A Perspective Paper on Black Carbon Mitigation as a Response to Climate Change

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A Perspective Paper on Black Carbon Mitigation as a Response to Climate Change

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PREFACE

ABSTRACT

Black Carbon (BC) aerosols have recently been identified as important contributors to radiative forcing on the global climate. BC reductions – especially those related to contained combustion – provide a win-win opportunity with both health and climate benefits. Emissions from contained combustion are responsible for a total of about 2 million deaths annually in the developing world. There is also a compelling case for their inclusion in a climate emission reductions regime because of their large abatement potential (~15% of current excess radiative forcing), as well as short-term timing considerations ("buying" a delay of ~10 years as part of a climate mitigation strategy). It is important, however, to recognize that BC reductions are not a substitute for reductions in emissions of CO2. The two approaches must be applied together to stabilize atmospheric concentrations of CO2 to acceptable levels of risk. We assess benefit-cost ratios for five different options to reduce BC emissions. Indoor combustion sources of BC such as clean burning household stoves using biomass or gaseous fossil fuels provide the greatest benefit per unit cost. Repair of super-emitting diesel vehicles may also have a benefit-cost ratio greater than one.

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The Copenhagen Consensus Center has commissioned 21 papers to examine the costs and benefits of different solutions to global warming. The project's goal is to answer the question:

"If the global community wants to spend up to, say $250 billion per year over the next 10 years to diminish the adverse effects of climate changes, and to do most good for the world, which solutions would yield the greatest net benefits?"

The series of papers is divided into Assessment Papers and Perspective Papers. Each Assessment Paper outlines the costs and benefits of one way to respond to global warming. Each Perspective Paper reviews the assumptions and analyses made within an Assessment Paper.

It is hoped that, as a body of work, this research will provide a foundation for an informed debate about the best way to respond to this threat.

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1 INTRODUCTION

Carbon dioxide (CO_2) is unavoidably emitted whenever a carbon-based fuel is burned, but other pollutants that are unintended byproducts of non-ideal combustion are also released. These pollutants include carbon monoxide (CO), oxides of sulfur and nitrogen (SO_X and NO_X), volatile organic compounds (VOCs), and particulate matter (PM or aerosols). Until recently these pollutants were regarded as having primarily ***local*** health and environmental impacts. There is increasing scientific consensus, however, that some of these species can also impact the global climate system by changing the Earth's radiative balance. In particular, scientists have turned their attention to aerosol particles that can have both cooling and heating effects. Sulfate and other reflecting aerosol particles tend to cool the Earth's atmosphere by reflecting incident solar radiation. On the other hand, some carbonaceous aerosols, and black carbon (BC) in particular, absorb incident solar radiation leading to warming. The 'win-win' prospect of reducing local air pollution while addressing climate change has led to calls for the inclusion of BC as a greenhouse agent under the United Nations Framework Convention on Climate Change (UNFCCC) (Grieshop et al., 2009).

This perspective paper addresses the potential for climate mitigation from reduction in BC emissions. The rest of the paper is structured as follows. We begin with a short scientific overview of BC and its climatic and health effects (Section 2). In Section 3 we analyze the arguments used in favor of BC reductions in the accompanying BC Assessment chapter by Baron, Montgomery and Tuladhar (BMT hereafter) in this volume (Baron et al., 2009). While the case for BC reductions is strong, we argue that BMT overstate the case in four ways. First, they overestimate the potential for BC reductions. Second, they overestimate the potential delay in needed CO_2 mitigation enabled by the inclusion of BC in global mitigation efforts. Third, the case they make for BC reductions as a way to cope with catastrophic climate change is far-fetched and not supported by current scientific evidence. Finally, they ignore the role of organic carbon that is co-emitted by a number of BC source types. This final point is a serious error that grossly overstates the role that BC emissions reductions – particularly those from open burning – might play in a climate control regime. In Section 4, we propose and analyze a set of additional options for reducing BC emissions. In Section 5, we provide a cost-benefit analysis of the proposed options. We recognize that quantifying the benefits of carbon reductions is a matter of much debate, and so use two different perspectives, viz., a "Stern" perspective (Stern, 2006) and a "Nordhaus" perspective (Nordhaus, 2007) to capture two polar views on the 'true' value of marginal damage from per ton of emitted CO_2. We conclude in Section 6 by briefly highlighting the institutional challenges associated with these proposed interventions that are not captured by the Benefit-Cost ratios.

2 THE CLIMATE AND LOCAL HEALTH IMPACTS BLACK CARBON EMISSIONS

While exact definitions of light-absorbing carbonaceous aerosols vary (Andreae and Gelencsér, 2006), there is uniform agreement that BC is a strong absorber of solar radiation; it absorbs approximately 1 million times more solar energy than CO_2 per unit mass (Bond and Sun, 2005). BC is thought to be the second-largest contributor to global excess radiative forcing after CO_2 (Ramanathan and Carmichael, 2008). During its weeklong residence in the atmosphere a BC particle directly absorbs radiation from below (Ramanathan et al., 2007), within (Koren et al., 2008; Jacobson, 2006), and above (Haywood and Ramaswamy, 1998) clouds. When deposited on bright ice and snow surfaces such as glaciers or in polar regions, BC particles may cause several more months of warming by reducing the reflection of light - this latter effect helps make BC an especially effective warming agent that is responsible for approximately 15% of global excess radiative forcing (Forster et al., 2007). Because of the short lifetime and varied atmospheric interactions, the climate impacts of BC vary with source location. For example, relative to those emitted near the equator, BC aerosols from sources in northern latitudes (>40°N) have a lower direct absorption effect because of the reduced solar irradiance in their location, but are more likely to have strong *indirect* effects due to proximity to arctic ice and snow sheets (Shindell and Faluvegi, 2009).

The relative contribution of BC compounds to the total aerosol from combustion sources varies considerably with source type (Bond et al. 2004). BC emissions from some sources are accompanied by emissions of organic carbon compounds and sulfate, which have a cooling effect via direct light scattering and interactions with clouds (Ramanathan and Carmichael, 2008). Though the net climate impact of BC and non-BC particles emitted by many source types is uncertain, analysis that includes most relevant uncertainties suggests that BC-dominated sources, such as residential combustion of solid fuels and high-emitting diesel engines, have a net warming impact (Bond, 2007). Open biomass burning is also a large source of BC, but its emissions are generally dominated by organic carbon (Bond et al. 2004) and thus likely have a net cooling effect.

Locally, BC and other products of incomplete combustion are among the largest contributors to ambient air pollution. Extensive use of solid fuel, particularly in the poorest developing countries, makes indoor exposures to PM the *fourth* largest contributor to the global burden of disease (Ezzati et al., 2002); the World Health Organization estimates that over 1.8 million people, mostly women and children, die from exposure to indoor smoke from solid fuels (Ezzati et al., 2006). Older vehicles, dirty industries and an array of other BC sources contribute to outdoor urban particulate air pollution levels that are up to ten or more times higher than those in developed nations' cities (Molina and Molina, 2004).

3 ASSESSING THE ARGUMENTS MADE BY BMT

BMT make several arguments in support of BC emissions reductions. These arguments fall into four main categories:

1. Those related to the ***magnitude*** of reductions in radiative forcing of climate from BC emissions reductions relative to mitigation of CO_2 emissions.
2. Those related to ***timing*** of emissions reductions. In particular, BMT claim that BC emissions reductions can "delay warming for a matter of decades" and "black carbon policies can buy time for R&D" to achieve reductions in the cost of carbon dioxide reduction.
3. Those related to BC reductions' potential for coping with ***catastrophic*** climate change.
4. BC reductions as a way to bring ***developing countries*** on-board the UN Framework while improving health and poverty-related illnesses.

In what follows we will examine these four arguments in turn.

3.1 Assessing the Magnitude of BC reductions

BMT note that "40% of current net warming (10-20% of gross warming)" is related to BC. Since use of net warming is scientifically inaccurate and inflates the role that BC plays[1], the attribution of between 10 and 20% of excess warming is more appropriate and consistent with other studies. Specifically, of the 2 °C rise in global mean temperature since pre-industrial times (from circa 1760), BC's contribution is approximately 0.3 °C (Jacobson, 2004; Bice et al., 2009). To the first order, eliminating current BC sources should reduce excess temperature forcing by about 15%.

BMT also assert that the benefits of reducing CO_2 are uncertain and "highly speculative" and "the calculation of expected benefits [from carbon dioxide reductions] is not a scientific possibility"[2]. In other words, BMT imply that climate impacts (e.g. such as those assessed and summarized by the IPCC) are simply conjectures that are based on speculation and not on rigorous scientific assessment. Further, despite the uncertainties they highlight, BMT also support an upper bound for the price of carbon of $25 per ton CO_2; in fact this is a 'low' value consistent with the belief that climate change is unlikely to be a significant problem in the future. Overall, BMT appear to be arguing that CO_2 emissions reductions have speculative benefits which are only realized over the longer term, while BC reductions have more certain and immediate benefits. Consequently, they claim that climate mitigation policies should focus on BC reductions rather than on CO_2 mitigation. We examine the implications of this contention in more detail below.

In a recent paper (Grieshop et al., 2009), we showed that BC emissions could add up to a carbon emissions reduction "wedge" as described in an influential article by Pacala and Socolow (2004). Pacala and Socolow identify 15 Greenhouse gas-reduction strategies each of which represents a "wedge" equivalent to one billion tons of carbon (1 GtC) mitigated over a 50-year period (2005-2055). The paper states that implementing a cluster of seven such wedges would help stabilize atmospheric concentrations of CO_2 to below double pre-industrial levels (500 ppmv). Examples of Socolow and Pacala's wedges include a doubling of the fuel economy of all cars in 50 years, tripling existing nuclear power capacity by 2055, and increasing solar photovoltaic power generation by a factor of 700.[3] If we take the climate problem seriously (rather than simply write off its impacts as 'speculative'), then meeting a target of limiting CO_2 concentrations in the year 2100 to twice-pre-industrial represents a pragmatic goal that seeks to balance emissions reduction costs and impacts[4]. Meeting such a

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[1] BMT define net warming as the aggregate warming effect of GHG emissions, black carbon, and urban heat island effect less the opposing effect of cooling particles. Gross warming is defined as the aggregate warming effect of GHG emissions, black carbon, and urban heat island effect. If one were to similarly attribute net warming to CO_2, methane, tropospheric ozone and nitrous oxide as BMT do the BC, the corresponding percentages would be 75%, 28%, 20% and 8%, and the aggregate attributions would well exceed 150%!

[2] By doing so, they write-off in one fell swoop the entire literature on decision-making with regards to climate change including the recent Stern-Nordhaus-Weitzmann debate on long-term costs of climate change.

[3] While technologically feasible each wedge represents a substantial commitment of resources whose implementation is an impressively daunting task.

[4] In fact, many argue that doubled CO_2 concentrations represent a risk that is well beyond the threshold for "dangerous" climate change.

target requires seven times as much carbon-equivalent reduction as BC reductions can alone provide. In other words, BC reductions are not a substitute for CO_2 reductions as BMT would have us believe, but instead are one among a range of strategies needed to meet climate change mitigation targets. BC reductions represent an opportunity that is complementary to CO_2 reductions and not a substitute for them. To treat them as substitutes to CO_2 emission reductions is tantamount to denying the seriousness of the global threat of climate change.

3.2 The timing impact of BC reductions

BMT find BC emission reductions attractive for two reasons. First, on a per-mass basis they are vastly more potent than greenhouse gases, with a 100-year global warming potential of approximately 450 times that of CO_2. Second, they are short lived so their removal can have a rapid impact on global temperature and thus represents an important short-term strategy. Consequently, BMT argue that "black carbon policies can buy time for R&D" needed to achieve cost reductions in CO_2 mitigation. BMT believe that "reductions in black carbon emissions can delay warming for a matter of decades"[5]. We have little disagreement with BMT on the broad strokes of these claims. However, BMT do not provide any quantitative assessment of the extent of the CO_2 mitigation delays that may be possible if BC reductions are introduced. We are only left with a vague sense that BC represents a very immediate and large opportunity to delay emissions of the order of "decades".

A coherent discussion of delays is possible only when targets and timetables for future CO_2 concentrations are in place. Comparing an emissions path that achieves a known CO_2 concentration target (e.g. 500 ppm) at a known future time (2100 AD) with and without BC reduction can help evaluate the extent of delay in CO_2 emissions reductions that BC reductions can facilitate. While BMT do not present such data, other researchers have done such calculations (Bice et al., 2009). They show that phasing out of ***all*** BC emissions from fossil fuel use can help delay CO_2 reductions by about 15 years when a stringent concentration target of 450 ppm is to be met by 2100. A higher concentration target (550 ppmv), consistent with BMT's low "cutoff" price for carbon, reduces the urgency of immediate CO_2 reductions. Thus BC reductions can help meet strict CO_2 concentration targets with greater flexibility but the amount of delay they can "buy" is smaller (on the order of a decade) than BMT's exposition might have us believe.

3.3 BC Reductions and Catastrophic Climate Change

BMT present BC reductions as a solution to possible catastrophic impacts of climate change. This view is inconsistent with the other arguments made for BC reductions, which are presented in the rest of the paper as a more immediate ***near-term*** reduction option. Catastrophic impacts are really not on the near-term horizon, and most experts agree that we are nowhere close to a climatic tipping point. The most commonly discussed (and the most well-studied) catastrophic impact is the shutting down of the North Atlantic Thermo-haline Circulation (THC). The current probability of a THC shutdown is very small and becomes a worry only with a ***quadrupling*** of pre-industrial CO_2 levels or a 4K increase in global mean

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[5] BMT cite Ramanathan and Carmichael (2007) to back up their claim that BC reductions can delay emissions reduction by a few decades. BMT do not mention, however, that the original reference states that delays are only possible "in tandem" with CO2 reductions. This is a crucial omission that overstates the climate mitigation role of BC while downplaying the role of CO2.

temperature (Zickfield et al., 2007). While catastrophic climate change is clearly a concern, it is one that exists mainly on multi-decadal and century long time-scales. Further, when catastrophe is imminent, the reduction of BC emissions (such as those from cook stoves in developing countries) is not likely to be the chosen rapid deployment option. Resource-constrained governments that lack adequate institutions are likely to find it difficult to change the way they their people live in a short period of time. Policymakers in the North are likely to adopt aggressive geo-engineering approaches, e.g. using nanoparticles to increase Earth's albedo (Wigley, 2006), which can be deployed rapidly and at relatively low cost on a mass scale. Consequently, we find BMT's argument for using BC reductions to stave off climate catastrophe far-fetched. The good news is that one does not need a climate catastrophe justification to engage in BC reductions.

3.4 BC Emissions and the Developing World

The final justification for BC reductions presented by BMT is that they provide a double dividend. BC reductions reduce health impacts (largely in the developing world) and climate warming at the same time. This is a sound justification for BC reductions, and one that both developing and developed countries can get behind (Grieshop et al., 2009). However, the case for BC reductions in the developing world is more nuanced than that presented by BMT. BC emissions can be classified into open burning sources (e.g., crop residue, forests, savannah) and contained combustion sources (e.g., household cookstoves, diesel vehicles, coal-powered industry). Organic Carbon (OC) tends to dominate open burning aerosol emissions by mass, while many contained combustion sources are dominated by BC. OC aerosols have a cooling effect that more than compensates for warming from the BC component in open burning. Consequently, open burning emissions are thought to lead to *net cooling* of the Earth's atmosphere (Bond, 2004, Bice et al., 2009). In reality, the picture is even more complex. Open burning emissions likely have global cooling effects, but by contributing to Atmospheric Brown Clouds (ABCs) has serious regional climate impacts (Ramanathan and Carmichael, 2008). For example, ABCs are implicated in reduced monsoon precipitation over the Indian sub-continent and reduced agricultural yields (Aufhammer 2006). BC-dominated closed combustion sources are linked much more strongly to warming, and are also linked directly to the deaths of 1.5 million individuals (mostly women and children) in the developing world, primarily through exposure to indoor air pollution from household combustion sources.

In their assessment paper BMT ignore the effect of co-emitted OC species altogether. This leads them to make incorrect conclusions about the magnitude of the responsibility of developing countries to BC-related warming. Consequently, they vastly overestimate the potential to reduce warming by mitigating open burning sources in the developing world. In fact, the single largest BC reduction proposed by BMT, biomass burning in Africa and South America, makes up 80% of their proposed reductions goal (19% of global BC emissions). However, because of co-emitted OC species - OC:EC mass ratio in biomass burning of forests is 9, and savannah is 7 (Bice, 2009) - this source contributes to net cooling!

In summary, BC reductions – especially those related to contained combustion – provide a win-win opportunity. Closed combustion sources are responsible for a total of about 2 million premature deaths annually in the developing world. There is also a compelling case for their inclusion in a climate emission reductions regime – because of their large abatement potential (~15 % of current radiative forcing), as well as short-term timing considerations ("buying" a delay of ~10 years). Their potential should not however be over-estimated and BC reductions are not a substitute for CO_2 reduction.

4 ASSESSING BC MITIGATION OPTIONS: COOKSTOVES AND DIESEL VEHICLES

BMT present various approaches to mitigating black carbon from key sources, namely indoor solid fuel use in developing countries, diesel transportation and open burning. For the former two sources, we have performed a cost-effectiveness analysis of several realistic interventions that use proven technologies and have relatively well-understood costs. We take into account the co-emitted cooling aerosol species, in particular organic carbon, and GHG emissions in estimating both climate change and health impacts. We have not analyzed interventions that promise to mitigate aerosol emissions from open burning, because as discussed in section 3.4 above such emissions are dominated by cooling species. The two approaches to reduce aerosols from cookstoves analyzed here are: 1) improved biomass-gasifier stoves replacing traditional stoves in India, and 2) LPG stoves replacing household coal use in China. Three interventions are evaluated for reducing BC from diesel-fueled buses and trucks in the urban areas of India and China: 1) converting urban heavy-duty vehicles to natural gas fuel, 2) retrofitting them with after-treatment devices (particulate traps), and 3) repairing "superemitting" vehicles, which have excessive emissions due to poor maintenance. Table 1 gives an overview of cost-estimates per unit for each intervention.

Table 1: Intervention cost ranges

	Cost	
Intervention to reduce BC	*Low (US$)*	*High (US$)*
Household solid-fuel use		
3-Stone fire to gasifier stove	30	100
Coal stove to LPG stove [a]	30 + $30/year	100 + $100/ year
Heavy duty diesel vehicles		
Diesel to CNG [b]	2,000 [b]	10,000
Retrofit with particle traps	6,000	12,000
Repair super-emitters	1000	5000

[a] LPG stove intervention assumes similar stove cost to biomass gasifier stove but includes a yearly expense due to the additional fuel expense relative to the base fuel (coal) associated with LPG use.

[b] The low estimate of costs for conversion to CNG is reduced because natural gas costs are estimated to be significantly less than diesel, so some of the cost of conversion could pay for itself in the first year. Over the remaining lifetime of the vehicle, there may be a net economic benefit to the vehicle owner due to fuel savings.

4.1 Indoor solid fuel use in developing countries

Cooking and heating fires using solid fuels are a major global emission source of BC and other aerosol species (Bond et al., 2004). Due to elevated indoor exposures to these emissions, such indoor fires represent one of the largest sources of premature mortality and illness in developing countries, especially among women and children (Ezzati et al., 2002). In the past several decades, interventions to replace such primitive cooking and heating fires with 'improved' stoves or those using cleaning burning fuels have been implemented, studied and advocated as an efficient means to protect global public health (Mehta and Shahpar, 2004). More recently, such interventions have also been suggested as cost-effective means to mitigate GHG (Smith and Haigler, 2008) and BC (Bond and Sun, 2005) emissions. Here we present cost-effectiveness analyses of two hypothetical stove interventions, building upon prior work, which demonstrate the potential efficiency of such interventions along with the powerful potential for significant co-benefits associated with climate mitigation.

The simple analyses presented here examine the health- and climate-cost-effectiveness of two distinct stove interventions: 1) replacing simple 'unimproved' stove or 3-stone biomass-fire cooking methods with improved biomass-gasifier stoves in India and, 2) the replacement of household coal-burning stoves in China with those burning liquefied petroleum gas (LPG). The 'scoping' analysis of Smith and Haigler (2008) presents calculations of the cost-effectiveness of these options in reducing the loss of Disability-Adjusted Life Years (DALYs) and emitted greenhouse gases (in tons CO_2-equivalent or tCO_2eq) from domestic fuel use during a 10-year stove-program implementation. Here, we adopt their major assumptions for the implementation of a stove program (see footnote of Table 4 in Smith and Haigler) but expand their analyses to include the climate effects of the reduced BC and OC emissions that accompany these interventions.

In brief, 100,000 stoves are distributed over a 10-year period, with the assumption that 10% of stoves in place must be replaced on a given year and that stove program effectiveness is 50% (half of distributed stoves are in active use). Both stove interventions are assumed to cost the same as that in Smith and Haigler's analysis ($60/stove, including 50% of stove cost for program expenses), but an additional cost of LPG fuel-use is added in the Coal-to-LPG stove use cost calculation, based on estimates of fuel-cost and annual usage for each fuel type (Table 1). Health cost-effectiveness values ($/DALY) can be directly taken from the earlier calculation while the climate cost effectiveness ($\$/tCO_2eq$) is a combination of their calculations for GHGs and ours for particles. BC, OC and SO_2 emission factors for the three stove types (MacCarty et al., 2008; Bond et al., 2004; Zhang et al., 2000) characterize emissions from fuel use before and after the stove program. Global warming potentials (GWPs) are used to convert particle (and particle precursor, in the case of SO_2) emissions to CO_2-equivalents (Reynolds and Kandlikar, 2008).

Biomass-gasifier program

Installing biomass-gasifier stoves to replace traditional household cooking methods in India is a cost-effective method to improve health (Smith and Haigler, 2008) with estimates for price per DALY ranging between $260 and $1400 (Table 2). Such an intervention is also effective way to reduce GHG emissions at a cost of $\$7/tCO_2eq$. Taking into account particles potentially improves the cost-effectiveness of climate mitigation to as low as $\$4/tCO_2eq$. Therefore the climate impacts associated with BC particles play a substantial but not over-whelming role in the climate mitigation effects of this intervention.

Table 2: Health impact and climate mitigation cost effectiveness values for two potential stove interventions in developing Asia.

Intervention	Health cost effectiveness ($/DALY)	Climate cost effectiveness ($/tCO$_2$eq)	Population affected [d] (millions)
3-stone fire to Gasifier Stove in India [a]	\$600 (\$260 - \$1400) [b]	\$6 (\$4 - \$7)	850
Household Coal to LPG stoves in China [c]	\$1400 (\$900 - \$2000)	\$45 (\$10 - \$60)	430

[a] Efficiency increases of an improved stove of ~ x2 are assumed to be offset by the 50% 'effectiveness' of stove programs assumed by Smith and Haigler in calculating improved stove fuel usage.

[b] The range in health cost effectiveness was estimated based on ranges presented by Mehta and Shahpar (2004).

[c] Fuel cost is assumed to increase due to purchase of LPG: central values for fuel price and usage are assumed to be \$0.25/kg and 1000 kg/stove/year for coal stoves and \$1.50/kg and 200 kg/stove/year for LPG stoves.

[d] Values estimated from (Mehta and Shahpar, 2004)

LPG Stove Program

The cost-effectiveness of switching from coal- to LPG-fired stoves in China is lower than for the biomass-gasifier stove, due to higher fuel costs for similar levels of CO$_2$eq emission reduction. The health cost-effectiveness of LPG-replacement is slightly worse than the gasifier case with estimates for price per DALY ranging between \$900 and \$2000 (Table 2). LPG is a non-renewable fuel and thus is a net-CO$_2$-emitter, a fact that leads to substantially lower climate cost-effectiveness based strictly on GHG emissions. Burning LPG emits very low levels of BC relative to coal combustion in simple stoves. Therefore including BC emissions in CO$_2$eq calculations can more than double the cost-effectiveness of this intervention (with up to 80% of the total benefits coming from the aerosol impacts), highlighting the importance of considering ***both*** GHGs and aerosols when determining the potential climate impacts of such programs.

4.2 Diesel vehicles in urban parts of developing countries

Heavy-duty diesel vehicles (HDDV) in cities are mostly goods vehicles and buses, and they play a critical role in the functioning of an economy. Worldwide, outdoor air pollution is estimated to result in at least 800,000 excess deaths annually (Rodgers et al., 2002). The greater health burden falls on urban populations in less-developed countries: about 60% of these excess deaths occur in Asia alone (Anderson et al., 2004). HDDVs in developing countries are in general older and more poorly maintained than in OECD countries. In addition, emissions controls are both less stringent for new vehicles, and emissions are not effectively monitored and regulated for in-use vehicles. Therefore particulate matter emissions are very high on a per-fuel-use basis. PM from diesel vehicles is mostly BC (50-80%) (Bond et al., 2004), which makes it an ideal candidate for the implementation of control interventions.

We calculate climate mitigation cost effectiveness ($\$/tCO_2eq$) according to the method introduced by Bond and Sun (2005), but extend their analysis to account for the cooling effect of co-emitted organic carbon and SO_2 (a precursor to reflective sulfate aerosol) and warming GHG emissions.[6] We take into account the change in fuel efficiency (hence direct CO_2 emissions) and increased methane emissions (GWP of 23) in the case of the diesel to CNG conversion. Health impact calculations were performed based on the results of epidemiology studies, which show correlation between the concentration of ambient fine particulate matter in urban areas (which includes BC, organic carbon, sulfates, and other species) and adverse health outcomes (cardiovascular disease, lung cancer and acute lower respiratory infection). Our approach follows that of Smith and Haigler (2008): for the cost-effectiveness assessment of health impacts, we evaluate the intervention cost (in US$1000s) per DALY reduced. The potential for ambient PM reduction is based on the three emission-control scenarios applied in the urban regions of India and China.

The average heavy-duty vehicle fleet is assumed to be composed of 85% "normal" trucks and buses with average PM emission factors of 2.2g/kg fuel, while the remainder are "super-emitters" with PM emission factors of 8.4g/kg, or almost four times higher than the regular vehicles (Subramanian et al., 2009). HDDVs are assumed to travel an average of 75,000 km per year, and have an average fuel consumption of 3.0 km/kg diesel; converted CNG vehicles have a lower fuel efficiency of 2.5 km/kg natural gas. Intervention cost ranges have been given in Table 1, and include the one-time capital cost as well as an estimate of lifetime fuel savings and change in maintenance costs; note however that the latter costs are highly discounted to reflect the barriers to capital investment in resource-constrained economies.

Diesel to compressed natural gas

Conversion of heavy-duty vehicles from diesel to compressed natural gas (CNG) fuel is a proven means of reducing PM emissions. For example in Delhi, India, all public transport vehicles were converted following regulation in 2001 (Reynolds and Kandlikar, 2008). The major barrier to conversion is the supply of natural gas, since it is not available in all cities. Therefore only vehicles that operate within range of the CNG refueling infrastructure would be eligible for conversion (we assume half of the urban fleet in Asia). In our cost-effectiveness analysis we do not include the cost of refueling infrastructure because this is assumed to be revenue-neutral for the private companies or governments who undertake the endeavor. If such infrastructure were taken into account, health and climate benefits would obviously be reduced. Switching to CNG results in a 90% reduction of PM per vehicle. Although this very significant PM reduction has a very positive climate benefit (-250 tCO_2eq over the lifetime of the vehicle), almost three-quarters of the benefit is offset by increased methane emissions (+110 tCO_2eq) and reduced fuel efficiency (+ 75tCO_2eq). Therefore the climate cost effectiveness is considerably less than the cookstove options, at around $100 per tCO_2eq (Table 3). The health cost effectiveness is $0.94M per DALY – 1000 times more expensive than the cookstove interventions – because exposure to outdoor transportation emissions is much lower than exposure to indoor smoke.

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[6] The estimated GWP for diesel PM we use is 350±200 based on aerosol component GWPs and emission fractions (Reynolds and Kandlikar, 2008).

Table 3: Health impact and climate mitigation cost effectiveness values for three potential interventions to reduce black carbon from heavy-duty transport in China and India. The exposed population is the combined urban population of the two nations, which is estimated to be 1,100 million people, however the diesel-CNG option may not be viable in all cities due to natural gas infrastructure.

Intervention	Health Cost Effectiveness (1000$/DALY) [a]	Climate Cost Effectiveness ($/tCO2e)
Diesel to CNG	$940 (310-1570)	$100 (35-165)
Retrofit with particulate trap	$2320 (1550-3090)	$115 (75-155)
Repair superemitters	$470 (160-790)	$15 (5-25)

[a] Health cost effectiveness values indicate diesel vehicle interventions are 1000 times more expensive than cookstove interventions because of the much lower exposure levels (and consequently less impact on health outcomes) and the higher cost of intervention.

Retrofit of in-use diesel vehicle with particle trap

Older model vehicles can be retrofitted with exhaust particulate traps that reduce PM emissions significantly. In our calculations we assume that they are 70% effective over their lifetime, which is assumed to be 8 years. Maintenance costs are assumed to increase and the fuel efficiency of retrofitted vehicles is reduced slightly, leading to both higher fuel costs and direct CO_2 emissions. The lifetime climate benefit of installing a particulate trap on a diesel vehicle is a reduction of approximately -80 tCO_2eq, taking into account the increased CO_2 emissions due to the fuel efficiency penalty. The technology is effective at reducing PM but it is expensive, so climate cost effectiveness is similar to that for diesel-CNG switch ($115 per tCO2eq), and health cost effectiveness is more than three times less than for the fuel-switching option ($2.3M per DALY).

Repair Superemitters

Although super-emitters by definition make up a relatively small proportion of the fleet (around 15%), they represent a great opportunity for emissions reduction because their PM emissions are many times higher than the bulk of the vehicle fleet. We assume that a viable inspection and maintenance program would identify (and ensure successful repair) of half of the super-emitters, and that the result of the repair would be a 50% reduction in PM emissions. Setting up a good inspection and maintenance is not a trivial task, but it can be done so that it is a revenue neutral endeavor that does not put an overly large burden on vehicle operators or the government (Hausker, 2004). This analysis suggests that identification and repair of super-emitters has a high climate impact per vehicle (approximately -200 tCO_2e). This approach could be one of the most cost-effective means of reducing both climate and health effects of PM from transport, at $15 per tCO_2eq and $0.47M per DALY (Table 3). However, since the proportion of super-emitters is small the scope of this intervention is limited.

5 BENEFIT COST RATIOS

From the analyses of options it is clear that indoor cooking interventions dominate the explored possibilities based on the health cost-effectiveness metric; the $/DALY metric for indoor cooking is lower than that from vehicular traffic controls by three orders of magnitude. From a climate cost-effectiveness perspective most proposed interventions are within an order-of-magnitude of each other. Conversion to biomass gasifier stoves and controlling super-emitting diesel vehicles are most attractive (<$15/t$CO_2$eq). The other interventions cost between $50 and $100 dollars per ton of CO_2eq. Indoor cookstove interventions affect large populations in China, South Asia as well as large parts of Africa. Consequently, pursuing indoor cookstove interventions is the most promising win-win strategy, followed by super-emitter repairs (although the latter may be limited in scope).

Before we delve into the question of how these costs compare with the benefits for the proposed interventions a few observations are in order. First, developing countries will benefit more immediately from health interventions, and so will be more interested in health effectiveness measures, while it is in the interest of industrialized countries to intervene based on climate cost-effectiveness. Consequently, we show Benefit-Cost (B/C) ratios for climate and health separately for each intervention in addition to the aggregate (Health+Climate) B/C ratio.

B/C evaluation should ideally include a comprehensive assessment of social and environmental costs and benefits, and not be limited to climate and health alone. Consequently, there are other important benefits of proposed interventions that are not we are not accounting for in this analysis. For example, gasification stoves may reduce the amount of time people spend gathering fuel (since they use less fuel overall), which in turn could influence the ability of women to engage in productive activities and allow more time for children to study (especially girls). Since the full social costs and benefits of the policy interventions cannot be easily accounted for, it is hard to pin-down a comprehensive cost-benefit ratio of each intervention.

Table 4 shows the monetized benefits and corresponding B/C ratio for proposed interventions. While the conversion of DALYs to a monetary value is now relatively uncontroversial, putting a monetary value on the benefits from carbon reductions are not. In recent years this debate has crystallized around the Stern report on the economics of climate change (Stern, 2007) and responses to it (Nordhaus, 2007; Weitzman, 2007). It is beyond the scope of this paper to go into to the details of the debate; we also eschew the question of who provides the "correct" estimate for the economic damages from carbon emissions[7]. For the purposes of this paper it suffices to say Stern and Nordhaus represent two strikingly different positions on economic damages from carbon emissions. Stern views climate change as a major threat to the global economy and estimates the damages at $310 per ton of carbon (i.e. $85 per ton of CO_2). Nordhaus estimates a far lower value of $35 per ton of carbon (around $10 per ton of CO_2). These differences are reflected in the benefits of interventions shown in Table 4.

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[7] Weitzmann (2007) argues that Stern "gets it right for the wrong reasons", while Nordhaus strongly believes that Stern's position is incorrect.

Table 4. Benefit-Cost ratios for the proposed BC reduction options. Benefits shown are per unit intervention (2005 dollars). The value of a DALY is taken to be \$7500, the average world GDP (PPP) per capita per Smith and Haigler (2008). The two scenarios of \$/CO_2eq are taken from the work of Stern and Nordhaus (See Section 5). Costs of intervention shown in Tables 2 and 3 are used to calculate B/C ratios.

BC Reduction Option	Health Benefits	Climate Benefit Scenarios		Health + Climate Benefits	
	DALYs (\$) (B/C ratio)	CO_2eq (\$) Stern (B/C ratio)	CO_2eq (\$) Nordhaus (B/C ratio)	Benefits (\$) Stern B/C ratio (range)	Benefits (\$) Nordhaus B/C ratio (range)
Biomass Gasifier Stove	\$760 (13)	\$880 (14)	\$100 (1.7)	\$1,600 27 (16-54)	\$870 14 (9-28)
Coal to LPG switch	\$1,390 (5)	\$490 (1.8)	\$60 (0.2)	\$1,880 7 (4-15)	\$1,450 6 (3-11)
CNG Fuel Switch	\$30 (0.03)	\$5,130 (0.9)	\$600 (0.1)	\$5,160 0.9 (0.5-2.6)	\$630 0.1 (0.06-0.3)
Particulate Traps	\$20 (0.02)	\$6,650 (0.7)	\$780 (0.08)	\$6,670 0.7 (0.6-1.1)	\$800 0.1 (0.07-0.13)
Super-emitter	\$40 (0.01)	\$17,270 (5.8)	\$2,030 (0.7)	\$17,320 5.8 (3.5-17.3)	\$2,070 0.7 (0.4-2.1)

From Table 4 it is clear that biomass gasifier stoves have B/C ratios well greater than one from a health perspective. It is also the only intervention that is justified from both the Stern and Nordhaus perspectives on climate damages. Interventions promoting the use of LPG fuel also have a large B/C ratio, primarily because of the large health benefits of such a switch. Reducing emissions from super-emitting trucks and buses also may be justified from a B/C perspective, though that option does not pass muster when the lower (Nordhaus) value for carbon damages is used. The other options tend to have B/C ratios < 1 from combined health and climate perspectives, though switching to CNG might be justified from a climate perspective under specific assumptions, viz., Stern's carbon damages and costs of implementation at the low end of the range. Interestingly, in all cases interventions are justified from either climate or health or both simultaneously. In no case do health and climate 'add up' to justify an option that is not justified on either basis alone.

6 POLICY CONCLUSIONS

One aspect of program effectiveness not easily captured by cost-based measures is the nature of institutions and governance that can facilitate the diffusion of these technological interventions. Institutional barriers in countries with resource-constraints may be significant enough to cause a seemingly viable project to fail. The evidence from cookstove diffusion is instructive in this regard. A recent reassessment (Sinton et al., 2004) of the astonishing success of the Chinese biomass cookstove program in the 1980s (Smith et al., 1993) provides some important lessons. Sinton et al. found that China implemented successful programs that delivered improved biomass stoves to a majority of targeted households, and that those stoves continue to be used. Strong administrative, technical, and outreach competence, as well as the use of local resources and sustained national-level attention were critical to success of these programs. The same cannot be said for coal stoves in China, which largely operate without flues even when they use cleaner burning briquettes. Consequently, hundreds of millions of Chinese are currently exposed to very high levels of indoor air pollution from 'improved' stoves.

The Chinese case of indoor coal-burning stoves highlights the difficulties faced by cookstove programs – they do not simply emerge from a market based consumer demand. They need to be carefully thought through and supported by concerted governmental efforts. Other countries like India have had much lower success in implementing stove programs despite their obvious and very large health benefits (Barnes et al., 1994). Reduction of BC emissions from heavy-duty diesel vehicles also faces the challenge of weak institutions, coupled with rapid growth in the transport sector. BC reduction provides an additional rationale – and potentially new funding – for putting programs in place, but the need for strong technical and administrative capacity and sound program design remains. These challenges will need to be overcome if BC reductions in the developing world and the concomitant health and climate benefits are to be realized.

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