PERGAMON

Chemosphere: Global Change Science 1 (1999) 65–72

CHEMOSPHERE–
GLOBAL CHANGE
SCIENCE

A global inventory of carbon monoxide emissions from motor vehicles

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Received 18 June 1998; accepted 2 September 1998

Importance of this paper: Automobile emissions are the major urban source of carbon monoxide, an atmospheric pollutant which causes human health problems and affects the oxidizing capacity of the troposphere. Long-term trends and year-to-year variations in the global CO abundance are not well established. The present research involves the creation of a global inventory of CO emissions from motor vehicle sources using data from on-road vehicle emissions measurements and socio-economic factors.

Abstract

Automobile emissions are the major urban source of carbon monoxide, and they are also important globally. One estimate by the Japanese Automobile Research Institute (JARI) of the 1990 global CO emissions from automobiles is 231 megatonnes (Mt). The same source gives the USA 1990 emissions as 21 Mt, whereas the US Environmental Protection Agency (EPA) estimate 57 Mt. The two sources agree that the mobile source (including airplanes) CO_2 emissions are about 1500 Mt. Thus the disagreement is in the CO/CO_2 molar ratio (JARI 0.022, EPA 0.062). We have developed a device which measures the CO/CO_2 ratio in the exhaust of motor vehicles passing in a single lane. At busy locations we measure over 1000 vehicles per hour. Over the last 10 yrs these ratios have been measured from over ten million vehicles in eighteen countries. The results can be directly converted into mass of emissions per liter of fuel burned. On-road CO emissions depend on the vehicle technology, its state of maintenance, and thus upon fleet age. Our estimate of the 1991 global CO emissions from motor vehicles is 213 Mt, of which 88% (188 Mt) were produced in the northern hemisphere, with 17% (36 Mt) produced in the USA. This estimate for USA 1991 emissions is intermediate between the JARI and EPA 1990 estimates. For 1995 relative to 1991, we estimate a 17% decrease in global CO emissions from motor vehicles, arising from fleet emissions technology upgrades, somewhat countered by increased fuel consumption.

Keywords: Carbon monoxide; Global inventory; Automobile exhaust; On-road measurements

1. Introduction

Carbon monoxide (CO) is a gaseous pollutant which enters the atmosphere from four major

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1465-9972/99/$ – see front matter
PII: S1465-9972(99)00017-3

sources: fossil fuel combustion and industrial emissions, biomass burning, oxidation of CH_4, and oxidation of non-methane hydrocarbons. The presence of CO causes problems to human health, particularly in cases of locally high concentrations, and affects the oxidizing capacity of the troposphere. High concentrations can occur in congested urban areas because of CO emissions from internal combustion engines. In fact, in 1981 Logan et al. (1981) estimated that, globally, transportation sources accounted for about 50% of the total industrial source of CO. CO concentrations are higher in the northern hemisphere, especially in urban industrial areas, than in the southern hemisphere, where there are fewer vehicles. Novelli et al. (1992) reported that background CO concentrations are subject to rather large seasonal variations, with higher values in the later winter and early spring. However, long-term trends and year-to-year variations in the global CO abundance are not well established. The present research is focused on the creation of a global inventory of carbon monoxide emissions from motor vehicle sources for the years 1991 and 1995, using data from on-road vehicle exhaust emissions measurements in eighteen countries (Zhang et al., 1995). The principles of using on-road data for fuel-based emissions inventories have been described by Singer and Harley (1996).

2. Data acquisition and analyses

The global inventory of CO emissions from motor vehicles is derived from data obtained by measuring the exhaust emissions of on-road vehicles using technology developed at the University of Denver. This on-road testing system, which has been described in detail previously (Bishop et al., 1989; Bishop and Stedman, 1996; Guenther et al., 1991), is based on nondispersive infrared spectroscopy. It measures the carbon monoxide to carbon dioxide ratio (CO/CO_2) and the hydrocarbon to carbon dioxide ratio (HC/CO_2) in the exhaust of any on-road vehicle passing through an infrared light beam that is directed across a single lane of roadway. The IR absorption caused by CO, HC, and CO_2 in the exhaust plume is determined using separate bandpass filters centered at 4.6, 3.4, and 4.3 μm, respectively. To eliminate any effect of source fluctuations or dust and smoke behind the vehicle, the results are ratioed to a reference absorption at 3.9 μm, where vehicle exhaust gases do not absorb. The signals are digitized and acquired by a computer system, and software computes exhaust %CO and %HC from the measured CO/CO_2 and HC/CO_2 ratios on a dry basis corrected for the presence of any excess air. With minimal inaccuracy caused by assuming a fuel carbon to hydrogen ratio of 1:2 and fuel density of 0.75 g/ml, these results can be directly converted into the instantaneous mass emission rates in grams of CO per liter of fuel consumed using the following equation (Bishop and Stedman, 1996):

$$\text{gCO/l fuel} = \frac{1409(\%\text{CO})}{15.06 + 0.285(\%\text{CO}) + 2.868(\%\text{HC})}. \quad (1)$$

For the year 1991, specific CO emissions data used in the global inventory arise from previous measurements (Zhang et al., 1995) at 22 sampling locations in 18 countries, chosen based upon abundant urban traffic flow and representation of different regions around the world with correspondingly different fleet profiles. The sampling locations and measuring dates are summarized in Table 1. Detailed descriptions of the measurement sites, as well as the number of measurements recorded at each location, have been presented previously (Zhang et al., 1995). Table 1 also includes values for the 1991 gross domestic product per capita (GDPpc) (United Nations, 1997), and for the number of grams of CO emitted per liter of gasoline consumed, for each country.

The values for grams of CO emitted per liter of gasoline consumed were obtained by first calculating the number of grams of CO emitted per liter of fuel consumed (Eq. 1), and then weighting to reflect the composition of the fleet. Fleet information was obtained for each country (Laboratory of Applied Thermodynamics, Aristotle University of Thessaloniki, 1998; Encyclopedia Britannica,

Table 1
On-road testing data used in global CO inventory: sampling locations, measuring dates, %CO, number of grams of CO per liter gasoline consumed, and 1991 gross domestic product per capita[a]

Letter code	Location (Country, city)	Date (month/year)	% CO	g CO/l gas (1991)	GDPpc (1991)
A	Australia, Melbourne	05/92	1.42	156	17602
C	Canada, Toronto	04/90	0.75	81	20751
F	France, Lyons	05/94	0.97	107	21063
D	Germany, Hamburg	05/94	0.57	58	21540
G	Greece, Thessaloniki	09/92	1.40	129	6884
H	Hong Kong	08/93	0.96	126	14888
I	Italy, Milan	05/94	1.25	138	20191
M	Mexico, Mexico City	02/91	4.30	497	3380
R	Nepal, Kathmandu	08/93	3.85	491	168
N	Netherlands, Rotterdam	05/94	0.55	60	19273
P	Portugal, Lisbon	05/94	1.48	162	7854
K	South Korea, Seoul	08/93	0.82	111	6798
Q	Sweden, Gothenburg	09/91	0.71	69	27803
E	Switzerland, Zurich	03/94	0.83	81	33455
J	Taiwan, Taipei	08/93	1.49	163	9850
B	Thailand, Bangkok	08/93	3.04	720	1747
L	UK, Edinburgh, Leicester, and London	11/92, 11/92, 11/92	1.48, 2.32, 0.96	146[b]	17464
U	USA, Chicago, Denver, and Los Angeles	06/92, 10/91, 06/91	1.04, 0.74, 0.79	78[b]	22033

[a] Value given in US dollars, at current and constant 1990 prices (United Nations, 19970).
[b] Value for country is statistical average of values from the three cities for which there are data.

1993), and the fractions of the fleet corresponding to gasoline (F_{gas}) and diesel (F_{diesel}) consumption were calculated. For diesel vehicles, the average CO emission was determined to be 0.2% (Stedman et al., 1997). This value was taken to be constant for all countries, because diesel measurements show consistently low, model-year independent CO emissions (Stedman et al., 1997), and because the diesel fleet has not been subjected to emissions controls likely to affect CO. The g CO/l for diesel vehicles was then calculated to be 46.36 g CO/l diesel, which was used for all countries worldwide. The values for g CO/l for gasoline vehicles for each of the 18 countries except the USA were then obtained from the following equation:

$$\text{gCO/l gas} = \frac{(\text{gCO/l fuel}) - (F_{diesel})(18.54\ \text{g CO/l diesel})}{F_{gas}}. \quad (2)$$

For the USA, most diesel emissions are at high elevation (i.e. originate from vertical exhaust pipes rather than tail pipes, which are closer to the ground) and have only very recently been measured by the on-road testing system. Therefore the measured emissions for USA in 1991–1992 were assumed to equal gasoline, and the diesel component was added.

In order to extrapolate to countries where measurements were not available, we investigated the relationship between a country's economy and its CO emissions by creating a plot of g CO/l gasoline versus 1/GDPpc (Fig. 1). Each data point is labeled by a letter which represents one of the eighteen countries, as listed in Table 1.

From this plot it is clear that the lower the GDPpc, the greater the amount of CO emissions per liter of gasoline consumed. Such a result is not surprising, as poorer countries will mostly have older, less well-maintained fleets of vehicles than more affluent countries, and they have not invested

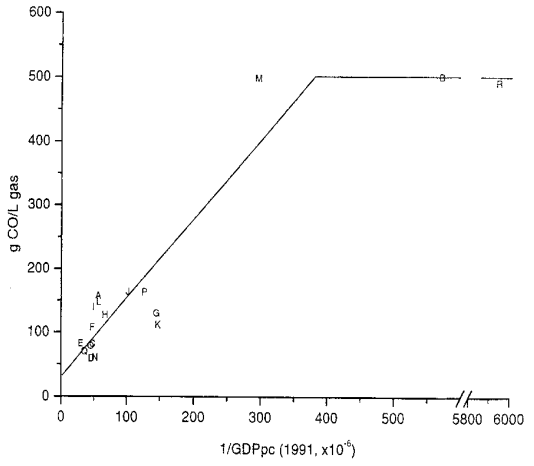

Fig. 1. Relationship between vehicle CO emissions and economic factors: g CO/L gasoline versus the inverse of gross national product per capita for 1991, reported in US dollars at current and constant 1990 prices. Data points represent values for each of the 18 countries for which remote sensing measurements have been made. Lines represent a fit to the data (segment with nonzero slope) and a cutoff value for average uncontrolled CO emissions (segment with slope of zero), as discussed in the text. Countries are represented by the letter designation given in Table 1.

in state-of-the-art emission controls. Superimposed onto the data points are two line segments. The segment with non-zero slope represents a least-squares linear fit to the data points, excluding Nepal ($x = 51900 \times 10^{-6}$ GDPpc^{-1}, $y =$ 491 g CO/l), whose GDPpc is at least an order of magnitude lower than the other countries included in the data set. This line has a slope of 1.23×10^{-6} (g CO/l)/(GDPpc^{-1}), a $y =$ intercept of 30.24 g CO/l, and a correlation coefficient of $r^2 =$ 0.96. This large correlation is quite remarkable in view of the fact that fleet age and owner maintenance behavior are really the most important variables (Bishop and Stedman, 1996). The segment at $y = 500$, with zero slope, represents an arbitrary cutoff point for CO emissions when considering GDPpc. The cutoff point was imposed based on Mexico's emissions in 1991, at about 500 g CO/l gasoline, which was taken as an average for the uncontrolled amount of CO emissions per liter of gasoline consumed for low GDPpc countries. This assumption is based on the fact that the fleet in Mexico appeared to be elderly, badly maintained, and representative of fleets found in third-world countries. The effects of the actual value selected for the cutoff point are discussed later. (Note that when fitting the first line segment, raw data for Thailand (719.91 g CO/l gasoline) were used; however, Thailand's data point was then readjusted to 500.00 g CO/l gasoline, based on the cutoff procedure, in creating Fig. 1.) These results were then extrapolated to the rest of the world, using each country's GDPpc data (United Nations, 1997) (Values for former USSR and Zaire were obtained from 1989 data in the Penn World Tables, which can be accessed via the World Wide Web at http://bized.ac.uk/dataserv/pennext.htm. Certain regions were combined (e.g. parts of Africa, Latin America, and Oceania), so their GDPpc information was obtained by taking a weighted average, based on population data from the United Nations (1997), and the two line segments in Fig. 1.

Gasoline (United Nations, 1996) and diesel (International Energy Agency, 1997a; International Energy Agency, 1997b) consumption data for 1991 for all countries were then obtained in gigaliters (Values for China, Puerto Rico, former USSR, former CSFR, and Taiwan were obtained from IEA data tables on the World Wide Web at http://www.eia.doe.gov/emeu/iea/table12.html). Multiplying the consumption data for each fuel type by their respective emissions data (g CO/l gasoline and g CO/l diesel), values for CO emissions per year from motor vehicle sources were calculated for all countries. These values were then summed over both hemispheres and the world. The final results for 1991 are presented in Table 2.

In order to estimate 1995 emissions, 1995 gasoline (United Nations, 1997) and diesel (International Energy Agency, 1997a; International Energy Agency, 1997b) consumption data were obtained for every country. Values for China, Puerto Rico, former USSR, former CSFR, and Taiwan were estimated from diesel values reported by the United Nations (1997) which, unlike the IEA source, include diesel consumption from sectors other than just road transportation. The estimated values are obtained by multiplying the raw 1995 UN diesel consumption value by a ratio of the 1991 IEA diesel consumption value to the 1991 UN diesel consumption value. Next the 1995 val-

Table 2
Estimated CO emissions per year from motor vehicles, by fuel type, for the years 1991 and 1995[a]

		Mt CO/yr, gasoline	Mt CO/yr, diesel	Mt CO/yr, total
1991	USA	32	4	36
	NH	161	27	188
	SH	22	3	25
	W	183	30	213
1995	USA	18	4	22
	NH	124	30	154
	SH	19	4	23
	W	143	34	177

[a] Values are given for USA, the northern hemisphere (NH), the southern hemisphere (SH), and the world (W), in Mt CO/yr (megatonnes of CO per year).

ues for grams of CO emissions per liter of gasoline and diesel were calculated. For g CO/l gasoline, the 1991 values were adjusted based on technology updates. For the year 1995, fleet technology upgrades for most countries were obtained from M.P. Walsh (private consultant, personal communication, 1998), who provided a table of new car mandated technologies in which values of 3 or 4 indicate 1983 US technology or better. Part of this table is summarized in Table 3.

Countries receiving a 3 or 4 were assigned a 50% reduction in CO emissions per liter of gasoline consumed. We have observed about a 45% reduction in fleet emissions in Mexico City between 1991 and 1994 when catalysts were introduced (Bishop and Stedman, 1996). The reduction in Sweden appears to be larger after catalyst introduction in 1988 (Sjödin, 1994). We estimate that most countries with new technology will have maintenance intermediate between Mexico City and Sweden, hence the 50% reduction for countries receiving a 3 or 4 in the Walsh table. Countries receiving a 0 or 1 were given no reduction, and countries not included in the table were assumed to receive a 0. For g CO/l diesel, the value 46.36 g CO/l diesel was again used for all countries, because there was no change in the diesel technology during the four year time span. Finally, the 1995 values for CO emissions per year for each fuel type were calculated in a manner analogous to that for the 1991 values. These 1995 values were then summed over both hemispheres and the world, and they are also included in Table 2.

Table 2 indicates that in 1991, an estimated 213 Mt (megatonnes) of CO emissions originated from motor vehicles world-wide. This value is somewhat lower than the 1990 JARI value of 231 Mt (Minato, 1996). Of our global 213 Mt, 88% (188 Mt) were produced in the northern hemisphere, with 17% (36 Mt) being produced in the USA alone. Thus, our USA value falls intermediate between the 1990 JARI (Minato, 1996) and EPA (US Environmental Protection Agency, 1994) estimates. In the years between 1991 and 1995, global fuel consumption increased by 11% (United Nations, 1996; United Nations, 1997; International Energy Agency, 1997a; International Energy Agency, 1997b) but at the same time new emissions technology was implemented or continued in many countries. For the 1995 global emissions from gasoline vehicles only, the influence of the technology upgrades results in a world-wide total of 143 Mt CO emissions, a 22% decrease from 1991 (183 Mt). In contrast, the slight increase in CO emissions from diesel vehicles, observed worldwide, results from the increase in diesel consump-

Table 3
Summary of new car mandated technologies for countries with 1983 US technology or better

Tech	Countries
3	Argentina, Australia, Brazil, Colombia, Ecuador, Guatemala, Japan, Malaysia, New Zealand, Paraguay, Singapore, South Korea, Taiwan, Thailand, Turkey, Uruguay
4	Austria, Belgium, Canada, Chile, Denmark, Finland, France, Germany, Greece, Hong Kong, Hungary, Ireland, Italy, Luxembourg, Mexico, Netherlands, Norway, Poland, Portugal, Puerto Rico, Romania, Spain, Sweden, Switzerland, UK, USA

tion with no corresponding technology updates for diesel. At a total of 154 Mt, the northern hemisphere still accounts for about the same percentage (87%) of total, world-wide emissions. For the USA, there is a 46% decrease in CO emissions from gasoline vehicles, a value which is less than the 50% reduction given its level 4 status, due to the corresponding increase in gasoline consumption. Considering total CO emissions from motor vehicles in the USA, we estimate a decrease of 39% from 1991 to 1995, in stark contrast to the approximately 6% decrease estimated by the EPA from 1990 to 1996 (US Environmental Protection Agency, Tier 2 study draft of EPA420-P-98-009, in preparation, April, 1998).

It is important to examine the potential sources of inaccuracy in our estimate. First, the measured data, which come mostly from individual locations in the eighteen countries, may not be representative of those countries as a whole. Also, GDPpc is surely not the only variable in the g CO/l equation; however, the r^2 of 0.96 and small intercept for the equation indicates that these two caveats are probably not major sources of error. Another concern is that some of the measurements were taken as late as 1994 but are considered "1991" data. This is of particular concern for countries such as Germany and the Netherlands, which, during the time period between 1990 and 1995, saw substantial increases in the percent of the total fleet that received the highest technical upgrades (Applied Thermodynamics, Aristotle University of Thessaloniki, 1998). In such cases we have investigated the effect of adjusting the measurements in time. This adjustment was achieved by defining a line that has a slope resulting in the 50% reduction from 1991–1995 and contains the measured data point at 1994. The resulting, extrapolated 1991 value was then used in creating a plot similar to Fig. 1, and the rest of the analysis was continued as described above. We find that the result of such a treatment is only about a 1% increase in the total, global CO emissions. Another concern is that the uncontrolled emissions average at 500 g CO/l may not be correct, although it seems reasonable. We calculated that even if the cutoff is actually 600 g CO/l, the difference in global total CO emissions is only 6%. Another potential source of inaccuracy is the possibility that the linear fit to measured values may not be correct for the countries not sampled, as the eighteen sampled countries represent only about 44% and 33% of the global emissions from gasoline and diesel consumption, respectively. Further, new technology was introduced in different countries at different times – for instance Sweden in 1987, UK in 1992, and Mexico in 1993.

The blanket 50% reduction from 1991 to 1995 is certainly an approximation, although Fig. 2 for two freeway sites in Denver, Colorado (G.A. Bishop et al., Final technical report for ITS for voluntary emission reduction: an ITS operational test using real-time vehicle emissions detection, report submitted to the Colorado Department of Transportation, 1998), shows approximately a 30% reduction during this time span, even though formally the level 3 technology was introduced in 1982. Additionally, we have investigated the effect of changing the emissions reduction to 40%, with the result being only a 7% increase in the total, global CO emissions from motor vehicles. A recent paper analyzing ambient CO in Mexico City (Riveros et al., 1998) shows only a 15% reduction in the amount of CO per liter of gasoline con-

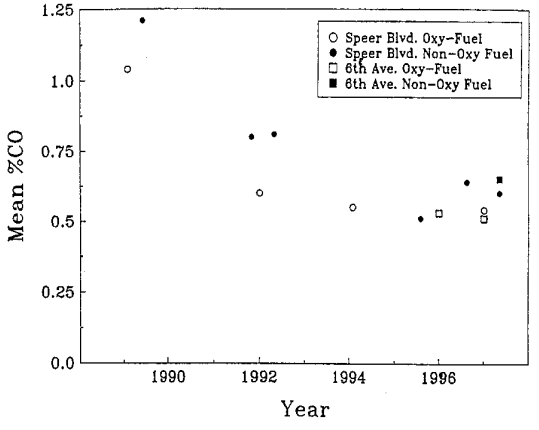

Fig. 2. Time dependence of mean CO measurements from the two Denver locations of Speer Blvd. &I-25 and 6th Ave. &I-25. Oxygenated fuel is used between November and February in Denver. The small study using oxygenated fuel in late 1995 was a fleet of vehicles on average 0.4 yrs newer than the averages for the other locations.

sumed. Since most of the CO in Mexico City is thought to originate from mobile sources (Los Alamos National Laboratory, 1994), this result shows that our 50% (or even 40%) reduction may be an overestimate, at least for Mexico.

Inaccuracies in these fuel-based emission inventories are probably larger than the inevitable inaccuracies in reported fuel usage. Overall, then, we estimate about a 20% error associated with our global inventory, and a further 20% in the 1991–1995 difference.

3. Conclusion

This work has presented a global inventory of the amount of CO emissions originating from motor vehicle sources for the years 1991 and 1995. These estimates are based on economic factors and on measurements of the exhaust emissions of on-road vehicles in eighteen countries made in or close to 1991. For 1995, the influence of fleet emissions technology upgrades is also incorporated. The resulting 1991 estimate indicates a global 213 Mt CO emissions, of which 188 Mt were produced in the northern hemisphere, and 25 Mt in the southern hemisphere. We estimate for the USA 36 Mt, a value intermediate between those reported for 1990 by JARI and EPA. USA was therefore responsible for about 17% of the global CO emissions from motor vehicles in 1991. However, we find that this value decreased by about 46% in the years between 1991 and 1995, with the USA responsible for about 12% (22 Mt) of the global emissions (177 Mt) world-wide in 1995. This emissions reduction, seen to a much greater extent in the northern hemisphere than the southern hemisphere, is a reflection of the emissions technology upgrades, which occurred primarily in more affluent countries in the northern hemisphere.

Acknowledgements

This work was supported by NSF Grant No. ATM-9417061 and by the Camille and Henry Dreyfus Postdoctoral Program in Environmental Chemistry.

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