CNG Conversion of Motor Vehicles in Dhaka: Valuation of the Co-benefits

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Abstract

The air quality in Dhaka is one of worst in the world and motor vehicles are one of the major polluters. Petroleum fuels used in motor vehicles are also a major source of greenhouse gas emissions in the city. There have been some recent initiatives that alleviate the local air pollution in the city, among other objectives, although there were no formal estimates for the benefits that can be achieved from the policy. This paper quantifies ex-post the social benefits due to the government initiative that led to widespread conversion of petroleum motor vehicles to CNG vehicles. Since CNG conversion policies can have important implications on GHG emissions, impact on GHG emissions is also considered. An impact-pathway model has been developed to relate the changes in emissions resulting from the policy to changes in ambient air quality and resulting number of avoided premature deaths. It is estimated that around 6,000 premature deaths were avoided in Dhaka in 2009 because of the switch from petroleum to CNG vehicles. This amounts to a saving of USD 1.15 billion in 2009, which is around 1.3% of the GDP of the country. For climate benefits, impacts of black carbon, organic carbon and SO_2 have been considered, in addition to the traditional GHGs- CO_2 and methane. Global warming factors were considered to normalize the effect of these global pollutants. Although CNG conversion was detrimental from climate change perspective using the changes in CO_2 and methane only (methane emissions increased), after considering all the global pollutants (especially reduction in black carbon) the conversion strategy was beneficial. Considering the damage costs of CO_2, we find a benefit of around USD 0.6 million in year 2009, which is small as compared to the health benefits. Even if the value of statistical life is one-tenth of what assumed here, local air pollution benefits outweigh climate change benefits by 100 to 1. This indicates that such policies can and should be undertaken on the grounds of improving air pollution alone.

CNG Conversion of Motor Vehicles in Dhaka: Valuation of the Co-benefits

Zia Wadud, Tanzila Khan

1. Introduction

Road transportation, especially motor vehicles, is a major source of air pollution in all large cities of the world. Extensive research linked motor vehicle induced air pollution to premature mortality in the developed world (Small and Kazimi 1995, McCubbin and Delucchi 1999 in the USA, Kunzli et al. 2000 in Europe, BTRE 2005 in Australia, etc.) as well as in the developing world (e.g. Delhi, Chattopadhyaya 2009). On top of it, motor vehicles are also a major source of carbon emissions, a potent greenhouse gas (GHG), adversely affecting the climate system. In the developed countries, local air pollution from motor vehicles has received attention decades ago, and the problem is alleviating (or at least not aggravating significantly) because of the various policy measures taken. The major concern now is the control of GHG emissions from the road transport sector. The situation is the opposite in many developing countries where local air quality is worsening, primarily because of increasing motor vehicle ownership resulting from a high economic growth and relatively lax emissions control. While, GHG emissions are also increasing and is of some concern, the priority to the policy makers in these countries or cities is reducing local pollutants from the motor vehicles in order to reduce adverse health impacts.

Dhaka, the capital of Bangladesh, has a poor air quality (one of the worst in the world, Gurjar et al. 2008), and a significant portion of the local air pollutants are generated from its motor vehicles. Local air pollution has recently been recognized as a major health hazard for the residents in Dhaka and various policy measures have been taken to reduce emissions. It is, however, important to understand the environmental, climate and economic benefits or costs of these policy measures to curtailing emissions. Without such an analysis, it is impossible for policy makers to make informed decisions, and often the choice of policy tools becomes an ad-hoc decision. Yet, at present, there are no models available in Bangladesh to carry out such an integrated analysis of health, climate and associated economic benefits from a policy intervention. Therefore, there is a dire need for such an integrated policy analysis tool to help the policy makers in informed decision making.

Developing a generic policy analysis tool for air pollution or GHG mitigation strategies is a challenging task, especially in a developing country like Bangladesh, where the lack of extensive and reliable data is a perennial problem. Therefore we narrow down our scope to modeling the aggregate impact of one specific policy measure that has already been implemented in the country:

converting the petroleum vehicles to Compressed Natural Gas (CNG) vehicles. This paper presents the findings of an ex-post evaluation of local air pollution and GHG related benefits that can be attributed to the policy as applied to Dhaka city. The model developed for the specific policy still has most of the components required for a generic model, but at a simpler form and coarser resolution, and will provide us with an understanding of the data and capacity requirements to develop a larger model to evaluate other policy options to improve the air quality in Dhaka city. The research also acts as a first demonstration in Bangladesh of the capabilities of such an integrated model in valuing air pollution and climate benefits resulting from a policy intervention.

The paper is organized as follows. Section 2 presents the background information on Dhaka city and policy initiatives. Section 3 describes the modeling approach to model health and climate benefits from policy interventions and the model components. Sections 4 and 5, describes the individual components along with results for health and climate benefits. Section 6 presents the uncertainties while section 7 discusses the results. Section 9 draws conclusions.

2. Background

Bangladesh is a low-income country with per capita GDP of around USD 550 (current dollar) in 2007, yet the growth rate is above 6% (Bangladesh Bureau of Statistics, BBS 2009a). Dhaka, the capital of the country, is one of the most populous and densely populated cities in the world with a population of 12.3 million in 2007 (BBS 2009a). Until recently, there was a lack of (or too lax) emissions standards for industries or motor vehicles in Bangladesh and Dhaka. Even when emissions standards exist, enforcement of these standards is also poor. The city is also surrounded by brick fields which use coal for burning bricks. All these made Dhaka's air one of the most polluted in the world. Gurjar et al. (2008) finds Dhaka to be ranked 3rdin terms of the highest Total Suspended Solids (TSP) concentration. Considering the impact of other pollutants, Dhaka is ranked the worst of all (Gurjar et al. 2008). The situation has been further deteriorating as a result of economic growth, with corresponding prosperity and increases in vehicle ownership, resulting in congested roads and higher vehicle emissions. A recent estimate concluded that air pollution in Dhaka alone can be related to about 15,000 premature deaths a year (IRIN 2009).

Responses to controlling the air pollution have not been quick enough. Monitoring ambient air quality at the government level started only recently, with four continuous monitoring stations set up in 2002 in Dhaka, Chittagong, Khulna and Rajshahi. However, recently some policy initiatives have been undertaken in order to improve the air quality of Dhaka, and in some cases, for the whole country. Leaded fuel was banned in the country in 1999, thus effectively reducing the lead content in the air. Emissions standards for motor vehicles were tightened in 2002, but these standards are still relatively relaxed as compared to the developed countries (even as compared to China or India). Initiatives to regulate emissions from brick field were undertaken. One major initiative that visibly improved the air quality was banning the two stroke three wheeler autorickshaws, from Dhaka on January 1, 2003. Vehicles older than 20 years of age were also banned from the city during the same period.

CNG as an automobile fuel was first introduced in Dhaka in 1995 (Rupantorito Prakritik Gas Company Limited, RPGCL 2009), although it did not gain a momentum initially. Use of CNG for petroleum vehicles had dual advantages for Bangladesh. Firstly, CNG is an indigenous resource, thereby it has the potential to save foreign currency that would otherwise be used to import petroleum for the transport sector. Secondly, the particulate emissions from CNG vehicles are much lower than corresponding petrol or diesel vehicle, helping improve the air quality (Kremer 1999). Accordingly the government made conscious attempts to increase the use of CNG in transportation. The CNG industry got some momentum during early 2000 when CNG run taxis were introduced in Dhaka city. Replacing the old two-stroke petrol run autorickshaws with 9,000 new CNG run autorickshaws also helped the industry gain a critical mass, especially to expand the CNG refueling network. At the same time the government instructed mandatory retrofitting of all government vehicles with CNG conversion kits. The government also encouraged the conversion of private vehicles by making several policy initiatives, e.g. by exempting import duty on CNG conversion kits and CNG storage cylinders, by increasing the prices of petroleum fuel (which were subsidized before), etc. All these initiatives led other vehicles (private cars, SUV’s, minibuses, buses) to gradually switch to CNG from petroleum. Although the air pollution improvement was one of the reasons for the switch, the associated benefits accruing to society because of the policy were not measured. In addition, the CNG conversion can have implications in GHG emissions. Converting petroleum vehicles to CNG results in reduced black carbon emissions, which has positive impact on climate change. On the other hand, the conversion can result in an increase in methane emissions, or reduction in SO_2 emissions, both of which can have an adverse impact on the climate system. We therefore focus on an ex-post analysis of these benefits (or costs) that can be attributed to CNG conversion of motor vehicles.

3. Modeling the Impact of Policy Intervention

This study concerns two different types of pollution, with different types of impacts. Local air pollution primarily affects health and wellbeing of the people within the city, whereas GHG emissions impact is global, through the changes in the climate system. This results in two different approaches to monetizing the impacts of intervention through CNG conversion.

In determining the benefits of a policy intervention to improve the local air quality, the reduction in emissions is linked with well defined improvements in damage end points and associated benefits through the impact-pathway approach, described graphically in Fig. 1 (European Commission 2003, ExternE 2005). The first step in an impact-pathway approach is to quantify the emissions (or changes in emissions for a policy intervention), which can be determined from a vehicle emissions inventory model for our current policy case. The changes in modeled emissions are then fed into an air quality model in order to determine the changes in ambient air quality (i.e. pollutant concentration) to which people are exposed. In the third step the modeled improvements in ambient air quality is coupled with population distribution and epidemiological concentration-response (CR) functions of the health impacts to determine the avoided health impacts of different types. Each of these health cases are then valued using the cost savings associated with those specific health impacts or willingness to pay to avoid those health cases (see Fig. 1) to determine the avoided costs, or benefits, of the policy intervention. The European Commission (2003) and United Stated Environmental Protection Agency (USEPA 2007) follow this approach for their regulatory impact analyses.

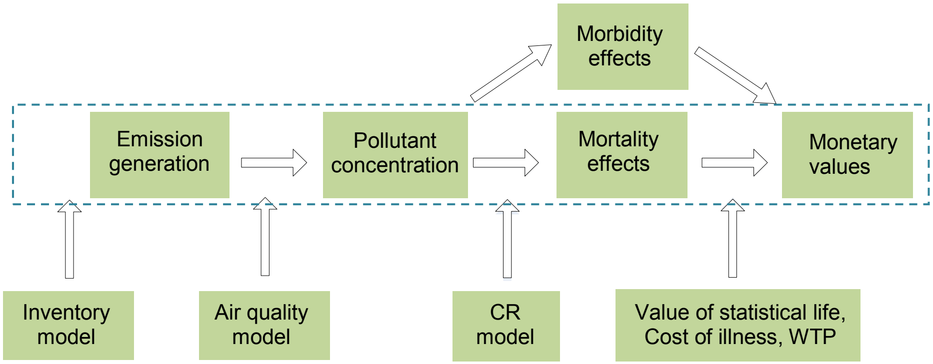

Fig. 1 Impact Pathway approach for air quality related premature deaths

Methods for determining the climate change benefits or costs from a policy intervention follow a different path. Since the changes in GHG emissions will generally be small in such a policy as considered in this study, a full scale impact pathway model coupled with climate and impact models will possibly not be able to pick up any differences. Also, unlike the impact pathway models above, modeling the changes in climate due to changes in emissions and modeling the corresponding damages is a challenging task, requiring large and specialized resources (e.g. damages due to climate change may include crop losses, coastal inundation, increased flooding, increased cyclones, increased diseases etc., each of which requires separate, extensive damage models). Impact of different GHGs on radiative forcing balance and thus climate is also different. However, it is possible to normalize the changes in emissions (from the emissions inventory model) of different GHGs due to the policy using global warming potentials (UNFCCC 2010, Reynolds and Kandlikar, 2008) and then use the market price of carbon, or social costs of a ton of carbon emission to determine the monetized benefits of avoided damages.

4. Local Air Quality Benefits

The primary local benefits of CNG conversion is the reduced emissions and reduced adverse health impacts. Studies modeling the health impacts of air pollution in the developed countries have found that the majority of the health impacts can be attributed to particulate matters, especially those with a diameter less than 2.5 µm, known as $PM_{2.5}$ (USEPA 2004 for a synthesis). Although $PM_{2.5}$ (or other local air pollutants) can have different effects on health(e.g. increase in mortality, asthma or respiratory troubles, eye irritation etc.) monetized health costs of air pollution are dominated by the premature mortality costs due to exposure to $PM_{2.5}$ (typically 85% to 95% of total health costs, USEPA 2007). We therefore focus on the reduced mortality impacts due to reduced $PM_{2.5}$ emissions arising from the policy (the dashed box in Fig. 1). The significant challenge lies in collecting all the relevant the data, especially in the context of a developing country like Bangladesh. We therefore have to simplify the underlying modeling techniques for different segments of our model.

4.1 Emissions inventory

A comprehensive and reliable emissions inventory from all emissions sources in Dhaka city is not available from a unified government source.[1] Therefore we have to model the emissions inventory from vehicles following the well known formulae:

$$Emissions_{i} = \sum_{j}\sum_{k} N_{jk} \times A_{jk} \times EF_{ijk} \qquad (1)$$

Where, N refers to number of vehicles, A activity of those vehicles per day, EF respective emission factors and subscripts i, j and k refer to pollutant type, vehicle type and fuel type respectively. Data on the number of vehicles registered in Dhaka roads are available from Bangladesh Road Transport Authority (BRTA 2010). However, fuel wise distribution is not available, for which we made some

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[1] There is currently an initiative ongoing at the Department of Environment, under the Government of Bangladesh to generate an emissions inventory for the whole country. A source apportionment study shows that the major sources of anthropogenic ambient $PM_{2.5}$ are motor vehicles (47~50%) and nearby brick kilns (3~12%), (Begum et al. 2007), but no estimate for source wise inventory is available.

reasonable assumptions. . Due to a lack of systematic emissions testing data for vehicles in Bangladesh, we turn to international literature for the emissions factors for different vehicle classes and fuel type. We use emissions factors primarily from Urbanemissions (2009), which has a focus on South Asian countries, with some modification. We correct the emissions factors to include the impact of the super-emitting vehicles using Bond et al. (2004). The proportions of super emitting vehicles for different vehicle classes were taken from Rouf et al. (2008) and Reynolds and Kandlikar (2008). Vehicle activity for different vehicles types and fuel types are determined from a field survey of sample vehicles and cross-checked with Khaliquzzaman (2006), which was based on subjective judgment. (Table 1). We determine the vehicle emissions inventory for year 2009 (most recent year for which vehicle stock data is available) for the base case, i.e. assuming no vehicles have been converted to CNG. Note that we are not considering the emissions benefits attributable to CNG conversion of autorickshaws, which happened earlier within a very brief period.

Table 1. Motor vehicle emissions inventory in 2009 and emissions if there were no CNG conversion

Vehicle types	Original fuel	Number of vehicles			Vehicle activity (km/day)	Emission factor (g/km PM_{10})	Total PM_{10} emissions (kg/day)	
		No policy	After CNG conversion				No policy	Current case
			CNG	Other fuel				
Motor cars	Petrol	147283	75323	71960	40	0.13	740	512
SUV/station wagons	Petrol[1]	29304	22160	7144[2]	40	0.14	2399	1741
SUV/station wagons	Diesel[1]	29304	7864[2]	21440	60	1.27		
Taxis	CNG	12000	12000	-	130	0.05	78	78
Buses	Diesel	8210	1052	7158	130	2.37	2534	2212
Minibuses	Diesel	8317	936	7381	130	2.24	2421	2155
Trucks	Diesel	30015	-	30015	60	2.82	5076	5076
Autorickshaws	CNG	14820	14820	-	130	0.10	193	193
Motor cycle	Petrol	219443	-	219443	30	0.10	658	658
Others	Petrol[1]	14953	-	14953	40	0.14	1224	1224
Others	Diesel[1]	14953	-	14953	60	1.27		
Total							15323	13849

[1] assumed a 50-50 split between petrol and diesel. [2] assumed three-fourths of the conversions were for petrol vehicles. A recent ongoing survey indicates even larger proportion is for petrol vehicles.

The number of vehicles that have been converted from petroleum to CNG is obtained from RPGCL (2009), which reports that around 134,000 CNG vehicles plied on the streets of Dhaka in 2009 (Table 1). This represents a conversion rate of around 43% (not including motorcycles in total). Emission factor for PM_{10} from the CNG vehicles was 0.05 g/km, except for bus (0.02 g/km since there are dedicated CNG buses with lower emissions) and auto-rickshaws. We find that the existing PM_{10} emissions from the motor vehicles are 13,849 kg/day, which would have been 15,323 kg/day if the CNG conversion were not encouraged. This represents a direct PM_{10} reduction of 9.6% as a result of the policy initiative. We also assume that the $PM_{2.5}$ to PM_{10} ratio from exhaust emissions remains the same. Thus around 9.6% reductions in PM_{10} and therefore $PM_{2.5}$ emissions can be attributed to the policy.

4.2 Air Quality Model

In order to relate the changes in emissions above to changes in ambient concentration, we follow a simple linear roll back model, since there is no state of the art air quality model calibrated for Dhaka or Bangladesh. For the linear roll back model,

$$\frac{\Delta c}{c} = \kappa . \frac{\Delta Emissions}{Emissions} \qquad (2)$$

where c and Δc represent concentration and change in concentration of the ambient pollutant (here $PM_{2.5}$) respectively. We make use of an earlier policy intervention and its impact on air quality in Dhaka to test the value of κ. On January 1, 2003, all petrol powered two stroke three wheeler autorickshaws (29,000 in total) were banned from Dhaka, and were replaced by 9,000 four stroke CNG autorickshaws. Begum et al. (2006) find a 40.9% reduction in $PM_{2.2}$ concentration immediately after the ban (from 88.5 $\mu g/m^3$ and 52.3 $\mu g/m^3$). We can relate the changes in $PM_{2.2}$ concentration to the 40% reduction in PM_{10} emissions inventory (from 10,260 kg/day to 6,155 kg/day) due to the policy intervention assuming fine particle emissions were reduced by the same proportion. This results in a $\kappa \approx 1.0$, which is also the value generally used in linear roll back models. Assuming the reduction in $PM_{2.5}$ is in the same proportions as in PM_{10}, a 9.6% reduction in $PM_{2.5}$ emissions results in a 9.6% reduction in ambient concentration.

In 2007, the only Continuous Air Monitoring Station in Dhaka registered a 24-hour average annual $PM_{2.5}$ concentration of 109 $\mu g/m^3$ (Department of Environment 2007). In the absence of the CNG conversion policy, the annual average $PM_{2.5}$ would have been 120.6 $\mu g/m^3$. Thus an improvement of 11.6 $\mu g/m^3$ can be attributed to the policy.

4.3 Modeling Premature Mortality

The effect of ambient $PM_{2.5}$ on premature deaths has been well established in literature (USEPA 2004, IEc 2006, Pope and Dockery 2006). CR functions for premature mortality (increases in premature mortality due to an increase in the ambient concentration) for a short term but acute exposure to $PM_{2.5}$ have long been available but recent studies show that CR functions due to a continued exposure to $PM_{2.5}$ are almost an order of magnitude higher than those for short term exposure (Dockery et al. 1993, Pope et al. 2002, Krewski et al. 2000, Laden et al. 2006, Pope and Dockery 2006). These CR functions, along with the changes in ambient concentration of $PM_{2.5}$ from the air quality model, existing mortality rate and population allows the estimation of avoided premature deaths attributable to the conversion of motor vehicles to CNG:

$$Deaths\ avoided = \Delta c \times CR \times mortality\ rate \times population \tag{3}$$

CR functions for increases in all cause mortality are generally used in modeling policy interventions (USEPA 2005, USEPA 2007, Kunzli et al. 2000). But since the causes of deaths vary significantly between the developed countries and developing countries (Cropper and Simon 1996), we employ cause-specific CR functions with cause-specific mortality rates for Bangladesh. We follow Kunzli et al.'s (2000) 'at least' approach and accordingly employ Pope et al.'s (2002) CR functions, which is lower than Dockery et al. (1993) or Laden et al. (2006). These CR functions stipulate 9.3% and 13.5% increases in mortality risks due to cardiovascular and respiratory diseases for every 10 μg/m^3 increases in the ambient PM$_{2.5}$ concentration. Thus, mortality rate would have been 11% and 16% higher from cardiovascular and respiratory diseases in Dhaka had the conversion not taken place.

We use WHO (2009) and BBS (2009b) to calculate the mortality risks of 5.36 and 3.4 per thousand adults (above the age of 30) from cardiovascular and respiratory diseases. Population in Dhaka metropolitan area in 2009 was around 13 million (estimated from BBS 2009a) of which the adults above 30 was 4.67 million. This results in 6,000 premature deaths avoided in Dhaka in 2009 alone due to the air quality improvements resulting from the conversion to CNG.

4.4 Valuation of Reduced Mortality Risks

The most common approach to determine monetary benefits due to avoided deaths is to use a Value of Statistical Life (VSL)[2], defined as the amount people are willing to pay (accept) to reduce (increase) the mortality risks (probability of death) they face. Although the VSL approach has its critics,[3] USEPA (2005, 2007) uses this approach. Health benefits are calculated as:

$$Health\ \ benefits = Deaths\ avoided \times VSL \tag{4}$$

VSL is a widely researched area with over hundreds of studies published, although estimates for developing countries are not as frequent. The published estimates also vary widely (see Viscusi and Aldi 2003 for a review). Krupnick (2006), on the other hand, find that the willingness to pay to reduce health risks are around USD 1 million for China, similar to those in developed countries when

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[2] More technically, VSL is the marginal rate of substitution between an individual's wealth and mortality risk Hammit 2007).

[3] Leskell and Rabl (2001) recommend using Loss of Life Expectancy (LLE) for valuing premature mortality due to long term exposure to PM$_{2.5}$. This approach is more popular in Europe, although there are large uncertainties in valuing a life-year.

estimated using the same techniques (contingent valuation) and corrected for purchasing power parity (PPP). Using a literature survey and income elasticity of VSL of 0.55 (Viscusi and Aldi 2003), we use a median VSL of USD 190,000 for Bangladesh, which is equivalent to BDT 13 million.

The total benefit of the 6,000 avoided premature deaths in year 2009 is BDT 78.5 billion or USD 1.15 billion. This represents a benefit of 1.3% of the GDP of the country in 2009.

5. Global Climate Change Benefits

As mentioned earlier, our climate change benefits model follows slightly different approach. While relevant emissions are required from the emissions inventory model as before, these emissions have different impacts through different global warming or cooling potentials. Also, some of the emissions may have beneficial impacts, so reducing these emissions can result in a negative impact. The following sections describe the benefits valuation model for climate change impacts resulting from the change in the emissions of the global pollutants.

5.1 Emissions Inventory

The emissions inventory model for climate change impacts is similar to the one in our local air quality model above. The pollutants, however, are different. Among motor vehicle emissions, CO_2 and CH_4 are established GHG, contributing directly to global warming (UNFCCC 2010). However, recent studies (Reynolds and Kandlikar, 2008) show aerosols such as sulphates (SO_2), black carbon (BC) and organic carbon (OC) can also have important influence on the earth's radiation balance and thus global climate. Black and organic carbons are the primary components of $PM_{2.5}$ of which black carbon has a potentially large impact on warming (Bond et al. 2004). On the other hand SO_2 (precursor to sulphates) and organic carbon have cooling effects on the climate through facilitating the formation of aerosols (Reynolds and Kandlikar 2008). Although NO_x emissions can also have an impact on global warming through secondary effects (formation of nitrates, shortening lives of CH_4 - both of which have a cooling effect, or formation of Ozone- which has a warming effect), we assume, following Reynolds and Kandlikar (2008) that NO_x changes from fuel switching have a negligible climate impact. We therefore concentrate on five global emissions (CO_2, CH_4, SO_2, black carbon, organic carbon) before and after the conversion of the vehicles.

Since there are no vehicle emissions testing program in the country, once again we turn to literature for the emissions factors. Exhaust emissions factors for SO_2 come from Urbanemissions (2010), which has a special focus on the south Asian region. We believe the CO_2 emissions factors from SUV/station wagons are on the higher side, therefore modify their emissions factors. As per Reynolds and Kandlikar (2008), we assume a 5% fuel economy penalty (but a net carbon benefits) for emissions of CNG vehicles converted from petrol, whereas for conversions from diesel, we assume a 25% fuel economy penalty (and smaller net carbon penalty). The emissions factors are given in Table 2.

Table 2. GHG, aerosol (or precursors) emission factors used in this study

Vehicle types	fuel	Emission Factors (gm/km)				
		CO_2	CH_4	SO_2	BC	OC
Motor cars	Petrol	258	0.14	0.07	0.04	0.04
Motor cars	CNG	237	2.53	0	0.01	0.03
SUV/station wagons	Petrol	331	0.14	0.07	0.03	0.03
SUV/station wagons	Diesel	332.5	0.14	0.3	0.72	0.23
SUV/station wagons	CNG-Diesel	363	2.53	0	0.01	0.03
SUV/station wagons	CNG-petrol	304	2.53	0	0.01	0.03
Taxis	CNG	237	2.53	0	0.01	0.03
Buses	Diesel	887	0.06	1	1.35	0.43
Buses	CNG	968	8.49	0	0.005	0.013
Minibuses	Diesel	665	0.06	1	1.28	0.40
Minibuses	CNG	726	8.49	0	0.01	0.03
Trucks	Diesel	887	0.06	1	1.60	0.51
Autorickshaws	CNG	75	1.41	0	0.02	0.07
Motor cycle	Petrol	40	0.08	0.02	0.03	0.03
Others	Petrol	331	0.14	0.07	0.03	0.03
Others	Diesel	332.5	0.14	0.3	0.72	0.23

Methane emissions are not available in urbanemissions, we therefore use Reynolds and Kandlikar (2008). In addition to the unburnt Methane emissions through the exhaust, Methane can escape during fueling as well as through leaks of the retrofitted vehicles. Since Methane is a more potent GHG than CO_2, leaked Methane can have a large impact on warming. We therefore add the Methane leakage emissions from Reynolds and Kandlikar (2008) to the exhaust methane emissions above.

Black carbon and organic carbon emissions are emitted as part of particulate matter. For emissions inventory, they are calculated as:

$$BC(OC) = PM_{10} \times \frac{PM_{1.0}}{PM_{10}} \times \frac{BC(OC)}{PM_{1.0}} \tag{5}$$

The fractions $PM_{1.0}/PM_{10}$, $BC/PM_{1.0}$ and $OC/PM_{1.0}$ depend may depend on vehicle and environmental characteristics such as vehicle type, combustion technology, fuel type, operating conditions. In the absence of Bangladesh or Dhaka specific information on these, we use Bond et al. (2004) to get the values of these factors for different vehicle and fuel types (petrol and diesel). Generally, the BC to $PM_{1.0}$ fraction is 0.66 in diesel vehicles and 0.34 for gasoline vehicles. The OC to $PM_{1.0}$ ratio is 0.21 for diesel and 0.36 for petrol vehicles. The ratio of $PM_{1.0}$ to PM_{10} is 0.86 for diesel and 0.85 for petrol vehicles. For PM_{10} emissions factors for different vehicle and fuel types, we use urbanemissions information as in Table 1, which incorporates corrections for the super-emitter fraction of the vehicles. Emission factors of black and organic carbon for CNG (as fractions of $PM_{2.5}$) are derived from Reynolds & Kandlikar (2008), assuming black and organic carbon constitute the entire $PM_{2.5}$. Again, this requires information on the ratio of $PM_{2.5}$ to PM_{10}, which is taken as 0.90 (Cadle et.al., 1999).

The emission factors used in this study are presented in Table 2. Changes in emissions inventory attributable to the conversion for different vehicle types for CO_2, methane, BC, OC, and SO_2 are presented in Table 3. There is a net reduction in CO_2 emissions but an increase in CH_4 emissions. Although there is a carbon penalty for conversion from diesel to CNG in our emissions factor, the benefits for conversion from petrol vehicles govern due to a larger frequency of conversion for petrol vehicles. CH_4 emissions are also set to increase because previously there were no (or negligible) CH_4 methane leakage emissions from the vehicles. SO_2, BC and OC all decrease, by 12.43%, 9.38% and 6.68% respectively, over pre-conversion emissions. The greatest reduction of BC is due to the conversion of rather small number of diesel vehicles to CNG, since diesel vehicles emit more particulates (and therefore more BC as well).

Table 3. Changes in GHG and aerosol (or precursors) emissions attributable to CNG conversion

Vehicle types	Changes in emission, kg/day (% changes)				
	CO_2	CH_4	SO_2	BC	OC
Motor cars	-63271.32(4.16)	7200.88(873.06))	-210.90(-51.14)	-75.59(-35.31)	-13.89(-6.15)
SUV/station wagons	-9541.68(0.98)	3246.19(791.26)	-203.6(-33.40)	-348.76(-26.93)	-89.02(-20.35)
Taxis	0(0)	0(0)	0(0)	0(0)	0(0)
Buses	11077.56(1.17)	1152.89(1800.32)	-136.76(-12.81)	-184.19(-12.76)	-56.91(-12.44)
Minibuses	7422.48(1.03)	1025.76(1581.19)	-121.7(11.25)	-153.78(-11.15)	-45.65(-10.45)
Trucks	0(0)	0(0)	0(0)	0(0)	0(0)
Autorickshaws	0(0)	0(0)	0(0)	0(0)	0(0)
Motor cycle	0(0)	0(0)	0(0)	0(0)	0(0)
Others	0(0)	0(0)	0(0)	0(0)	0(0)
Total	-54312.96(-0.77)	12625.72(142.32)	-672.94(-12.43)	-762.33(-9.38)	-205.46(-6.68)

5.2 Valuation of GHG emissions

The impact per unit of different global pollutants calculated above is not the same. We use the 100 year global warming potentials of each of these pollutants to normalize them to an equivalent scale. The normalization allows us to use a common metric, CO_2 equivalent emissions, which can be added or subtracted (depending on net warming or cooling effect) to generate net warming-weighted emissions of the different pollutants. The global warming potentials used are presented in Table 4. Although, global warming potentials for CO_2, CH_4 and NO_x are well established in the literature, the factors for BC, OC and SO_2 are still not well established. We use Reynolds and Kandlikar's (2008) estimates for 100 year global warming factors of BC, OC and SO_2. Note, however, that there are significant uncertainties associated with these. The global warming factors for OC and SO_2 are negative, because an increase in these emissions results in net cooling of the atmosphere.

Table 4. Total changes in emissions, global warming factors and benefits in 2009 attributable to the policy

GHG's and Particulates	Changes in emission Tons/year	Global Warming Potential	Equivalent changes in CO_2 emissions (1000 Tons/year)
CO_2	-19824.23	1	-19.82
CH_4	4608.39	23	105.99
SO_2	-245.62	-100	24.56
BC	-278.25	455	-126.60
OC	-74.99	-35	2.62
Total		_	-13.61

Table 4 also presents the CO_2 equivalent changes in emissions, considering the warming or cooling impacts. Therefore, although SO_2 emissions decrease, considering the cooling impact of SO_2 there is net warming as a result of the reduction in emissions, and the CO_2 equivalent changes in SO_2 are positive. We find that there is a net warming impact due to increases in CH_4 emissions and decreases in SO_2 and OC emissions, while there is a net cooling impact due to reduction in CO_2 and BC emissions. Considering the warming impact of only CO_2 and CH_4 emissions, the CNG conversion has a net warming impact. However, once we include the impact of the aerosols and its precursors, there is a net cooling effect resulting from the policy.

Once we determine the net CO_2 equivalent emissions (total in column 4 in Table 4), we then use the costs of carbon to determine the benefits (or costs) associated with the changes in emissions. In determining the benefits associated with saving a ton of carbon, there are two approaches. Since carbon is now traded in forums such as the EU-Emissions Trading Scheme, we can use the price of carbon in that market. However, the EU-ETS prices work under a given carbon cap. In the past few months, carbon prices have been low as a result of the recessions, which reduced emissions, and failure to commit to a binding target in the Copenhagen Summit. The price volatility and dependence on carbon caps encourage us to use the social cost of carbon instead. The social costs of carbon in the literature vary by three orders of magnitude, from USD 1 to USD 1,500 per ton (Yohe et al. 2007). Peer-reviewed literature on the social costs of carbon finds that the mean social cost of carbon is USD 43 per ton, with a standard deviation of USD 83 per ton. We use a social cost of carbon of USD 45 in 2009 for our calculations. We note that the UK government uses a carbon cost of GBP 25 (around USD 43, year 2007 prices, Price et al. 2007), and therefore believe our carbon cost is within reasonable limits. This results in a net carbon saving of USD 0.6 million in year 2009.

6. Discussion on Results and Uncertainties

Clearly there are large air quality benefits occurring to the resident of Dhaka as a result of CNG conversion of the vehicles. Local air pollution benefit of 1.3% of the GDP for a single policy initiative appears significant, especially since only a portion of the emissions of the air pollutants was reduced. As a comparison, total air pollution costs in China were estimated to be 3% of China's GDP (World Bank and State Environmental Protection Administration 2007). The rather high accrual of benefit from this policy in Dhaka is a result of different factors: a) Traffic is a major source of air pollution in Dhaka, and any reduction in emissions results in an almost proportional improvement in air quality; b) Dhaka is a densely populated city, which means any improvement in the air quality directly benefits a large number of people, c) Bangladesh is a poor country with a small GDP, therefore benefits to GDP ratio gets inflated.

Although conversion of buses and minibuses to CNG is smaller than those for personal vehicles, the air quality benefits are relatively large. Of the total 134,000 vehicles converted, only around 2,000 (1.5%) were buses or minibuses, but these vehicles were responsible for around 40% of emissions reduction. The large reduction is a result of larger vehicle activity of buses and minibuses and of higher emissions from the buses or minibuses, which run on diesel. In fact 79% of the PM_{10} reductions are due to the conversion of 9,852 diesel vehicles, the conversion of the 97,483 petrol vehicles result in only 21% emissions reduction. This clearly indicates that diesel to CNG conversions have larger health benefits.

The global warming impact of the CNG conversion is not straight forward. Considering the established greenhouse gas emissions (CO_2, CH_4), the conversion policy aggravates the global warming problem. However, if we consider the net warming impacts of aerosols and their precursors, the CNG conversion results in net cooling of the atmosphere. This is primarily because of the lower emissions of BC, which has the largest impact on warming per unit of emissions among the pollutants considered. Once again diesel vehicles are responsible for most of the benefits, which is not surprising since higher PM emissions resulting from these vehicles also contain higher BC.

The monetary benefits (USD in year 2009) of avoided damages due to global warming attributable to the policy, however, is far smaller (smaller by three order of magnitude) than the monetary benefits of reduced local air pollution in Dhaka. This is especially true since we did not consider the impacts of secondary pollutants or health impacts other than mortality. We note that the local air pollution and climate change benefits would have been higher had we included the air quality improvements due to banning the two-stroke autorickshaws which took place in 2003. Also, we considered only the annual benefit in a year. A typical net present value analysis will increase the benefits further, for both air quality and climate change benefits.

Each step in our model can have significant uncertainties associated, depending upon the performance of the underlying modeling techniques. Especially for air pollution, the successive models are directly dependent on previous ones, and therefore the uncertainties increase from left to right of Fig. 1. Thus, the final estimates of the monetary benefits due to the policy intervention would generally be associated with more uncertainty than the estimates for changes in the air quality or GHG emissions and as such. We believe our estimate air pollution and climate benefits have a larger uncertainty than similar estimates in the developed countries, primarily because of the lack of reliable data for the emissions inventory model and the air quality model. The CR function also possibly has some uncertainties, since they have been derived for the developed countries. We present in Table 5 our qualitative evaluation of the uncertainty in the individual components of our model. We are currently working on quantifying the uncertainty of the individual elements through

Table 5. Qualitative evaluation of the uncertainties in this study

Model component	Uncertainty	Remarks
Vehicle data	Small	Accurate scrappage information not available.
CNG vehicle data	Small	Reporting can be slow.
Vehicle emission factors	Large	No testing on in-use vehicles in Bangladesh, especially black carbon, organic carbon, and CH_4 emission factors have large uncertainties; Uncertainty in black carbon and CH_4 emissions have large impact.
Vehicle activity data	Medium to large	No survey of in-use vehicles for travel activities. CNG vehicles possibly run longer because of lower running costs. The climate and health benefits will then be smaller than calculated here. Climate benefits could even be negative. We are currently conducting a survey to determine the distances travelled by vehicles under different fuels.
Fuel breakdown	Medium to large	For some vehicle types (SUV/stationwagon, others) assumed fuel breakdown has large. Uncertainty in diesel to CNG conversion has large impact on health and climate result due to diesel higher PM and BC emissions. We are currently conducting a survey to better understand the fuel split.
Air quality model and pollution exposure	Medium to large	Assumed linear relationship between concentration and emissions was somewhat validated (using information on two three-wheeler ban); Secondary particulate formulation ignored; Only one PM monitor, but exposure can be different in other places.
CR function	Medium	CR could be lower than what we used, since people could be less susceptible to pollutants, could be higher if Laden et al. (2006) is the true CR.
Value of Statistical Life	Large	Our central estimate for VSL appears reasonable, but there are uncertainties in original estimates and on VSL's income elasticity, uncertainty in VSL is especially important when comparing the health and climate benefits
Global warming factors	Small to Medium	Uncertainty for CH_4 is small, global warming potentials for black carbon, organic carbon and SO_2 are still not well established
Carbon price	Medium	Although market price for carbon now available from EU-ETS, the market price is a function of the 'cap'. Damage cost estimates are larger

	than the market price, but have larger uncertainty

statistical distributions and their impact on the final valuation, which would allow us to provide a quantified confidence range on our valuation. We note that even if the VSL is an order of magnitude lower and carbon prices an order of magnitude higher, the air pollution benefits would still be an order of magnitude larger than the climate change benefits for our estimate. However, given the uncertainties in Table 5, it is also possible that there are no net benefits to climate changing emissions or even net penalties (e.g. if CNG vehicles run longer than pre-conversion petrol vehicles due to lower running costs).

7. Conclusions

We carry out an ex-post evaluation of a government policy to convert motor vehicles to CNG. We determined the benefits resulting from improved local air quality in Dhaka and reduced impact on global warming. To our knowledge, this is the first attempt of an integrated approach to model economic benefits resulting from air pollution alleviation and climate change in Bangladesh. We estimate that in 2009, around 6,000 premature deaths were avoided due to the implementation of the policy. This results in a saving of USD 1.15 billion annually in the country, which represents 1.3% of the annual GDP of Bangladesh.

There are also benefits from reduced impact on global warming through reduced GHG and BC emissions, yet, we find that the economic impact of the climate benefits are smaller by a few orders of magnitude than the local air pollution benefits. Therefore, the carbon credit generation and associated financial benefits from such CNG conversion projects or policies under the Clean Development Mechanism may not be large.[4] This means that the conversion of petroleum vehicles to CNG can be justified simply on the basis of local air pollution benefits alone. For large metropolitans in the developing countries with poor air quality, this general conclusion is likely to hold. In order to obtain greater co-benefits, mode switch to less carbon intensive modes (e.g. mass rapid transit, bus rapid transit etc.) will possibly be more effective.

The CNG conversion workshops in Dhaka are still working at full capacity, indicating conversion is still undergoing and will continue for several more years. Once the conversion is complete, and we consider the benefits of the future years (with proper discounting), the health and climate benefits for the conversion policy would possibly be large. It is therefore very important to consider these monetized environmental benefits during cost-benefit analysis for different policy strategies.

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[4] However, the ‘cash’ nature of the CDM funding/carbon credits may help initiate such projects, and then generate those non-monetary health benefits

Several caveats still remain. The emissions inventory has different levels of uncertainty associated because of the lack of good quality data. This means our estimate of 6,000 lives saved is not a point estimate, rather it has a large confidence interval, which we are working to quantify currently. We are also conducting a survey to collect information on fuel wise break-down of the vehicles, vehicle activity and fuel economy data to improve the precision of the result. Future efforts should focus on collecting information on emissions performance of in-use vehicles, especially of converted CNG vehicles and their emissions factors. The air quality model also is a basic one, although with some validation. Despite the shortcomings, we demonstrate that a simple model can still be useful to determine economic evaluation of a CNG conversion policy. We believe our simple approach will be beneficial for application in other developing countries as well, at least as a first order approximation of the health and climate benefits arising from environmental improvement projects or policies. Considering environmental benefits such as this during the policy making in developing countries can positively affect the outcome of the decision process.

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