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On-road assessment of light duty vehicles in Delhi city: Emission factors of CO, CO_2 and NO_X

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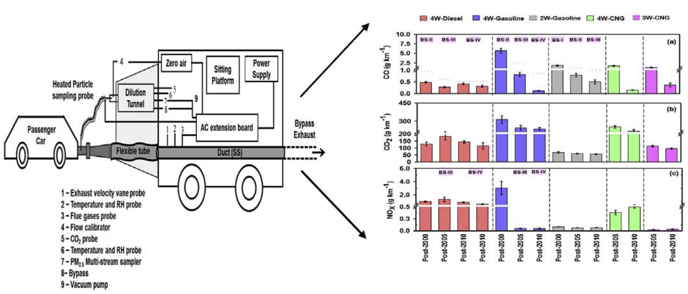
GRAPHICAL ABSTRACT



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ABSTRACT

This study presents the technology based emission factors of gaseous pollutants (CO, CO_2, and NO_X) measured during on-road operation of nine passenger cars of diesel, gasoline, and compressed natural gas (CNG). The emissions from two 3-wheelers, and three 2-wheelers were measured by putting the vehicles on jacks and operating them according to Modified Indian Driving Cycle (MIDC) at no load condition. The emission factors observed in the present work were significantly higher than values reported from dynamometer study by Automotive Research Association of India (ARAI). Low CO (0.34 ± 0.08 g km^{-1}) and high NO_X (1.0 ± 0.4 g km^{-1}) emission factors were observed for diesel passenger cars, oppositely high CO (2.2 ± 2.6 g km^{-1}) and low NO_X (1.0 ± 1.6 g km^{-1}) emission factors were seen for gasoline powered cars. The after-treatment technology in diesel vehicles was effective in CO reduction. While the use of turbocharger in diesel vehicles to generate high combustion temperature and pressure produces more NOx, probably which may not be effectively controlled by after-treatment device. The after-treatment devices in gasoline powered Post-2010, Post-2005 vehicles can be acclaimed for reduced CO emissions compared to Post-2000 vehicles. This work presents a limited data set of emission factors from on-road operations of light duty vehicles, this limitation can be improved by further measurements of emissions from similar vehicles.

1. Introduction

The road transport in India relay on heavy duty vehicles (HDV), light motor vehicles (goods and passenger vehicles/auto rickshaw), buses, four wheeler (passenger cars/jeep/taxis), two wheeler (motorcycles/mopeds/scooters both 2-stroke and 4-stroke), and others (tractor/trailers) (Ramachandra and Shwetmala, 2009). Emissions from road transport sector mainly depend on vehicle technology (engine capacity, power, and sizes), type of fuel (diesel/gasoline/gas) and vintage of vehicles (Maricq, 2007). The preference of private mode of transportation over public transport in urban cities of India and switch of older diesel vehicles (> 10 years) from urban cities to other small

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towns or rural areas, and their poor maintenance and fuel adulteration may lead to high emissions in cities and rest of India as well (Baidya and Borken-Kleefeld, 2009). Vehicles emit more unburnt hydrocarbon (HC) and carbon monoxide (CO), particulate matter (PM), oxides of nitrogen (NO_X) and non-methane volatile organic carbon (NMVOC) due to high-temperature combustion (Sadavarte and Venkataraman, 2014).

Chassis dynamometer approach using a standard driving cycle is most common method for emission measurement from vehicles. Generally, this facility is associated with very high cost (Wang et al., 2012) and do not represent the real world emissions. Many studies (Alves et al., 2015; Adak et al., 2016; Choudhary and Gokhale, 2016; Goel et al., 2015) have stated that the standard driving cycles are not representative of real-world driving pattern. Alternative approaches such as remote sensing (Carslaw et al., 2011; Schifter et al., 2008; Hueglin et al., 2006), tunnel studies (Gillies et al., 2001; McGaughey et al., 2004; Phuleria et al., 2006; Handler et al., 2008), and on-board studies (Gordon et al., 2013; Liu et al., 2009; Weiss et al., 2011) have also been reported in recent past. Remote sensing and tunnel studies represent only the emissions of the road fleet, but emissions from individual vehicle could be more variable depending upon technology, driver's habit, road conditions and traffic flow etc. (Chen et al., 2007; Fontaras et al., 2012).

Recently, few studies have measured on-road emission factors of gaseous pollutants (Yao et al., 2011; Boughedaoui et al., 2008; Huo et al., 2012a,b; Chikhi et al., 2014; Wang et al., 2014; Adak et al., 2016; Choudhary and Gokhale, 2016) and reported the influence of various parameters such as speed, acceleration, and traffic congestion on emissions. However, such efforts are very limited in countries like India, where several factors such as road fleet composition, driving pattern, driver's behavior, engine capacity, fuel composition, traffic density and road conditions are expected to be entirely different than developed countries. However, understanding the influence of all the parameters on emission requires a large number of measurements. The objective of present work was to determine the emission factors of gaseous pollutants (CO, CO_2, and NO_X) and to assess the measurement variability among 3 experiments of each vehicle, while the driving route, hour of the day and duration of the experiments remained same for each experiment.

2. Material and methods

2.1. Experimental set-up

On-road experiments with passenger cars were carried out using Aerosol Emission Measurement System (AEMS) (Fig. S1 in the online supplementary information [SI]) mounted on a trolley. The trolley was towed behind the passenger car during each experiment. The AEMS consists of five main components including dilution tunnel, heated duct, and heated particle sampling probe, zero air assembly, and a power supply unit. The details of the AEMS and description of various instruments are published in Jaiprakash et al. (2016) and Jaiprakash and Habib (2017). The concentrations of CO, CO_2, and NO_X were measured inside the heated duct during on-road operation of nine passenger cars. The exhaust velocity (m s^{-1}), temperature (°C), and relative humidity (%) were also monitored each minute. The instruments used for exhaust velocity, temperature and relative humidity measurement can record data at 1 min resolution, therefore same time interval was selected for all the parameters.

The vehicles were selected from various age groups (BS-II/post-2000; BS-III/post-2005, and BS-IV/post-2010) and fuel type (diesel, gasoline and CNG). The vehicles characteristics i.e model age, engine capacity, after-treatment device, and odometer reading are tabulated in Table 1. During experiments the vehicles were driven by their owner on a fixed route of 10 km consisted of heavy traffic ring road, road with lean traffic inside the institutional area, and six traffic signals (Jaiprakash and Habib, 2017). As the MIDC cycle consists of 10 km distance travel in 20 min, therefore, the route length of 10 km was selected in present work which was covered in 40 ± 5 min due to traffic congestion. For each vehicle the experiments were performed at least 3 times and total 49 experiments were conducted. The vehicles assessed here were hired on hourly payment basis, therefore, the limited vehicles were assessed and 3 repeated experiments were done for each vehicle. Before each test vehicle's engine was allowed to cool down for half an hour. However, no soaking was performed, therefore, the emission measured in the present work must be considered as emissions from hot start operation. The vehicle speed was recorded with pocket global positioning monitor (Garmin Model 60 CSx).

The emissions from three 2-wheelers and two 3-wheelers (auto-rickshaw) of various BS categories were measured by placing the vehicles on jacks and operating them according to MIDC (ARAI, 2008) under no load condition. The MIDC cycle of 108 s was repeated 20 times therefore, total run time was 36 mins. The wheels were suspended during measurement, therefore, the emissions from two wheelers and three wheelers did not include the effect of drag due to wind or the effect of resistance due to road friction, hence, the emissions might be lower than values reported from chassis dynamometer.

It shall be noted that the emissions highly depend upon the road type (urban, rural, freeway highway, hilly roads), road conditions, speed, power level and stop go conditions, traffic congestion and distance travel. In the present work, traffic count was not recorded and also the effects of other parameters have not been assessed. To minimize the effect of various parameters the same road, route length and hour of the day were selected during each experiment. The emissions measured in present work would be representative of real world emissions on a typical urban road in Delhi. It should be noted that the limitations of present work may result in unquantified uncertainty in emission data set. However, in view of limited measurement available for Indian vehicles, the present work has important contribution for building the emission factor database for these vehicles. The national representative data set incorporating the effect on emissions due to variability in above mentioned factors can only be acquired through a systematic and large number of real world emission measurements at different locations in India.

2.2. Emission factor calculation

The concentration (C) of gases (g m^{-3}) corrected for standard temperature and pressure (STP: 25 °C, 1 atmospheric pressure) was multiplied with STP corrected exhaust velocity (V, in m s^{-1}), cross sectional area of duct A_d (m^2), and sampling time (t) to estimate pollutant mass and then divided by km of distance travelled (d) by vehicle to calculate the emission factor in terms of gram of pollutant emitted per km of distance travelled (Eq. (1)).

$$EF\cdot(g\cdot km^{-1}) = \frac{\boldsymbol{C \times V \times A_d \times t}}{\boldsymbol{d}} \quad (1)$$

3. Results and discussion

3.1. Emission rate with speed

In on-road experiments the average speed of tested 4-wheelers ranged from 25 to 35 km h^{-1}, whereas minimum and maximum speeds were observed as 09 and 55 km h^{-1} respectively. The emissions of CO, CO_2, NO_X and other pollutants vary with speed and acceleration/deceleration (Alves et al., 2015; Chen et al., 2007). In present work real time emissions of gaseous pollutants CO, CO_2, and NO_X were recorded each minute during on-road experiments, and then emission rates were calculated as gram (g) of pollutants emitted per unit of sampling time (min). Present work discusses the emission rate (g min^{-1}) from single vehicle of each category and fuel type operated on 10 km route. A contour plots of emission rates of CO, CO_2, and NO_X, with respect to