Sharma and Chung *Future Cities and Environment* (2015) 1:13
DOI 10.1186/s40984-015-0013-8

Future Cities & Environment
a SpringerOpen Journal

TECHNICAL ARTICLE Open Access

Climatic benefits of black carbon emission reduction when India adopts the US on-road emission level

Ashish Sharma[1] and Chul E. Chung[2*]

Abstract

India is known to emit large amounts of black carbon (BC) particles, and the existing estimates of the BC emission from the transport sector in the country widely range from 72 ~ 456 Gg/year (for the 2000's). First, we reduce the uncertainty range by constraining the existing estimates by credible isotope analysis results. The revised estimate is from 74 ~ 254 Gg/year. Second, we derive our own BC estimate of the transport section in order to gain a new insight into the mitigation strategy and value. Our estimate shows that the transport section BC emission would be reduced by about 69 % by adopting the US standards. The highest emission reduction comes from the vehicles in the 5–10 year old age group. The minimum emission reduction would be achieved from the vehicles in the 15–20 year old age category since their population is comparatively small in comparison to other age categories. The 69 % of 74 ~ 254 Gg/year is 51 ~ 175 Gg/year, which is the estimated BC emission reduction by switching to the US on-road emission standard. Assuming that global BC radiative forcing is 0.88 Wm^{-2} for 17.8 Tg/year of BC emission, we find that the reduced BC emission translates into −0.0025 ~ −0.0087 W m^{-2} in global forcing. In addition, we find that 51 ~ 175 Gg of BC emission reduction amounts to 0.046 – 0.159 B carbon credits which are valued at 0.56 – 1.92 B US dollars (using today's carbon credit price). In a nutshell, India could potentially earn billions of dollars per year by switching from the current on-road emission levels to the US levels.

Keywords: Indian road transport, Diesel emissions, Gasoline emissions, Black carbon, BC forcing, Climatic benefits

Introduction

Black carbon (BC) is a product that results from incomplete combustion. Black carbon (BC) is also known as "soot" or "soot carbon" [1]. BC aerosols are emitted as primary aerosols from fossil fuel combustion, biomass burning and biofuel burning, and thus largely anthropogenic. Specifically, the combustion of diesel and coal, the burning of wood and cow dung, savanna burning, forest fire and crop residue burning are the common sources for BC. In order to improve air quality, developed countries have reduced ambient aerosol concentration by a variety of measures in the last few decades. For instance, wood as the fuel for cooking was replaced by natural gas or electricity. This kind of clean-air act not only reduced the overall aerosol concentration (including BC concentration) but also reduced the relative amount of BC to other anthropogenic aerosols such as sulfate, as evident from the state-of-the-art emission estimate dataset by [2]. Developing countries, conversely, have high levels of aerosol concentration and also a relatively large amount of BC [2]. India too, as a developing nation, exhibits these characteristics. The BC emission in India has steadily increased [3].

BC has many unique aspects. First, while most aerosols scatter solar radiation and thus act to cool the earth, BC strongly absorbs sunlight and contributes to the global warming [4]. Second, while CO_2 itself is not an air pollutant, BC is both an air pollutant and climate warmer. Thus, reducing BC concentration is more easily justified than reducing CO_2 concentration. Third, BC emission is generally much easier to mitigate than CO_2 emission, since the former originates largely from poor life styles in developing countries. For example, it is much easier and cheaper to replace a cow-dung burning facility by a modern natural-gas stove in a kitchen than installing a solar panel. Fourth, since aerosols stay in the

* Correspondence: Eddy.Chung@dri.edu
[2]Desert Research Institute, Reno, NV 89512, USA
Full list of author information is available at the end of the article

atmosphere for less than a few weeks, reducing BC emission results in an immediate reduction in BC concentration, whereas reducing CO_2 emission leads to a reduction in CO_2 concentration many decades later. In view of this fourth aspect, Ramanathan and Xu [5] and Shindell et al. [6] demonstrated using climate models that reducing BC emission is among the most effective tools to slow down the warming immediately.

In the current study, we aim to quantify the BC emission from the transport sector in India and how much this BC emission can be reduced by adopting the US on-road emission rates immediately. We do this because vehicles in India emit far more particulate matter (i.e., far more aerosols) per vehicle than in the West. The aerosols emitted from vehicles consist largely of black carbon [7]. In comparison, biofuel combustion emits a relatively more organic carbon and less black carbon [7]. While BC is definitely a climate warmer, organic carbon may be a cooler [8, 9]. Thus, BC emission decrease in the transport sector seems more appealing in combating the global warming than that in biofuel or biomass burning. Accordingly, [10], for instance, suggested that diesel engine is one of a few good examples for reducing BC emission and fighting the global warming. Diesel engines are the main contributor to aerosol emission from the transport sector [11–13]. Furthermore, mitigating diesel engine emissions would reduce BC concentration with a relatively small reduction in sulfate (a cooling agent), whereas mitigating emissions from coal combustion in power plants would reduce both BC and sulfate substantially [14]. Thus, quantifying the BC emission in the transport section is very valuable in the global warming mitigation study.

Studies exist that estimated the BC emission from the road sector in India [7, 15–18]. These estimations give a widely-varying range of 71.76 ~ 456 Gg in the annual emission, and also a wide range of 6.5 % ~ 34 % in the percentage of the total BC emissions by the road transport sector. This large uncertainty in estimated BC emission or its contribution to total BC emission makes it difficult for policy makers to make decisions. Thus, one of the objectives in the present study is to reduce this uncertainty.

The novelty of our study is also that it quantifies the potential climatic benefits of mitigating the road transport sector BC emissions in India via implementation of the US on-road emission levels, which are more stringent than the Indian levels. Previous studies in this regard [19–21] quantified the percentage reduction by applying EU standards and our study is the first study to quantify the percentage reduction by applying the US standard. Applying the US standard has advantages because US standards have similar emission requirements for both diesel and gasoline vehicles. Europe emission regulations, relative to the counterpart U.S. program, tolerate higher PM emissions from diesel vehicles. Applying the US emission standards in India is particularly more important in order to target BC emissions from the heavy duty diesel vehicles (buses and trucks) in India. Not only do we quantify the BC emission reduction in switching to the US standard, we also translate this reduction into the climatic benefit by applying observationally-constrained (thus accurate) BC climate forcing estimation studies and today's carbon emission price.

Lastly, in the present study, we will also attempt to quantify the contribution of different categories of vehicles towards the transport sector BC emissions in India for the year 2010 according to vehicle age. We do this, because this further information would be very valuable to environmental policy makers. We organize the paper in 4 sections. In Section 1, we provided a general overview of how this study was conducted and we highlighted the present state of transport sector emissions in India. Here, we also clarified some of the key findings from the similar studies conducted in the past and the shortcomings of the existing studies. In section 2, we discuss the methods we adopted for revising the existing estimates of the transport-sector BC emission in India and what approach we adopted for providing our own estimate the transport-sector BC emission in India. In Section 3, we discusses results. Here, we provided our own estimate of transport section BC emission and BC emission reduction by implementing higher emission standards. Section 3 also pertains to the BC forcing reduction and its monetary value and Section 4 is dedicated for discussions and conclusions.

Methodology

Revising the existing estimates of the transport-sector BC emission in India

As stated earlier, the previous estimates of the BC emission from the road sector in India give a widely-varying range of 71.76 ~ 456 Gg in the annual emission, and also a wide range of 6.5 % ~ 34 % in the percentage of the total BC emissions by the road transport sector [7, 15–18]. The aforementioned estimates are based on a bottom-up approach, and there is a wide range in the estimates due to uncertainty in (a) fleet average emission factors and (ii) modelling of the on-road vehicle stock. Additionally, emission inventories without calibrating the national fuel balance would have much higher uncertainties [22].

The aforementioned previous BC emission estimates did not utilize the isotope analysis results by Gustafsson et al. [23]. Most of carbon in the earth is carbon-12 (^{12}C). ^{14}C, also referred to as radiocarbon, is a radioactive isotope of carbon, and decays into nitrogen-14 over thousands of years. Live plants and animals maintain a high ratio of ^{14}C to ^{12}C by photosynthesis, vegetable eating and carnivores eating herbivores, as the source for ^{14}C is cosmic rays in the atmosphere. Thus, biomass contains a high ratio of ^{14}C to ^{12}C. On the other hand, fossil fuel arose from vegetation and animals that died a long time ago, and therefore contains no ^{14}C. The ratio of ^{14}C to ^{12}C is thus proportional to the ratio of biomass to fossil fuel. Gustafsson et al. [23] analyzed ^{14}C mass and ^{12}C mass data in collected aerosols, and apportioned the carbon between fossil fuel combustion and biomass/biofuel burning sources. Unlike in the previous BC emission estimates, the apportionment based on carbon isotope data should be considered non-controversial and credible. Furthermore, the aerosols collected for the analysis were in the South Asian outflow instead of near emission sources, which means that the results by Gustafsson et al. [23] represent the overall conditions in India. In view of this, in the present study we apply the results of Gustafsson et al. [23] to existing BC estimates.

Here is how we use Gustafsson et al.'s [23] results. According to Gustafsson et al. [23], the corresponding share of fossil fuel combustion and biomass/biofuel burning to total BC emissions is 32 ± 5 and 68 ± 6 % respectively in South Asia. Existing BC emission estimates for the transport sector in India also give the BC emission estimates for other sectors. We adjust the ratio of estimated BC emission from fossil fuel combustion (including transportation) to estimated BC emission from biomass and biofuel burning in each past estimation study so that the adjusted ratio would be $32 \pm 5 : 68 \pm 6$ in all the BC estimates, as consistent with that from Gustafsson et al. [23]. During the adjustment, we do not adjust the magnitude of total BC emission from all the sectors. The adjusted ratio leads to adjusted BC estimates for the transport sector, and the adjusted estimates must be more accurate. The original and adjusted estimates of the percentage share of road transport BC emissions to the total BC emissions in India are shown in Table 1. We propose that the community uses the adjusted estimates shown in Table 1.

Figure 1 compares the two (i.e., original and adjusted) estimates in the magnitude of BC emission. In this figure, we removed the estimate for the 90's and only retained those for the 2000's. As clearly shown in Fig. 1, the original estimates varied from $72 \sim 456$ Gg/year (with the arithmetic average of 264 Gg/year), while the adjusted estimates now vary from $74 \sim 254$ Gg/year (with the arithmetic average of 164 Gg/year). We computed the average estimate to develop the consensus, and do not intend the average estimate to be the best estimate. The average was obtained by assigning the same weight to each estimate. To summarize the results, the mean BC estimate is reduced by 38 % after adjustments with Gustafsson et al.'s [23] results. More importantly, we have sharply reduced the uncertainty in the transport sector BC emission (from $72 \sim 456$ Gg/year to $74 \sim 254$ Gg/year) by employing Gustafsson et al.'s [23] results.

Our own estimate of the transport-sector BC emission in India

In the present study, we develop our own estimate of the BC emission from the transport section in India because our own data would facilitate the quantification of BC emission reduction in the implementation of other emission standards. In addition, we provide BC emission according to the age categorization of the vehicles – a feature not represented in the previous studies and yet important for policy makers. In our estimation, we adopt an emission factor (EF) based approach with an aim to estimate the emissions for the year 2010. Emission factors (EFs) are relations between a specific emission and the concerned activity leading to that emission, and normally determined in an empirical manner. Road vehicle EFs represent a quantity of pollutants emitted given a unit distance driven, amount of fuel used or energy consumed [24]. In addition to an EF-based technique, many other techniques are being used in the community for quantifying emissions from a large number of real world vehicles. These techniques include remote sensing of tailpipe exhaust, chassis dynamometer tests, random roadside pullover tampering studies, tunnel studies, and ambient speciated hydrocarbon measurements [25]. Employing some of these techniques for determining actual vehicle emissions in our study would be very costly as it requires dedicated human resource. Thus, we use an emission factor based approach here.

As for the emission factors for Indian vehicles, we use the data from Baidya et al. [22]. We use the emission factors from Baidya et al. [22] for the following main reasons. (a) Most importantly, they utilized the data in South Asia and South East Asia. (b) They constrained the categorization of vehicles by the data availability and data authenticity, thus accounting for the characteristics of data in South Asia. (c) In particular, the following key factors were considered within each vehicle category: Fuel vs. engine, and kinds of engine (e.g., two or four strokes). Thus

Table 1 Percentage share of road transport BC emissions to total BC emissions in India. (Adjustment in accordance with Gustafsson et al.'s isotope analysis)

Reference	Emission year	Original estimate	Adjusted estimate
Lu et al., 2011 [15] (Emission year 2010)	2010	11.00 %	4.00 – 5.00 %
Klimont et al., 2009 [16] (Emission year 2010)	2010	6.50 %	17.00 – 23.00 %
Bond et al., 2004 [7] (Emission year 2009)	2009	30.00 %	21.00 – 29.00 %
Sahu et al., [17] (Emission year 2001)	2001	34.00 %	10.67 – 14.62 %

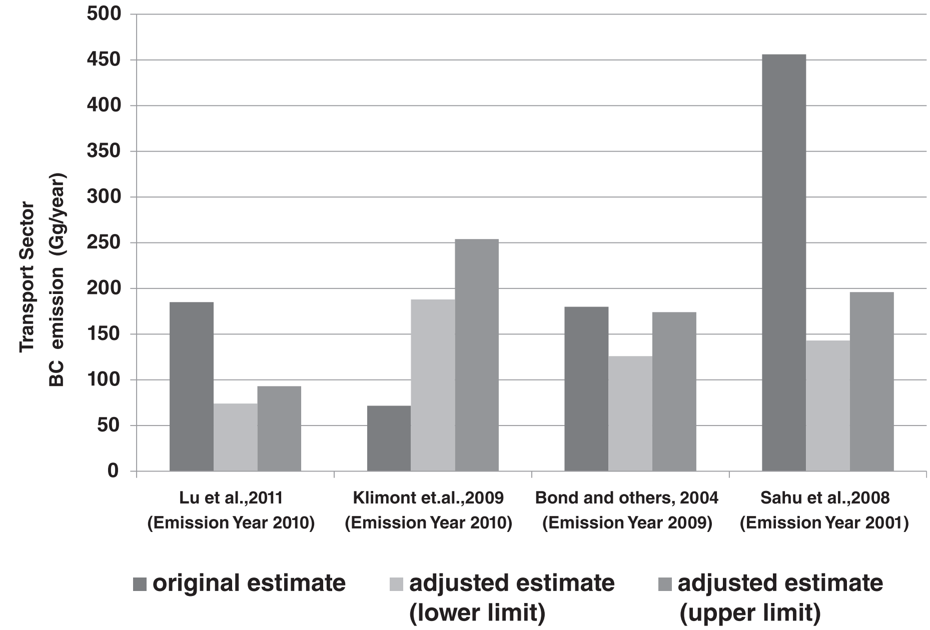

Fig. 1 Original vs. adjusted estimates of BC emissions in India (adjusted according to [23])

their EF's are well representative of local conditions in India and useful for the present study. Please note that Baidya et al. [22] provided the emission factors for particulate matter (PM) instead of BC, and they also gave the estimates of PM emission instead of BC emission. Here, we give BC emission estimates using known PM/BC ratios and these data for various categories.

We differentiated vehicles at different levels and obtained the emission factor for each category. First, on the basis of vehicles type such as heavy duty trucks, buses, cars and motorbikes. Motor bikes are further disaggregated as 2-stroke motorbikes and 4-stroke motor bikes. Second, the vehicles are differentiated on the basis of fuel type used – diesel or gasoline. Third, vehicles are further differentiated according to four age groups as: 0–5 year old, 5–10 year old, 10–15 year old and 15–20 year old. These age groups correspond to the 5-years brackets of the Indian exhaust emission regulations: Until 1990; 1991–1995; 1996–2000 and 2001–2005. For further classifying the vehicles according to age differentiation, we assumed the percentage of vehicle belonging to a specific age group such as 0 ~ 5 years old; 5 ~ 10 years old; 10 ~ 15 years old and 15 ~ 20 years old. Then we further assume the percentage distribution of trucks and buses for specific fuel types such as diesel and petrol. This disaggregation of vehicles into specific age groups is important for the purpose of this study because India has a significant percentage of the old vehicle fleets which have not yet retired and such old vehicles have considerably higher emission rates as the emission relevant parts deteriorate [25]. The calculation of PM emissions using age specific emission factors is crucial for identifying the vehicles responsible for higher PM emissions and thus this could be used to design vehicular emission mitigation strategies.

The scientific justification for the chosen EFs is not only explained in Baidya et al.[22] but is also supported in independent reports [19, 26]. All the EFs are defined in g/km. The EFs used in the present work are tabulated in Table 2. We are aware that EFs vary from region to region, and the given EFs in Table 2 are meant to be for the country-average values of various vehicle types.

In the next step, we multiply the total vehicle activity (vehicle kilometers traveled) and the fuel specific emission factors (Eq. 1) to estimate PM emission in Gigagram. This multiplication method is a common approach of emission calculation and it has been widely used in similar studies conducted in the past [17, 22, 27–29]. Please note that the unit of emission factors used in this equation is g/km. The annual emissions of pollutants are estimated for each individual vehicle type *a*, fuel type *b*, and emission standard *c* according to the following standard equation –

$$\mathbf{E_{T(a,b,c)}} = \sum \left(\mathbf{Pop_{a,b,c} x\ EF_{a,b,c} x\ VKT_a} \right) \qquad (1)$$

where,

$E_{T(a,b,c)}$ = Total Emissions

$Pop_{a,b,c}$ = vehicle population

VKT_a = annual vehicle kilometers traveled by vehicles of type a

$EF_{a,b,c}$ = Emission factor for vehicle per driven kilometer for vehicle type *a*, fuel type *b*, and emission standard *c*

We obtained the statistics of registered motor vehicles in India from various agencies in India, including the

Table 2 PM emission factor by vehicle category and age group in India (from Baidya et al. 2009)

Gram/km	Vehicles manufactured			
	2001- 2005	1996–2000	1991–1995	Before 1991
Heavy duty truck (diesel)	0.49	1.22	2.03	2.7
Bus (diesel)	0.59	1.49	2.48	3.3
Diesel car (diesel)	0.19	0.46	0.77	1.03
Diesel car (gasoline)	0.06	0.07	0.09	0.1
Motorbike (2 stroke, gasoline)	0.18	0.26	0.32	0.46
Motorbike (4 stroke, gasoline)	0.06	0.08	0.1	0.14

Ministry of Shipping, Road Transport & Highway. The data collection was extremely tedious due to an inferior information storage system in India. Data were obtained by combining internet search, peer-reviewed literature and reports, and personal communication with multiple research groups and agencies (both private and government agencies) in India and abroad via e-mails and phone calls. The annual average distance in kilometers travelled by various Indian vehicles was obtained from the Road Transport Yearbook [30] published by the Government of India. Upon analyzing the data, we found that older vehicles travelled lesser distance compared to the newer vehicles. The data are sorted out in terms of vehicle category, fuel type (diesel or gasoline), type of engine (two or four strokes), operation (e.g. taxi and private use for passenger cars and the emission control standard compliance. Driving conditions are defined as either urban or rural conditions. We categorized vehicles broadly into the following four categories: trucks (diesel), buses (diesel), passenger cars (including taxis and private cars powered by diesel and gasoline) and motor bikes (2-stroke and 4-stroke motor bikes powered by gasoline). The percentage share of each categoriy of vehicles on the basis of fuel type has been obtained from The Automotive Research Association of India (ARAI). Motorized two wheelers are differentiated by two stroke and four stroke engine.

For compliance with the latest emission regulation (i.e., emission regulation for 2010), we assumed that vehicles manufactured in a specific emission year are in compliance with the emission legislation enforced by Indian government in that model year and the vehicles were not improved (in terms of emission factor) afterwards. So, the compliance with the latest emission legislation is factored in this fashion. For example, let us say, a vehicle is manufactured in the model year 1998. Then we can say that this vehicle can be assigned an age group of 10–15 year old from the year 2010 standpoint. This will correspond to the Indian exhaust emission regulation during the 5-year bracket of 1996–2000. The emission factor for this specific vehicle is calculated from the emission standards during the 5-year bracket of 1996–2000. Please note that there is a lack of Inspection and Maintenance (I & M) data for Indian vehicles. If such data were available, we did not need to make the aforementioned assumptions.

In our own estimate, the total PM emission from the road transportation in India is 507 Gigagram for the year 2010 at the present Indian on-road emission levels (shown in Fig. 2). The total PM emission for a specific vehicle category is shown in Table 3. In the last step, we convert this PM emission into BC emission by applying the ratio of $BC/PM_{2.5}$. We obtain this ratio for on-road mobile sources from the EPA's report on black carbon [31], assuming that this ratio is primarily controlled by whether fuel and engine are either gasoline or diesel based. The $BC/PM_{2.5}$ ratio is 0.74 and 0.19 for diesel and gasoline mobile sources respectively. We obtain the total BC emission separately for diesel and gasoline vehicles. The details of conversion calculation are illustrated in Table 4. The total BC emission following Indian emission levels is estimated to be 344.5 Gg/year and 7.84358 Gg/year for on-road diesel and gasoline vehicles respectively. From Fig. 2, it is quite evident that heavy duty diesel trucks are the main culprits with the largest contribution of 64 % towards total PM emissions in India following the present Indian on-road emission levels. The 2nd largest source of on-road PM emissions are diesel buses. For the heavy commercial vehicles including buses and trucks we assumed that there is 100 % diesel penetration. The 3rd largest contribution to total PM emission comes from diesel passenger cars which are used as personal as well as multi utility passenger vehicles as a taxi, etc. The 4th largest emission sources are 4 stroke gasoline motor bikes followed by diesel passenger cars and 2 stroke gasoline motor bikes.

BC emission reduction when India adopts the US on-road emission levels

In section 2.1, we revised the estimates for on-road BC emission in India from existing studies to be 74 ~ 254 Gg/year using adjustment with isotope analysis results. This section pertains to calculating the reduction in BC emission. This is accomplished in the following steps:

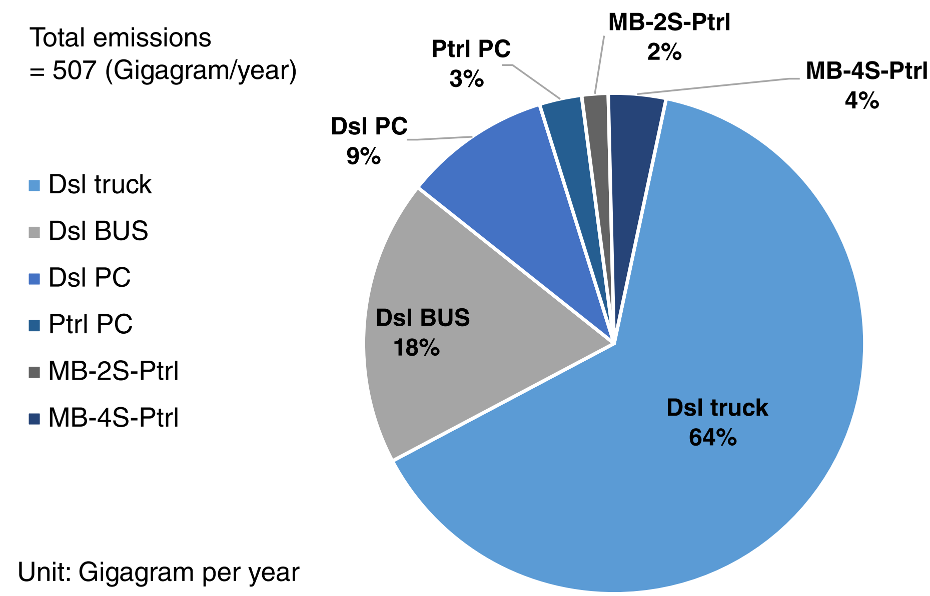

Fig. 2 Estimated PM emission of Indian vehicles with Indian emission levels

a) First, we obtain the emission factors for US vehicles using US EPA MOVES.
b) We compare the emission factors for Indian vehicles, as discussed in section 2.2, with those for US vehicles obtained in this section.
c) Then, we calculate the reduction in BC emission in switching from Indian emission levels to the US emission levels.

Emission factors for US vehicles

The emission factors for US vehicles were derived using the EPA's MOVES model for the year 2010. MOVES is currently the US state-of-the-art model for estimating on-road emissions. MOVES2010b is the latest version of MOVES. MOVES gives an emission for each driving mode and in this regard is considered a modal emission model. In the following, we summarize the main features of the model based on the work by Bai et al. [32] and the model documentation. Owing to the modal nature of the MOVES emission rates, MOVES is capable of quantifying emissions accurately on various scales (e.g., individual transportation projects as well as regional emission inventories). The current improved design of the model has the following advantages – a) the databases can be easily updated as per the availability of the new data; and b) the model permits and simplifies the import of data relevant to the user's own needs. The MOVES model applies various corrections for temperature, humidity, fuel characteristics, etc., before it comes up with emission estimates. MOVES also bases emission estimates on representative cycles, not on single emission rates. Furthermore, MOVES is different from traditional models such as MOBILE and EMFAC, in that a) instead of using speed correction factors, MOVES uses vehicle specific power and speed in combination; and b) it factors in vehicle operating time instead of mileage for determining emission rates. In view of this, we believe MOVES is a superior analysis tool.

Table 3 PM emission reduction if India adopts US on-road emission level

Vehicle category	Present Indian on-road emission levels PM emission (kilotons/year) (Total-all age category)	Present U.S on-road emission levels PM emission in kilotons/year) (Total-all age category)	Reduction in PM emission in switching from Indian emission levels to the US on-road emission levels
Diesel truck	323.9	128.9	352.3
Diesel bus	93.6	12.8	Gigagram
Diesel PC	48.1	3.5	
Petrol passenger car	13.9	1.0	
Motor Bike-2S petrol	8.6	6.5	
Motor Bike-4S petrol	18.8	1.7	

Table 4 Estimated BC emission from on-road mobile sources in India

Vehicle technology	$BC/PM_{2.5}$	PM emission (Gigagram/year)	BC emission = (BC/PM) ratio PM emission (Gigagram/year)
Indian on-road emission level			
On-road diesel vehicles	0.74	465.5	344.5
On-road gasoline vehicles	0.19	41.3	7.8
US on-road emission level			
On-road diesel vehicles	0.74	145.2	107.5
On-road gasoline vehicles	0.19	9.3	1.8

BC emission reduction in switching from Indian emission levels to US emission levels = 243 Gigagram

In this study, we specified the following parameters as the input parameters while running the MOVES model: a) geographic bound, we chose the national level; b) time span, the year 2010; c) road type, we specified urban road with unrestricted access; and d) in the emission source, we selected all the exhaust processes (consisting of running exhaust; start exhaust; crankcase running exhaust; crankcase start exhaust ; crankcase extended idle exhaust ; extended idle exhaust) but did not include the emissions from fueling or evaporation since our BC emission estimate in section 3 did not include the latter source either.

The model output we used is the total travelled distance and annual $PM_{2.5}$ emission. This output data was selected against specific vehicle types from the MySql output database of MOVES. Then, we compute emission factors by dividing total emission by total distance traveled and this gave us emission factors in gram/km for corresponding vehicle types. The emission factors were further sorted based on vehicle age. The vehicle age is calculated as a difference of reference year (year 2010) and the manufacturing year and finally, we inserted these emission factors in equation 1 discussed in chapter 3, to obtain total PM emission according to the US emission levels.

Results

Comparison of emission factors: Indian vehicles vs. US vehicles

As we compare the PM emission factors from the India motor vehicles with those from US vehicles, we clearly see that the Indian vehicles have significantly higher emission factors than those in the US (see Fig. 3). Moreover, this difference becomes even larger for older vehicles. Higher emission factors associated with older vehicles can be attributed to the deterioration of the vehicle engines upon aging and accumulation of the mileage. The vehicle engine seemingly deteriorates on aging due to poor maintenance of the vehicles. The vehicles in India are often poorly maintained and have higher average age relative to those in the US. We believe that this faster deteriorating also stems due to lack of effective inspection and maintenance systems to be enforced by the combination of government policies. Figure 3 also shows that the difference in the emission factors is highest for the heavy commercial vehicles (diesel buses and diesel trucks). In addition, considering the case of motor bikes, we can see that the emission factors for the motor bikes in US seems to be constant with the aging because the MOVES model does not incorporate age deterioration factor for motor bikes, however, the emission factors for motor bikes in India shows an increasing trend with an increasing age. In India, there is a significant share of on-road 2-stroke motor bikes as they are an attractive option to the middle and lower middle classes in India [33]. This is contrary to the motor bike ownership scenario in US where 2-stroke motor bikes are completely out of use and are superseded by 4-stroke motorbikes. Thus, almost all of the on-road motorcycles in MOVES at this point are 4-stroke.

Here, we summarize the merits of four stroke engines over two stroke engines and vice-versa from the study by Kojima et al. [34] published with the World Bank. Their study primarily focused on reducing emissions from two-stroke engines in South Asia. The key advantages of 4-stroke engines over 2-stroke gasoline engine vehicles are: lower particulate and hydrocarbon emissions, better fuel economy, and moderate noise levels while in operation. However, the only relative advantages of 2-stroke engines are: lower purchase prices; mechanical simplicity leading to low maintenance costs; and lower NO_2 emissions. Our comparative analysis of the emission factors from 2-stroke and 4-stroke engine technologies clearly points out the need for encouraging 4-stroke two wheelers over 2-stroke two wheelers in India. This implies that the pollution levels can be brought down to safer levels in spite of the rising two-wheeler population if the 4-stroke technology for the two-wheeler segment is promoted in India.

Reduction in BC emission in switching to the US emission levels

We combine the US emission factors with the driving activities in India to estimate total on-road PM emission in India if India hypothetically adopts the US emission levels (using Eq. 1). The result is the 155 Gigagram for the year 2010, as shown in Fig. 4. This PM emission is further converted to equivalent BC emission by applying the ratio of $BC/PM_{2.5}$

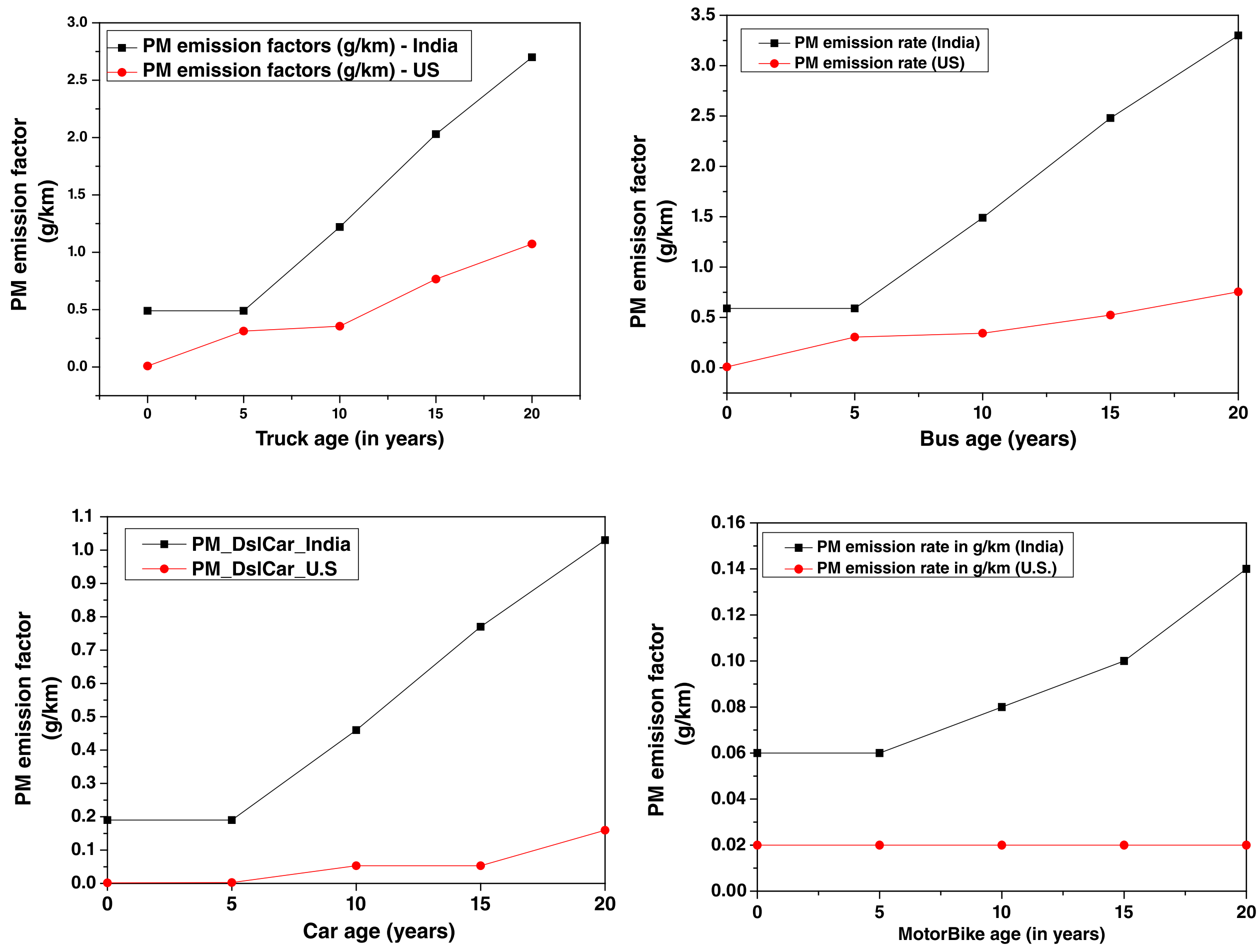

Fig. 3 Comparison of PM emission factors of Indian vehicles and US vehicles

(discussed in section 2.2) and details of calculation are presented in Table 4.

The reduction in BC emission in switching to the US emissions levels is expressed in terms of reduction in PM emission (Table 3 and Fig. 5) and reduction in BC emission (Table 4). The total BC emission reduction following the US emission levels is estimated to be 243 Gg (equaling 69 % reduction), and this number is split into 236.7 Gg and 6 Gg for on-road diesel and gasoline vehicles respectively. Please note that this reduction is in BC emission. In Fig. 5, we analyze the emission reduction in terms of age category of the vehicles. We find that the highest emission reduction in switching to US on-road emission levels would result from the vehicles in the age group of 5–10 years old followed by the vehicles in the age group of 0–5 years old and vehicles in the age group of 10–15 years old. The least emission reduction will result from the vehicles which are in the age group of 15–20 years old. This estimate incorporating vehicle age categorization is one of the novelties of the present study.

Our estimate of BC emission in section 3 is not necessarily a better estimate than previous ones. Thus, we restrict our BC emission estimate to the use of the ratio of the emission factors in India to those in US. This ratio is combined with the adjusted previous estimates (according to Gustafsson et al. [23], as discussed in section 2) to yield the reduction of BC emission. For the total BC emission reduction from all the vehicles in India, we apply the 69 % BC emission reduction to the adjusted previous estimates. The 69 % of 74 ~ 254 Gg/year is 51 ~ 175 Gg/year. This is the estimated BC emission reduction by switching to the US on-road emission standard.

BC radiative forcing reduction and its value

We calculated earlier that 51 ~ 175 Gg/year of BC emission reduction is possible in India (year 2000's) from the road transport sector if India adopts the US on-road emissions levels. Based on the study by Cohen and Wang [35] and Bond et al. [10], 17.8 Tg/year (i.e. 17800 Gigagram/year) of global BC emission makes 0.88 W/m^2 of global BC forcing.

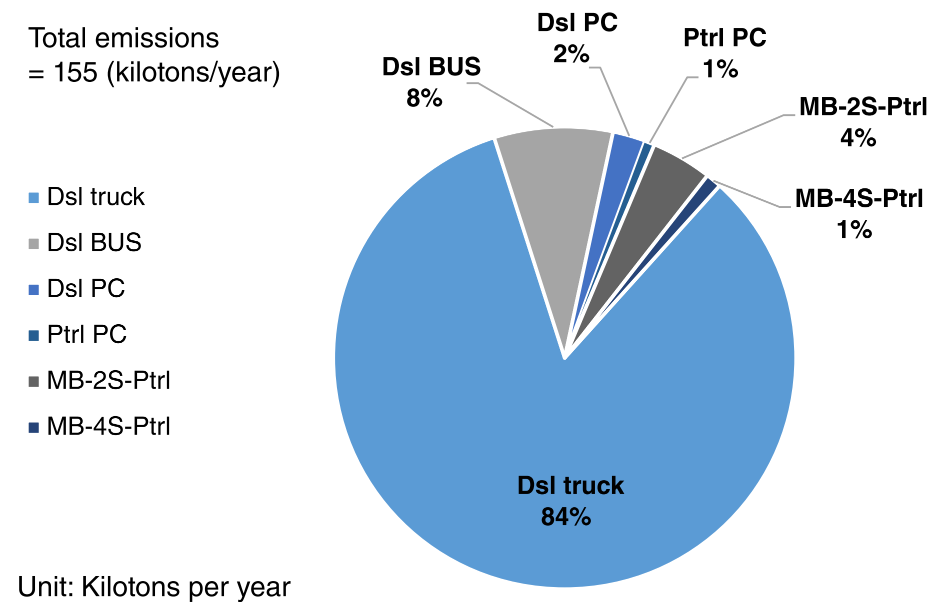

Fig. 4 Estimated PM emission of Indian vehicles with US on-road emission levels

We estimate that 51 ~ 175 Gg/year of BC emission reduction contributes to a reduction of −0.0025 ~ −0.0087 W m^{-2} in global BC forcing. Thus, we conclude that a reduction in BC forcing of −0.0025 ~ −0.0087 W m^{-2} is possible if India adopts the US on-road emissions levels.

Quantifying climatic benefits of a reduction in BC forcing (in USD)

Both CO_2 emission and BC emission contribute to the global warming. The Kyoto Protocol introduced a concept called "carbon credit". 1 carbon credit is a permit to emit 1

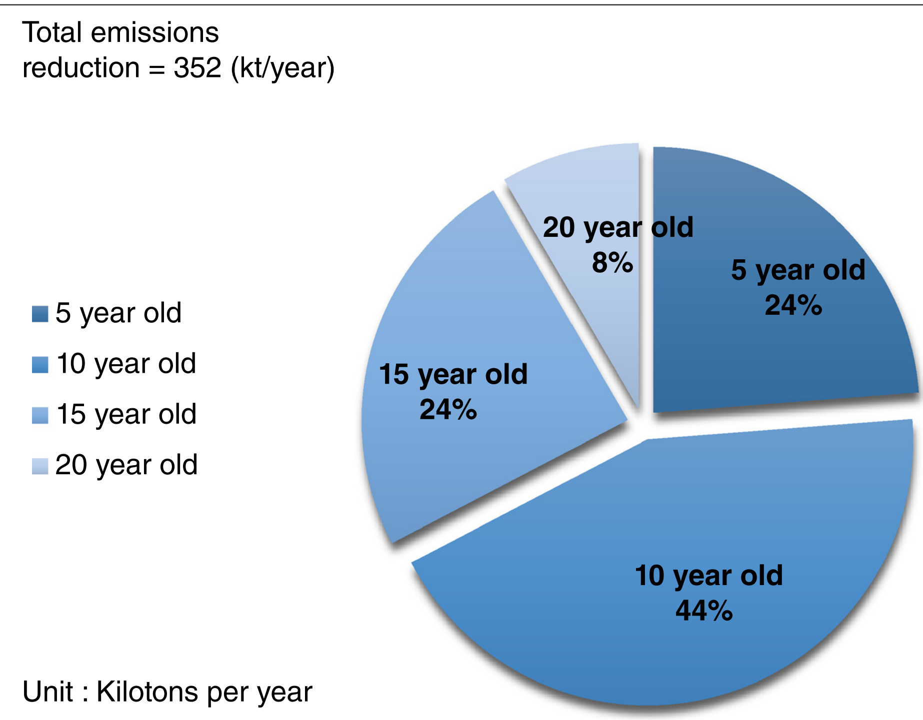

Fig. 5 PM emission reduction from Indian vehicles according to their age (US on-road emission levels)

tonne of CO_2. Such permits can be sold and bought in a market, and Fig. 6 shows the market price moves of 1 carbon credit in the last 12 months. The Kyoto Protocol also allows for other climate warmers (such as methane) than CO_2 to be traded in carbon credit markets. For non-CO_2 warming matters, 1 carbon credit is a permit to emit an amount of the matter equivalent to 1 tonne of CO_2 in the global warming. Each warming agent (such as methane) has its own atmospheric-residence time scale, spatial distribution, etc., and so comparing a particular warming agent to CO_2 is not always straightforward. For BC, 100 year (or 20 year) global-warming-potential (GWP) is commonly used in this regard. According to Bond et al. [10], the 100 year GWP value for BC is 910. This means 1 tonne of BC emission adds as much energy to the earth over the next 100 years as 910 tonnes of CO_2. Please note that the mass of BC refers to that of the carbon component while the CO_2 mass refers to the combined mass of carbon and oxygen.

Applying Bond et al.'s [10] estimate for the BC GWP, we find that 51 ~ 175 Gg/year of BC emission reduction amounts to 0.046 billion - 0.159 billion carbon credits. Using $12.104 (US dollars) as the average price of 1 carbon credit, as shown in Fig. 6, 0.046 billion - 0.159 billion credits are valued at $ 0.56 B – $ 1.92 B (US dollars). In short, India could earn $ 0.56 B – $ 1.92 B (US dollars) every year by switching from the current on-road emission levels to the US levels. Please note that the Kyoto Protocol did not address BC but the next climate treaty will likely include BC.

We furthermore note that the 5th IPCC report [36] endorsed Bond et al.'s [10] study as a credible estimate of BC GWP. Bond et al.'s [10] estimate can be considered credible for many reasons. First, observationally-constrained estimates of BC forcing were used, and thus these estimates are similar to that of Cohen and Wang [35]. Second, the rapid adjustment due to the atmospheric heating by BC (i.e., semi-direct forcing) was included as well, and in this aspect the best semi-direct forcing estimate was used.

Conclusion and discussions

The existing estimates of the BC emission from the transport sector in India have a wide range of values, giving huge uncertainties in this regard. In the present study, we have substantially reduced the uncertainty by constraining the existing estimates with credible isotope analysis

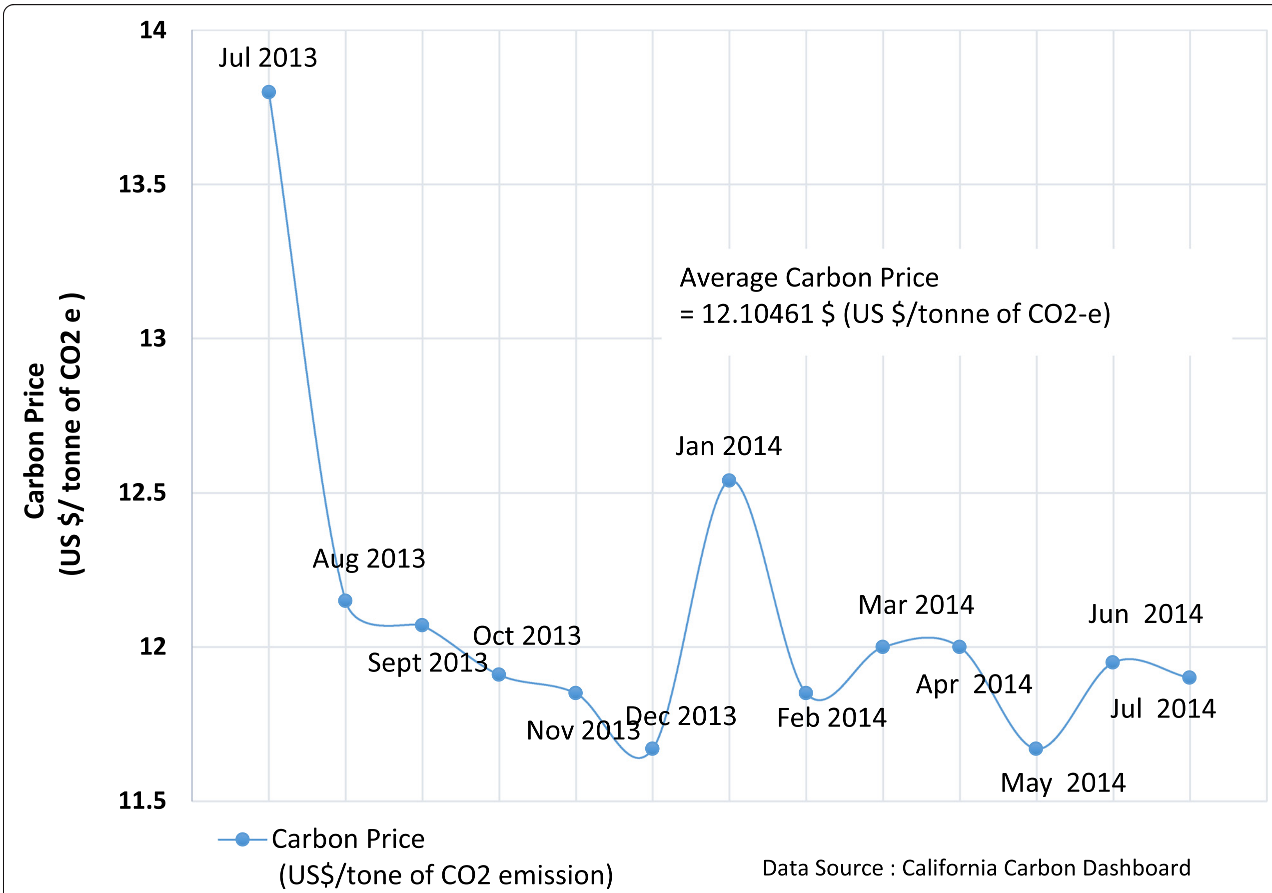

Fig. 6 Average Carbon Price in US Dollar per tonne of CO_2 emission or its equivalent (July 2013 – July 2014)

results. Next, we have derived our own BC estimate of the transport section, and then we have provided the estimate of anticipated BC emission reduction possible in India as a result of switching to the more stringent US on-road emission levels. This emission reduction is found to be about 69 %, and coupled with the adjusted previous BC emission estimates the emission reduction is expected to be in the range of 51 ~ 175 Gg of BC per annum. What is more, we have expressed the proposed BC emission reduction in terms of global BC radiative forcing, which is estimated to range from $-0.0025 \sim -0.0087$ W m^{-2}, i.e., a reduction of global BC forcing by $0.0025 \sim 0.0087$ W m^{-2} due to a reduction of BC emission in India. We have also quantified the climate benefits of the BC emission reduction in USD. The BC reduction of 58.2 ~ 151.3 Gg is equivalent to 0.046 billion - 0.159 billion carbon credits which are valued at $ 0.56 B US dollars – $ 1.92 B US dollars (using today's carbon credit price).

Although we fully accounted for uncertainties in estimating the BC emission from the transport section in India, we did not address the uncertainties in the 69 % reduction estimate, nor did we assess the uncertainties in local BC forcing or BC GWP. In our view, addressing these uncertainties is beyond the scope of the current paper and deserves a separate study. To elaborate, BC GWP is not globally uniform. BC emission in some areas can contribute to the global warming more than the emission of the same amount in other areas, since BC forcing depends on sunlight, low cloud fraction, etc. Even if we consider the uncertainty in global BC GWP, we also need to evaluate local BC GWP and address its uncertainty. To simplify the computation, we used the best estimate of global BC forcing and BC GWP and scaled these numbers to estimate the climatic benefit of reducing the BC emission in India. Nevertheless, we believe the ranges of all the estimates in our study are sufficiently large to cover most uncertainties, because we maximized the uncertainties in estimating the BC emission from the transport sector (by picking possibly the most extreme values to represent the range), and the other estimates are based on the BC emission estimates.

Overall, our study provides another reason that vehicles should be cleaner in India. Why the vehicles in India emit more aerosols than those in the US needs additional discussions, as there are many factors behind this. There are studies [21, 22, 29] and government reports [19, 37] which highlight key reasons accountable for excessive particulates emission from Indian vehicles. One of the key reasons relates to the Indian emission controls, as they have been traditionally based on Euro style emission standards. Such emission standards allow higher particulate emissions from diesel vehicles compared to the gasoline vehicles. In comparison, the US has been setting and reinforcing the same standards without considering any specific type. In another reason, emission standards in India are lax compared to international best practices. The lax standards in India reflect that Indian schedules for adopting emission and fuel quality standards lag those in the West. Other reasons include a weak enforcement of emission standards; and a significant percentage of older vehicles in India which are poorly maintained and have poor fuel economy.

An additional and important cause of excessive emission from Indian vehicles might be that transport fuels in India have high sulfur content which results in higher sulfate emissions. During combustion, sulfur in diesel fuel is emitted in the form of sulfur dioxide (SO_2) gas which later condenses and becomes sulfate aerosols in the atmosphere. SO_2 emission is not part of PM emission in typical PM estimation studies (since gas is not aerosol) but SO_2 gas (at least some of it) ultimately becomes aerosols. Since the present study is about BC aerosols, we refrain from discussing high sulfur content extensively here.

In the end, vehicles in India emit excessive aerosols because such dirty vehicles are cheap to buy and operate. Such dirty vehicles are common among poor countries and so this is not limited to India. Clean technological solutions are available but unfortunately at additional costs. We discuss some technology examples in the next. Compared to gasoline engines, diesel engines have lower CO and HC gas emissions but higher NOx and PM emissions [38]. In gasoline engines tailpipe emissions can be significantly reduced by an efficient use of three-way catalytic converters, but at the expense of fuel economy [39]. In general, the emission control technologies for diesel and gasoline engines can be broadly divided into two groups: in-cylinder control and after-treatment control [40]. Posada et al. [41] give a good review of these emission control technologies. For instance, for diesel emission controls, PM filters are an example of after-treatment tools. Minjares et al. [13] and EPA [31] report that these particle filter devices reduce diesel PM emissions by as much as 85 to 90 % and BC emissions by up to 99 %.

Despite all these costs, the benefits could be substantial. Here, we have discussed the benefits by adopting the US on-road aerosol emission levels immediately. The idea of switching the on-road emission to the US levels immediately is unrealistic. Thus, our results can be taken as the upper limit of the benefit and such results are still useful to policymakers. On the other hand, while we only discussed the climate benefits, the benefits are not limited to the climate, and more importantly pertain to health benefits. A number of studies [31, 39, 42–45] substantiated the health benefits of BC emission reduction. It has been well established that fine particulates emitted from diesel motor vehicles contain toxic substances and the exposure to these fine particles can prompt lung tumor, serious respiratory grimness and mortality including wellbeing results, for example, worsening of asthma, interminable bronchitis, respiratory tract contaminations, coronary illness and stroke.

Besides the issues of outdated vehicle technology in India, there are other issues (behavioral and psychological issues) such as a lack of environmental conviction in the Indian car consumers that leads to higher traffic emissions [46–48]. They often dump old tires, battery or even scrap car. Irrespective of a large number of consumers who are conscious about the environment, very few people are actually willing to adapt their lifestyle in order to solve the issues such as deteriorating air quality. There is a very negligible percentage of people who actually push themselves out of their comfort zone by acting at their personal expenses, such as paying premiums for environmentally friendly products and making a sacrifice in their present lifestyles. Therefore, there is a need of behavioral changes at personal level which includes - (i) raising public awareness to prefer public transportation to using personal vehicles; (ii) living near the workplace rather than commuting a long distance to workplace every day; (iii) car pool; and (iv) commuting to workplace with bicycles. The increasing use of public transportation would mean fewer vehicles on the road, which means less emission and less negative effects on climate and health [49]. Hence, there is not a single effective tool to mitigate transport sector emissions. Taken together, we propose that in order to assure effective environmental protection, psychological as well as technological measures need to be in place.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
CEC conceptualized the work, and interpreted the results. AS carried out the work. All the authors worked together for writing.

Acknowledgement
The authors are thankful to Dr. George Scora of University of California Riverside University of California, Riverside), Dr. Sarath Guttikunda of Urban Emissions, India, Mr. Michael P. Walsh, Mr. Gaurav Bansal, Mr. John German of ICCT (Washington, DC), Mr. Stevens Plotkins of Argonne National Laboratory, and Mr. Narayan Iyer of Bajaj Auto-India for their expertise. We are also thankful to the government and semi-government agencies such as US EPA, CARB, CSE (Delhi), SIAM (India) and ARAI (India) for their prompt responses to our data requests and doubts in using emission models. This research was funded by the Korea Meteorological Administration Research and Development Program under Grant Weather Information Service Engine (WISE) project (#: KMA-2012-0001).

Author details
[1]Department Civil Engineering, University of Toledo, Toledo, OH 43606, USA.
[2]Desert Research Institute, Reno, NV 89512, USA.

Received: 13 July 2015 Accepted: 20 December 2015
Published online: 29 December 2015

References
1. Andreae M, Gelencsér A (2006) Black carbon or brown carbon? The nature of light-absorbing carbonaceous aerosols. Atmos Chem Phys 6(10):3131–3148
2. Lamarque J-F, Bond TC, Eyring V, Granier C, Heil A, Klimont Z, Lee D, Liousse C, Mieville A, Owen B (2010) Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application. Atmos Chem Phys 10(15):7017–7039
3. Novakov T, Ramanathan V, Hansen J, Kirchstetter T, Sato M, Sinton J, Sathaye J: Large historical changes of fossil-fuel black carbon aerosols. Geophysical Res Letters 2003, 30(6). doi:10.1029/2002GL016345.
4. Chung CE, Ramanathan V, Decremer D (2012) Observationally constrained estimates of carbonaceous aerosol radiative forcing. Proc Natl Acad Sci 109(29): 11624–11629
5. Ramanathan V, Xu Y (2010) The Copenhagen accord for limiting global warming: criteria, constraints, and available avenues. Proc Natl Acad Sci 107(18):8055–8062
6. Shindell D, Kuylenstierna JC, Vignati E, van Dingenen R, Amann M, Klimont Z, Anenberg SC, Muller N, Janssens-Maenhout G, Raes F (2012) Simultaneously mitigating near-term climate change and improving human health and food security. Science 335(6065):183–189
7. Bond TC, Streets DG, Yarber KF, Nelson SM, Woo JH, Klimont Z: A technology-based global inventory of black and organic carbon emissions from combustion. J Geophysical Res Atmospheres (1984–2012) 2004, 109(D14). doi: 10.1029/2003JD003697.
8. Myhre G, Bellouin N, Berglen TF, Berntsen TK, Boucher O, Grini A, Isaksen IS, Johnsrud M, Mishchenko MI, Stordal F (2007) Comparison of the radiative properties and direct radiative effect of aerosols from a global aerosol model and remote sensing data over ocean. Tellus B 59(1):115–129
9. Stier P, Seinfeld JH, Kinne S, Boucher O (2007) Aerosol absorption and radiative forcing. Atmos Chem Phys 7(19):5237–5261
10. Bond TC, Doherty SJ, Fahey D, Forster P, Berntsen T, DeAngelo B, Flanner M, Ghan S, Kärcher B, Koch D (2013) Bounding the role of black carbon in the climate system: A scientific assessment. J Geophysical Res Atmospheres 118(11):5380–5552
11. Kroeger T: Black Carbon Emissions in Asia: Sources, Impacts and Abatement Opportunities. Contractor Report Prepared by International Resources Group for USAID, ECO-Asia Clean Development and Climate Program USAID Regional Development Mission for Asia. USAID: Bangkok, Thailand 2010.
12. Liggio J, Gordon M, Smallwood G, Li S-M, Stroud C, Staebler R, Lu G, Lee P, Taylor B, Brook JR (2012) Are emissions of black carbon from gasoline vehicles underestimated? Insights from near and on-road measurements. Environ sci Technol 46(9):4819–4828
13. Minjares R, Wagner D, Baral A, Chambliss S, Galarza S, Posada F, SHARPE B, Wu G, Blumberg K, Kamakate F (2014) Reducing black carbon emissions from diesel vehicles: impacts, control strategies, and cost-benefit analysis. The World Bank
14. Garg A, Shukla P, Bhattacharya S, Dadhwal V (2001) Sub-region (district) and sector level SO< sub > 2</sub > and NO< sub > x</sub > emissions for India: assessment of inventories and mitigation flexibility. Atmos Environ 35(4):703–713
15. LU J (2011) Environmental Effects of Vehicle Exhausts, Global and Local Effects:
A Comparison between Gasoline and Diesel. Thesis, Halmstad University
16. Klimont Z, Cofala J, Xing J, Wei W, Zhang C, Wang S, Kejun J, Bhandari P, Mathur R, Purohit P (2009) Projections of SO2, NOx and carbonaceous aerosols emissions in Asia. Tellus B 61(4):602–617
17. Sahu S, Beig G, Sharma C: Decadal growth of black carbon emissions in India. Geophysical Research Letters 2008, 35(2). DOI:10.1029/2007GL032333.
18. Reddy MS, Venkataraman C (2002) Inventory of aerosol and sulphur dioxide emissions from India. Part II—biomass combustion. Atmos Environ 36(4):699–712
19. ARAI.: The Automotive Research Association of India, 2007. Emission Factor Development for Indian Vehicles, As a Part of Ambient Air Quality Monitoring and Emission Source Apportionment Studies. AFL/2006-07/IOCL/Emission Factor Project/2007.
20. Baidya S (2008) Trace Gas and particulate matter emissions from road transportation in India: quantification of current and future levels. Reports in University of Stuttgart, Stuttgart
21. Bansal G, Bandivadekar A (2013) OVERVIEW OF INDIA'S VEHICLE EMISSIONS CONTROL PROGRAM. ICCT, Beijing, Berlin, Brussels, San Francisco, Washington
22. Baidya S, Borken-Kleefeld J (2009) Atmospheric emissions from road transportation in India. Energy Policy 37(10):3812–3822
23. Gustafsson Ö, Kruså M, Zencak Z, Sheesley RJ, Granat L, Engström E, Praveen P, Rao P, Leck C, Rodhe H (2009) Brown clouds over South Asia: biomass or fossil fuel combustion? Science 323(5913):495–498
24. Franco V, Kousoulidou M, Muntean M, Ntziachristos L, Hausberger S, Dilara P (2013) Road vehicle emission factors development: A review. Atmos Environ 70:84–97

25. Sawyer RF, Harley RA, Cadle S, Norbeck J, Slott R, Bravo H (2000) Mobile sources critical review: 1998 NARSTO assessment. Atmos Environ 34(12):2161–2181
26. Central Pollution Control Board MoEF (2011) Air Quality Monitoring, Emission Inventory and Source Apportionment Study for Indian Cities. Ministry of Environment & Forests: India
27. Ramachandra T (2009) Emissions from India's transport sector: Statewise synthesis. Atmos Environ 43(34):5510–5517
28. Nagpure AS, Sharma K, Gurjar BR (2013) Traffic induced emission estimates and trends (2000–2005) in megacity Delhi. Urban Climate 4:61–73
29. Sahu SK, Beig G, Parkhi N (2014) Critical emissions from the largest on-road transport network in south Asia. Aerosol Air Qual Res 14(1):135–144
30. Ministry of Road Transport and Highways I (2012) India road transport year book 2009–2011. Ministry of Road Transport and Highways (India), New Delhi, India
31. EPA U: Report to Congress on black carbon. US Environmental Protection Agency, Washington, DC. 2012, EPA-450/R-12-001 388pp.
32. Bai S, Eisinger D, Niemeier D: MOVES vs. EMFAC (2009) A Comparison of Greenhouse Gas Emissions Using Los Angeles County. In: *Transportation Research Board 88th Annual Meeting, Paper: Washington DC*. 09–0692.
33. Das S, Schmoyer R, Harrison G, Hausker K (2001) Prospects of inspection and maintenance of two-wheelers in India. J Air Waste Manage Assoc 51(10):1391–1400
34. Kojima M, Brandon C, Shah JJ: Improving urban air quality in South Asia by reducing emissions from two-stroke engine vehicles. In.: World Bank; 2000
35. Cohen JB, Wang C: Estimating global black carbon emissions using a top-down Kalman Filter approach. J Geophysical Res Atmospheres 2014 199;307-323
36. Randall, D.A., R.A. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J. Shukla, J. Srinivasan, R.J. Stouffer, A. Sumi, K.E. Taylor, 2007: Cilmate Models and Their Evaluation. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor, H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
37. Ministry of Shipping RTH, Government of India; ARAI.: 2007.
38. Mondt JR (2000) Cleaner Cars: The history and technology of emission control since the 1960s; Society of Automotive Engineers, Inc.
39. Zelenka P, Cartellieri W, Herzog P (1996) Worldwide diesel emission standards, current experiences and future needs. Appl Catal B Environ 10(1):3–28
40. Faiz A, Weaver CS, Walsh MP (1996) Air pollution from motor vehicles standards and technologies for controlling emissions. World Bank, Washington, D.C
41. Minjares R, Blumberg K, Posada Sanchez F (2013) Alignment of policies to maximize the climate benefits of diesel vehicles through control of particulate matter and black carbon emissions. Energy Policy 54:54–61
42. Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, Adair-Rohani H, AlMazroa MA, Amann M, Anderson HR, Andrews KG (2013) A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet 380(9859):2224–2260
43. Ghose MK, Paul R, Banerjee S (2004) Assessment of the impacts of vehicular emissions on urban air quality and its management in Indian context: the case of Kolkata (Calcutta). Environ Sci Pol 7(4):345–351
44. Sydbom A, Blomberg A, Parnia S, Stenfors N, Sandström T, Dahlen S (2001) Health effects of diesel exhaust emissions. Eur Respir J 17(4):733–746
45. Morgan W, Reger R, Tucker D (1997) Health effects of diesel emissions. Ann Occup Hyg 41(6):643–658
46. Klocke U (2000) Conditions of environmental mobility decisions: environmental protection through government action, at the individual. In: Scholl W, Sydow H (eds) Association for European transport and contributors 2009 16 modal choice and when buying a car. Mobility in adolescence and adulthood, Waxmann, Münster
47. Kruger N, Pareigis J: Influencing Car Buying Decisions from an Environmental Perspective-A Conceptual Framework Based on Real Option Analysis. In: European Transport Conference, 2009: Netherlands 2009
48. Joshi N, Rao P: Environment Friendly Car: Challenges ahead in India. Global J Manage Business Res 2013, 13(4):11-19.
49. Laffel N (2006) Promoting Public Transportation for Sustainable Development. Thesis, Princeton University