India

Anthropogenic Emissions from Energy Activities in India: Generation and Source Characterization

Emissions from Vehicular Transport in India

Part II

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Anthropogenic Emissions from Energy Activities in India: Generation and Source Characterization

Part II: Emissions from Vehicular Transport in India

Introduction

Part II of this research involves emissions from vehicular transport using petroleum fuel. Part I contained emission estimates of greenhouse and other trace gases including suspended particulate matter and soot carbon from India's coal-based thermal power plants. The United States Agency for International Development/India's Office of Environment, Energy & Enterprise has sponsored the project, *Anthropogenic Emissions from Energy Activities in India,* to assess the emissions of greenhouse and other trace atmospheric gases from energy activities in India.

This study is part of an effort to look at India's present and projected emission inventory, study the transport and distribution patterns of emitted pollutants, and develop a long-term air quality database covering the country's various geographical areas.

Petroleum Fuel Consumption in India

India's population, the second largest in the world, grows at a rate of about 2% per year[1] and has grown from 300 million in 1947 to more than a billion today. Rising population and changes in lifestyles consistent with rapid economic growth have accelerated the demand for all kinds of energy. Major sources of energy in India include coal, petroleum, biomass, nuclear power, and hydropower. Hydropower and nuclear power are less than 25% and 4%, respectively, of the total installed capacity. Fossil fuels -- coal and petroleum -- fulfill the remaining demand for energy. However, combustion of these fuels is the main source of pollution in the natural environment and is also considered responsible for global warming. Part I of this research discussed the emissions from coal-fired thermal power plants in India. This report deals with emissions from petroleum fuels used for vehicular transport in India.

The consumption of petroleum and consequent carbon dioxide (CO_2) emissions for the USA, China, and India are given in Tables 1 and 2 for 1990-1999, with projections up to 2020. Figures 1 and 2 show the petroleum fuel usage and corresponding CO_2 emissions during 1991-2000 respectively for the USA, China, and India. Petroleum fuel usage in India has grown from 1.2 million barrels per day in 1990 to 1.9 million barrels per day in 1999. The Energy Information Administration (EIA)[2] has projected an average annual percentage change (AAPC) in petroleum oil consumption as 4.3 and 3.7, and in CO_2 emissions from petroleum fuel use as 4.6 and 4.3 for India and China, respectively.

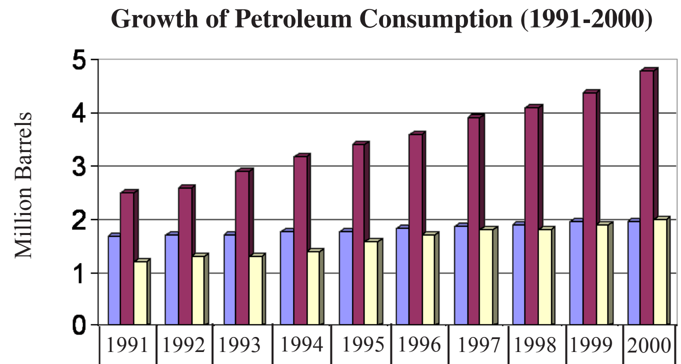
Table 1: Petroleum Oil Consumption (Million Barrel per Day)

Country	1990	1998	1999	2005	2010	2015	2020	AAPC
USA	17.0	18.9	19.5	21.3	23.2	25.1	26.7	1.5
China	2.3	4.1	4.3	5.3	6.8	8.6	10.5	3.7
India	1.2	1.8	1.9	2.5	3.2	4.1	4.9	4.3

[1] World Development Indicators – Annual report of the World Bank on development indicators (www.worldbank.org/data/wdi2000/pdfs/tab3-7.pdf, tab3-8.pdf, and /countrydata/aag/ind-aag.pdf)

[2] www.eia.doe.gov

Figure 1: Growth of Petroleum Consumption in the USA, China, and India

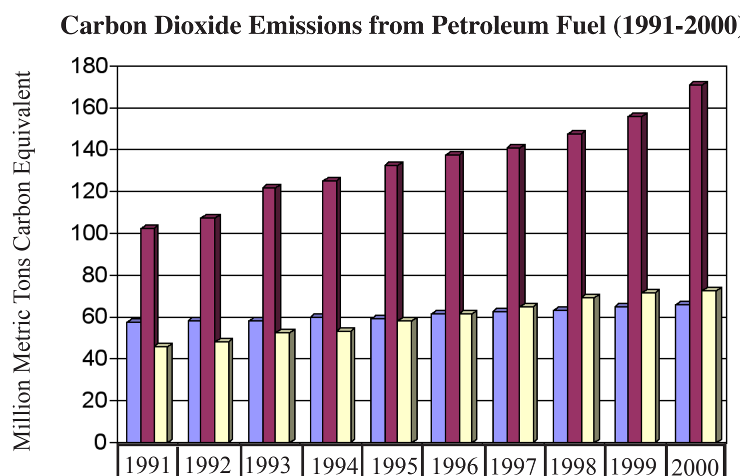


	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
USA X 0.1	1.67	1.7	1.72	1.77	1.77	1.83	1.86	1.89	1.95	1.97
CHINA	2.5	2.6	2.9	3.2	3.4	3.6	3.9	4.1	4.4	4.8
INDIA	1.2	1.3	1.3	1.4	1.6	1.7	1.8	1.8	1.9	2

Table 2: Carbon Dioxide Emissions from Petroleum Fuel Use (Million Metric Tons Carbon Equivalent)

Country	**1990**	**1998**	**1999**	**2005**	**2010**	**2015**	**2020**	**AAPC**
USA	590	635	650	705	711	835	891	1.5
China	94	152	160	196	251	317	390	4.3
India	45.0	69.5	71.4	85.3	106.7	131.6	157.6	4.6

Figure 2: Growth of Carbon Dioxide Emissions from Petroleum Fuel in the USA, China, and India



	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
USA X 0.1	57.6	58.7	58.8	60	59.6	61.9	62.5	63.4	65.8	65.8
CHINA	102.3	107.4	121.2	125	132	137.6	140.9	147.6	155.8	170.6
INDIA	45.7	48.8	52.4	53.7	58.5	61.8	65	69.5	71.4	72.6

Vehicular Transport in India

Many different types of vehicles are used in India for transporting goods and passengers. These vehicles use different types of internal combustion (IC) engines and petroleum fuels like gasoline (commonly referred to as petrol in India) and diesel. A broad classification of vehicles for the purpose of emission inventory can be made as:

(1) Two-Wheeler (2W)
(2) Three-Wheeler (3W)
(3) Car and Taxi (4W)
(4) Bus and Truck (B&T)

Table 3 gives the population and the effective daily distances[3] traveled by these vehicles in kilometers per day (km/day) in India's seven major cities and also for the entire country for the year 1997.

Table 3: Population (P: in thousands) and Distance Traveled (D: km/day) by Vehicles

	2W*		3W**		4W#		B&T###		All Veh##
	P	D	P	D	P	D	P	D	
Delhi	1,992	39	80	69	782	43	179	127	3,033
Mumbai	355	38	113	64	347	43	34	106	860
Kolkata	299	18	10	50	271	43	68	105	664
Chennai	713	39	41	56	185	43	26	100	975
Bangalore	839	36	74	69	167	45	29	98	1130
Hyderabad	712	31	57	54	93	40	21	70	887
Ahemdabad	530	31	44	54	87	30	24	70	686
All India	28,342	24	4,125	52	5,056	33	3,064	82	40,939

*includes two-stroke and four-stroke engines
** includes two-stroke and four-stroke engines
# includes cars, taxis, and jeeps
also include tractors, trailers and other vehicles
includes buses and trucks
P: Population of the vehicle in thousands
D: Effective daily distance[3] traveled (km/day) by vehicles

Methodology for Emission Estimation

The main emissions from IC engines used in vehicular transport are carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx), sulfur oxides (SOx), particulate matter, carbonaceous material (soot), hydrocarbons (HC), and other trace gas species. Emissions of these pollutants depend on the combustion technologies, the fuel used, the intake air, the engine conditions, and possible technologies that are used to control emissions.

Concentrations and mass emission factors of CO, CO_2, SO_2, nitric oxide (NO), particulate and carbonaceous matter, and HC in the exhaust emissions from every kind of vehicle plying on Indian roads are computed using basic principles of combustion and respective Indian driving cycles. HC emissions in the exhaust are considered only from scavengingb in the two-stroke engines. HC emissions due to unburnt oil (which is mixed with gasoline) are not taken into account in the present analysis. Concentration values depend on the chemical composition of the fuel (gasoline or diesel) and the air-to-fuel ratio. Mass emission factor depends additionally on fuel consumption at different speeds including, at the idling stage. These are calculated for Indian driving cycles from the computed values of emissions. Kilometer traveled per unit of time for different vehicles is based on industry standard Indian Driving Cycle (IDC) as given in Appendix-A.

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[3] Personal communication
[a] Pollutant species mass per unit volume
b Operation of clearing the cylinder of burned gases and filling it up with fresh mixture of air and fuel

The following eight categories of vehicles are considered for emission estimations:

1. Two-wheeler two-stroke (2W2S)
2. Two-wheeler four-stroke (2W4S)
3. Three-wheeler two-stroke (3W2S)
4. Three-wheeler four-stroke (3W4S)
5. Four-wheeler gasoline (4WG)
6. Four-wheeler diesel (4WD)
7. Heavy-duty diesel low sulfur (HDDLS)
8. Heavy-duty diesel high sulfur (HDDHS)

Computed and measured mass emission factors for each of these vehicles are given in Tables B1 and B2 respectively. Table B3 provides the Indian norms for mass emission factors for the vehicles.

Species Emissions

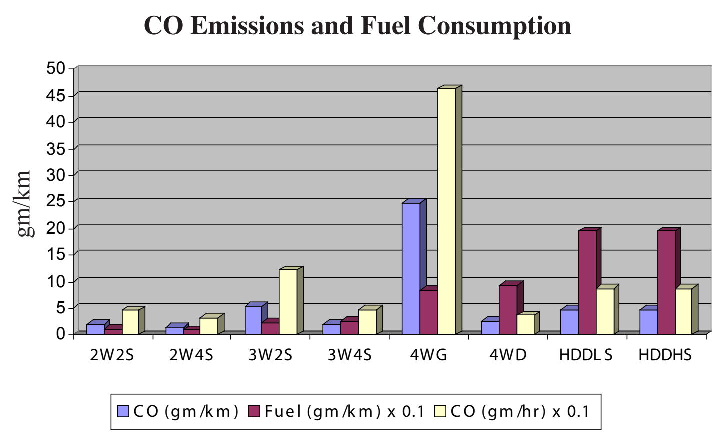
Species emission characteristics from different vehicles are discussed and compared with available measurement values.

Carbon Monoxide Emissions

CO results from the incomplete oxidation of fuel to CO_2. The most important parameter influencing CO emissions is the air-fuel ratio during engine operation. CO emissions increase with a decreasing air-fuel ratio. Gasoline engines often operate close to stoichiometric[c] at part load and fuel rich at full load. As a result, CO emissions are significant from gasoline engines. Diesel engines operate well on the lean side of stoichiometric, thus, CO emissions from diesel engines are minimal. The computations show that CO emissions from 2W2S vehicles are 2.0 gm/km compared to 1.16 gm/km for 2W4S vehicles. CO emissions from 4WG vehicles are computed as 24.75 gm/km, from 4WD vehicles as 2.0 gm/km, and from HDDHS vehicles using diesel fuel as 4.45 gm/km.

As the Tables B1, B2, and B3 show, computed CO emissions are comparable with the norms for two-wheeled two-stoke engines (2W2S), underestimated for two-wheeled four-stroke engines (2W4S), overestimated for three-wheeled two-stroke engines (3W2S), and underestimated for three-wheeled four-stroke engines (3W4S). Computed CO emissions for diesel vehicles are comparable with the norms. One reason for this discrepancy might be the difference in the quantity of fuel consumption at different speeds as prescribed by the manufacturers. The computed values of CO emissions and fuel consumption are shown in Figure 3. Total annual CO emissions in the year 1997 from all the vehicles are estimated as 2.163 million tons.

Figure 3: CO Emissions and Fuel Consumption by Indian Vehicles per IDC



[c] Amount of air needed for complete combustion of fuel

Carbon Dioxide Emissions

All the carbon in the fuel should be oxidized to CO_2 in an ideal condition. However, part of the carbon does not get completely oxidized and is emitted either as carbonaceous material or as CO. CO_2 emissions increase with fuel consumption; hence, heavy duty vehicles have much higher CO_2 emissions.

Calculated values of CO_2 emissions from the vehicles are given in Table B1. CO_2 emissions for 2W2S and 2W4S are estimated as 26.6 and 28.3 (gm/km) respectively. These estimates are lower than the measured values. For 3W2S and 3W4S, CO_2 emissions are estimated as 60.3 and 78.5 (gm/km) respectively, which are higher than the measured values. Estimates for CO_2 emissions from four-wheeler gasoline vehicles (4WG) as 223.6 (gm/km), are slightly higher than the estimates of 208.3 (gm/km) from four-wheeler diesel vehicles (4WD). CO_2 emission from buses and trucks is 515.1 (gm/km). This is more than double the emission from 4WG or 4WD vehicles. Measured values of CO_2 emissions from vehicular transport in India is not available in public domain. Presently, there are no norms for CO_2 emissions in India.

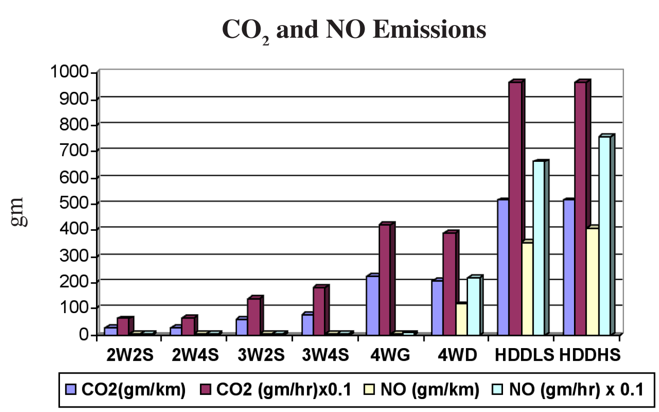
Figure 4 shows the CO_2 emissions (gm/km) and (gm/hr) from the Indian vehicles along with NO emissions. Total CO_2 emissions are estimated as 42.884 million tons from all vehicles in the year 1997.

Emissions of Oxides of Nitrogen

Nitrogen dioxide (NO_2) and NO grouped together are known as NO_x. NO_2/ NO ratios are negligibly small for gasoline engines. Diesel engines have a relatively higher percentage of NO_2. NO is formed during combustion as the high flame temperature breaks down molecular oxygen and nitrogen of the inducted air, which then recombine to form NO. Reactions forming NO are temperature dependent, and, hence, NO emissions are relatively low during engine start-and warm-up phases. NO concentrations are higher for slightly lean mixtures. Dilution of the charge by residual gas or by moisture in the inlet air reduces NO concentrations.

Estimated values of NO are higher than the measured values, as the calculations are based on a constant temperature of 2500 K. Actual temperatures may be lower. Diesel engines run on the lean side (higher air to fuel ratio), and hence estimated values of NO are much higher for four- wheeler diesel vehicles (116.9 gm/km) compared to gasoline vehicles (3.3 gm/km). NO emissions from buses and trucks are very high at (354.3 to 405.3 gm/km). Total NO emissions from all the vehicles in the year 1997 are estimated as 4.829 million tons. NO emissions are shown in Figure 4 along with CO_2 emissions.

Figure 4: CO_2 and NO Emissions by Indian Vehicles per IDC



Hydrocarbons Emissions

Unburned hydrocarbons result from multiple processes during which fuel escapes the main combustion event. Oil leakage also results in hydrocarbon emissions. HC emissions from two-stroke engines during the scavenging of unburned fuel for premixed type engines is a major problem. The exhaust from a two-stroke engine contains both unreacted fuel that did not burn or react at all, as well as organic compounds formed from partial reaction of fuel molecules. Oil added to the fuel or air stream to lubricate a piston in a two-stroke engine also may not fully burn and manifest itself as particulate emissions. In four-stroke engines, the main source of hydrocarbon emissions is fuel-air mixture in crevices[d].

HC emissions from two-stroke engines are estimated as 6.6 gm/km and 152.7 gm/hr from two-wheeler vehicles and 5.9 gm/km and 137.8 gm/hr from three-wheeler vehicles. The estimated values are higher than the measured values from the manufacturer[3]. HC emissions are estimated as 1.485 million tons from all the vehicles with two-stroke engines for the year 1997.

Sulfur Dioxide Emissions

The sulfur is oxidized during the combustion process to produce SO_2. A fraction of SO_2 is oxidized to sulfur trioxide, (SO_3); which combines with water to form a sulfuric acid aerosol. Gasoline fuel has a negligible amount of sulfur, therefore, SO_2 is not computed for gasoline vehicles. Diesel fuel in India contains sulfur between 0.05 and 0.5%. SO_2 emissions increase with fuel consumption as all the sulfur in the fuel is assumed to have oxidized in the combustion process.

SO_2 emissions are estimated as 10.3 gm/km for passenger cars with diesel engines, while for buses and trucks using high sulfur diesel, SO_2 emissions are estimated as 25.4 gm/km. In metropolitan Delhi, where low sulfur diesel is used, SO_2 emissions are estimated as 2.5 gm/km. SO_2 emissions from different vehicles are shown in Figure 6. Total SO_2 emissions in the year 1997 are estimated as 0.897 million tons.

Particulate Matter: Carbonaceous Material (Soot) Emissions

Incomplete and/or inefficient combustion processes of fuel generate carbonaceous material (soot); the lubricating oil also contributes some soot. Soot is formed under fuel-rich conditions. If anywhere in the engine cylinder there are fuel air pockets where the air-fuel mixture is very rich, there will be a tendency for the formation of species that include soot C(S), hydrogen cyanide (HCN), acetylene (C_2H_2), and methane (CH_4). This occurs normally in diesel engines. These species may freeze when mixed with leaner pockets or when the temperature drops, so these species can appear in the exhaust. With diesel engines, the maximum power is limited by the appearance of solid carbon (smoke and soot) in the exhaust, even though the engine is running lean. When the combustion is in the mixing controlled phase, the fuel passes through a very rich premixed reaction stage and then burns out in the turbulent diffusion flame at the edge of the jet. Most of the soot is burned with the fuel at the diffusion flame. The fraction of soot that is not oxidized becomes an exhaust emission.

Soot analysis ranges from C_8H to $C_{12}H$. Soot particles are essentially sub-micronic (i.e., less than one micron in size). A recent National Aeronautical and Space Administration's climate study[4] has found that large amounts of black carbon (soot) particles and other pollutants may be at least partially responsible for the change in the regional precipitation pattern.

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[d] A narrow region in the combustion chamber into which a flame cannot propogate

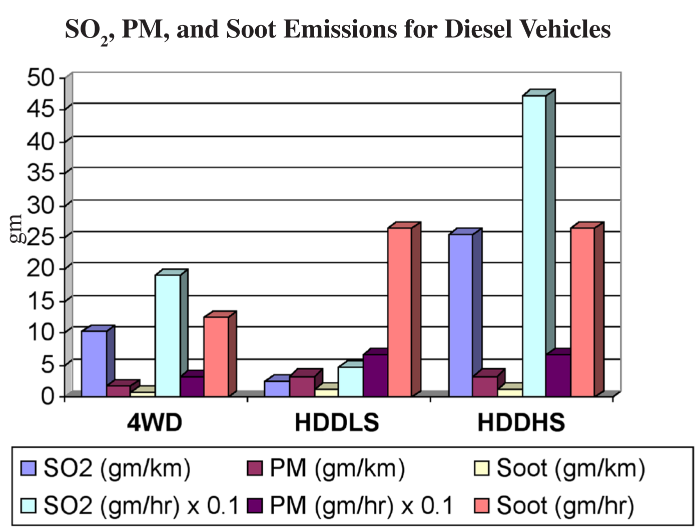
[4] http://www.gsfc.nasa.gov/topstory/20020822blackcarbon.html

Diesel particulates consist primarily of combustion-generated soot on which some organic compounds have become absorbed. A high concentration of PM is manifested as visible smoke or soot in the exhaust gases. Some four-stroke engines with highly worn out piston rings or valve guides also lead to the emission of visible smoke due to an increased consumption of lubricating oil that fails to burn. Smoke forms in diesel engines due to heterogeneous combustion. Blue smoke consists mainly of oil and unburnt fuel, black smoke consists of soot, oil, and unburnt oil, while white smoke consists of water droplets and unburnt fuel.

Soot carbon is estimated as 42 gm/hr based on the composition and particulate emission value (105gm/hr) obtained by Needham et al.[5] for 40% load and 20 km/hr speed in a Turbo Charged Direct Injection (TCA DI) Engine (standard build). It may be noted here that for different speed and loads, particulate emissions have been reported to be different. The 40% load has been selected based on the average load observed by diesel vehicles in India in test conditions, and the average speed (i.e., 20 km/hr) is based on the BEST bus's average speed in Mumbai. The average speed for trucks is much higher than for buses. This provides a good basis for estimating PM and soot carbon. Otherwise, soot carbon from vehicles, so far, has not been measured or estimated in Indian conditions.

Soot emissions are estimated as 829 thousand tons while PM emissions are estimated as 2.073 million tons from all the vehicles in the year 1997. The estimated PM emissions (gm/km) from diesel vehicles are higher than the norms. PM and soot emissions from gasoline engines are negligible, and hence, are not considered in the analysis.

Figure 5: SO_2, PM, and Soot Emissions by Indian Vehicles per IDC



[5] 'Technology for 1994' J.R. Needham, D.M. Doyale, S.A. Faulner & H.D. Freeman, SAE Paper No. 891949

Emissions and Vehicles

The behavior of emissions, with time and distance traveled at different speeds for each vehicle type is discussed below. Tables C1 to C5 (Appendix-C) give the mass emission factor, as calculated with the present methodology for each type of vehicle at different speeds. Figures 9 to 13 (Appendix-C) plot the relation between emissions and speed.

Two-Wheeler Vehicles

India has a large population of two-wheeler vehicles. These vehicles are widely used for transportation in urban areas. Most two-wheeler vehicles have two-stroke engines, because of low initial and maintenance costs. These vehicles use gasoline fuel. CO and CO_2 emissions and fuel consumption (gm/km) are lowest at 30 to 40 km/hr speeds for 2W2S vehicles. NO emissions are higher at higher speeds but HC emissions also decrease with speed. *The ideal speeds for 2W2S vehicles would be between 30 to 40 km/hr. Improving the average speed of 2W2S vehicles from 15 km/hr to 25 km/hr will decrease fuel consumption by 17%, CO emissions by 36%, CO_2 emissions by 11%, NO emissions by 9%, and HC emissions by 46%. For two-wheelers, with the exception of NO, emissions are lowest at the cruising speed of 40 km/hr.*

Since the mid 1990s, 2W4S vehicles have also been introduced in India. These vehicles are used mostly for extra power and long distance traveling on rough roads. *Improving the average speed of 2W4S vehicles from 15 km/hr to 25 km/hr will decrease fuel consumption by 23%, CO emissions by 22%, CO_2 emissions by 23%, and NO emissions by 21%. In 2W4S vehicles, 30 km/hr seems to be the optimum speed for lowest fuel consumption as well as lowest emissions for most of the pollutants, although NO emission decreases as the speed increases.*

Table C1 and Figure 9 (Appendix-C) show the values and variation of the species emissions at different speeds. Total emissions for the year 1997 from all the two-wheeler vehicles (two-stroke and four-stroke) in India are estimated as:

Km traveled	CO (tons)	CO_2 (tons)	NO (tons)	HC (tons)
225 billion km	450,000	5,990,000	180,000	1,490,000

Three-Wheeler Vehicles

3W2S vehicles are very common in urban areas. These vehicles are used for conveyance as well as the transport of goods. Estimates of emissions for 3W2S vehicles show that CO, CO_2, and fuel consumption (gm/km) start increasing substantially for speeds lower than 20 km/hr and higher than 40 km/hr. NO emissions are low at all speeds but HC emissions also decrease with speed. *Hence, the ideal speeds for 3W2S vehicles would be 20 to 40 km/hr. Improving the average speed of 3W2S vehicles from 15 km/hr to 25 km/hr will decrease fuel consumption by 20% and CO, CO_2, NO, and HC emissions by 20%, 17%, 18%, and 56%, respectively. For 3W2S vehicles, 30 km/hr seems to be the optimum speed for lowest fuel consumption as well as lowest emissions with an exception of CO_2 emission.*

3W4S vehicles were not common until recently. Their usage is increasing due to HC emission concerns. CO_2 emissions from 3W4S vehicles are higher than those from 3W2S vehicles but CO and NO emissions are lower than those from 3W2S. *Present calculations show that improving the average speed of 3W4S vehicles from 15 km/hr to 25 km/hr will decrease fuel consumption by 25%, CO emissions by 78%, and*

CO_2 emissions by 22%. However, NO emissions will increase by 41%. In 3W4S vehicles, again the 30 km/hr speed seems to be the optimum speed although NO emissions are slightly higher at this speed while other pollutants' emissions are lower.

Table C2 shows the values, and Figure 10 (Appendix-C) shows the variation of the species emissions at different speeds for three-wheeler vehicles. Total emissions for the year 1997 from all the three-wheeler vehicles (two-stroke and four-stroke) in India are estimated as:

Km traveled	CO (tons)	CO_2 (tons)	NO (tons)	HC (tons)
78.3 billion km	157,000	6,150,000	156,000	462,000

Four Wheelers

Population of four-wheeler vehicles is rapidly increasing in India, particularly in metropolitan cities. Earlier, mostly taxis were in use as four wheelers. With the availability of roads and because of other economic factors, the number of privately-owned four-wheeler vehicles is increasing every year.

Four-Wheeler Gasoline Vehicles

Gasoline fuel is most commonly used for four-wheelers. For 4WG vehicles, CO emissions are high but CO, CO_2, and NO emissions (gm/km) decrease with speed. Fuel consumption is lowest at 50 km/hr speed. *Present calculations show that improving the average speed of 4WG vehicles from 15 km/hr to 25 km/hr will decrease fuel consumption by 25%, CO emissions by 79%, and CO_2 emissions by 22%. However, NO emissions will increase by 46%. Speeds between 40 and 60 km/hr would be ideal for 4WG vehicles.*

Emissions at different speeds for gasoline four-wheeler vehicles are shown in Table C3. Figure 11 (Appendix-C) shows the variation in the species emissions with speed. Total emissions from all the four-wheeler vehicles in India are estimated as:

Km traveled	CO (tons)	CO_2 (tons)	NO (tons)
56.2 billion km	1,390,000	12,600,000	185,000

Four-Wheeler Diesel Vehicles

Four-wheeler vehicles using diesel fuel are in a minority though very popular with taxi and tour operators due to the low cost of diesel. These vehicles are used for extra power. For these reasons, the sale of these vehicles has been increasing steadily all over India. There are two types of diesel engine vehicles. Engines with direct injection (DI) of fuel are used in passenger cars, and engines with indirect injection (IDI) of fuel are used in jeeps and light commercial vehicles.

For these diesel vehicles, speeds greater than 40 km/hr are good for fuel economy as well as reducing emission of most pollutants. CO_2 and NO emissions from diesel vehicles are higher than from gasoline vehicles, but CO emissions are much lower. *According to present estimates, improving the average speed of 4WD IDI vehicles from 15 km/hr to 25 km/hr will decrease fuel consumption by 52% and CO, CO_2, NO, soot, SO_2, and PM emissions by 53%, 52%, 38%, 22%, 52%, and 13%, respectively. Corresponding* *improvement for DI vehicles would be 37%, 38%, 37%, 36%, 25%, 37%, and 22%. For DI diesel vehicles, a cruising speed of 50 km/hr gives minimum emissions with the exception of CO_2. For IDI vehicles, again the cruising speed of 50 km/hr gives minimum emission, with an exception of NO. In general, speeds in the range of 40 to 60 km/hr are good for fuel economy as well as for reducing emissions of most of the pollutants.*

Table C4 shows the values, and Figure 12 (Appendix-C) the variation of the species emissions at different speeds for diesel four-wheeler vehicles.

Buses and Trucks

In India, buses are the most common means of passenger transport in urban cities and for intercity transport. Trucks are used for transport of goods and mostly travel between cities. These vehicles use diesel fuel and mostly run overloaded. In the Delhi city area, a low sulfur diesel fuel is used. The driving cycle for buses and trucks should be different, but in these calculations the same (regulatory standard) driving cycle is used. Overloading has not been accounted for in the calculations.

As Table C5 shows, the ideal speed to reduce fuel consumption and emissions per kilometer for these vehicles is 40 to 60 km/hr. The sulfur dioxide emissions do not vary appreciably with speed. SO_2 emission (gm/km) would be 10 times lower for low sulfur diesel (used by vehicles in Delhi). *Present estimates show that even improving the average speed of the heavy-duty diesel vehicles from 15 km/hr to 25 km/hr will decrease fuel consumption by 16% and CO, CO_2, NO, SO_2, soot, and PM emissions by 16%, 16%, 20%, 16%, 19%, and 20%, respectively. Improving the average speed from 25 km/hr to 35 km/hr will further reduce the emissions and fuel consumption by approximately 8%.*

Table C5 gives the emission values and Figure 13 (Appendix-C) shows the variation at different speeds for buses and trucks. Total emissions from all the diesel buses and trucks in India for the year 1997 are estimated as:

	Km traveled	CO (ton)	CO_2 (ton)	NO (ton)	Soot (ton)	SO_2 (ton)	PM (ton)
Buses	8.9 billion km	42,000	4,590,000	3,610,000	18690	226,000	934,500
Trucks	26.4 billion km	124,000	13,600,000	10,700,000	34,848	670,000	87,120

Vehicular Transport and Emission Trends

The vehicular population in India is rapidly increasing. Emissions per kilometer traveled and annual emissions are estimated based on available data. Figure 6 shows the kilometer traveled by different kinds of vehicles for 1990-1997.

Figure 6: Trends in Vehicular Transport (kilometers traveled) for 1990-1997

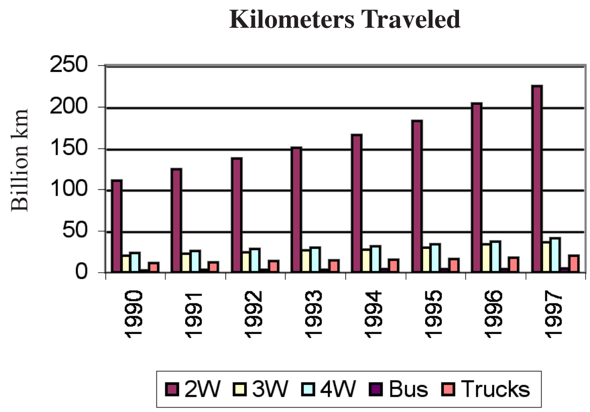
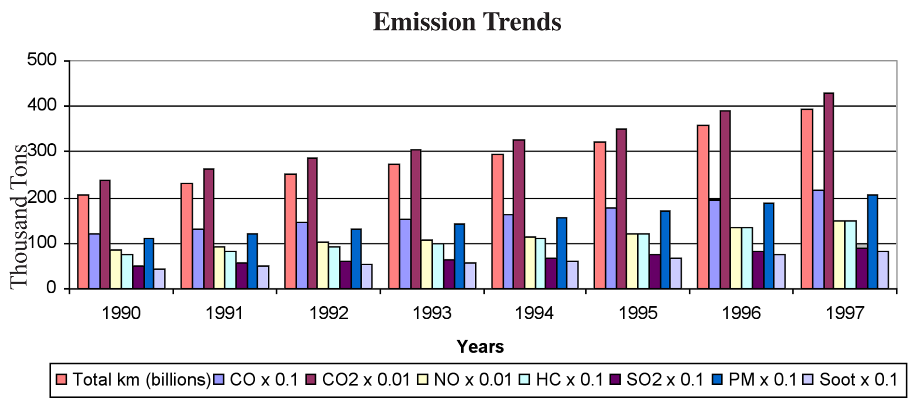


Figure 7 shows the computed annual emission estimates of different species and the total vehicle kilometer traveled for 1990-1997. Emissions per kilometer (with the exception for PM) are decreasing, while the total annual kilometer traveled and total emissions are increasing. Total kilometers traveled by all the vehicles increased by 92%, while the emissions such as CO increased by 80%, CO_2 and NO by 78%, PM and soot (black carbon) by 91%, and HC by 104%. However, a large increase in HC and black carbon emissions reflect a loss of fuel usage and needs the attention of owners, pollution controlling agencies, etc. Periodic maintenance to check the pollution levels is recommended.

Figure 7: Yearly Kilometers Traveled and Emissions (thousand tons) for 1990-1997



Emissions Scenario in Seven Metropolitan Cities

Table D2 (Appendix-D) provides emission estimates from transport sectors in seven major Indian cities for the year 2002. Using the computed emission factors, preliminary estimates of emissions from vehicular transport in seven Indian metropolitan cities are shown in Figure 8. Numbers about vehicle population and distance traveled, which are quoted in various published documents[6,7,8,] are used to calculate cumulative emissions. These estimates are made for the year 2002, assuming that 5% of the total two-wheeler population is four-stroke, all the three-wheelers have two-stroke engines, diesel is of high sulfur content, and buses and trucks travel the same average distances as given in Table 3. Emissions from vehicles belonging to other categories have not been calculated and are not included in the city totals. The computed values show that transport-related emissions in Delhi are far more in comparison to any other Indian cities.

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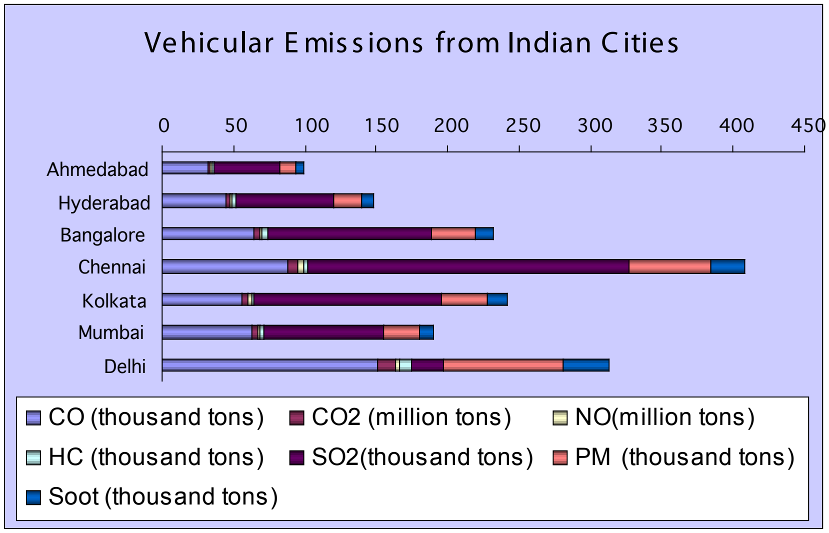
[6] Handbook of Urban Statistics 1995, published by National Institute of Urban Affairs, New Delhi

[7] TERI Energy Data Directory & Yearbook 2001/2002

[8] Transport Fuel Quality for Year 2005, published by Central Pollution Control Board, New Delhi, http:envfor.nic.in/cpcb

Figure 8: Cumulative Emissions from Vehicular Transport in Seven Mega Cities of India for 2002



Limitations of Calculations and Results

The calculations, given in Table-B1 are based on a theoretical ideal. Real conditions may differ from the ideal (theoretical) conditions. Gasoline is considered as C7H13O0.1 and diesel as C15H34N0.01S0.05 for Delhi city and C15H34N0.01S0.5 for the rest of India. Calculations have the inherent assumption of a new engine without any fuel or oil leakage, and the estimates do not account for engine deteriorations due to aging (Table D2) or vehicle overloads. No account is taken of any emission control devices such as catalytic converters (during the period 1997-98, the only control measures in place were the use of unleaded gasoline) to limit the emissions. Before 1997, catalytic converters were not mandatory for vehicles except in a few of India's metropolitan cities. After 2000, stricter emission standards were implemented, necessitating the use of catalytic converters in most gasoline vehicles. Hence, the estimates of species emissions for which control devices are used would be lower than the measured values of the species from the exhaust of the vehicles on the road. Following are some other limitations:

- The automobile industry is a private industry in India. The data about fuel consumption and air-to fuel ratio at different speeds is considered proprietary. This data was made available to us as a personal communication.
- These values are computed based on the operation of a new engine. This means that perfect maintenance of the vehicles is assumed. The deterioration in engine performance relating to age is not taken into account.
- Other parameters that are not accounted for are road roughness and vehicle overload.
- HC emissions are from exhaust of two-stroke engines only. HC emissions while fueling the vehicle or from other sources are not accounted for this inventory.

Policy Relevance

The transport sector has been identified as one of the major sources of pollution in India's urban centers. Urgent actions are needed to implement viable policies to reduce the emissions of pollutants from this sector to reduce health hazards to human beings and to mitigate greenhouse gases emissions. Considering the growth of urbanization in India, it is important that this issue be dealt with immediately based on scientific knowledge. The urgency and importance are also reflected by the policy interventions already implemented in India.

A number of policy options are available to reduce the emissions of pollutants. These include both technical options (like changes in vehicle technologies and changes in fuel types and characteristics) as well as traffic management options. The latter can be easily implemented and provides a low cost option. The computed values for emissions of different pollutants from various vehicles as mentioned earlier clearly show that if traffic management increases the average cruising speed of the vehicles to 30 to 50 km/hr, it would result in a substantial decrease in the emission levels of most of the species. City authorities and urban local bodies throughout India can implement these measures for traffic management. Further, rising emission levels and traffic flow should be given consideration in long-term planning of land use by city authorities.

Next Steps/Recommendations

1. This study provides valuable tools for inventory preparation of emissions from vehicular transport in actual as well as simulated conditions. Simulations include changes in driving patterns, vehicles or technology, and fuel composition. Emission estimates are based on a theoretical ideal and the input data available from published information and personal communications. Currently, the methodology used in this study is most suitable for the conditions in India. The results provide a valuabl e benchmark. The exercise should be followed with efforts to increase accuracy with more realistic input information and verification/validation measurement.

2. To decrease emissions, traffic bottlenecks should be minimized, and optimum speeds (best fuel consumption per km and minimum emissions per km) should be prescribed.

3. Fuel quality has a big impact on overall emissions. The effect of fuel adulteration should be investigated. Similarly, the effect of fuel quality improvement such as blending 5% ethanol with gasoline and diesel can also be investigated using this tool.

4. With an increasing vehicular population and consequent pollution levels from the transport sector, state and local authorities should encourage the deployment of electric, hybrid, and alternate fuel (e.g. CNG, LPG) vehicles. Steps should also be taken to promote a robust public transport system to check the growth rate of pollution as well as to reduce congestion.

5. Dispersion and transport of emitted pollutants from different activities over the entire Indian region need to be mapped to better understand their impact on the climate, as well as on human, animal, plant, and ecological systems.

6. Further research is needed on population exposure to these polluting gases.

Some of these recommendations/suggestions call for additional studies. Dispersion and transport of emitted pollutants from energy activities over the entire Indian region and population exposure to these polluting gases will be part of the project's next phase. Analyses of detailed air characteristics and associated meteorological parameters will help us understand and illustrate the full impacts of greenhouse gases and other pollutants on human health and climate in India.

To learn more about emissions in India, please visit **www.osc.edu/pcrm/emissions**
or contact Moti Mittal, Director, Program for Computational Reactive Mechanics, at moti@osc.edu.

The Indian driving cycles (urban driving) for four-wheeler and two- or three-wheeler vehicles are given in Appendix-A (Tables A1 and A2). This also includes computed values of CO_2 emissions at different stages of IDC for different vehicles. Appendix-B indicates the computed, measured, and prescribed norms for mass emission factors. Appendix-C contains the computed values for different vehicles along with corresponding graphs. Appendix-D gives the emission estimates from major cities in India and the useful average life span of vehicles in India.

Appendix-A

Table A1: IDC for Four-Wheelers and CO_2 (gm) Emissions at Different Stages

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	I	1		0	11	11	5.16	5.18	10.26
2	A	2	1.04	0-15	4	15	3.11	3.42	6.95
3	SS	3		15	8	23	8.34	9.20	18.5
4	D	4	-0.69	15-10	2	25	1.74	1.95	3.98
5	D, CD		-0.92	10_0	3	28	1.64	1.71	3.44
6	I	5			21	49	9.86	9.90	19.59
7	A	6	0.83	0-15	5	54	3.84	4.21	5.53
8	GC				2	56	2.30	4.63	4.62
9	A		0.94	15-32	5	61	8.62	16.07	16.07
10	SS	7		32	24	85	51.32	93.04	93.05
11	D	8	-0.75	32-10	8	93	11.04	21.26	21.27
12	D, CD		-0.92	10_0	3	96	1.88	3.81	3.81
13	I	9			21	117	9.90	19.59	19.60
14	A	10	0.83	0-15	5	122	4.38	8.90	8.90
15	GC				2	124	2.30	4.62	4.63
16	A		0.62	15-35	9	133	15.86	29.65	29.65
17	GC				2	135	4.39	8.30	8.31
18	A		0.52	35-50	8	143	19.21	40.62	40.62
19	SS	11		50	12	155	30.86	69.87	69.88
20	D	12	-0.52	50-35	8	163	18.59	37.85	37.86
21	SS	13		35	13	176	28.56	53.98	53.99
22	GC	14			2	178	4.39	8.30	8.31
23	D		-0.86	32-10	7	185	10.42	19.87	19.87
24	D, CD		0.92	10-0	3	188	1.80	3.62	3.63
25	I	15			7	195	3.30	6.53	6.53

(1): Serial number
(2): Operation
(3): Phase
(4): Acceleration (m/s/s)
(5): Speed (km/hr) I: Idling

(6): Time (second)
(7): Cumulative time (second)
(8): CO_2 emissions (gm) for 4WG
(9): CO_2 emissions (gm) for 4WD
(10): CO_2 emissions (gm) for heavy-duty diesel vehicle

I: Idling
A: Acceleration
D: Deceleration
SS: Steady speed

GC: Gear change
CD: Clutch depressed
S: seconds

Cycle duration = 195 seconds
Number of cycle/test = 4
Total distance traveled = 1.013km x 4 = 4.052 km
Average speed (with idling) = 18.7 km/h
Average speed (without idling) = 27.01 km/h
Maximum speed = 50 km/h

Table A2: Indian Driving Cycle for Two- and Three-Wheelers

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	I	-	-	16	16	0.73	0.99	1.64	2.87
2	A	0.65	0-14	6	22	0.54	0.55	1.06	1.76
3	A	0.56	14-22	4	26	0.60	0.52	1.10	1.77
4	D	-0.63	22-13	4	30	0.54	0.49	1.01	1.63
5	SS	-	13	2	32	0.23	0.22	0.44	0.72
6	A	0.56	13-23	5	37	0.75	0.65	1.37	2.21
7	A	0.44	23-31	5	42	0.99	0.81	1.85	2.78
8	D	-0.56	31-25	3	45	0.58	0.48	1.07	1.63
9	SS	-	25	4	49	0.73	0.61	1.32	2.05
10	D	-0.56	25-21	2	51	0.33	0.28	0.60	0.96
11	A	0.45	21-34	8	59	1.62	1.32	3.05	4.55
12	A	0.32	34-42	7	66	1.95	1.62	6.81	5.68
13	D	-0.46	42-37	3	69	0.84	0.69	1.73	2.43
14	SS	-	37	7	76	1.86	1.50	3.75	5.31
15	D	-0.42	37-34	2	78	0.50	0.40	0.99	1.39
16	A	0.32	34-42	7	85	1.94	1.61	6.78	5.68
17	D	-0.46	42-47	9	94	2.15	1.74	4.24	6.15
18	D	-0.52	27-14	7	102	1.18	1.03	2.18	3.49
19	D	-0.56	14-00	7	109	0.44	0.48	0.89	1.50

(1): Serial number
(2): Operation
(3): Acceleration (m/s/s)
(4): Speed (km/hr)
(5): Time (second)
(6): Cumulative time (second)
(7): CO_2 emissions (gm) for 2W2S
(8): CO_2 emissions (gm) for 2W4S
(9): CO_2 emissions (gm) for 3W2S
(10): CO_2 emissions (gm) for 3W4S

Appendix-B

Table B1: Computed Mass Emission Factors for Different Vehicles

Species		2W2S	2W4S	3W2S	3W4S	4WG	4WD	HDDLS	HDDHS
FC	gm/km	11.0	9.7	22.1	25.9	84.3	92.7	195.2	195.2
	gm/hr	254.9	225.2	511.2	599.8	1576.5	1733.2	3649.9	3649.9
CO_2	gm/km	26.6	28.3	60.3	78.5	223.6	208.3	515.1	515.2
	gm/hr	617.0	655.6	1397.2	1817.1	4181.3	3896.4	9633.3	9634.8
CO	gm/km	2.0	1.4	5.25	2.0	24.8	2.0	4.7	4.7
	gm/hr	46.4	33	121.6	46.9	462.9	36.8	88.4	87.4
NO	gm/km	0.8	1.4	1.2	2.0	3.3	116.9	354.3	405.3
	gm/hr	20.5	32.9	28.1	46.0	62.4	2185.5	6626.6	7579.2
SO_2	gm/km	-	-	0	0	0	10.3	2.5	25.4
	gm/hr	-	-	0	0	0	192	47.4	474.4
HC	gm/km	6.6	-	5.9	0	0	0	0	0
	gm/hr	152.7	-	137.8	0	0	0	0	0
PM#	gm/km	-	-	0	0	0	1.56	3.3	3.3
	gm/hr	0	0	0	0	0	31.5	66	66
Soot	gm/km	0	0	0	0	0	0.63	1.32	1.32
	gm/hr	0	0	0	0	0	12.6	26.4	26.4

FC: Fuel consumption

PM: Particulate matter, values derived from Needham, et al. 1994

Table B2: Measured Mass Emission Factors (gm/km) for 1996-2000 period[9]

Species	2W2S	2W4S	3W2S	4WG	4WD	Buses	Trucks
CO	4	2.6	8.6	3.9	1.2	4.5	4.5
NOx	0.06	0.3	0.09	1.1	0.69	16.8	8.4
HC	3.3	0.7	7	0.8	0.37	1.21	1.21
PM	0.1	0.06	0.15	0.05	0.42	1.6	0.8

Table B3: Norms (India 2000) for Mass Emission Factors for Different Vehicles per IDC[9]

Species	2W2S gm/km	2W4S gm/km	3W2S gm/km	3W4S gm/km	4WG gm/km	4WD gm/km	Buses (Low S*) gm/kwh	Buses (High S) gm/kwh
CO	2.0	2.0	4.0	4.0	2.72	2.72	4.0	4.5
$HC+NO_x$	2.0	2.0	2.0	2.0	0.97	0.97	1.1-HC 7.0-NO_x	1.1-HC 8.0-NO_x
PM							0.15	0.36

*Low sulfur = Bharat (India) Stage 2000 (Norm applicable in metro cities only)

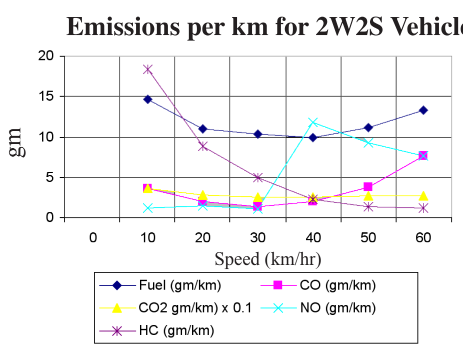
[9] M. Saxena, A.K. Jain, and S. Singhal, Science and Culture, Vol. 68, No.9-12, 2002

Appendix–C

Table C1: Emissions from Two-Wheeler Vehicles (2W2S and 2W4S)

Speed	0 (km/hr)		10 (km/hr)		20 (km/hr)		30 (km/hr)		40 (km/hr)		50 (km/hr)		60 (km/hr)	
	2W2S	2W4S	2W2S	2W4S	2W2S	2W4S	2W2S	2W4S	2W2S	2W4S	2W2S	2W4S	2W2S	2W4S
FC (gm/hr)	87	76	146.5	120.3	220.5	164.7	309	209	412	310	560	540	800	806
FC (gm/km)			14.7	12.0	11.025	8.2	10.3	7.0	10.3	7.8	11.2	10.8	13.33	13.4
CO_2 (gm/hr)	165.4	222.1	361.8	352.6	558.2	483.2	754.6	613.8	1043.4	879.5	1340.9	1430.4	1608.1	2219.1
CO_2 (gm/km)			36.2	35.3	27.9	24.2	25.15	20.5	26.1	22.0	26.8	28.6	26.68	36.9
CO (gm/hr)	33.1	9.8	36.1	16.1	39.0	22.4	42	28.7	81.3	56.6	187.4	163.2	455.7	190.0
CO (gm/km)			3.6	1.6	1.95	1.1	1.4	1.0	2.03	1.4	3.75	3.3	7.59	3.2
NO (gm/hr)	1.9	12.0	11.5	20.4	21.0	28.8	30.6	37.1	471	30.3	463.1	27.5	455.7	56.5
NO (gm/km)			1.2	2.04	1.5	1.4	1.02	1.2	11.8	0.8	9.26	0.55	7.59	0.9
HC (gm/hr)	200.1	-	183.4		166.7		150		89.9		65.1		69.7	
HC (gm/km)			18.3		8.84		5.0		2.25		1.302		1.16	

Figure 9: Fuel Consumption and Exhaust Emissions from Two-Wheeler Vehicles



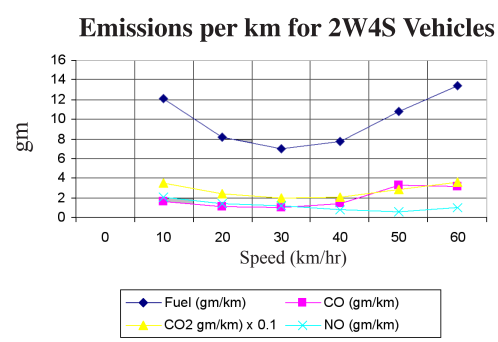
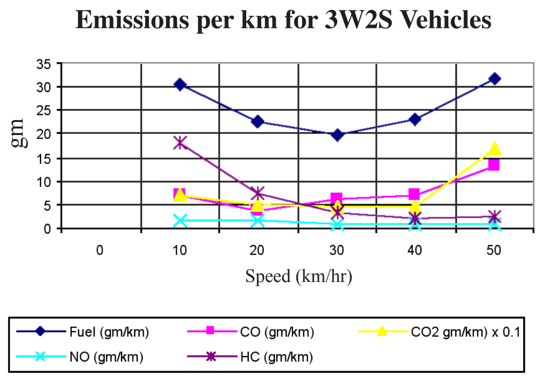


Table C2: Emissions from Three-Wheeler Vehicles (3W2S and 3W4S)

Speed	0 (km/hr)		10(km/hr)		20(km/hr)		30(km/hr)		40(km/hr)		50(km/hr)	
	3W2S	3W4S	3W2S	3W4S	3W2S	3W4S	3W2S	3W4S	3W2S	3W4S	3W2S	3W4S
FC (gm/hr)	180	250	305	395	430	540	590	690	920	990	1580	1490
FC (gm/km)			30.5	39.5	22.5	27	19.7	23	23	24.8	31.6	29.8
CO_2 (gm/hr)	339	646.5	683.7	1152.4	1028.3	1658.4	1364.9	2135.	2189.9	3056.4	8500.8	4533.5
CO_2 (gm/km)			68.4	115.2	51.415	82.917	45.49	71.2	44.75	76.5	170.	90.67
CO (gm/hr)	66.9	85.5	69.6	51.8	72.3	18.02	186.8	13.1	270.4	22.99	654.0	78
CO (gm/km)			7.0	5.2	3.615	.9	6.22	.434	6.76	.575	13.08	1.6
NO (gm/hr)	4	1.0	18.1	14.8	32.2	22.2	22.2	75.5	39.1	81.9	44.5	47.6
NO (gm/km)			1.8	1.5	1.61	1.1	.74	2.5	.98	2.5	.89	.95
HC (gm/hr)	210	-	180		150		100		90		120	
HC (gm/km)			18.0		7.5		3.33		2.25		2.4	



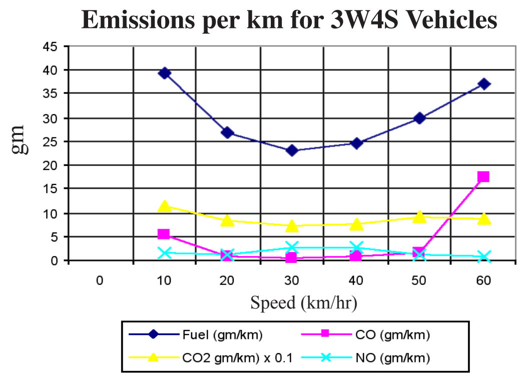


Table C3: Emissions from Four-Wheeler Gasoline Vehicles

Speed (km/hr)	0	10	20	30	40	50	60
FC (gm/hr)	600	1000	1600	2200	2720	3300	4200
FC (gm/km)		100	80	73.3	68	66	70
CO_2 (gm/hr)	1690	2870	4640	6380	6620	7240	8220
CO_2 (gm/km)		287	232	212.67	165.5	144.8	137
CO (gm/hr)	110	160	230	310	1190	1950	3120
CO (gm/km)		16	11.5	10.33	29.75	39	52
NO (gm/hr)	26	52	99	140	42.	33	28
NO (gm/km)		5.2	4.95	4.67	1.05	0.66	0.47

Figure 11: Fuel Consumption and Exhaust Emissions from Four-Wheeler Gasoline Vehicles

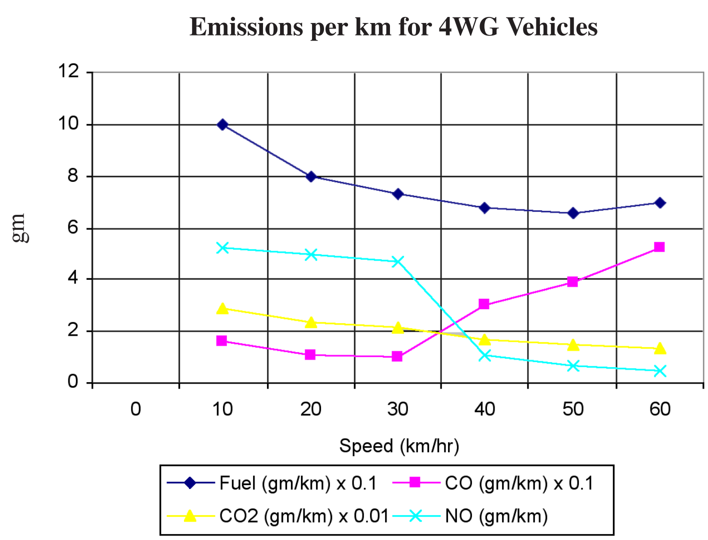


Table C4: Emissions from 4WD (DI and IDI Engine) Vehicles

Speed	0 (km/hr)		10(km/hr)		20(km/hr)		30(km/hr)		40(km/hr)		50(km/hr)		60(km/hr)	
	DI	IDI	DI	IDI	DI	IDI	DI	IDI	DI	IDI	DI	IDI	DI	IDI
FC (gm/hr)	500	600	786.7	1146	1117	1783	1515.4	2674.5	1757.7	2923.3	2099.2	3277	2583	3775
FC (gm/km)			78.7	114.6	55.8	89.2	50.5	89.15	43.7	73.08	42.0	65.6	43.1	62.9
CO_2 (gm/hr)	1322.2	1697.	2080.	3240	2953	5040	4007	758.1	4647	8260	5548	9257	6824	10655
CO_2 (gm/km)			208.	323.9	148	252	133.6	252.7	116.2	206.49	111.0	185.1	113.7	177.6
CO (gm/hr)	12	15.5	19	30.5	27.1	48.1	36.8	72.6	42.7	80.32	51.8	92.2	65.6	110.3
CO (gm/km)			1.9	3.1	1.4	2.4	1.2	2.4	1.1	2.0	1.0	1.8	1.1	1.84
NO (gm/hr)	1004	1242.	1545	1824	2168.	2503	2903	3485	3054	3436	3180	3362	3223	3252
NO (gm/km)			154.5	182.4	108.4	125.1	96.8	116.2	76.3	85.9	63.6	67.2	53.7	54.2
SO_2 (gm/hr)	65.1	83.6	102.4	159.6	145.4	248.3	197.3	372.5	228.9	407.1	273.3	456.4	336.3	525.7
SO_2 (gm/km)			10.2	16	7.3	12.4	6.6	12.4	5.7	10.1	5.5	9.1	5.6	8.8
Soot (gm/hr)	5.8	6.9	9.1	13.2	12.9	20.6	17.5	30.9	20.3	33.7	24.2	37.8	29.8	43.6
Soot (gm/km)			0.8	1.24	0.6	0.96	0.5	0.96	0.5	0.79	0.45	0.71	0.46	0.68
PM (gm/hr)	9.1	10.9	14.2	20.7	20.2	32.3	27.4	48.4	31.8	52.9	38	59.3	46.7	68.3
PM (gm/km)			1.42	2.07	1.01	1.61	0.91	1.61	0.8	1.32	0.76	1.19	0.78	0.99

Figure 12: Fuel Consumption and Exhaust Emissions from Four-Wheeler Diesel (DI and IDI) Vehicles

Emissions per km for 4WD (DI) Vehicles **Emissions per km for 4WD (IDI) Vehicles**

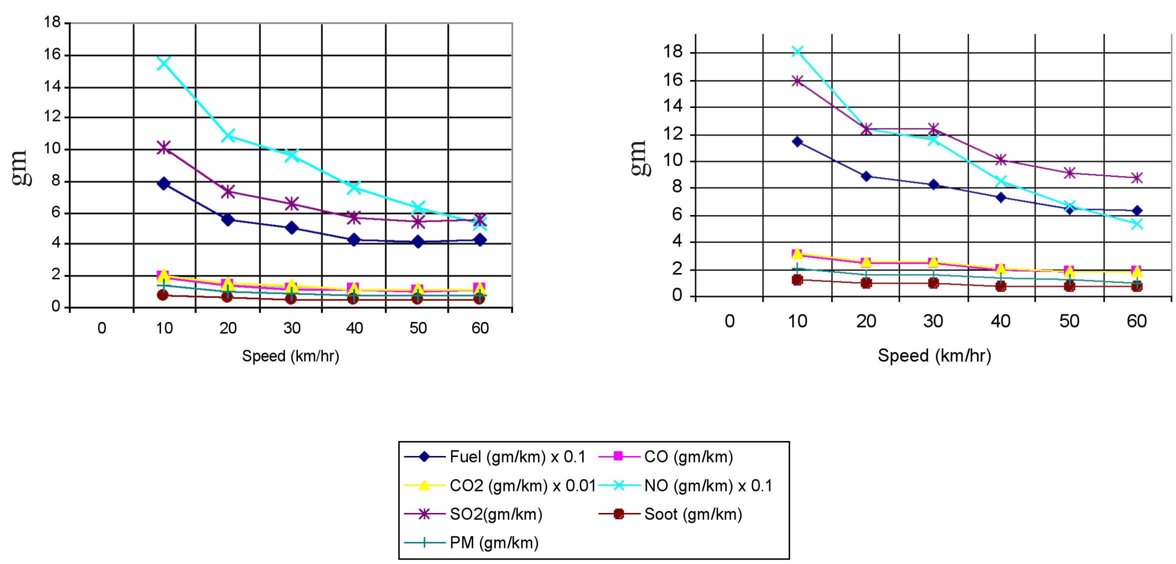
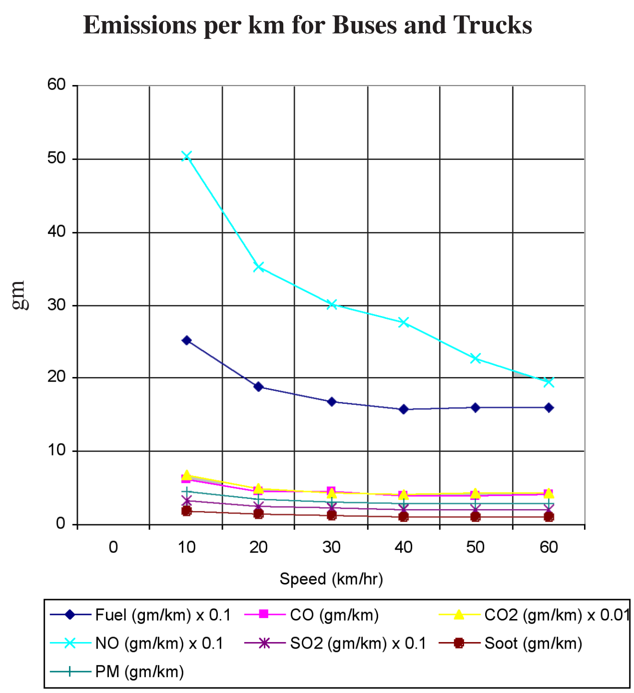


Table C5: Emissions from Buses/Trucks

Speed (km/hr)	0	10	20	30	40	50	60
FC (gm/hr)	1270	2522.6	3775.2	5027.8	6280.4	7931.1	9581.7
FC (gm/km)		252.3	188.8	167.6	157	158.6	159.7
CO_2 (gm/hr)	3359	6670.6	9982.3	13293.9	16605.6	20960.1	25314.3
CO_2 (gm/km)		667.1	499.1	443.1	415.1	419.2	421.9
CO (gm/hr)	30	60.6	91.2	121.8	152.4	197.5	242.6
CO (gm/km)		6.1	4.6	4.6	3.8	3.9	4
NO (gm/hr)	3048.4	5043	7037.7	9032.3	11027	11345.7	11665
NO (gm/km)		504.3	351.9	301.1	275.7	226.9	194.4
SO_2 (gm/hr)	16.5	32.9	49.2	65.5	81.8	103.3	124.8
SO_2 (gm/km)		3.2	2.5	2.2	2	2.1	2.1
Soot (gm/hr)	9.14	18.2	27.2	36.2	45.2	57.1	69
Soot (gm/km)		1.8	1.4	1.2	1.13	1.14	1.15
PM (gm/hr)	23.0	45.7	68.3	91.0	113.7	143.6	173.4
PM (gm/km)		4.6	3.4	3.0	2.8	2.9	2.9

Figure 13: Fuel Consumption and Exhaust Emissions from Heavy-Duty Diesel Vehicles



Appendix-D

Table D1: Emission Estimates (in Thousand Tons) from Seven Major Indian Cities for the Year 2002

	CO	CO_2	NO	HC	SO_2	PM	Soot
Delhi	150	12498	3551	8	23	83	33
Mumbai	63	4532	1352	2	85	24	10
Kolkata	56	5086	2291	1	132	33	13
Chennai	88	7153	3709	4	224	58	23
Bangalore	64	4334	1883	4	115	31	12
Hyderabad	45	2736	1075	3	68	20	8
Ahmedabad	32	1988	757	2	45	12	5

Table D2: Average Service Life and Annual Distance (km) Traveled by Indian Vehicles

Vehicle	Life Years	Annual kms
2-Wheeler	15	10,000
3-Wheeler	10	40,000
Passenger car	20	15,000
Taxis	10	30,000
MUV	15	37,000
Trucks	15	40,000
Buses	8	30,000
LCV	5	60,000

MUV – Multi-Utility Vehicles; LCV – Light Commercial Vehicles

Source: Transport Fuel Quality for Year 2005, page 208, Central Pollution Control Board, New Delhi.

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