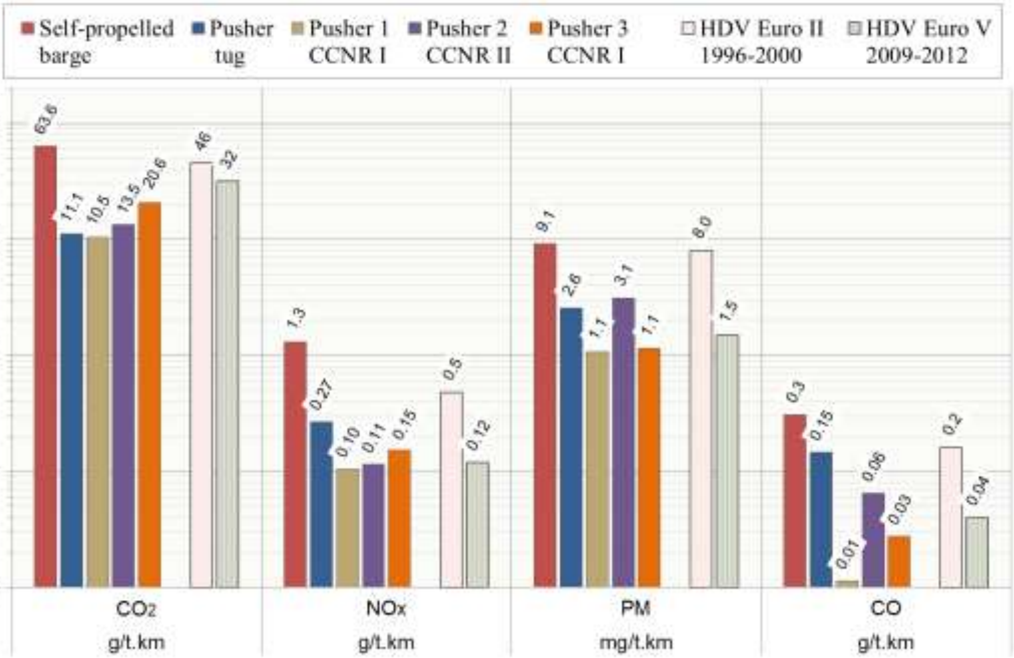

Figure 5: Emissions rates (g/t.km) for the tested vessels and for the Euro II and Euro V heavy-duty trucks (HDV) along various trips or driving cycles

The pusher tug with its 2700 tons of cargo uses almost 6 times less fuel per tonne transported than the self-propelled barge. It also ranks as the best pusher compared to the 2011 ones in terms of consumption and CO_2 emitted per tonne transported and per km. Euro V HGV use or emit 3 times more fuel or CO_2 respectively with the maximum 25-t load per trip. The self-propelled barge appears to be poorly efficient in terms of energy consumed per tonne transported compared to the whole pushers, and above all, versus the trucks that are better, and even 2 times better for Euro V trucks.

Thus, inland waterways vessels could be less efficient for goods transport in some cases, unless the cargo is above a 2000-t threshold as far as the tested self-propelled barge is concerned. This economic threshold would be around 1000 t of freight for the other tested vessels.

NOx emissions from pusher tugs measured in 2011 are in line with the Euro V

trucks, but this is not the case of both cargo vessels of this study which are more in the NOx range of the Euro II trucks, of similar engine technology as regards exhaust pollutants. If Euro V trucks have already benefited from nitrogen oxides treatment devices (SCR or EGR), far lower values are given for Euro VI trucks by Reixis and al. (2013), from models based on NOx realistic measurements.
Particulate emissions from the best pusher tugs in this domain are the same as the Euro V trucks emissions. However, the other monitored vessels are more polluting than the Euro V trucks as regards PM and much bigger sources of particulates than the most recent trucks which are equipped with particulate filter.

4.3 Emission modelling

Beyond the mean vessels emissions recorded along trips and presented so far, emission factors that could be obtained from realistic usage cycles would be better candidates to represent the typical emissions of the 3 vessels. This emission calculation from cycles had been made possible thanks both to the multiple steady-state running phases from which simple functions could be derived and also through the setup of specific operating cycles carried out by Vinot and Derollepot (2016). The operating cycles were defined by successive steady engine speeds for a total of 1000 seconds and the breakdown in different engine speeds is representative of the whole monitoring along dozen of running days for each of the 3 vessels. Emission models are also function of the various engine speeds.

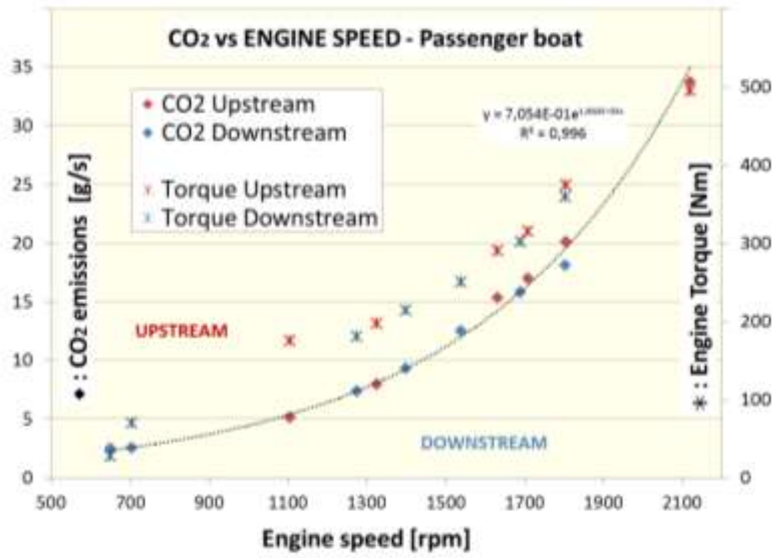

Figure 6: "CO2 vs engine speed" correlation graph according to the steady-state points identified during one trip of the passenger vessel - Distinction of both navigation directions

Due to the fixed relationships between engine speed and torque, hence linked with the involved energy as well, CO2 emissions are highly correlated with engine speed (Figure 7). Accordingly, no distinction of the navigation direction can be made on this graph, whereas vessel speed would take two distinct values according to the direction (up and downstream) if plotted against engine speed or torque.

A unique function allows then valid calculation of the CO2 emissions from the engine speed. The equation was set up by using the CO2 values for both engines (as regards the passenger vessel) and for all registered trips, after selection of the steady-state phases. This method is used for the other components, NOx, PM and CO the same way.

$$E_{CO_2} = 0{,}7054 e^{0{,}00184 \times Speed} \qquad R^2 = 0{,}996$$

$$E_{NOx} = 1{,}91.10^{-10} \times Speed^3 - 6{,}98.10^{-7} \times Speed^2 + 1{,}03.10^{-3} \times Speed - 0{,}406 \qquad R^2 = 0{,}983$$

$$E_{PM} = 4{,}87.10^{-9} \times Speed^3 - 1{,}32.10^{-5} \times Speed^2 + 1{,}17.10^{-2} \times Speed - 3{,}335 \qquad R^2 = 0{,}972$$

$$E_{CO} = 3{,}63.10^{-11} \times Speed^3 + 3{,}16.10^{-8} \times Speed^2 + 1{,}07.10^{-4} \times Speed + 0{,}1 \qquad R^2 = 0{,}583$$

with: E_{XX}: emission of the pollutant xx in g/s (in mg/s for PM)
Speed: Engine speed (rpm)

The function for CO is an attempt of modelling because values are quite scattered, due to measurement problems on the CO analyser. HC emissions are even more dispersed, to the point that no equation can be set up.

A satisfying number of steady-states phases could be identified for one engine of the self-propelled barge as well.

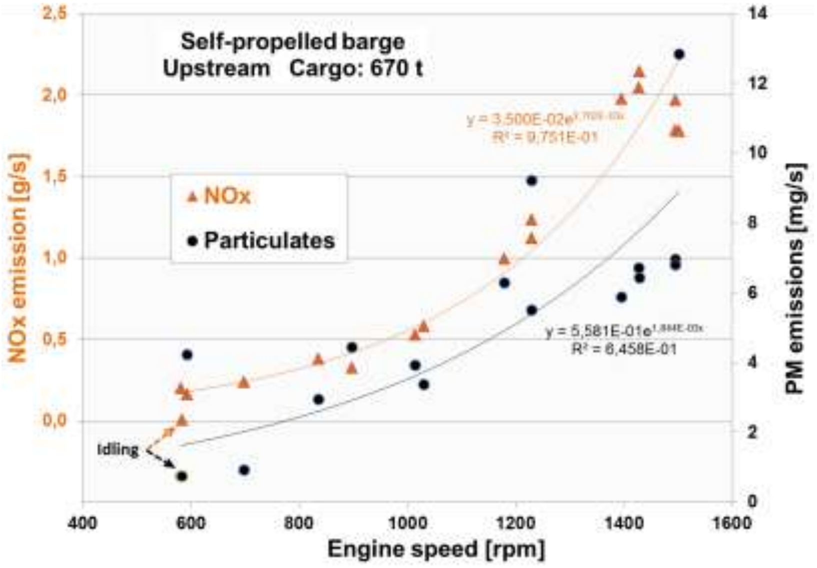

Figure 7: "NOx and PM vs engine speed" correlation graph according to the steady-state points identified during one trip of the self-propelled barge

The determination coefficient for the CO2 emission vs engine speed correlation is excellent (0.996) and it outlines again the direct relation between propeller speed and engine energy, and by extension, between engine speed and CO2 emissions in stable conditions. Emission values (g/s) for NOx are also well in line with the various steady speeds. Relation for PM with engine speed is less strong but reliable enough to derive mean PM emission from the running cycle (Figure 8) with a larger uncertainty in the lowest and the highest value ranges.

With emissions models set up for each vessel, we can assign an emission factor to each class or operating point of the cycle, and in the same way for each measured pollutant. It is done for the engine power as well, and hence it makes it possible to calculate the energy used. We can deduce the average emissions along the representative usage cycle. Comparisons of emissions rates per kWh with the regulatory limits are then possible, even if the conditions of running are not the same. Table 7 gives the 3 vessels emission rates besides recent and future emission standards.

Comparisons between vessels as regards CO_2 or fuel use performances and pollutants bring new information when calculated relatively to the energy used. CO_2 emission rates per kWh are quite the same between barge and pusher, which was not expected with the higher emissions of the self-propelled barge in g/s or g/km, while the cargo was lower (670 against 2715 t). The higher absolute CO_2 levels for the barge do not come from weaker engine efficiency, but from higher power involved during its trips.

Moreover, NOx emissions rates per kWh are slightly smaller for the barge; it also produces 2 times less particulates for the same dissipated power, which was also the result of comparison with raw data, in g/s (Table 6). The self-propelled barge produces also about 2 times less CO than the pusher, for the same energy supply.

The passenger boat is penalized by its excessive engines power which generates high emissions per kWh, compared to the cargo units. This is about twice as CO_2, NOx and CO, and nearly 40% higher than the pusher for PM emission rates. The mismatch between the characteristics of its engines and vessel architecture is part of the explanation. Its engines are far too powerful but the vessel was designed originally to reach high speed and lift off from the water.

The IMO limit (MarPol) Tier 1 which addresses only NOx –for which the self-propelled barge has been certified– is not displayed in table 7 but it is the same regulation as CCNR I: the limit is 10.0 g/kWh for a rated engine speed of 1800 rpm. As already mentioned, the level of NOx in actual usage has been measured around 14 g/kWh, which is 40% above its maximum value for registration in 2006.

The emission rates of NOx and CO from the pusher tug are far above the CCNR I limits (x 1.8). On the contrary, according to our measurements on both cargo vessels, particulate levels are well below current limits.

Table 7: Emissions rates (in g/kWh) for the 3 vessels compared with the CCNR and European standards

Standard emissions or Vessel id.	**Year**	**Conditions**	**NOx** g/kWh	**PM** g/kWh	**CO** g/kWh	**THC** g/kWh	**CO_2** kg/kWh
CCNR I	2002	P * ≥ 130	9.8	0.54	5.0	1.30	
CCNR II	2007	130 ≤ P * < 560	6.0	0.20	3.5	1.00	
EC IWP -3 (proposal)	2019	130 < P * ≤ 300	2.1	0.11	3.5	1.00	
Passenger boat 2x 160 kW		**cycle**	**24.1**	**0.17**	**19.5**	**7.30**	**1.43**
CCNR I	2002	P * ≥ 130	10.0	0.54	5.0	1.30	
CCNR II	2007	P * ≥ 560	7.0	0.20	3.5	1.00	
Self-prop. barge 2x 970 kW		**cycle**	**14.1**	**0.06**	**3.9**	**0.22**	**0.69**
EC V1:4	2009	2.5 < D ** ≤ 5	≈ 7.0	0.20	5.0	**HC + NOx**	
EC IWP -4 (proposal)	2020	300 < P ≤ 1000	1.2	0.02	3.5	0,19	
Pusher tug 2x 920 kW		**cycle**	**17.6**	**0.12**	**8.9**	**1.33**	**0.71**

* P : rated Power (kW) ** D : Displacement per cylinder (dm^3)

Actually, the very low levels to be reached for new engines (by 2020) will require the use of particulate filters or to switch to an alternative fuel such as natural gas (compressed or liquefied - GNL) which produces no measurable particles mass. As regards NOx emissions, EGR and SCR systems that proved to be efficient on truck engines, have to be adapted to marine engines to comply with future limits. Reduction potentials are large and the division by 2 for the NOx emissions from the 2011 pushers relatively to the pusher tug from 2006 is an illustration.
Experimental programs (e.g. The "Cleanest Ship Project" on the tanker Victoria, Schweighofer, 2010) have already demonstrated that reductions of 80% in NOx emissions could be achieved with SCR devices.

5 Conclusion

In the frame of the PROMOVAN program, pollutant measurements were carried out on board two cargo vessels and one passenger boat; they provide interesting data for this transport mode which is rarely evaluated in actual operation for its impact on air quality. Outlets of the propulsion engines were equipped to collect and analyse mass of the usual regulated pollutants NOx, PM, CO, THC and CO_2 as well.
Emission profiles observed directly during measurements produce average emission factors in g/s or g/km to identify the most polluting operations and to compare vessels. If the vessel with the largest cargo –the tug had a freight of 2700 t to push– is the highest emitter every second, this rule is not respected when

emissions are rated per km, the self-propelled vessel being penalized by greater power requirements. These emission factors in g/s obtained on average trips (averages of several hours of recording) are corrected by the results obtained from the representative running cycles. Emission modelling offers to extrapolate measurements made on some steady-state operating points to those composing the cycle and representative of the mean usages.

Moreover, the emission factors can be expressed per km and tonne transported to compare with road transport typical rates. Euro II trucks (1996-2000) with their 25-t payload emit more pollutant and use more fuel relatively to the cargo vessels, except for CO and HC. The ratio is 5 times less for the pusher tug as regards fuel and CO2, 3 times less for particulates and almost 2 times less for NOx. But tighter reductions of emissions obtained on recent heavy goods vehicles (mostly Euro V) have resulted in better rates in g/t.km, and below those of the pusher tug for the main pollutants, but not as regards CO2 and fuel use. The huge mass capacity of transportation (about 3000 t) by industrial vessels enable them to keep the advantage of reduced fuel consumption per tonne transported, and the gap remains large. In terms of impact on air quality, the pusher tug produces 2 times more NOx, particulate and CO than trucks for 1 tonne of freight. But these mixed results are going to be corrected with future emission regulations and potential of improvement is large for marine engines as they have not benefitted from aftertreatment devices so far. These devices have been largely tested and improved by the automotive sector. Examples of successful adaptation of such equipment on marine vessels or IVW show that new vessels will become greener quite rapidly. Unfortunately the fleet renewal is a long process.

Acknowledgements

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References

[1] D. Pillot, C. Pruvost, P. Tassel and R. Vidon, Simplified functions for calculating heavy-duty vehicle emissions, *Proceedings of the 9th Int. Symposium Transport and Air Pollution, Les collections de l'INRETS,* **Vol.2**, (2000), 425-430.

[2] M. Rexeis, S. Hausberger, J. Kühlwein and R. Luz, Update of Emission Factors for EURO 5 and EURO 6 vehicles for the HBEFA Version 3.2, Final Report, *IVT pub.*, Graz Univ. of Tech., 2014.

[3] RVBR-CCNR, Règlement de visite des bateaux du Rhin, **Ed. 2016**, *CCNR pub*. http://www.ccr-zkr.org/files/documents/reglementRV/rv1f_042016.pdf

[4] European Barge Union, Revision of Directive 97/68/EC on NRMM, *Joint position paper by EBU and ESO*, press pub., 2014.

[5] J. Schweighofer, Recent Developments in Ship Technology and Fleets, *Danube Commission – Workshop on Future Fairway Parameters of the Waterway Danube*, Budapest, 2010.

[6] TL&A & CERTAM, Étude comparée de rejet de polluants locaux - Transport de marchandises, *Rapport de phases 3 & 4*, TL&A / CERTAM pub, 2011.

[7] E. Vinot and R. Derollepot, Comparison and sizing of different hybrid powertrain architectures for fluvial boat application, *13th Vehicle Power and Propulsion Conference*, IEEE 2016.