Climate Impacts of Air Quality Policy: Switching to a Natural Gas-Fueled Public Transportation System in New Delhi

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Between 2001 and 2003, public transport vehicles in New Delhi were required to switch their fuel to natural gas in an attempt to reduce their air pollution impacts. This study examines the climatic impacts of New Delhi's fuel switching policy, and outlines implications for such efforts in rapidly industrializing countries. Natural gas is mostly composed of methane, an important greenhouse gas. Emitted aerosols (black carbon, particulate organic carbon, and sulfate) also cause radiative forcing. We find that methane and black carbon emissions are critical contributors to the change in carbon dioxide equivalent [CO_2(e)] emissions. In New Delhi, the switch to natural gas results in a 30% increase in CO_2(e) when the impact of aerosols is not considered. However, when aerosol emissions are taken into account in our model, the net effect of the switch is estimated to be a 10% reduction in CO_2(e), and there may be as much as a 30% reduction in CO_2(e). There is significant potential for emissions reductions through the United Nations Framework Convention on Climate Change (UNFCCC) Clean Development Mechanism for such fuel switching projects.

1. Introduction

Compressed natural gas (CNG) fueling for vehicles is seen as a means of reducing environmental and human health costs of transportation, since internal combustion engines running on CNG produce inherently less pollutant emissions than comparable liquid-fuel engines. This is especially attractive to developing nations, where advanced liquid-fuel vehicles with low-emitting engines and tailpipe pollution controls may not be affordable. Various jurisdictions, for example, New Delhi, Mumbai, Mexico City, and Rio de Janeiro, have already converted vehicle fleets to natural gas fueling (*1*, *2*). When conventional vehicles, especially heavy-duty trucks and buses fueled by diesel, are converted to natural gas, mass emissions of particulate matter (PM) can be reduced by one to two orders of magnitude (*3*). This is certainly important from a public health perspective, because PM emissions from diesel engines are carcinogenic and cause cardio-pulmonary health effects (*4*), and the health impacts of PM concentrations in Delhi are well-known (*5*). Although an analysis of the health effects of the fuel-switch is outside the scope of the present study, air pollution and climate change are inextricably connected because the combustion of fossil fuels releases greenhouse gases, aerosols, and criteria air contaminants. Policy analyses that take into account potential climate/air pollution synergies have been called for and are clearly needed (*6*). The present study takes this approach, by quantifying the change in climate-forcing emissions that result from a fuel-switching policy that was designed with air quality in mind.

One of the most significant fuel-switching examples has been in Delhi, where the entire public transportation fleet—buses, taxis, and autorickshaws (three-wheeled motorcycle taxis)—were converted to run entirely on natural gas (*7*). The switch was mandated by a Supreme Court of India directive (as a response to a public petition), which required that the Delhi Government tackle the problem of air pollution from public transport vehicles. Initially scheduled to be completed in 2001, technical difficulties with retrofitting so many vehicles (and the limited number of NG fueling stations) caused the process to be completed only in 2003. Although there has been wide acclaim for this move, the jury is still out regarding the magnitude of air quality improvements that resulted (*8–12*). In one of the most recent analyses, spectral analysis methods were used to examine changes in pollutant concentrations since 2000 at a "hotspot" for traffic pollution in New Delhi (*9*). Ambient levels of carbon monoxide (CO) and sulfur oxides (SO_x) were observed to have been reduced coincident with the switch to CNG fuel, but PM_{10} (PM with an aerodynamic diameter of less than 10 μm) concentrations remained essentially unchanged over the whole period, and nitrogen oxide concentrations rose until 2004, followed by a decline thereafter. There is no doubt that public transportation emissions changed following the fuel switch. However, the signal-to-noise ratio (as evidenced in the air concentration data) appears to be too low for the effects of the policy to be discernible from other sources such as industry and power generation, for all pollutants with the exception of carbon monoxide. One aspect of this fuel change in New Delhi that has thus far been left unexplored is the climate forcing implications of switching to CNG. This work aims to fill that gap.

2. Methods

2.1. Fuel Efficiency and Emissions Factors. As of April 2005, there were almost 90,000 public transportation vehicles in the New Delhi metropolitan area operating on CNG fuel (*13*). Annual average vehicle activity data (km per year) for each type of vehicle are not well characterized in India. Only one vehicle study was found to have measured the daily distance traveled for a randomly selected statistical sample in India. The study was conducted in the Indian city of Pune in 2003 (*14*) and yielded results similar to estimated activity data for different transportation categories in Indian cities (*15*), and for buses in Mumbai (*16*). We assumed public transportation vehicle activity in Delhi to be similar to that in Pune, while also recognizing that the difference between CNG and gasoline/diesel emissions on a per-vehicle basis is not sensitive to activity levels. The total activity for each category was then calculated (see Table S1 in the Supporting Infor-

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TABLE 1. Summary of Climate-Forcing Emissions Factors for Liquid-Fuel and CNG Public Transportation Vehicles: Gaseous and Aerosol Species

	liquid-fuel emissions factors (g/km)			cng emissions factors (g/km)		
	buses	cars	autorickshaws	buses	cars	autorickshaws
			gaseous emissions			
carbon dioxide	1063	157	67	1160	144	62
methane (exhaust)	0.06	0.14	0.08	6.50	2.28	1.30
methane (leakage)	0	0	0	1.99	0.25	0.11
			aerosols			
black carbon	1.52	0.16	0.01	0.002	0.001	0.008
organic carbon	0.48	0.17	0.19	0.005	0.003	0.024
SO_2	0.233	0.015	0.006	0	0	0

mation). Although an average autorickshaw travels the lowest distance annually, this category makes up the greatest number of CNG vehicles by a factor of 5, and hence represents the greatest total activity.

The CNG vehicles were assumed to be all direct retrofits (rebuilt engines and fueling systems) from the original diesel and gasoline vehicles, rather than new vehicles with purpose-built CNG engines. In New Delhi, resources were not available to purchase large numbers of new CNG vehicles prior to 2005, and even in the future, "new" CNG vehicles are likely to be technologically equivalent to retrofitted vehicles due to the prohibitive expense of state-of-the-art CNG-engine technology. Consequently, because vehicle weight, engine size, transmission, aerodynamics, and general mechanical condition are likely to be unchanged, the CNG vehicles' fuel consumption can be assumed to be proportional to that of preconversion vehicles. However, some fuel efficiency losses must be attributed to the conversion, in particular for the heavy-duty CNG engines converted from diesel engines. A throttle must be added in the air intake to control the engine power, resulting in a significant efficiency loss (diesel engines do not need a throttle; simply changing the amount of injected fuel results in more or less engine power output). Other efficiency losses arise from suboptimal design related to the following: the spark-ignition system that must be installed in retrofitted diesel bus engines; inappropriate combustion chamber design for its new fuel; the compression ratio being too low in the gasoline engines (natural gas has a much higher octane number than gasoline); low CNG pressures; the extra mass of CNG tanks; and problems with the fuel carburetor/injectors.

There is a lack of specific technical information published about the retrofitted fleet in New Delhi. Therefore, we assumed a 25% fuel efficiency penalty for the bus conversions, which is typical of diesel−CNG conversions described in the literature (*17*). For gasoline−CNG conversion, we assume only 5% fuel efficiency penalty since these vehicles already have spark-ignition and hence do not suffer additional throttling losses (*18*). CNG has a higher hydrogen to carbon ratio than liquid hydrocarbon fuels, so it produces less CO_2 per unit energy released during combustion, and this partially offsets the loss in fuel efficiency from conversion. Average fuel consumption values (expressed as kg per 100 km so that a comparison can be made between liquid and gaseous fuels) and CO_2 emissions factors are given in the Supporting Information (Table S2). CO_2 emissions factors for each vehicle/fuel type have been derived using the assumption that all fuel is completely burned. In reality a small fraction of fuel carbon is emitted in the form of carbon monoxide (CO) and volatile organic compounds. However, CO is ultimately oxidized to CO_2 in the atmosphere, so this source of uncertainty has no impact on the CO_2 emissions factors. We capture the impact of volatile organic compounds through the effect of organic aerosol PM on atmospheric radiative forcing. Net CO_2 emissions factors increase by about 9% after diesel−CNG conversion, but are approximately 8% lower after gasoline−CNG conversion.

Non-CO_2 climate-forcing emissions addressed in this study fall into two categories: (a) methane emissions, from both "evaporative leakage" of natural gas from the CNG vehicles only, and as a component of the exhaust from both liquid-fuel and CNG vehicles; and (b) aerosol emissions (BC, OC, and sulfate) from both liquid-fuel and CNG vehicles. Nitrous oxide (N_2O), another potent greenhouse gas, is not included here because net mass emissions of this species are not appreciably different for diesel vs CNG engines (*19*). Refrigerants in vehicle air-conditioning systems (such as HCFCs) are strongly climate-forcing species, and are problematic if leaked to the atmosphere. However we assume that there is no net change in refrigerant leakage attributable to the fuel-switching policy. Nitrogen oxide (NO_x) emissions can also have an indirect climate forcing impact, via mechanisms that form nitrates, shorten the atmospheric lifetime of CH_4 (both of which cause negative forcing), and the formation of ozone (positive forcing) (*20*). It is unclear therefore whether increased ambient NO_x concentration will lead to increases or decreases in radiative forcing. Further, increases in NO_x directly attributable to the fuel-switch are small (*9*) to negligible (*12*). Consequently, we assume that NO_x changes from fuel switching have a negligible climate impact.

Table 1 summarizes the representative emissions factors for climate-forcing emissions of the three categories of public transportation vehicles (buses, taxis, and autorickshaws) before and after the switch to CNG fueling. In particular, the published CH_4 emissions factors for retrofitted CNG vehicles are highly uncertain. We have chosen to use medium emissions factors for both CH_4 and PM from the range found in the literature, and then explore the implications of varying these emissions across the range of uncertainty. Details on the derivation of emissions factors for CH_4 and aerosols are provided in the Supporting Information (Section S.2.1).

2.2. Global Warming/Cooling Metrics for Climate Forcing Aerosols. Different types of particles in the atmosphere reflect or absorb radiation depending on their optical properties. Light-colored sulfate and organic carbon aerosols reflect solar radiation, which has a cooling effect (*21*). They are also understood to cause indirect cooling, through increased cloud albedo. In contrast, black carbon (BC) particulate matter absorbs light, and consequently warms the atmosphere. In addition to direct and indirect atmospheric radiative forcing effects, black carbon deposited on snow and ice reduces the albedo of the frozen surface, which has been shown to accelerate melting rates (*22*). Recent research has demonstrated that there are regional and global climate impacts of atmospheric black carbon (BC) (*23, 24*), and it has been proposed that control of BC emissions could be an economical means of reducing anthropogenic climate impacts, especially in rapidly industrializing countries (*25–27*).

Tropospheric aerosols are relatively short-lived, and remain in the atmosphere for weeks rather than years. Despite significant uncertainty regarding the climatic effects of aerosols, a number of studies have presented calculations of the global warming potential (GWP) for atmospheric BC. Hansen (*28*) has calculated a GWP for fossil-fuel derived BC of 500, which includes both positive forcing from soot particles, as well as negative forcing (direct and indirect) from coemitted organic carbon (OC). This value compares well with other published values: Bond and Sun calculate a GWP for BC of 680 for the same time horizon, not including the effect of coemitted organic carbon (*25*). There are some lower GWP estimates, for example 90−190 for BC plus OC (*29, 30*), and 120−230 for BC only (*31*). However, these studies tend to underestimate forcing effects (*25, 32*). Although the cooling effect of sulfates and organic carbon has long been recognized (*33*), a GWP-like metric to represent their climatic impact has not yet been developed.

To evaluate the climatic impacts of aerosols with respect to carbon dioxide, we need a value for their *global warming or cooling* potential. For this study, we have estimated the GWP for BC using radiative forcing and atmospheric lifetime information presented in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (*21*). This approach allows us to also estimate a cooling metric for SO_2 and OC, which we refer to as Global Cooling Potential (GCP).

IPCC defines GWP for component i as:

$$GWP_i \equiv \frac{\int_0^{TH} RF_i(t)\,dt}{\int_0^{TH} RF_r(t)\,dt} = \frac{\int_0^{TH} a_i \cdot [C_i(t)]\,dt}{\int_0^{TH} a_r \cdot [C_r(t)]\,dt} \quad (1)$$

where TH is the time horizon (typically set to 100 years), RF_i is the global mean radiative forcing (RF) of component i, a_i is the RF per unit mass increase in atmospheric abundance of component i (radiative efficiency), $C_i(t)$ is the time-dependent abundance of a single unit of i emitted to the atmosphere at $t = 0$. The corresponding quantities for the reference gas (r) are in the denominator. GWPs are normally calculated with CO_2 as the reference gas. Equation 1 is equivalent to:

$$\frac{GWP_i}{GWP_{CO_2}} = \frac{\overline{RF_i}/S_i}{\overline{RF_{CO_2}}/S_{CO_2}} \quad (2)$$

where $\overline{RF_i}$ is the integrated RF contribution (over 100 years) of a single emission pulse of magnitude S_i released at $t = 0$. To calculate GWP/GCP for aerosols, the best estimates for $\overline{RF_i}$ (including indirect effects) are given for the year 2000 in the IPCC's Fourth Assessment Report (*21*), hence S_i is the source strength (Tg year^{-1}) of species i for that year. $\overline{RF_{BC}}$, $\overline{RF_{OC}}$ and $\overline{RF_S}$ are estimated to be 0.26 (0.11 to 0.41) Wm^{2-}, −0.10 (−0.02 to −0.25) Wm^{2-}, and −0.91 (−0.42 to −1.95) Wm^{2-}, respectively for year 2000 global emissions (uncertainty bounds in parentheses after each value). Average source strengths for BC, OC, and SO_2 were obtained from the Aerocom experiment used in the IPCC calculations (*34*), and were approximately 6.32, 32.5, and 100.7 Tg year^{-1} respectively for year 2000 emissions. Carbon dioxide has a RF of 2.40 ± 0.4 Wm^{2-}, and its source strength in 2000 was 26,400 Tg year^{-1}.

Using eq 2, we calculate the mean GWP for BC to be 455 (193−716), which compares well with other estimates. The mean GCPs for SO_2 and OC are calculated as being −100 and −35, respectively. The 95% confidence intervals for the aerosols' GWP/GCPs have been calculated from uncertainties in $\overline{RF_i}$, and are summarized in the Supporting Information (Table S4). The implications of these uncertainties for our results are discussed in Section 3.3.

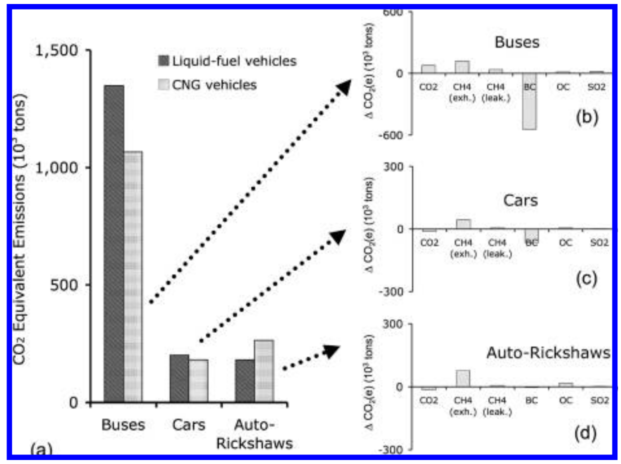

FIGURE 1. Emissions inventories, demonstrating the change in climate-forcing emissions attributable to the switch from diesel- and gasoline-fueled vehicles to CNG vehicles. Units are 10^3 tons of CO_2 equivalent emissions [CO_2(e)]. (a) All climate forcing emissions, including black carbon, particulate organic carbon, and sulfur dioxide (precursor to sulfate particulate) aerosol species, are included. (b)−(d) Change in climate-forcing emissions [ΔCO_2(e)] due to fuel-switching buses, cars, and autorickshaws, respectively. Note that the vertical scale on panel (b) is twice that of panels (c) and (d).

Finally, we note that while there are undoubtedly challenges with using metrics such as GWP/GCP to include aerosols in global climate agreements, a detailed discussion of this topic is outside the scope of this paper. Interested readers should consult Bond (*32*) for an assessment of some of the barriers to more comprehensive climate agreements and arguments to overcome them.

3. Results

3.1. Change in CO_2-Equivalent Emissions. Climate-forcing emissions can all be converted to a common metric, namely units of carbon dioxide equivalent emissions [CO_2(e)]. In this way, a comprehensive assessment of the climatic impacts of the CNG fuel switch can be made that includes all climate-forcing species. CO_2(e) emissions are calculated using the following formula:

$$CO_2(e) = \sum_{V,i} A_V \cdot N_V \cdot EF_{V,i} \cdot P_i \quad (3)$$

where N_V and A_V are the numbers and average activity (km per year per vehicle) of vehicle type V (buses, cars or autorickshaws), $EF_{V,i}$ is the emission factor for emissions species i from an average vehicle of type V, and P_i is the global warming or cooling potential of that species with respect to the reference species, carbon dioxide. CO_2(e) emissions are reported by vehicle and by species, for before and after the switch to CNG fueling, in the Supporting Information (Table S5).

If only carbon dioxide and methane are considered, overall we find that there is approximately a 30% *increase* in conventional greenhouse gases (GHGs) attributable to the switch to CNG fueling in New Delhi. Although we argue that aerosols should be included in the assessment of climate impacts, we start from this point because aerosols are not currently recognized under the Kyoto Protocol. All vehicle categories show an increase in conventional GHGs, in part due to the increase in fuel consumption, but primarily due to exhaust and leakage emissions of methane. However, the inclusion of aerosol emissions has a very important impact on radiative forcing. This is illustrated in Figure 1, which graphically summarizes the results of this study.

Figure 1a represents the results aggregated by vehicle type, and Figure 1b−d illustrate the breakdown of climate-forcing emissions in more detail for buses, cars, and autorickshaws. After conversion to CNG-fueling, buses (Figure 1b) emit more direct CO_2 emissions, and more CO_2(e) due to an increase in CH_4 from almost zero, but the CO_2(e) from BC is very significantly reduced. OC and SO_2 emissions have very little effect on the results. Both cars and autorickshaws (Figure 1b and c) exhibit a reduction in direct CO_2 emissions, due to similar fuel consumption of retrofitted spark-ignition engines and the lower carbon content of methane. The climate impact of postconversion methane emissions is significant for both vehicle types, but more so for autorickshaws because they are likely to be fitted with less high-technology engines. The CO_2(e) reduction attributable to reducing BC emissions from cars is significant and about the same order of magnitude (though with opposite sign) to the impact of methane emissions. Autorickshaws' CO_2(e) emissions are affected by the reduction in BC and OC. The reduction in reflective OC particulate matter reduces its cooling effect, and so actually increases the net CO_2(e) emissions. However, OC is strongly suspected to have important human health impacts (*35*), so its reduction is an important outcome of CNG policy, climate impacts notwithstanding. As with diesel buses, SO_2 has little impact on net CO_2(e) emissions from gasoline cars or autorickshaws.

When aerosol emissions are included, the switch to CNG fueling results in a climate benefit, largely because of the dramatic reduction of black carbon emissions from the diesel bus engines. In total there is about a 10% reduction of net CO_2(e) emissions, and if buses are considered separately, net CO_2(e) emissions are reduced by about 20%. In a similar manner, if cars and autorickshaws are considered as independent subgroups, fuel switching results in a net reduction in CO_2(e) of approximately 10% for cars, and a net increase of about 50% for autorickshaws. In the case of autorickshaws, the net CO_2(e) increase is primarily due to the significantly increased exhaust emissions of unburned methane that occurs when vehicles are converted to run on natural gas. Autorickshaws are a special case, since there was a high proportion of two-stroke gasoline engines prior to conversion, most of which would have been scrapped and replaced with new vehicles. The majority of CNG autorickshaws are assumed to operate on a four-stroke cycle, producing inherently lower mass emissions of particulate matter. Overall, black carbon emissions from diesel buses dominate the aerosols' contribution, and methane emissions from converted vehicles are also very important. The results are very sensitive to uncertainty in these emissions factors. We analyze this further in the following section.

3.2. Uncertainty in Emissions Factors. The results presented above are based on the best data about emissions factors currently available in the literature. The use of average emissions factors (and, indeed, average annual vehicle activity) is a significant simplification of reality, given the enormous variation in vehicle types and conditions. Emissions factors are highly sensitive not only to the engine technology, but also to influences as diverse as driver behavior, vehicle loading, fuel quality, local topography, climatic conditions, and traffic conditions. Ideally, emissions factors would be based on direct measurement of the exhaust from representative vehicles being driven over a realistic drive-cycle, but this information is not generally available for countries outside the Organization for Economic Co-operation and Development (OECD), and even within the OECD, few emissions models use this approach. Consequently, uncertainty in the emissions factors could have considerable impact on our results, namely the change in net CO_2(e) emissions resulting from the CNG switch. This is particularly true for methane emissions factors from the retrofitted buses and particulate matter emissions from preconversion diesel and gasoline vehicles because (i) there is a significant change in the emissions rate of these species, and (ii) the global warming/cooling potentials for these species are high.

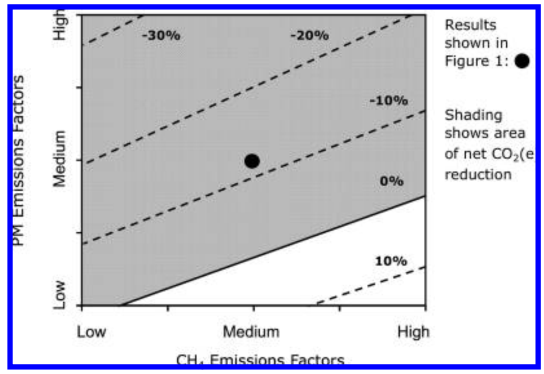

FIGURE 2. Effect on the overall model results (change in net CO_2(e) emissions) when CH_4 and PM emissions factors are varied around the "medium" emissions factors used for the detailed analysis described in Section 3.1 (indicated here by the black point in the center of the figure). The *x* and *y* axes refer to CH_4 and PM emissions factors respectively. The contours on the graph indicate the percentage change in CO_2(e) after the CNG switch, for the range of CH_4 and PM emissions factors tested ("low", "medium", and "high" values), and the shading shows the area of net climate benefit (CO_2(e) reduction).

We have investigated the sensitivity of our model results (the change in net CO_2(e) emissions) to variation in the CH_4 and PM emissions factors inputs, as shown in Figure 2. The range of uncertainty in these emissions factors was estimated to be on the order of factor of 3. For the diesel buses, "low", "medium", and "high" PM emissions factors corresponded to 1.0, 2.0, and 3.0 g/km of total PM respectively (76% of PM from buses was assumed to be BC and the remainder OC). The "low", "medium", and "high" CH_4 emissions factors for the retrofitted CNG buses corresponded to 3.0, 6.5, and 10.0 g/km of CH_4, respectively. The range of emissions factors tested for cars and autorickshaws was scaled proportionally to the range of values for buses. The results of this analysis indicate that there is more likely to be a net reduction in CO_2(e) emissions. The shaded area in Figure 2 is 85% of the total area, indicating that a net reduction is 5 times more likely than a net increase (unshaded area) once uncertainties in aerosol emissions are accounted for. This supports our conclusion that there may be significant climate benefits of switching to CNG fueling when the aerosol forcing effect is included in the calculations. Furthermore, if PM emissions from the old diesel engines are in fact "medium" or "high", then there is a net climate benefit of the fuel-switch, no matter what the CH_4 emissions factors are.

3.3. Uncertainty in GWP/GCP. There is an ongoing debate about the influence of various parametric and other uncertainties on GWP values of the major non-CO_2 greenhouse gases (*27, 36, 37*). However, under the Kyoto protocol CO_2 equivalence is established using a single representative value for the GWP (100 year horizon) of the non-CO_2 greenhouse gases, which is the approach we take in this paper. The impact of uncertainties in GWP/GCP of aerosols was investigated, and it was found that its effect on our results depends directly on the net annual emissions of each aerosol species. For cooling aerosols (OC and SO_2) the net emissions from public transportation vehicles are small when compared to emissions of CO_2, BC, and CH_4 emissions. Consequently, even large uncertainties in the GCP of OC and SO_2 (resulting primarily from indirect forcing effects of the cloud-albedo feedback) have little impact on our conclusion. Uncertainties

TABLE 2. Net Present Value of Carbon Credits Due to Replacing Retrofitted CNG Engines with New (or Improved) CNG Engines. Two Mitigation Options are Shown, Corresponding to 45% and 100% Reduction in CH_4 Emissions Factors, Respectively

change in CH_4 emissions factors	buses	cars	autorickshaws
45% reduction	$1463	$313	$121
100% reduction (i.e., negligible CH_4)	$2716	$580	$225

[a] Emissions reduction over vehicle lifetime (lifetime is assumed to be 20, 15, and 12 years for buses, cars, and autorickshaws, respectively); 1 ton CO_2(e) is valued at U.S. $20 (current dollars), and this value is assumed to increase by 5% per year (to $51 in year 20); discount rate is 10%.

in the GWP of BC are more important. To examine their effect we replicated the sensitivity analysis (described in Section 3.2) using the lower (GWP = 193) and upper (GWP = 716) 95% confidence bounds. For the lower bound GWP value for BC, net reductions are possible only when emission factors for BC are "medium" or greater and when the CH_4 emissions factor is lower than "medium". For the upper bound of GWP = 716, net reductions of CO_2(e) emissions occur almost independent of the either set of emission factors (see Figure S1 in the Supporting Information).

4. Discussion

Our analysis demonstrates that the Indian Supreme Court-mandated policy to switch New Delhi's public transportation to CNG fueling in 2002 resulted in a very substantial increase in CO_2 and CH_4 emissions. However, in light of recent research about the climatic impacts of atmospheric aerosols, we argue that it is essential to consider particulate matter emissions in the assessment of this policy. We find that the fuel-switching policy resulted in a dramatic reduction in BC emissions from buses. Therefore, when we include aerosols, the climate impact results change from "strong positive forcing" to "neutral/strong negative forcing". Sulfates and organic carbon from diesels and gasoline vehicles have a global cooling effect, although the magnitude of their impact relative to BC is small. Our findings confirm the assertion by Bond and Sun (*25*) and others that addressing BC emissions from public transport is likely to be a promising way to reduce climate interference.

Methane emissions factors from the retrofitted vehicles figure prominently in net climate forcing calculations, so emissions of methane from CNG vehicles may also provide a near-term opportunity for reducing climate interference. The potential benefit of methane reduction can be understood by referring back to Figure 2: a reduction in methane emissions factors is equivalent to reducing uncertainty and finding that they are "low" rather than "medium". The net climate benefit would increase to 20% from 10%. Tailpipe methane emissions are not regulated in many jurisdictions, so there is little incentive for engine technology providers to target reductions in the amount of methane emitted in the exhaust. Consequently, there may be an opportunity to further reduce the climate impacts of fuel switching by stipulating reasonable emissions levels for methane from CNG vehicles. Inspection and maintenance programs are one way of ensuring that all engines are tuned for low emissions, but such programs can be expensive and administratively challenging. Another possibility would be to ensure all retrofitted vehicles are equipped with three-way catalytic converters, which reduce emissions of NO_x and CO as well as CH_4, but retrofitted catalysts have durability issues on older engines. Replacing the current standard of retrofitted engines with entirely new CNG engines (or improved retrofits) may represent an opportunity for emissions reduction, and may be fundable under the UN Framework Convention on Climate Change (UNFCCC) Clean Development Mechanism (CDM). Such reductions would meet the additionality criteria and would be an easily verifiable source of carbon credits, although BC reductions would not be admissible under current CDM rules (*38*). In Table 2 we show the value of carbon credits for two levels of improvement in methane emissions from CNG vehicles, assuming the base case emissions factors are those used in this study: the "100% reduction" case refers to a reduction of methane emissions in the exhaust to levels that are negligible from a climate perspective, which is possible using state of the art CNG engine technology but may not be viable in rapidly industrializing countries due to high cost. For the scenario where a 45% reduction below original methane emissions factors is realized (achievable using readily available technology), the net present value of reduced CO_2(e) emissions over the vehicles' lifetimes is approximately US$1463 per bus, US$313 per car and US$121 per autorickshaw, assuming a value per ton of CO_2(e) that starts at $20 and grows annually by 5%, and a discount rate of 10%. It is clear there are substantial economic incentives to reduce methane tailpipe emissions by optimizing CNG engine design to meet low methane emission criteria. The estimated value of these carbon credits is sufficient to justify further investigation into the cost of CNG-engine upgrades and applicability to the CDM.

There are some lessons that may be drawn from the Delhi case for similar fuel-switching projects. First, buses (and other heavy-duty diesel vehicles) are more important than the other vehicle types to convert; this is because they emit significant BC compared to gasoline vehicles, and BC has adverse impacts from both health and climate perspectives. Second, since eliminating OC from two-stroke engines may have substantial health impacts, switching to CNG in 2-stroke autorickshaws may also be highly beneficial. Finally, exhaust methane emissions are very important contributors to climate forcing from CNG vehicle operation, so regulation of tailpipe methane emissions from new or retrofitted CNG vehicles would go a long way toward reducing their climate impact.

More generally, there is an emerging literature on the tradeoffs between local and global benefits from fuel switching (*6, 39, 40*). Here we add to that literature by demonstrating that the climate impacts of policies put in place for reasons other than the climate need to be characterized, especially in rapidly industrializing countries where climate mitigation is not currently being implemented. The climate benefits of nonclimate policies can be substantial, especially when aerosol emissions are included.

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Supporting Information Available

Additional details about the public transportation fleet in New Delhi, emissions factors, and the role of uncertainties in climate forcing due to black carbon. This information is available free of charge via the Internet at http://pubs.acs.org.

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