A new inventory for two-wheel vehicle emissions in West Africa for 2002

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Rather surprisingly, urban atmospheric particulate levels in West Africa compare with measured concentrations in Europe and Asia megacities (Liousse, C., Galy-Lacaux, C., Assamoi, E.-M., Ndiaye, A., Diop, B., Cachier, H., Doumbia, T., Gueye, P., Yoboue, V., Lacaux, J.-P., Guinot, B., Guillaume, B., Rosset, R., Castera, P., Gardrat, E., Zouiten, C., Jambert, C., Diouf, A., Koita, O., Baeza, A., Annesi-Maesano, I., Didier, A., Audry, S., Konare, A., 2009. Integrated Focus on West African Cities (Cotonou, Bamako, Dakar, Ouagadougou, Abidjan, Niamey): Emissions, Air Quality and Health Impacts of Gases and Aerosols. Third International AMMA Conference on Predictability of the West African Moosoon Weather, Climate and Impacts. Ouagadougou, Burkina Faso. July 20–24). This pollution mainly derives from road traffic emissions with, in some capitals (e.g. Cotonou), the strong contribution of two-wheel vehicles. Two key questions arise: are presently available emission inventories (e.g. Junker, C., Liousse, C., 2008. A global emission inventory of carbonaceous aerosol from historic records of fossil fuel and biofuel consumption for the period 1860–1997. Atmospheric Chemistry Physics, 8, 1–13; Bond, T.C., Streets, D.G., Yarber, K.F., Nelson, S.M., Woo, J.H., Klimont, Z., 2004. A technology-based global inventory of black and organic carbon emissions from combustion. Journal of Geophysical Research, 1009, D14203, DOI:10.1029/2003JD003697) able to account for these emissions? And, if not, how can we remedy this? The aim of this paper is to develop a methodology to estimate emissions produced by two-wheel vehicles in West Africa for 2002 in a context where reliable information is hardly available. Fuel consumption ratios between two-wheel engines (in this work) and all vehicles issued from UN database (http://data.un.org/Data.aspx?d=EDATA&f=cmID%3aMO%3btrID%3a1221) are as high as 169%, 264% and 628%, for Burkina Faso, Mali and Chad respectively, indicating that this global database does not properly account for regional specificities. Moreover, emission factors for black carbon (BC) and primary organic carbon (OCp) have been measured for two-stroke engines in Benin (Guinot, B., Liousse, C., Cachier, H., Guillaume, B., et al. New emission factor estimates for biofuels and mobile sources. Atmospheric Environment, in press.), giving significantly higher values than in Europe. This is particularly true for OCp, and consequently the calculated emissions for two-stroke engines are also significantly larger than total road traffic previously estimated in global inventories (Junker and Liousse (2008) with United Nations database for 2002; Bond et al., 2004). The ensuing discussion illustrates the importance of two-stroke engines in the West Africa transport sector and the strong need for inventory updating.

1. Introduction

Air pollution is a major issue emerging in Africa, though until recently, it has been largely underestimated or even not considered in global studies (Diaz Olvera et al., 2007; McGranahan and Murray, 2003; Findings, 2002; Mage et al., 1996). In fact, it is a critical issue affecting large, rapidly growing African cities (Cadle et al., 2001; Tsai et al., 2000; Ikeda et al., 1998).

Rapid urban growth has a large impact on air quality due to increased traffic emissions. This is especially true in developing countries, mainly due to the high proportions of poorly-maintained engines, large numbers of two-stroke vehicles and poor fuel quality (Gwilliam, 2003; Baumbach et al., 1995). This is particularly the case in West and North Africa where the transport sector is a major contributing factor to urban pollution (Yang et al., 2005; Chen et al., 2003; Findings, 2002; Leong et al., 2002). Moreover, the transport sector in West Africa is largely unorganized (Godard and Ngabmen, 2002). Firstly, road networks are critically underdeveloped and generally in

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bad condition, with asphalted roads only in downtown areas. Secondly, as a result of strong policy deregulation, public transport companies have progressively collapsed in most towns, mainly to the exclusive benefit of private enterprises. In this context, two-stroke motorbikes have been for the purposes of small-scale public transport in this region. This phenomenon first appeared in the late 1980's in Benin, and spread thereafter to neighbouring countries, Niger, Nigeria, Cameroon, Chad and Togo (Trans-Africa, 2009; Sahabana, 2006; Agossou, 2003) and is now of widespread use throughout West Africa. Generally these motorcycle-taxis have two-stroke engines (Ouedraogo, 2005; BOAD, 2002; Findings, 2002; Diallo, 2001) and are heavily polluting (BOAD, 2002; Findings, 2002). They are used for transporting both people and goods and are known under different names: zemidjan in Benin, oleyia in Togo, bendskin in Cameroon, okada in Nigeria, kabu-kabu in Niger and boda-boda in Uganda (Diaz Olvera et al., 2007; Godard and Ngabmen, 2002). Motorcycle-taxi use is also strongly favoured by massive oil smuggling out of Nigeria, which renders the price of petrol much cheaper than that officially sold at gas stations. The Benin government has estimated that smuggled oil amounts to about 75% of national hydrocarbon consumption (Chantereau and Kpoledji, 2006). In the year 2005, the Nigerian National Petroleum Corporation (NNPC) estimated losses at a level of 661,810 tons compared to a loss of 396,880 tons in 2004, thus annual increases in estimated losses of up to 264,920 tons (67%). The large losses are attributed to the high incidence of pipeline vandalism across Nigeria as revealed by 2005 statistics (NNPC, 2005).

In addition, the number of two-wheel vehicles in West Africa is growing very rapidly, as illustrated by the recent construction of a motorcycle assembly factory in Burkina Faso. Also, motorcycles ("Jakartas") from Asia (mainly from Indonesia) have recently begun to be imported into the West African market. These motorbikes are very popular, since they cost approximately half the price of European ones (Godard and Ngabmen, 2002). Unfortunately statistics on the numbers of two-wheel vehicles are few and poorly documented. These factors explain why motorcycle-taxi emissions are only poorly, or not at all considered in official global or regional inventories. Clearly, however, there is a strong need to consider their emissions in such inventories because their widespread use in the region. The lack of official data though, is a considerable limiting factor and various assumptions need to be made when producing emissions estimates. The objective of this paper is to develop detailed inventories of particulate black carbon (BC) and primary organic carbon (OCp) emitted by two-wheel vehicles in West Africa for the year 2002, with a special focus on motorcycle-taxis. The methodology is described in part 2, with the results obtained in part 3. These new ad hoc emission inventories for West Africa are then compared to previous inventories (Junker and Liousse (2008) methodology used with United Nations data for the year 2002; and Bond et al. (2004)) for this region.

2. Methodology

Fourteen West African countries (Benin, Burkina Faso, Gambia, Ghana, Guinea, Guinea Bissau, Ivory Coast, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone and Togo) and two Central African countries (Cameroon and Chad) are considered. For simplification, we classified these sixteen countries under the same label "West Africa".

BC and OCp emissions from two-wheel vehicles are calculated using a bottom-up procedure. Let us note that two-wheel vehicles are all considered to be two-stroke engines (Ouedraogo, 2005; BOAD, 2002; Findings, 2002; Diallo, 2001) and that these vehicles use a mixture of motor gasoline and oil. Emissions are estimated using the following relationship:

$$E_{i,j} = C_i \times \mathrm{EF}_{i,j}$$

where $E_{i,j}$ is the total emissions (in g), with C_i the total fuel consumption (in kg), and $\mathrm{EF}_{i,j}$ emission factors (in g kg^{-1}), for country *i* and aerosol species *j* (BC or OCp), respectively.

There are many uncertainties in terms of the determination of the C_i and $\mathrm{EF}_{i,j}$ parameters. In order to provide an envelope covering the range of this uncertainty two extreme cases, a minimum and a maximum, were developed using different assumptions regarding emission factors and fuel consumption calculations. Different values of two-wheels vehicles, proportion of motorcycle-taxis, number of traffic-days per week, daily fuel consumption and fuel density were used in each assumption.

2.1. Fuel consumption estimates C_i

2.1.1. Estimates of the number of two-wheel vehicles for 2002

Estimates of the numbers of two-wheel vehicles are issued from the literature for eight countries (Benin, Burkina Faso, Cameroon, Chad, Mali, Niger, Nigeria and Togo), though only few studies on two-wheel vehicles are available in Africa (Etissa et al., 2008; Spezzano et al., 2008; Lindén et al., 2008; Fanou et al., 2006; Chen et al., 2003; Tsai et al., 2000). Due to the scarcity of data regarding two-wheel vehicle traffic in West Africa, much effort has been devoted to collect data in each country from respective national public departments. However, even when such data are available, they are highly disparate and thus questionable (Diaz Olvera et al., 2007; Agossou, 2004; Godard and Ngabmen, 2002). For example, no clear information about the methodology of data collection for the numbers of such vehicles is available. Uncertainties regarding these values are partly due to the fact that two-wheel vehicles are not subject to any technical controls in the countries considered in this study. Also, vehicles with motors smaller than 50 cm^3 require no registration, another strong reason why the total number of such vehicles is largely unknown. In contrast, in most developed countries all two-wheel vehicles must be legally registered. For example, in France, the Netherlands and Belgium, two-wheel vehicles have needed to be registered since July 2004, September 2005 and September 2009 respectively (http://www.senate.be/www/?MIval=/-publications-/viewPubDoc&TID=50349877&LANG=fr).

Two-wheel vehicles in West Africa are not only for private use but, in six of the sixteen countries (Benin, Cameroon, Chad, Niger, Nigeria and Togo) they are widely used for public transportation as well (Trans-Africa, 2009). For the ten other countries, no publications regarding the use of motorcycles as taxis are available. It is thus assumed that all two-wheel vehicles are used for private purposes only, even though motorcycle taxis do perhaps exist in some of these countries. In terms of the proportion of two-wheel vehicles currently used as motorcycle-taxis, data are only available from Benin. Worou (2005) suggests that between 45% and 50% of two-wheel vehicles in Cotonou (the capital of Benin) are used as motorcycle-taxis. Adjovi (1999) suggests that 40,000 of a total of 100,000 two-wheel vehicles were used as motorcycle-taxis in Benin in 1998, a ratio of 40%. Since data were only available for Benin, this data were also used for the other five countries where the use of motorcycle-taxis is prevalent. In our assumptions, we opted for a range of 40% and 50% of two-wheel vehicles being motorbike-taxis. It is important to note that there is a risk for double counting of two-wheel vehicles. Given that in many cases these vehicles are not declared officially as motorcycle-taxis and that others may be used as taxis only on a part-time basis, the proportion between privately-used two-wheel vehicles and motorcycle taxis may be questionable.

In eight of our sixteen countries (Benin, Burkina Faso, Cameroon, Chad, Mali, Niger, Nigeria and Togo), "direct" estimates of the total number of motorbikes used as taxis can be obtained from literature (Table 1). In Cameroon, the Land Transport Ministry gives a total

Table 1
Numbers of two-wheel vehicles in 2002, issued from literature. Values in bold were obtained from the literature, and values highlighted in grey were used in the minimum assumption.

	Population[a]	Total number of four-wheel vehicles [b]	Motorcycle-taxis	Non-motorcycle-taxis	Total number of two-wheel vehicles	Ratio two/four wheel vehicles	Motorcycle-taxis	Non-motorcycle-taxis	Total number of two-wheel vehicles	Ratio two/four wheel vehicles
			40%	60%			50%	50%		
NIGER	11,940,800	58,256	***2500***	3750	6250	0.1	***2500***	2500	5000	0.1
CHAD	9,118,890	25,330	12,800	19,200	***32,000***	1.3	16,000	16,000	***32,00***0	1.3
CAMEROON	16,627,400	173,202	21,165	31,747	***52,912***	0.3	26,456	26,456	***52,912***	0.3
TOGO	5,553,170	25,709	***45,000***	67,500	112,500	4.4	***45,000***	45,000	90,000	3.5
BENIN	7,112,930	62,594	***160,000***	240,000	400,000	6.4	***160,000***	160,000	320,000	5.1
NIGERIA	131,336,000	2,521,651	523,600	785,400	***1,309,000***	0.5	654,500	654,500	***1,309,000***	0.5
BURKINA FASO	10,606,700	56,501	/	/	***300,000***	5.3	/	/	***300,000***	5.3
MALI	12,664,000	70,711	/	/	***300,000***	4.2	/	/	***300,000***	4.2

[a] Population was given by World Bank (2002).
[b] Four-wheel vehicles given by DHS (2006) are added to calculate the ratio of two:four-wheel vehicles.

figure of 52,912 motorcycles for the whole country (Institut National de la Statistique, 2006). Diaz Olvera et al. (2007) and Godard and Ngabmen (2002) suggest a number of 22,000 motorcycle-taxis in the single city of Douala, Cameroon. However, a recent study by Kumar and Barrett (2008) questions this value, due to unclear methodology. These authors suggest a figure closer to 10,000 motorcycles in Douala, using data from the same Ministry of Transport. We choose a value of 52,912 for the total number of two-wheel vehicles in Cameroon. Thus, using a ratio of 50% (40%) as assumed above, we obtain a reasonable value of approximately 26,456 (21,165) for the number of motorcycle-taxis in Cameroon.

For Togo, Akakpo (1998) quotes a total of 8000 motorcycle-taxis in 1996, whereas Godard and Ngabmen (2002) estimate that between 10,000 and 20,000 vehicles circulated in 1997. The West African Development Bank (BOAD, 2002) suggests a value of 45,000 motorcycle-taxis for the year 2002. This value is consistent with the other two references (Godard and Ngabmen, 2002; Akakpo, 1998) and taking into account the 50% (40%) ratio between taxis and private vehicles, the total number of two-wheel vehicles in 2002 is 90,000 (112,500)*.

In Nigeria, information about two-wheel vehicle numbers in 2002 is issued from A. Jalal. (Director General of the National Automotive Council of Nigeria) based on internal reports. There are approximately 1,309,000 two-wheel vehicles in Nigeria with 654,500 (523,600) used as motorcycle-taxis considering the 50% (40%) ratio. In Benin, the BOAD (2002) gives estimates of 160,000 motorcycle-taxis. This corresponds to a total of 320,000 (400,000) two-wheelers considering the 50% (40%) ratio.

In Chad, there are an estimated 32,000 two-wheel vehicles in circulation (Trans-Africa, 2009). Under the 50% (40%) ratio, we obtain values of 16,000 (12,800) used as motorcycle-taxis. Finally, for Niger, the BOAD (2002) suggests a figure of 2500 motorcycle-taxis. Thus, there are a total of 5000 (6250) two-wheel vehicles with the 50% (40%) ratio. For Burkina Faso and Mali, no data is available suggesting the use of motorcycle-taxis, however, the total numbers of two-wheel vehicles is still significant. In Burkina Faso, Ouedraogo (2005) suggests that there are 120,000 two-wheel vehicles with cubic capacity over 50 cm^3. On the other hand, CCIC (2008) suggests a total of 300,000 two-wheel vehicles. We chose to use the latter value (300,000), including all types and cylinder of two-wheel vehicles. For Mali information regarding the number of two-wheel vehicle for 2002 is derived from O. Koita (University of Bamako-Mali), based on internal reports. This data suggests about 300,000 two-wheel vehicles in Mali.

Table 1 summarizes the total number of two-wheel vehicles used for motorcycle-taxis and for private-use for the year 2002 in Benin, Cameroon, Niger, Nigeria, Togo and Chad. The total number of two-wheelers from Burkina-Faso and Mali has also been included.

To compensate for the lack of official and reliable information, estimates of the total number of two-wheel vehicles have been made using data from several sources. Thus, in parallel to the "direct" values obtained (described above), "indirect" estimates of the numbers of two-wheel vehicles were obtained for most countries using data from Demographic Health Surveys reports (DHS, 2006). As an example, for Niger, the 2006 DHS report mentions that 5.6% of all households have at least one motorcycle. With a total of 2 million households, this results in a total of approximately 100,000 two-wheel vehicles. This value is much higher than the one suggested by the BOAD (2002) (5000–6250). Similar methodology was applied to the other countries investigated, except for Gambia and Guinea Bissau where DHS (2006) does not give any information. Values obtained using DHS (2006) data are, in all cases, considerably higher than "direct" values obtained from the literature. We therefore considered a range of values for the number of two-wheel vehicles: a minimum assumption (using "direct" values taken from the literature) and a maximum assumption (using values taken from the 2006 DHS study). Values for the minimum and maximum assumptions are gathered in Tables 1 and 2 respectively. Values in bold in Table 1 were used in the minimum assumption. This choice is as follows: when we have the number of motorcycle–taxis, the minimum values are found using the 50% ratio. Whereas when only the total number of two-wheel vehicles is known (for example for Chad, Cameroon and Nigeria), we considered the ratio of 40:60% (taxi:private use).

As mentioned above, data are missing for certain countries. In terms of the minimum assumption, there are eight West African countries (Gambia, Ghana, Guinea, Guinea Bissau, Ivory Coast, Liberia, Senegal and Sierra Leone) for which no "direct" estimates are available. Therefore, the number of two-wheelers was estimated using two parameters: the ratio of two:four-wheel vehicles and the total number of four-wheel vehicles (cars, pick-ups, buses, etc) according to data from IRF (2009) and DHS (2006). As seen in Table 1, which presents these data, the lowest ratio of two:four-wheel vehicles is obtained for Niger (0.1). This value was selected for the minimum assumption when calculating the number of two-wheelers for all the countries where "direct" data are missing. These data are displayed in Table 3.

DHS (2006) does not give any information for Gambia and Guinea Bissau. Thus in the maximum assumption the highest ratio of two:four-wheel vehicles, 8.3 for Burkina Faso, (IRF, 2009; DHS, 2006); was then selected to calculate the numbers of two-wheel vehicles in these two countries. Table 2 summarizes all our selected values used in the maximum case.

Finally, the numbers of two-wheel vehicles for our 16 countries in the minimum and maximum assumptions are presented in Table 4.

Table 2
Numbers of two-wheel vehicles in 2002 issued from calculation in the maximum assumption using population data, number of persons per household, households with motorcycles, households with four-wheel vehicles and the total number of households.

Country	Population[a]	Number of persons per household	Households with motorcycles (%)	Households with cars (%)	Total number of			Ratio two/four-wheel vehicles
					Households	Two-wheel vehicles	Four-wheel vehicles[b]	
GUINEA BISSAU	1,368,530	/	/	/	/	16,476	1,985	**8.3**
GAMBIA	1,391,380	/	/	/	/	97,202	11,711	**8.3**
LIBERIA	3,056,860	5.0	1.7	2.1	611,372	10,394	12,839	0.8
SIERRA LEONE	4,540,320	5.9	4.0	2.0	769,546	30,782	15,391-19,130	2.0-1.6
TOGO	5,553,170	5.4	10.4	2.5	1,028,365	106,950	25,709	4.2
BENIN	7,112,930	5.0	35.6	4.4	1,422,586	506,440	62,594	8.1
GUINEA	8,705,980	6.1	8.6	4.0	1,427,210	122,740	57,088	2.2
CHAD	9,118,890	5.4	4.3	1.5	1,688,683	72,614	25,330	2.9
SENEGAL	10,432,700	8.7	5.9	7.3	1,199,161	70,750	87,539	0.8
MALI	10,606,700	5.7	29.7	3.8	1,860,825	552,666	70,711	7.8
NIGER	11,940,800	6.1	5.6	2.0	1,957,508	109,620	39,150-58,256	2.8-1.9
BURKINA FASO	12,664,000	6.5	24.2	2.9	1,948,308	471,490	56,501	**8.3**
CAMEROON	16,627,400	4.8	7.5	5.0	3,464,042	259,804	173,202	1.5
IVORY COAST	18,074,900	5.5	11.8	4.1	3,286,345	387,790	134,740	2.9
GHANA	20,474,900	4.0	2.1	5.4	5,118,725	107,494	276,411-400,522	0.4-0.3
NIGERIA	131,336,000	5.0	15.1	9.6	26,267,200	3,966,348	2,521,651	1.6

[a] Population was given by World Bank (2002).
[b] Number of four wheel-vehicles given by IRF (2009) and DHS (2006) are added in order to calculate the ratio of two:four-wheel vehicles.

2.1.2. *Number of traffic-days per week for two-wheel vehicles*

Two-wheel vehicles are the main mode of transport in the large West African capitals, e.g. Bamako in Mali, Cotonou in Benin and Ouagadougou in Burkina Faso (DHS, 2006; Bultynck, 1999). We assume two values for the number of days these vehicles circulate, a minimum value of five days per week and a maximum value of seven days per week (cf. Table 5). These assumptions seem plausible, since the minimum number of days worked is usually five (Monday to Friday); and the maximum that can be worked is seven. For example, in Benin, motorcycle-taxi drivers have to pay motorcycle owners every night from Mondays to Saturdays, but are allowed to operate on their own on Sundays (Sahabana, 2006).

2.1.3. *Daily fuel consumption*

To estimate daily two-wheel vehicle consumption, one needs to consider their usage, whether private or in public transport. For this purpose, minimum and maximum assumptions are again considered. For private transport, values of fuel consumption and distances traveled by two-wheel vehicles, are tentatively based on European data (ADEME, 2005), since no data are available for Africa. It must be kept in mind that these values are based on a context in which fuel quality is controlled, two-wheel vehicles are generally in good condition and road infrastructure is well maintained. In African countries, however, this situation is very different and fuel consumption is likely considerably higher. For our minimum assumption, European fuel consumption by two-wheel vehicles less than 125 cm^3 was selected. These vehicles travel on average 4000 $km\ year^{-1}$ with average consumption of 3.4l/100 km, corresponding to a total of 136 liters per year. Considering the minimum case of 5 days per week (minimum assumption in Table 5) resulting in 260 days of circulation per year, we obtain a daily fuel consumption of 0.5 liters per day. Fuel consumption for private transport in the maximum case is based on consumption by "large" European two-wheel vehicles (over 125 cm^3) traveling 8000 kilometers per year with an average consumption of 4.5 l/100 km (ADEME, 2005), corresponding to a daily consumption of 1 liter per day. Table 5 summarizes these data.

Average fuel consumption of motorcycle-taxis used for public transport in West Africa were estimated by Kaffo et al. (2007) as 4 liters per day. This is the only data available and this value will be adopted for daily consumption for public transport in the maximum assumption (Table 5). No value has been found to be used in the minimum assumption. There is a factor of 2 difference between fuel consumption of two wheel-vehicles for private use between our two assumptions (0.5 liter in the minimum case vs. 1 liter in the maximum). Therefore, this factor of 2 will be kept for two-wheel vehicle fuel consumption in the public transport sector, resulting in a value of 2 liters/day in the minimum assumption. All fuel consumption values are shown in Table 5.

Table 3
Number of two-wheel vehicles for the year 2002 in the minimum assumption.

Country	Population[a]	Total number of		Ratio two/four-wheel vehicles
		two-wheel vehicles	four-wheel vehicles[b]	
GUINEA BISSAU	1,368,530	199	1985	0.1
GAMBIA	1,391,380	1171	11,711	0.1
SIERRA LEONE	4,540,320	1539	15,391−19,130	0.1
LIBERIA	3,056,860	1284	12,839	0.1
GUINEA	8,705,980	5709	57,088	0.1
GHANA	20,474,900	27,641	276,411−400,522	0.1
SENEGAL	10,432,700	8754	87,539	0.1
IVORY COAST	18,074,900	13,474	134,740	0.1

[a] Population was given by World Bank (2002).
[b] Number of four wheel-vehicles given by IRF (2009) and/or DHS (2006) are added to calculate the total number of two-wheel vehicles. We consider the minimum value of four-wheel vehicles to calculate the number of two-wheel vehicles.

2.1.4. *Fuel density*

As mentioned above, most two-wheel vehicles in the 16 West African countries investigated have two-stroke engines (Ouedraogo, 2005; Findings, 2002; BOAD, 2002; Diallo, 2001; Bultynck, 1999) operated with mixtures of gasoline and oil. For gasoline, we have adopted an average fuel density (unleaded 95 and 98) of 747.50 $kg\ m^{-3}$ (http://www.total.mu/os/content-/NT000357FE.pdf). For oil, an average of 875.75 $kg\ m^{-3}$ is used in the mixture for two-stroke engines (Z 2-stroke, racing 2-stroke, sport 2-stroke and scooter 2-stroke) (http://www.lubrifiants.total.fr/lub/lubfrancetotal.nsf/VS_OPM/2C8C5CDFB5467392C1257521004EFB1D?OpenDocument). According to manufacturer's instructions, the proportion of oil to gasoline can vary between 2 and 8% (Boko et al., 2003; Diallo, 2001; Jüttner et al., 1995). With 2% as a minimum ratio typical of European

Table 4
Number of two-wheel vehicles for our 16 countries in the minimum and maximum assumptions.

	Minimum assumption			Maximum assumption		
	Motorcycle-taxis	Non-motorcycle-taxis	Total number of two-wheel vehicles	Motorcycle-taxis	Non-motorcycle-taxis	Total number of two-wheel vehicles
BENIN	160,000	160,000	320,000	253,220	253,220	506,440
BURKINA FASO	0	300,000	300,000	235,745	235,745	471,490
CAMEROON	21,165	31,747	52,912	129,902	129,902	259,804
CHAD	12,800	19,200	32,000	36,307	36,307	72,614
GAMBIA	0	1171	1171	48,601	48,601	97,202
GHANA	0	27,641	27,641	53,747	53,747	107,494
GUINEA	0	5709	5709	61,370	61,370	122,740
GUINEA BISSAU	0	199	199	8238	8238	16,476
IVORY COAST	0	13,474	13,474	193,895	193,895	387,790
LIBERIA	0	1284	1284	5197	5197	10,394
MALI	0	300,000	300,000	276,333	276,333	552,666
NIGER	2500	2500	5000	54,810	54,810	109,620
NIGERIA	523,600	785,400	1,309,000	1,983,174	1,983,174	3,966,348
SENEGAL	0	8754	8754	35,375	35,375	70,750
SIERRA LEONE	0	1,539	1,539	15,391	15,391	30,782
TOGO	45,000	45,000	90,000	53,475	53,475	106,950

conditions, we get a density of 750.1 kg m^{-3} against 757.8 kg m^{-3} for the maximum 8% ratio observed in some African countries (Diallo, 2001). Again these values are shown in Table 5.

2.2. Emission factor estimates $EF_{i,j}$

Aerosol emissions heavily depend on emission factors, which in turn are dependent on technologies and fuels used (Junker and Liousse, 2008; Bond et al., 2004). In Guillaume and Liousse (in press), emission factors of 0.28 g kg^{-1} and 7.36 g kg^{-1} are used for typical European two-stroke two-wheel vehicles for BC and OCp respectively. In Bond et al. (2004), emission factors of 0.71 g kg^{-1} for BC and 16.25 g kg^{-1} for OCp are used. Emission factors for two-stroke motorcycles were directly measured during the AMMA campaign (Guinot et al., in press) in May 2005 in Cotonou (Benin). These emission factors are 2.31 g kg^{-1} and 30.56 g kg^{-1}, for BC and OCp respectively (Guinot et al., in press). Such high values are in agreement with Nuti (1998) and Volckens et al. (2008) who have shown that high particle emissions result from gasoline-oil mixtures used in two-stroke vehicles under incomplete combustion. Thus, the emission factors measured in Benin indicate the high level of carbonaceous particles emitted during combustion by two-wheelers. These emission factors (i.e. 2.31 g kg^{-1} and 30.56 g kg^{-1}) have been used in the maximum assumption and those of Europe (i.e. 0.28 g kg^{-1} and 7.36 g kg^{-1}) of Guillaume and Liousse (in press) in the minimum case, and applied to all countries in our study. These values are displayed in Table 5.

2.3. New emission spatialization

Emissions were calculated for each country and then spatialized according to population densities. For this purpose, we use a new census from CIESIN (2005) with higher 0.25° × 0.25° resolution. Such increased spatial resolution is clearly an asset in air quality modeling.

3. Results

3.1. Two-wheel vehicle fuel consumption in the minimum and maximum assumptions

Fig. 1 shows total motor gasoline consumption (in tons per year) of two-wheel vehicles for 2002, based on the minimum and maximum assumptions applied in each of our sixteen countries. Countries are ranked according to increasing fuel consumption according to the maximum assumptions. In this classification, maximum fuel consumption ranges from 2875 tons in Liberia to 2,742,555 tons in Nigeria. In the minimum case, total consumption range from 20 tons to 285,125 tons, for Guinea Bissau and Nigeria, respectively. On the whole, in all 16 countries and for both assumptions, total fuel consumption ranges from 471,665 tons (minimum) to 3,988,931 tons (maximum). Total fuel consumption in the 16 countries in the maximum assumption is eight times greater than in the minimum case.

Comparing differences between estimated fuel consumption in the maximum and minimum assumptions, we get values ranging from 2748 tons to 2,457,430 tons in Liberia and Nigeria, respectively. Furthermore, and as expected, we find that the relative differences between the maximum and minimum cases are higher in countries where the numbers of two-wheel vehicles are only estimated (over 91%), whereas these differences are lower (over 70%) in countries where these values are available.

3.2. Emissions

Annual West African BC and OCp combustion particle emissions in 2002 for two-wheel vehicles were calculated using our adjusted fuel consumption estimates through the relationship in section 2.

Table 5
Other characteristics in the minimum and maximum assumptions.

	Minimum assumption		Maximum assumption	
	Non-motorcycle-taxis	Motorcycle-taxis	Non-motorcycle-taxis	Motorcycle-taxis
Number of traffic day(s) per week	5	5	7	7
Daily consumption (in liter)	0.5	2.0	1.0	4.0
Fuel density (in kg m^{-3})	2% oil: $\rho = 750.1$	2% oil: $\rho = 750.1$	8% oil: $\rho = 757.8$	8% oil: $\rho = 757.8$
Emission factors (in g kg^{-1})	BC = 0.28	BC = 0.28	BC = 2.31	BC = 2.31
	OCp = 7.36	OCp = 7.36	OCp = 30.56	OCp = 30.56

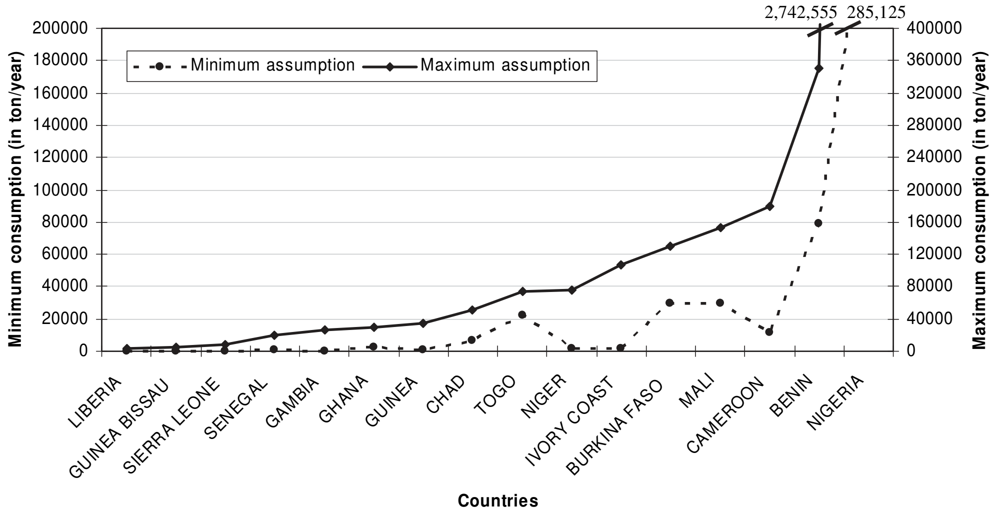

Fig. 1. Two-wheel vehicles motor gasoline consumptions in 2002 in the minimum and maximum assumptions in the sixteen West African countries.

3.2.1. *BC emissions*

Fig. 2 shows total two-wheel vehicle BC emissions in the minimum and maximum assumptions in each of the 16 countries. These estimates are ranked from smallest to largest according to the maximum values. BC emissions are 6.7 and 6329 tons, respectively for Liberia and Nigeria in the maximum case. In the minimum case, values range from 0.01 tons for Guinea Bissau to 80 tons for Nigeria. In all 16 countries, total BC emissions are 132 tons and 9206 tons, in the minimum and maximum assumptions respectively, a difference of 9074 tons. Differences between the maximum and minimum assumptions for BC emissions vary from 6.6 tons in Liberia to 6249 tons in Nigeria. The relative differences amount to almost 100% (over 99.5%) in countries where the numbers of two-wheel vehicles are only estimated, whilst these difference are approximately 98% in the other countries. Total BC emissions in the 16 countries in the maximum assumption are on average seventy times greater than in the minimum case. As mentioned in the previous paragraph, there is a factor of eight between the maximum and minimum assumptions in terms of fuel consumption. In addition, there is also a factor eight difference between BC emission factors used in the two cases. This appears coherent with the significant differences in emissions observed between the two assumptions.

3.2.2. *OCp emissions*

OCp emissions are considerably higher than those for BC. Fig. 3 shows that OCp emissions vary between 88 tons in Liberia compared to 83,801 tons in Nigeria in the maximum case. In the minimum case, values range from 0.1 tons for Guinea Bissau to 2098 tons for Nigeria. The smallest difference between the maximum and minimum assumptions for OCp emissions are 87 tons in Liberia compared to a maximum of 81,703 tons in Nigeria. On average, a difference of 99.5% is obtained in countries where the numbers of two-wheel vehicles have only been estimated, as compared to a value of 95% in countries where these values were available. Total emissions in all 16 countries amount to 3470 and 121,885 tons, in the minimum and maximum cases, respectively, corresponding to a difference of 118,415 tons. Total OCp emissions for the 16 countries in the maximum assumption are on average thirty five times greater than in the minimum one. This is again a result of the difference in fuel consumption and emission factors values used in the two assumptions. The OCp emission factor

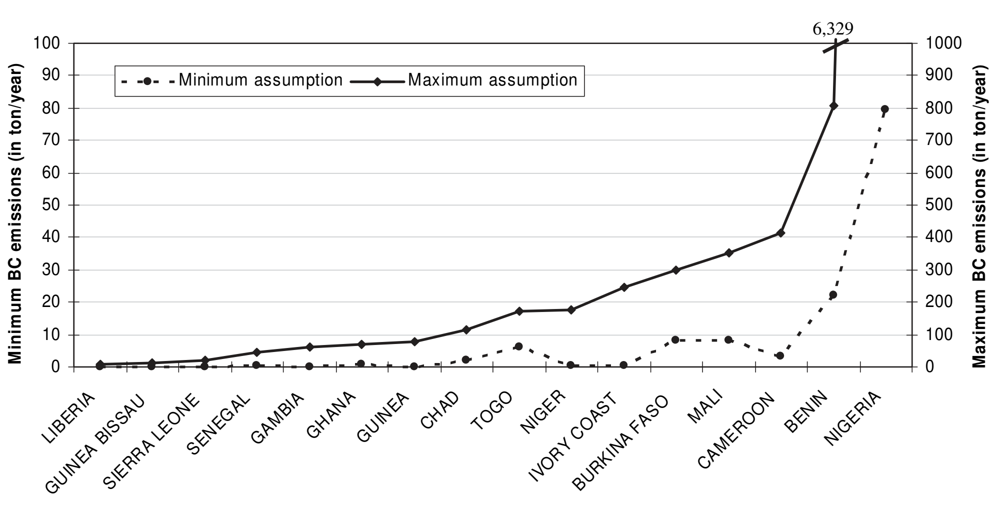

Fig. 2. Total BC emissions for two-wheel vehicles in West Africa in the minimum and maximum assumptions in 2002.

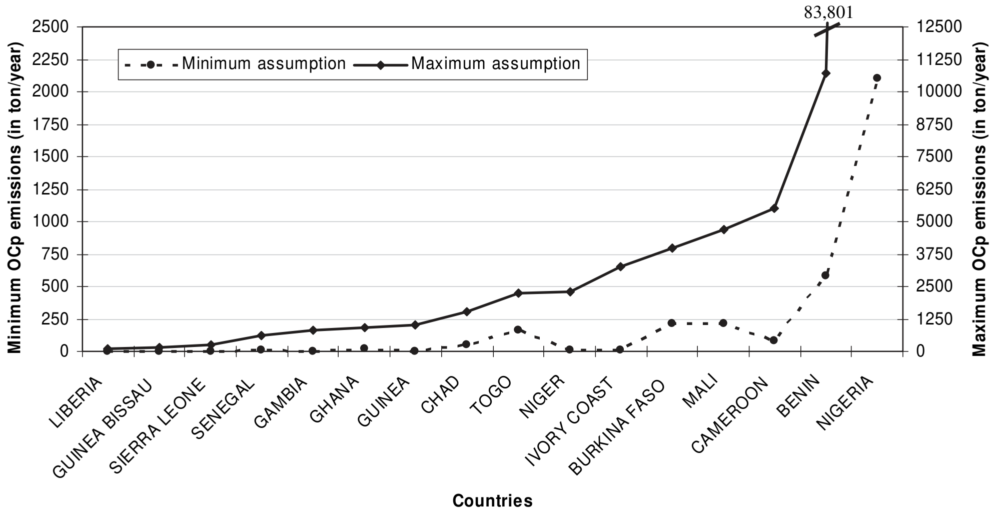

Fig. 3. Total OCp emissions for two-wheel vehicles in West Africa in the minimum and maximum assumptions in 2002.

value used in the maximum case is 4 times larger than in the minimum one.

4. Discussion

4.1. Generalities

For emission purposes, total fuel consumption estimates appear more critical than the total number of two-wheel vehicles assumed. Indeed, under our two assumptions, motorcycle-taxis consume four times more fuel on a daily basis than private two-wheel vehicles, as shown in Table 5. In Fig. 1, some of the 16 countries have fewer two-wheel vehicles, but consume more fuel than countries with greater numbers of such vehicles. For example, in the maximum assumption in Cameroon, there are 259,803 two-wheel vehicles, and fuel consumption in the maximum case is 179,642 tons. In comparison, in Ivory Coast, where the estimated number of two-wheel vehicles is much greater (387,789 vehicles), fuel consumption is much lower (107,256 tons only). Similar results are obtained for Mali and Burkina Faso. This is a result of motorcycles being used mostly for private purposes in these countries (thus consuming much less fuel than countries where the use of motorcycle-taxis is prevalent). Let us note that the use of motorbike-taxis is not directly related to the total population (see Table 2), but rather on other factors, such as the socio-political situation, economical crisis, war, geographical situation, etc….

In all figures, countries have been ranked from smallest to largest in terms of fuel consumption (i.e. from smallest to largest emitters) based on the maximum assumption. Among countries where the numbers of two-wheel vehicles are available, Chad consumed the least amount of fuel (and thus is the smallest BC/OCp emitter), whilst Nigeria is the largest fuel consumer (with ensuing largest BC and OCp emissions) in the maximum assumption. In other countries where the numbers of two-wheel vehicles could only been estimated, Guinea Bissau has the lowest fuel consumption (smallest BC and OCp emitter), whilst Ivory Coast is the largest consumer (and BC and OCp emitter) in the maximum assumption. This classification is different considering the minimum assumption: Liberia consumed the least amount of fuel (and thus is the smallest BC and OCp emitter), whilst Ghana is the largest fuel consumer (with ensuing largest BC and OCp emissions). Overall, in both minimum and maximum assumptions, two-wheel vehicle emissions are largest in Burkina Faso, Mali, Cameroon, Benin and Nigeria.

4.2. Comparison of two-wheel vehicles against global road traffic consumptions

We now discuss the results of a comparison between our two-wheel vehicle fuel consumption estimates and road traffic fuel consumption data for motor gasoline from the UN (2002) and IEA (2000) databases. Comparisons with IEA (Bond et al., 2004) and our results are carried out on total road traffic (motor gasoline fuel consumptions) in all 16 West African countries, whereas the comparison with UN data (2002) is made on a country by country level.

Fig. 4 displays the ratios between two-wheel vehicle fuel consumption in our two assumptions against fuel consumption values given by the UN (2002). This consumption ratio is computed using the following relationship:

$$\text{consumption ratio}\,(\%) = (\text{two-wheel consumption in our study (minimum or maximum)} / \text{all traffic consumption for UN database in 2002}) \times 100$$

Considering all 16 countries, these ratios vary between 6% (total in our min. case/total UN) and 47% (total in our max./total UN). Now considering the comparison with IEA database (not presented in detail here), ratios vary from 5% to 45%, in the minimum and maximum assumptions respectively (Table 6). It is important to note that the IEA data are for the year 2000. Importantly, however, these ratios are of similar orders of magnitude between the two global databases, both UN and IEA.

On a country by country basis, under the minimum assumption, the comparison between our data and the UN data, 11 out of the 16 countries have ratios below 5% and it is only Mali (51%) and Chad (87%) that exceed a ratio of 40%. In the maximum assumption, these ratios vary between 5% in Ghana to 628% in Chad, with nine countries having ratios above 50%. Of these nine countries, Togo has the lowest ratio (54%), indicating that more than half of total traffic fuel consumption result from two-wheelers. In Benin, Niger, Burkina Faso and Mali, these values are even higher, 144%, 149%, 169% and 264%, respectively. The contraband petrol sold in Nigeria, Benin and Togo is likely not accounted for in databases produced by international organizations such as the UN and IEA. The problem of

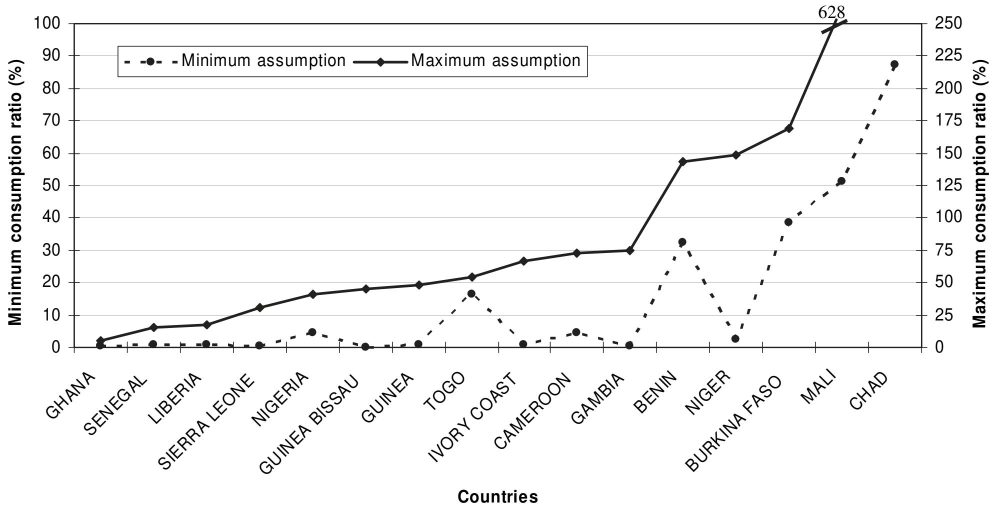

Fig. 4. Ratios (in %) between two-wheel vehicle fuel and total vehicle road traffic fuel consumptions (United Nations database) in the minimum and maximum assumptions (year 2002).

contraband gasoline is relevant for all vehicles, requiring a similar investigation to be carried out for other vehicle types (e.g. cars and trucks). Finally, our results strongly stress the importance of two-wheel vehicle fuel consumption in West Africa (particularly in Benin, Niger, Burkina Faso, Mali and Chad), also raising the serious question of representative data collection.

4.3. Comparison of road traffic BC and OCp emissions: this study vs. global inventories

BC and OCp emissions estimates from our study were compared with other data from global emission inventories. We considered the Bond et al. (2004) inventory for total traffic BC and OCp emissions in West Africa for the year 2000 as well as the global Junker and Liousse (2008) inventory. However, the Junker and Liousse (2008) inventory covers only up to the year 1997. In order to make a more suitable comparison, we applied the Junker and Liousse (2008) methodology (using their BC and OCp emissions factors for traffic) to motor gasoline consumption estimates obtained from the UN database (UN, 2002) for the year 2002. BC and OCp traffic road emissions were calculated for each country. For clarity, these new data will be called "Junker and Liousse calculated for 2002". For comparison, we present emission ratios (in %) for both assumption cases (minimum and maximum) for each country. This ratio is calculated using the following formula:

$$\text{emission ratio}(\%) = (\text{two-wheel emission}\,(\text{BC or OCp})\ \text{in our study}\,(\text{minimum or maximum})/\text{all traffic emissions}\ (\text{BC or OCp})\ \text{from Junker and Liousse calculated for 2002}) \times 100$$

Table 6
Consumption and emission percentages, for the minimum and maximum assumptions respectively vs. Bond et al. (2004) for the year 2000 and Junker and Liousse (2008) calculated for the year 2002.

	Minimum. assumption	Maximum assumption	Minimum assumption	Maximum assumption
	Bond et al. (2004) values		Junker and Liousse (2008) values	
Consumption (%)	5	45	6	47
BC emissions (%)	12	835	10	728
OCp emissions (%)	21	751	56	1980

4.3.1. BC comparisons

As shown in Table 6, throughout our West African domain, ratios of total BC emissions in our study versus those of Junker and Liousse calculated for 2002 amount to 10% in the minimum assumption compared to 728% in the maximum one. Similar ratios can be found when comparing these total BC emissions with those from Bond et al. (2004) for 2000: 12% in the minimum assumption and as much as 835% in the maximum one.

Fig. 5 displays ratios between BC two-wheel vehicle and total vehicle road traffic emissions (the latter from Junker and Liousse calculated for 2002) in the minimum and maximum assumptions for 2002 on a country by country basis.

In the low assumption, two-wheel vehicle BC emissions in Benin, Burkina Faso and Mali are roughly half of all road traffic emissions provided by Junker and Liousse calculated for 2002. The BC emission ratio is largest in Chad where the ratio is 162%. In the maximum assumption, all countries have two-wheel vehicle BC emissions at least two times greater than the total road traffic emissions estimated by Junker and Liousse calculated for 2002, except for in Ghana where the ratio is 84%. This reflects the large difference in motor gasoline emission factors used, with those of the minimum assumption ($0.28\ \text{g kg}^{-1}$) being about twice as large as those used by Junker and Liousse (2008) ($0.15\ \text{g kg}^{-1}$). For comparison, BC emission factors in the maximum assumption are about 15 times larger than in Junker and Liousse (2008). Such significant differences result in considerably larger emissions. Similar differences can also be found between this study and Bond et al. (2004).

4.3.2. OCp comparisons

Table 6 shows the ratios between two-wheel vehicle (minimum and maximum assumptions) and all road traffic OCp emissions for 2002. Total OCp emissions for 2002 in all 16 countries amount to 56% (1980%) of total road traffic emissions from Junker and Liousse calculated for 2002, compared to 21% (751%) of the estimates of Bond et al. (2004) for 2000, in the minimum (maximum) assumption. As can be seen, OCp emissions in Bond et al. (2004) are 2.6 times higher than in Junker and Liousse calculated for 2002. These differences are related to different fuel consumption values and emission factors used; with those utilized by Bond et al. (2004) being higher than those used in Junker and Liousse (2008) calculated for 2002. Indeed, OCp emission factors in Bond et al. (2004) include high values for two-stroke engines whereas Junker and Liousse (2008) do not. Fig. 6 displays similar ratios between our

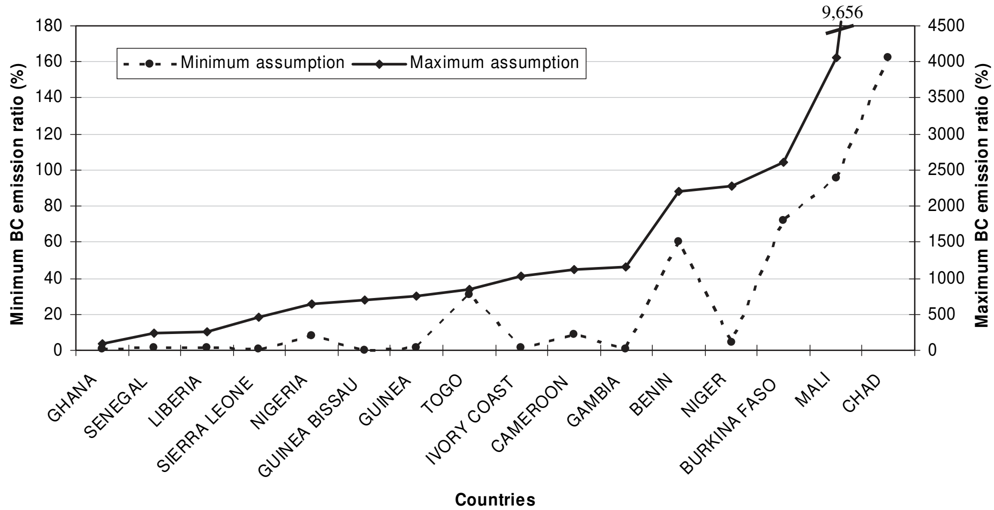

Fig. 5. Ratios (in %) between two-wheel vehicle and total vehicle road traffic BC emissions (the latter from Junker and Liousse calculated for 2002) in the minimum and maximum assumptions for 2002.

study and values from Junker and Liousse calculated for 2002 for each country for the minimum and maximum assumptions. In the minimum case, five countries (Togo, Benin, Burkina Faso, Mali and Chad) display OCp two-wheel vehicle emissions greater than total road traffic emissions (more than 100%). This is even more marked in the maximum assumption, in which all countries show two-wheel vehicle emissions at least twice as large as total traffic emissions (more than 200%), and amounting to as much as 100 times greater in Mali (11,031%) and Chad (26,270%). It is clear that large differences exist between our present inventory and that of Junker and Liousse calculated for 2002, both in the minimum and maximum cases. This is due to the high OCp emission factors adopted for two-wheel vehicles in our study. For motor gasoline, there is a factor of 10 (42) differences in OCp emission factors between our minimum (maximum) assumption and that of Junker and Liousse calculated for 2002. This is attributable to significant quantities of oil mixed with gasoline, effectively taken into account here in the emission factors, but not by Junker and Liousse (2008). If no regulation or control of the fuel:oil mixture is enforced, higher emissions yet still could be expected: in our maximum assumption, average mixtures with 8% oil have been adopted, but values of up to 20% have been measured (Boko et al., 2003). Plans are underway, however, in Benin to replace about 10% of all two-stroke motorcycle taxis with new, less polluting four-stroke motorcycles (Ouedraogo, 2005; Findings, 2002; Diallo, 2001).

Finally, we have shown that BC and OCp emissions in West Africa due to two-wheel vehicles represent a large part and sometimes even exceed the total road traffic emissions of Junker and Liousse calculated for 2002. This is particularly true for OCp where even in our minimum assumption, two-wheel vehicle emissions in five countries (Togo, Benin, Burkina Faso, Mali and Chad) are greater than those for total road traffic.

One question remains, however, assuming that the UN fuel consumption database and the BC and OCp emissions inventories of Junker and Liousse calculated for 2002 did not include two-wheel vehicles, what values would we obtain when taking into account our present results? One answer can be found in Fig. 7 which displays BC and OCp emissions at high resolution ($0.25^{\circ} \times 0.25$), for Junker and Liousse calculated for 2002 (left) and when adding our maximum BC and OCp emission estimates to Junker and Liousse

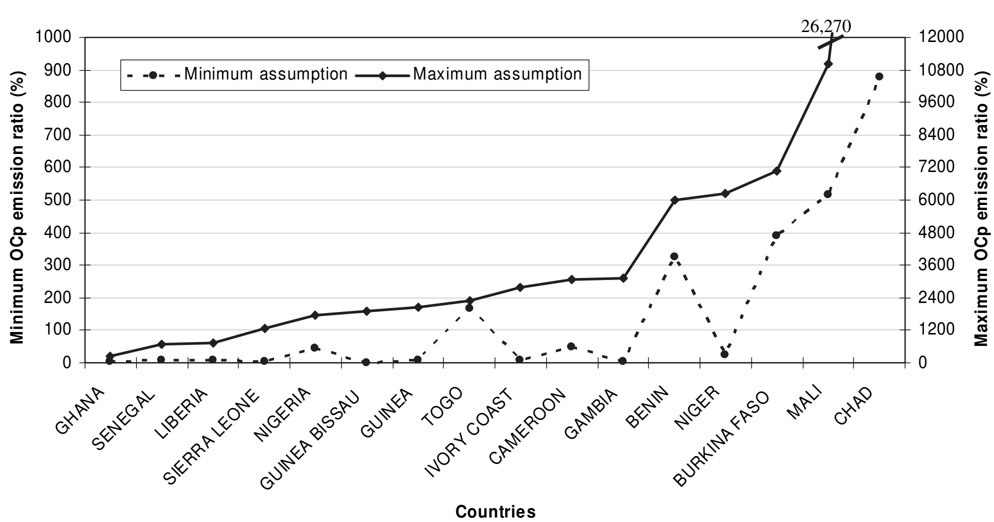

Fig. 6. Ratios (in %) between two-wheel vehicle and total road traffic OCp emissions (the latter from Junker and Liousse calculated for 2002) in the minimum and maximum assumptions for 2002.

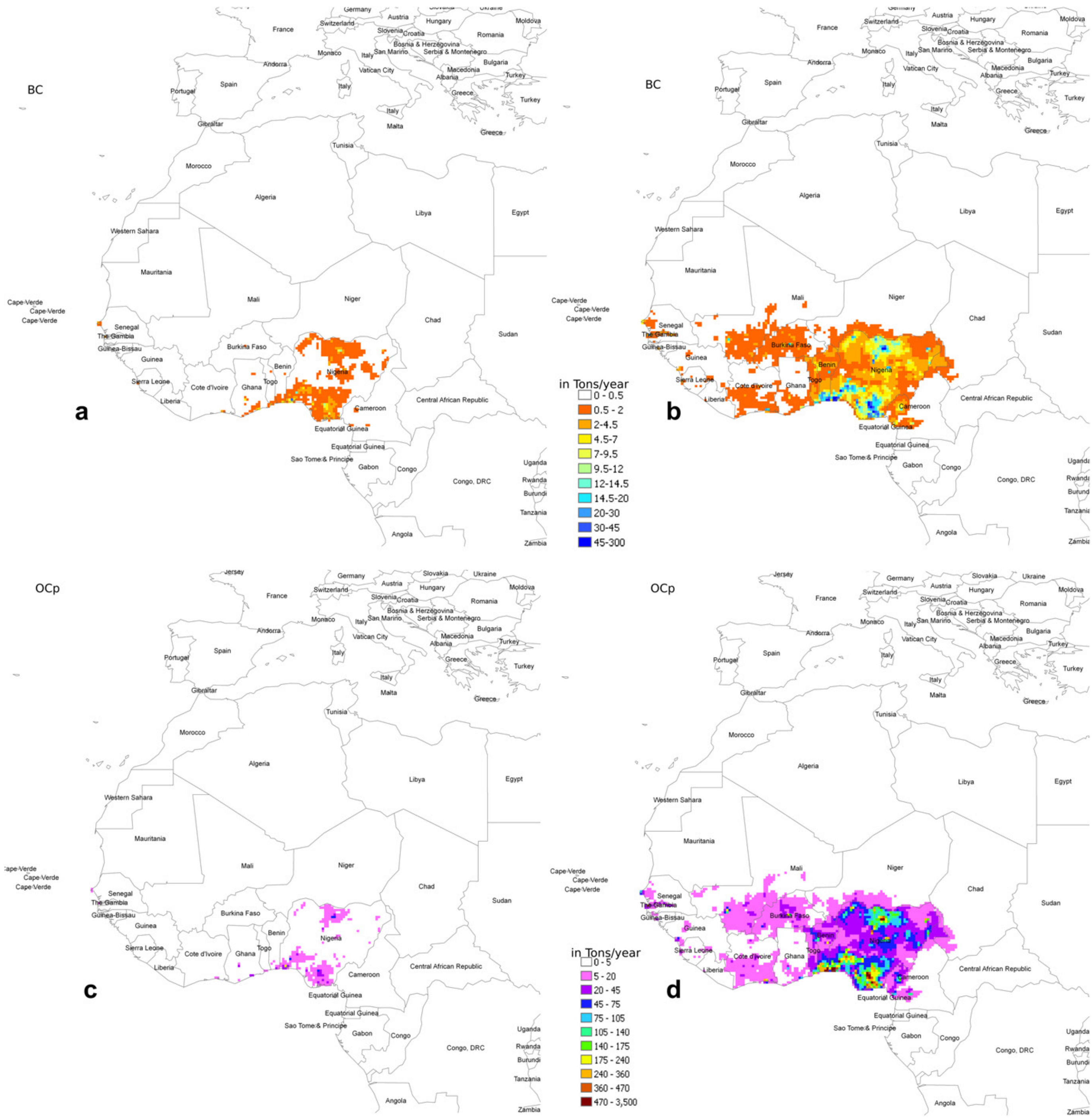

Fig. 7. BC and OCp emissions in West Africa in 2002. a and c: Junker and Liousse calculated for 2002. b and d: our maximum assumption for two-wheel vehicles added to Junker and Liousse calculated for 2002.

calculated for 2002 (right). Fig. 7 shows emission hotspots in the Gulf of Guinea, clearly highlighting the importance of Nigeria and other West African capitals.

It is more likely that our maximum assumption is closer to reality in West Africa, since the emission factor values used in our maximum assumption were directly measured in West Africa (e.g. Benin), while those quoted in the minimum assumption were derived from European studies (Guillaume and Liousse, in press; Guinot et al., in press). Furthermore, parameters such as daily fuel consumption and fuel density in our minimum assumption are for clean European vehicles, whereas the ones used in the maximum assumption were again derived from observations undertaken in West Africa.

5. Conclusion

Due to their ease of use, good performance and low cost, two-stroke engines are of increasingly used throughout West Africa. Unfortunately these vehicles are strong emitters of combustion particles. This study has focused on two-wheel vehicle emissions in West Africa, highlighting the importance and significance of this source. This is particularly the case in countries such as Benin and Togo, where the hydrocarbon market is dominated by oil smuggled out of Nigeria, but also in countries where high percentages of two-wheel vehicles are used in the public transport sector (Burkina Faso and Mali). Due to a general lack of reliable data, this preliminary study has been carried out based on several assumptions, for example, in terms of fuel consumption and emission factor values. In spite of large efforts to collect further, new data from the sixteen countries investigated, many uncertainties still remain. Moreover, this region is rapidly evolving, thus requiring constant updating. Future work is needed to generate more accurate regional estimates. A new area of high anthropogenic emissions is seen to emerge in developing West African countries.

In our proposed methodology, we have put forward two assumptions, a minimum and a maximum one. We consider that the maximum assumption more closely reflects the reality in West Africa, because the parameters used in the minimum one are more relevant to cleaner, Western Europe conditions. In this context, we have obtained large differences between our present regional emission estimates and those from global inventories, the differences being greater between Junker and Liousse calculated for 2002 and our study than between Bond et al. (2004) and this study. The difference is greatest for OCp. These results emphasize the urgent need to take two-wheel vehicle emissions into account in the West African region, since they contribute a large proportion of total road traffic emissions. Improvements in other African anthropogenic emission inventories (e.g. motor gasoline vehicles using smuggled fuels, biofuel, diesel consumption, industries, etc) are still ongoing, also using regional data obtained through direct local enquiries. Field campaigns for counting vehicle numbers, estimating emission factors, etc need to be organized in the various West African countries. This study has also highlighted the significant abundance of OCp emissions from motorcycles, with ensuing severe impacts upon local public health (EPA, 2005, McGranahan and Murray, 2003). This work has strongly demonstrated the importance of the various factors required for assessing road traffic emissions, and to highlight the necessity of local governments for establishing regulatory policies aiming at reducing air pollution.

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