Quantifying the Health Benefits of the Greater Dhaka Sustainable Urban Transport Corridor Project

Final Report

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List of Abbreviations

Abbreviation	Description
ADB	Asian Development Bank
ATMoS	Atmospheric Transport Modeling System
BRT	Bus Rapid Transit
C-R	Concentration-response
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CPI	Consumer Price Index
DCC	Dhaka City Corporation
DR	Discount rate
EF	Emission factor
FY	Fiscal year
GDP	Gross domestic product
GHG	Greenhouse gas
GNI	Gross national income
GPW	Gridded Population of the World
HC	Hydrocarbons
HDSS	Health and Demographic Surveillance System
i/m	Inspection and Maintenance program
IMF	International Monetary Fund
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NMHC	Non-methane hydrocarbons
NO_x	Nitrogen oxides (including NO and NO_2)
OR	Odds ratio

Abbreviation	Description
OECD	Organisation for Economic Co-operation and Development
PDV	Present discounted value
$PM_{2.5}$	Fine particulate matter, with aerodynamic diameter less than 2.5 microns
PM_{10}	Coarse particulate matter, with aerodynamic diameter less than 10 microns
PPP	purchasing power parity
RAINS	Regional Air Pollution Information System
RR	Relative risk (or risk ratio)
SEDAC	Socioeconomic Data and Applications Center
SO_2	Sulfur dioxide
TGPA	Tongi and Gazipur Pourashavas Area
U.S. EPA	United States Environmental Protection Agency
VKT	Vehicle-kilometers traveled
VSL	Value of a statistical life
WTP	Willingness to pay

List of Units

Unit	Description
g/km	grams pollutant emitted per kilometer driven
metric tons/year	metric tons per year (1 metric ton = 1000 kg)
$\mu g/m^3$	micrograms per meter cubed
ppm	parts per million
VKT per day	kilometers per day

Executive Summary

Introduction

The construction of a bus rapid transit (BRT) line in Dhaka, Bangladesh, with the concurrent replacement of some existing buses with compressed natural gas (CNG) buses will result in air quality improvements leading to potential public health impacts as well as changes in greenhouse gas (GHG) emissions. These potential benefits were previously unquantified, as the Asian Development Bank (ADB) had focused on the economic benefits of travel-time and operating-cost savings, as well as increased land values. The present analysis aims to illustrate some of the public health benefits expected to result from the construction of the BRT line and replacement of diesel buses with CNG buses. Abt Associates Inc. obtained information to define the "without BRT" (baseline) and "with BRT" (control) scenarios from ADB's project preparation report. Where information was lacking, we made assumptions using information from the literature. We focused our analysis on endpoints where there was sufficient available evidence; however, our analysis is limited by the assumptions we made and the approaches/models we employed.

Methods

We followed an analytical framework that included four main components to estimate: (1) the change in primary (direct $PM_{2.5}$ emissions) and secondary particulate emissions (SO_2 and NO_x leading to secondary sulfate and nitrate, respectively) from "without BRT" to "with BRT" conditions; (2) the reductions in ambient $PM_{2.5}$ concentrations resulting from emission changes, using a simplified dispersion model; (3) the improvements in health outcomes using suitable concentration-response functions and population and incidence data; and (4) the value of avoided morbidity and mortality using unit values for adverse health outcomes. Additionally, we estimated the change in specific GHG emissions (namely, CO_2 and methane, CH_4) as well as in emissions of CO and non-methane hydrocarbons (NMHC) resulting from the BRT project. We combined measured emissions factors for BRT and non-BRT buses and minibuses with vehicle-kilometers traveled (VKT) estimates obtained from ADB's project preparation report to estimate the emissions in the "without BRT" and "with BRT" scenarios. These emissions, along with meteorology data for the year 2006, were inputs into a simplified atmospheric dispersion model, ATMoS, which yielded concentration change estimates for primary and secondary $PM_{2.5}$. Given that there were no suitable $PM_{2.5}$ concentration-response functions for morbidity and mortality for Bangladesh, we adjusted U.S.-based functions for use in Bangladesh or used functions from the region. We focused on estimating reductions in premature mortality in adults and children, and reductions in chronic bronchitis in adults. Population estimates for Dhaka and the surrounding area were obtained from Gridded Population of the World datasets. The valuation for premature mortality and chronic bronchitis relied on a benefit transfer approach by Hammitt and Robinson (2011).

Results

We obtained results for each year from 2014 to 2044. Based on our assumptions, we estimated reductions in emissions of primary $PM_{2.5}$ (~1,800 metric tons during 2014–2044) and SO_2 and NO_x (~4,400 and ~9,600 metric tons, respectively, during 2014–2044) that could lead to secondary $PM_{2.5}$. For GHG emissions, we estimated a reduction in CO_2 (~541,000 metric tons during 2014–2044), but an increase in methane (~5,000 metric tons during 2014–2044). Due to the high global warming potential of methane, this results in a net reduction of 434,000 CO_2 equivalents. Though not monetized, we also estimated reductions in emissions of CO and NMHC, which could lead to reductions in adverse health effects. The reduction of primary $PM_{2.5}$ emissions as well as SO_2 and NO_x emissions led to reductions in overall ambient $PM_{2.5}$ concentrations in Greater Dhaka ranging from 1.29E-05 to 1.01E+00 μg/m^3, depending on the year of analysis. Combining the concentration reductions with the concentration-response functions, background incidence rates, and population estimates, we estimated 798 fewer premature deaths for adults over age 30, 55 fewer premature deaths for children under age 5, and 819 fewer cases of chronic bronchitis in adults over age 25. Using our valuation approach, the total undiscounted monetized benefits that we were able to quantify were $116 million (2010 U.S. dollars), with a present discounted value of $9.5 million (2010 U.S. dollars, discounted to 2010 using a 12 percent discount rate).

Discussion

The results that we obtained are dependent on the available input data, our assumptions and the models used. First, for the current characterization of "with BRT" and "without BRT" emissions scenarios, we could not estimate all possible types of health benefits for all pollutants because epidemiological information on the relevant relationships than can be applied to Bangladesh is lacking. However, premature mortality, which was assessed in this study, is typically the most important health endpoint in benefits assessment. Note that it was not possible to estimate premature mortality benefits for people aged 5–30, which comprises more than half of the population in Bangladesh, because epidemiological evidence is lacking in this age group. Second, we assumed that the buses that would be removed from circulation as a result of the BRT project were large diesel buses and diesel minibuses. This assumption would result in larger $PM_{2.5}$ improvements than if CNG buses and CNG minibuses were removed. Third, while it was possible to analyze changes in bus counts associated with the project, there was little information on the impact of the BRT project on average vehicle speeds in the corridor or on the impact of the BRT project on vehicle types other than buses. It is unclear whether the change in vehicle speeds would increase or decrease the overall public health benefits estimate. Fourth, the BRT project does have an inspection and maintenance component, but information on this program was not detailed enough to enable estimation of its impact on emissions. Accounting for this program would likely have increased public health benefits.

Conclusions

This is the first effort to monetize the potential public health benefits of the BRT line in Greater Dhaka. We examined two health endpoints that might result from reduced exposure to $PM_{2.5}$ exposure: premature mortality (in children under age 5 and adults over age 30) and chronic bronchitis (in adults over age 25). We estimated public health benefits attributable to the BRT line, as well as effects on emissions of certain GHGs. These results are illustrative and limited to the assumptions we made and approach we took. A full characterization of the emissions profiles associated with the "without BRT" and "with BRT" conditions would refine these estimates.

1. Introduction

ADB is looking for solutions to help deal with stresses associated with current congestion and air pollution in Dhaka, Bangladesh. The urban growth that the Dhaka area is experiencing is likely to exacerbate these problems. ADB evaluated six transportation corridors in Greater Dhaka on the basis of their potential to organize urban development and support a mass-transit infrastructure. The most promising transportation corridor is located in the northern part of Dhaka's metropolitan area, with 20 percent of its length located within the Dhaka City Corporation (DCC) area, and 80 percent located within the Tongi and Gazipur Pourashavas Area (TGPA). Bus rapid transit (BRT) was recommended and selected as the best mass-transit mode for this corridor. See Exhibit 1-1 and Exhibit 1-2.

ADB conducted an initial economic analysis associated with the BRT line that evaluated savings in vehicle operating costs and journey time, as well as an increase in land values. The economic analysis was carried out for a 30-year evaluation period. The base-case scenario estimated benefits equal to a net present value of approximately $71 million (at a 12 percent discount rate). However, the initial economic analysis did not attempt to estimate potential public health benefits that might result from improvements in air quality associated with the BRT project, nor did it attempt to estimate effects on greenhouse gas (GHG) emissions as a result of the BRT project. The present analysis is the first attempt to quantify some of these public health and GHG benefits, though the analysis was limited by the information presently available for the study inputs.

The BRT project will result in emission reductions from replacing a portion of the existing diesel fleet with larger-capacity, cleaner compressed natural gas (CNG) buses and establishing improved emission standards and enforcement practices. While the BRT project does have an inspection and maintenance component, information on this program was not detailed enough to enable estimation of its impact on emissions. Thus, there will be environmental and public health benefits associated with the project, some of which are estimated in this report and some of which may be described as more information from the BRT project becomes available. The benefits estimated in this report include avoided mortality and morbidity due to improved air quality and reductions in GHG emissions.

Abt Associates Inc. performed this analysis to estimate public health benefits associated with the BRT project in Greater Dhaka. In this report, we describe our approach and present the results of our analysis. Due to the limited inputs, these results should be considered illustrative in nature. The approach is detailed in **Section 2**. The inputs to the specific models are summarized in **Section 3**. The results are presented in **Section 4**. Finally, a discussion of the results is provided in **Section 5**.

Exhibit 1-1: Locator Map of Bangladesh Showing Dhaka Division and BRT Study Area

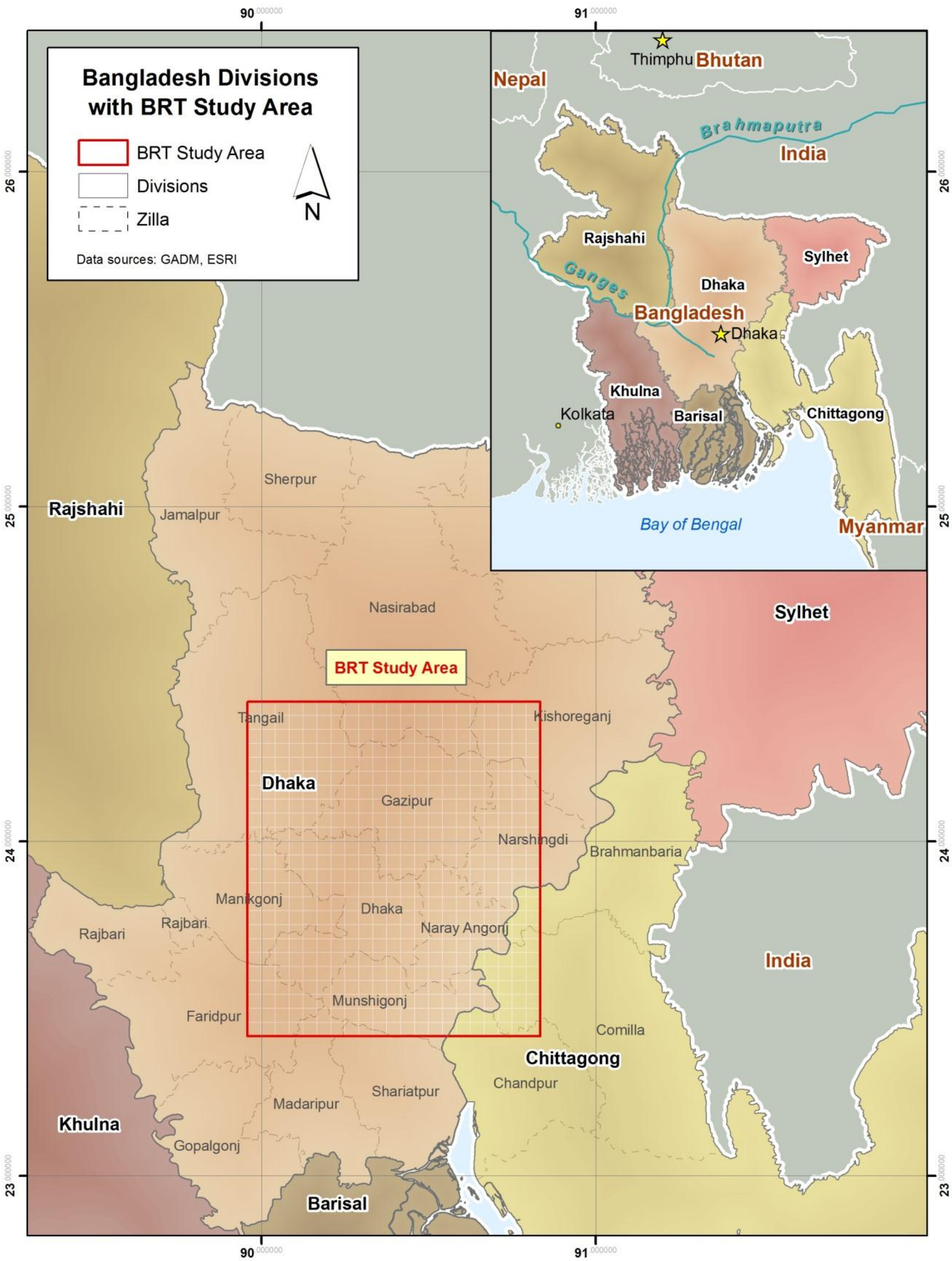
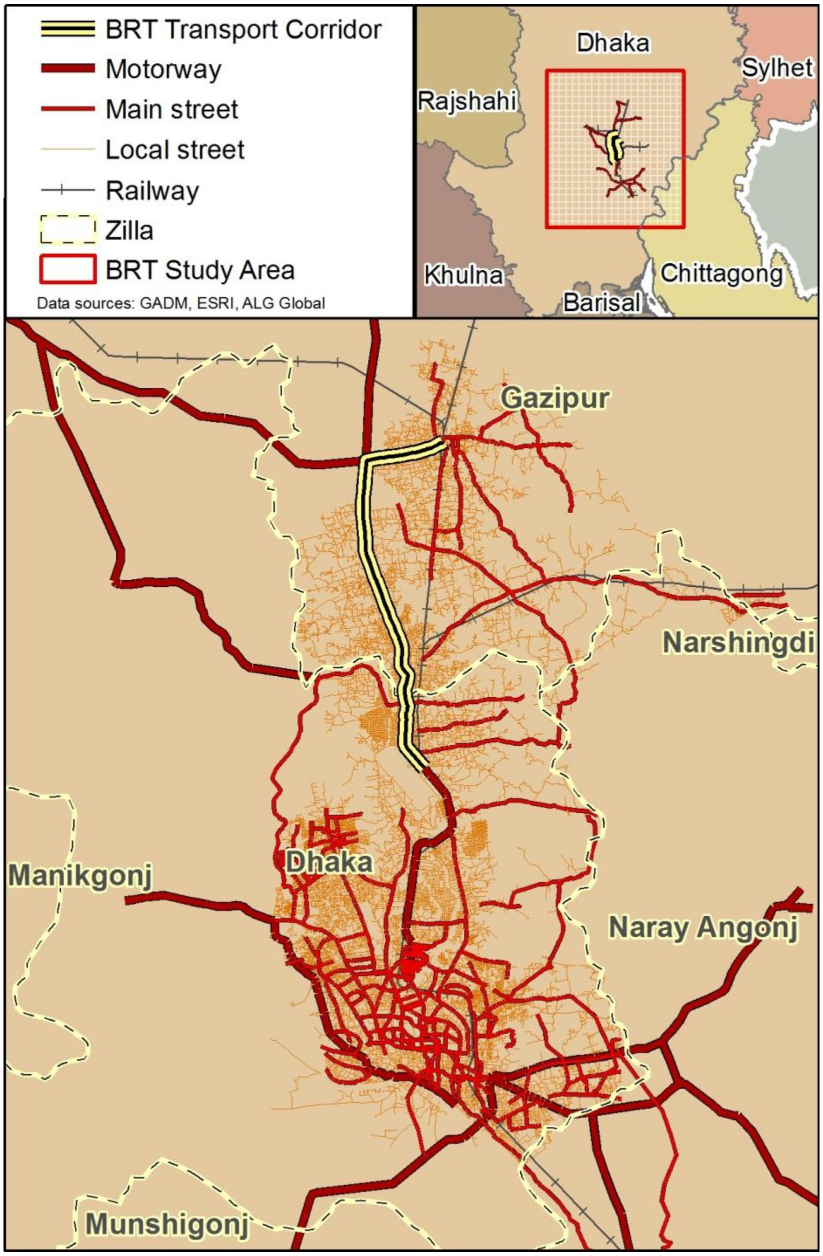


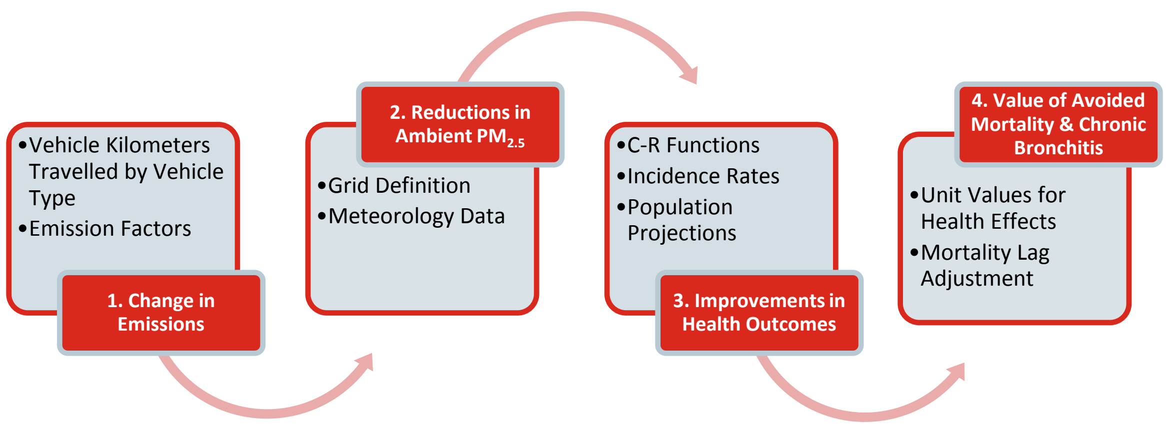
Exhibit 1-2: BRT Study Area in Detail, Including BRT Transport Corridor



2. Approach

We have separated the full description of our approach in this section from the actual inputs used for each of the models, which are provided in Section 3. The analytical components of the health benefits assessment model are provided in Exhibit 2-1. The subsequent subsections describe our general approach for quantifying each component, namely (1) the change in emissions, (2) reductions in fine particulate matter ($PM_{2.5}$), (3) improvements in health outcomes, and (4) the value of avoided premature mortality and chronic bronchitis.

Exhibit 2-1: Analytical Components of the Health Benefits Assessment Model



2.1 Change in Emissions

To fully characterize the "with BRT" and "without BRT" project scenarios for emissions, we would ideally have the following information for both scenarios:

1. The number of vehicles in each vehicle class (examples of classes are buses, minibuses, and non-motorized modes of transport);
2. The emission factors associated with each vehicle class (emission factors provide the emissions per kilometer traveled by the vehicle);
3. Estimates of vehicle-kilometers traveled (VKT) for each vehicle class;
4. Estimates of average vehicle speeds; and
5. Impact of the inspection and maintenance (i/m) program on emission factors, via establishing emissions standards and enforcement practices.

We used available traffic information from the BRT project preparation report, "Preparing the Greater Dhaka Sustainable Urban Transport Corridor," submitted to ADB in May 2011 by Advanced Logistics Group, BETS Consulting Services Limited, and Transports Metropolitans de Barcelona (referred to hereafter as the "project preparation report"). From the project preparation report and supporting documents, we were able to obtain some information on (1) the number of vehicles in each class and VKT for each vehicle class. We obtained information on (2) emission factors from on-road tests of certain vehicle types. We estimated (3) VKT as described in this section and in Section 3.1. We were not able to obtain information on (4) average vehicle speeds or (5) the potential impacts of the i/m program.

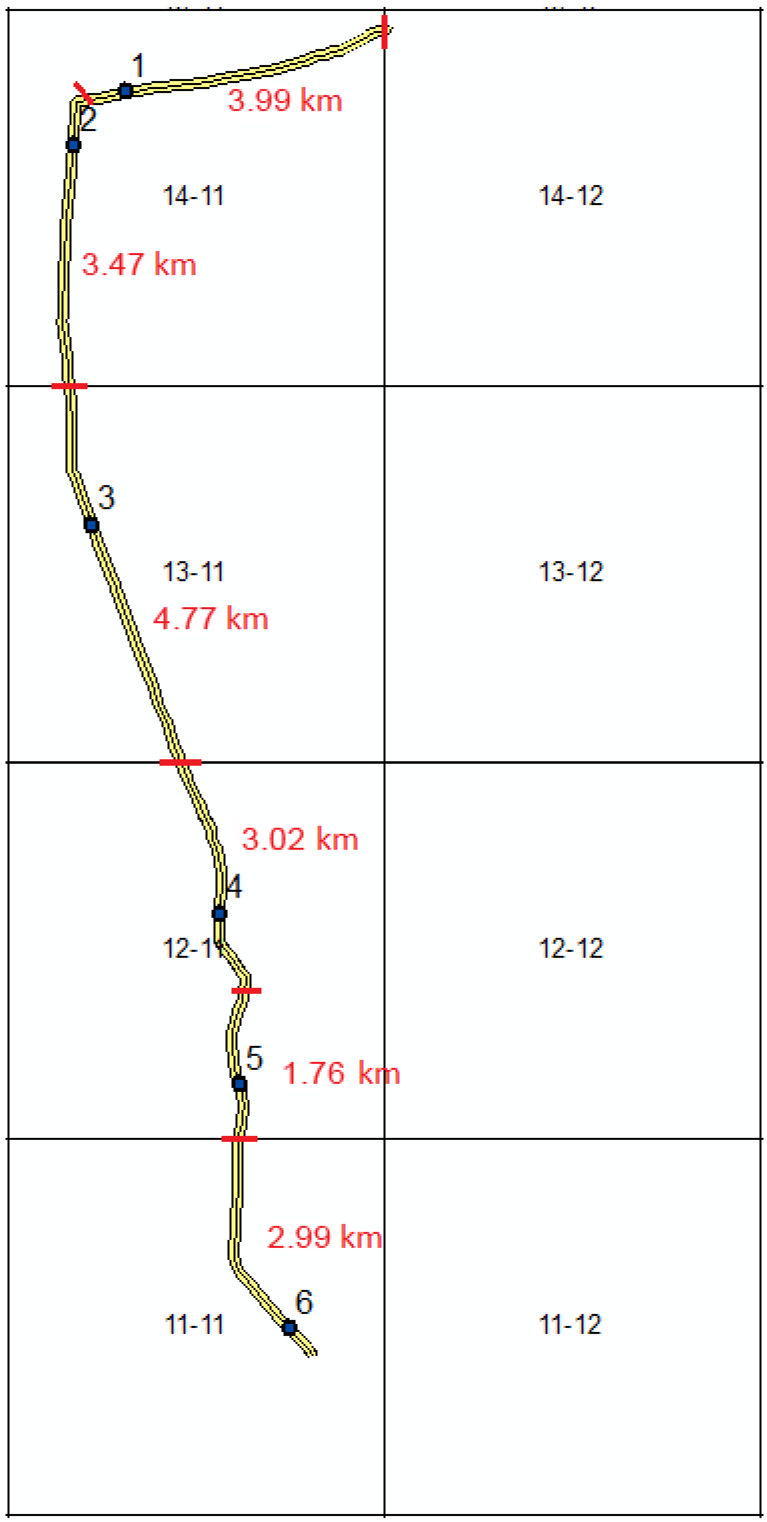
Using information available from the project preparation report, we calculated the change in emissions from the BRT line as a function of the change in VKT and the emissions factors for the vehicle classes.

In this analysis, we generated "with BRT" and "without BRT" estimates for large buses and minibuses. The VKT in the BRT corridor were calculated using data from the traffic count studies conducted as part of the project preparation report. The length of the corridor was divided into six segments, with one traffic count location in each segment. The segments were divided to include one traffic count monitor, as well as to correspond with the borders of our grid cells for the atmospheric modeling domain. The six segments, along with the traffic count locations included in the segments and the segment length, are shown in Exhibit 2-2 and Exhibit 2-3. To calculate vehicle-kilometers traveled, the vehicles at each traffic count location were assumed to traverse the full length of each segment.

Exhibit 2-2: Definition of BRT Road Segments, along with Traffic Count Location Included in the Segment

Road Segment	1	2	3	4	5	6
Traffic Count Location	Chow-Joy Rd	N3 @ Gazipur	National University	Cherag Ali Market	Tongi Bridge	Airport
Length (km)	3.99	3.47	4.77	3.02	1.76	2.99

Exhibit 2-3: BRT Corridor Segments and Traffic Count Locations



Notes: Numbers near the blue points correspond to the locations where traffic was measured
Distances shown in red are road segment distances (between the red hatch marks), calculated to line up with the boundaries of the atmospheric concentration modeling domain.
Cell numbers (e.g., 14-12) correspond to grid numbers in the atmospheric concentration modeling domain.

While there are many vehicle classes, the project preparation report did not contain information on vehicle classes other than buses. For vehicle classes other than buses, we expect that the BRT project might have differential impacts on local traffic and congestion. On one hand, over most of the length of the corridor, the BRT would reduce the number of traffic lanes available from three to two. This would be expected to increase congestion and divert traffic to other routes and/or modes of transport. On the other hand, it would improve signalization and traffic engineering, reduce bus traffic, restructure feeder operations, and establish a segregated lane for non-motorized traffic. These changes would be expected to reduce congestion, allowing more traffic on the road. For this analysis, we assumed that the traffic-suppressing and traffic-generating effects would cancel each other out, so that there would be no net change in VKT in vehicle classes other than large buses and minibuses.

We used the following information (from the project preparation report) to calculate the VKT by the buses and minibuses in the "with BRT" and "without BRT" scenarios: data on the present number of buses operating on each route, including the number of round trips per bus per day; the proposed changes to the existing bus routes due to the BRT; and estimates of BRT and non-BRT bus passengers per day in the corridor for the years 2014, 2019, 2024, 2034, and 2044.

For emission factors, extensive data are available on emissions from large diesel buses in the United States and Europe, but the bus characteristics and bus engine technologies used do not correspond to those common in Bangladesh and other developing Asian countries. As such, we used information from an emission testing study in Thailand (corroborated by a study in Mexico) that examined in-use diesel buses and minibuses typical of those found in Bangladesh. We also used emission factors from a test of an articulated CNG bus design meeting Euro 3 standards (produced in China) as representative of the buses that could be expected on the BRT line. Emission factors for SO_2 were calculated from the sulfur content of the fuel. For Bangladeshi natural gas, the sulfur content is negligible. For diesel fuel, the legal limit in Bangladesh is 0.5 percent sulfur by weight. For this analysis, we assumed that in the "with BRT" scenario, articulated CNG buses would replace a portion of conventional diesel buses and minibuses, based on VKT calculations.

To summarize, we estimated "with BRT" and "without BRT" scenarios for buses and minibuses, using information available from the project preparation report as well as the results of on-road vehicle testing. Our approach combined VKT estimates with emission factor estimates by vehicle class. The main difference between the "with BRT" and "without BRT" scenarios is that a portion of large diesel buses will be replaced with higher-capacity articulated CNG buses in the "with BRT" scenario. We made estimates for 2014 using data from the project preparation report, and we made projections for the years 2014, 2019, 2024, 2034, and 2044 based on estimates of BRT and non-BRT bus passengers.

2.2 Reductions in Ambient $PM_{2.5}$

We estimated the change in ambient $PM_{2.5}$ using the Atmospheric Transport Modeling System (ATMoS) model. This model allowed us to estimate primary $PM_{2.5}$, along with SO_2 and NO_x, which can be converted to secondary $PM_{2.5}$. While we could estimate the change in other pollutants, we focused on $PM_{2.5}$ given its predominance in benefit-cost analyses of other air pollution rules and well-studied concentration-response functions.

ATMoS is a meso-scale, three-layer, forward trajectory, Lagrangian puff-transport model.[1] The model was developed for sulfur pollution modeling, as part of the Regional Air Pollution Information System for Asia (RAINS-Asia).[2] ATMoS is applicable for use in regional and urban-scale studies, analyzing seasonal and annual air quality for long-term trends and evaluating "what-if" scenarios. It has been extensively applied for sulfur and particulate modeling studies in Asia for regional, national, and urban-scale studies, including a study of brick kiln emissions in Bangladesh.[3] ATMoS separately models PM_{10} and $PM_{2.5}$ fractions because of varying dry and wet deposition functions. In addition, secondary sulfate and nitrate contributions are added to the PM_{10} and $PM_{2.5}$ fractions.

2.3 Improvements in Health Outcomes

The improvements in health outcomes due to air pollution reduction are estimated based on concentration-response (C-R) functions. The C-R functions used here are empirically estimated relationships between average ambient concentrations of particulate matter (either $PM_{2.5}$ or PM_{10}) and the health endpoints of interest (e.g., mortality or chronic bronchitis) reported by epidemiological studies. This section first describes the basic method used to estimate changes in the incidence of a health endpoint associated with changes in $PM_{2.5}$, using a "generic" C-R function of the most common functional form. We then consider application of U.S.-based C-R functions to developing countries, following Ostro (2004).

The most commonly used C-R function is in log-linear form (equation 2-1). In the log-linear C-R function, the natural logarithm of the health incidence is a linear function of $PM_{2.5}$:

$$y = Be^{\beta x} \qquad \text{2-1}$$

where x is the ambient $PM_{2.5}$ concentration, y is the incidence of the health endpoint of interest at $PM_{2.5}$ concentration x, β is the coefficient on the ambient $PM_{2.5}$ concentration, and B is the incidence at $x = 0$ (i.e., when there is no ambient $PM_{2.5}$).

If we let x_0 denote the baseline ("without BRT") $PM_{2.5}$ concentration, and x_1 denote the control ("with BRT") $PM_{2.5}$ concentration, and y_0 and $y_1$denote the corresponding incidences of the health effect, we can derive the following relationship between the change in x, $\Delta x = x_0 - x_1$, and the corresponding change in y, Δy, from equation 2-1:

$$\Delta y = y_0 - y_1 = y_0\left(1 - e^{-\beta \Delta x}\right) \qquad \text{2-2}$$

The difference in health effects incidence can also be calculated indirectly using the concept of relative risk. The relative risk (RR) is an epidemiological measure that can characterize the comparative health effects associated with a particular air quality comparison. Given a C-R function of the form shown in equation 2-1, the RR can be expressed as

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1 ATMoS is an open source model, available at http://urbanemissions.blogspot.com/2009/01/tools-for-air-pollution-analysis.html.

2 Developed and distributed by the International Institute of Applied Systems Analysis (IIASA), Laxenburg, Austria, http://www.iiasa.ac.at.

3 The study is accessible at http://www.urbanemissions.info/model-tools/sim-air/dhaka-bangladesh.html.

$$RR = \frac{y_0}{y_1} = e^{\beta \cdot (x_0 - x_1)} = e^{\beta \cdot \Delta x} \qquad \text{2-3}$$

The difference in the health effects incidence, Δy, corresponding to a given difference in ambient $PM_{2.5}$ concentration, Δx, can then be calculated based on this RR as

$$\Delta y = y_0 - y_1 = y_0(1 - \frac{1}{RR}) \qquad \text{2-4}$$

Relative risks relating adverse health effects resulting from air pollution levels in the United States are often well established. However, it may not be appropriate to apply these RRs to developing countries because of the higher $PM_{2.5}$ concentrations generally experienced in developing countries. Applying RRs developed for lower $PM_{2.5}$ concentrations to higher $PM_{2.5}$ concentrations can result in implausibly high numbers of health effects attributable to air pollution. To obtain more realistic estimates, Ostro (2004) recommended using a log-linear function for exposure (equation 2-5), whose slope flattens at higher concentrations. A value of 1 was added to the concentration (x) term in the formula to ensure that the logarithm of this term is defined at $x = 0$.

$$y = Be^{\beta \cdot \ln(x+1)} \qquad \text{2-5}$$

Based on equation 2-5, the relative risk can be expressed as:

$$RR = \frac{y_0}{y_1} = \left(\frac{x_0+1}{x_1+1}\right)^{\beta} \qquad \text{2-6}$$

The use of equation 2-6 requires air quality data in the baseline and control scenarios. In estimating the reductions in ambient $PM_{2.5}$, the Δx was obtained from the air quality modeling output (baseline, or “without BRT,” concentrations minus control, or “with BRT,” concentrations) and the baseline air quality data (i.e., x_0) was obtained from monitoring data reported in Begum et al. (2010) for the year 2006, corresponding to the year the meteorology data was available. With the baseline and change in air quality, we then calculated the control air quality (i.e., x_1).

2.4 Value of Avoided Premature Mortality and Chronic Bronchitis

Estimating the value of avoided adverse health impacts associated with air pollution involves calculating the total number of cases of various health effects (as described in Section 2.3), and then multiplying each by a corresponding *unit value*. The unit value represents the cost of a single case of that health adverse effect (or, correspondingly, the benefit of avoiding a single case) due to air pollution. In this report, we looked at unit values for premature mortality and chronic bronchitis.

The value of a statistical life (VSL) represents the willingness to trade income for small changes in mortality risks. In the developed countries, VSL values are typically derived from either contingent valuation studies or meta-analyses of occupational risk studies. Mahmoud (2009) was the only primary contingent valuation study that has looked at the willingness to pay (WTP) for changes in mortality risk in Bangladesh.[4] Although Mahmoud (2009) does estimate WTP for changes in

[4] Mahmoud (2009) surveyed 780 random rural household heads in Netrokona, Mymensingh, Manikganj, Gazipur, and Narayanganj districts and found that training related to probability and risk concepts affected respondents’ willingness to pay for mortality risk reductions.

mortality risks, we could not use this study to develop VSL estimated for Bangladesh. This is because the study focused in WTP for a 25 percent or a 50 percent reduction in risks that would be attained through a vaccination program. Thus, the mortality risk reductions evaluated in Mahmoud (2009) were much higher than those that would be expected from improvements in air quality. Therefore, the VSL based on Mahmoud (2009) would underestimate the VSL for the purpose of our study. In addition, the survey respondents were rural households and may not represent Greater Dhaka, which is the project site of the current study. We therefore used a benefit transfer approach that consists of extrapolating a relevant VSL estimate from the United States to generate a VSL estimate for Bangladesh.

There were no studies that looked at the WTP for an avoided case of chronic bronchitis in Bangladesh. We identified several primary studies that estimated the cost of air pollution-related illness in Bangladesh (Chowdhury and Imran, 2010) and in India (Gupta, 2008; Murty et al., 2003). However, these studies looked at the overall cost of air pollution-related illness and did not provide the unit cost estimates for particular health effects. Given that there were no readily applicable unit cost estimates to value cases of chronic bronchitis in Bangladesh based on primary studies, we relied on the benefit transfer approach to value our morbidity endpoint as well.

2.4.1 Benefit Transfer Approach

We have followed the approach of Robinson and Hammitt (2009) to derive a VSL estimate and a WTP per case of chronic bronchitis avoided using the U.S. values. Robinson and Hammitt (2009) estimated VSL for Sub-Saharan Africa by extrapolating values from the United States, with adjustments for differences in income between the two regions. The key assumptions of their method were that (1) WTP depends on income and (2) mortality and morbidity risk reductions are a luxury good in developing countries.[5]

We use the following relationship to transfer values from the United States to Bangladesh in time period t:

$$V_{B,t} = V_{US,t}\left(I_{B,t}/I_{US,t}\right)^{e} \qquad \text{2-7}$$

where $V_{B,t}$ is an estimated value (a VSL or a WTP per case of chronic bronchitis avoided) for Bangladesh; $V_{US,t}$ is a corresponding U.S. estimate; $I_{B,t}/I_{US,t}$ is the ratio of per capita income in Bangladesh to per capita income in the United States; and e is Bangladesh's income elasticity of WTP for mortality or morbidity risk reductions. For luxury goods, $e > 1$ should be used. Smaller values of e will result in WTP estimates that are a larger fraction of income per capita in the developing country to which WTP is being transferred (Hammitt and Robinson (2011)).

Note that the benefit transfer method may result in biased estimates of the unit values for Bangladesh because behavioral responses of households differ between developed and developing countries.[6]

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[5] This assumption is at variance with the primary study by Mahmoud (2009), who estimated the income elasticity to be less than 1, suggesting that risk reduction is a normal good in Bangladesh.

[6] In addition to income, VSL may vary due to a host of other reasons not captured in our present approach. These factors include characteristic features of individuals (e.g., age, life expectancy, health conditions). The nature of the risk also affects VSL estimates. For example, mortality risks associated with illness could

2.4.2 Income Growth Adjustments

As mentioned above, WTP for risks reductions is a function of real income. The present analysis is concerned with valuing cases of avoided premature mortality and chronic bronchitis from 2014 through 2044. Therefore, the current time VSL and WTP per case of chronic bronchitis avoided derived from the U.S. values need to be projected. We use equation 2-8 to project the values of interest to year $t+n$ from the base year t:

$$V_{B,t+n} = V_{B,t}(1+g_I)^{ne} \qquad \text{2-8}$$

where $V_{B,t}$ is an estimated value at base year t; $V_{B,t+n}$ is this value n years later; g_I is the annual compound per capita income growth rate in Bangladesh; and e is income elasticity of WTP for mortality or morbidity risk reductions.

In our modeling framework, we assume that the same elasticity e is used to transfer benefits from the United States, and to adjust the WTP for future income growth. However, as income changes over time, it reflects shifts in individual preferences. Thus, our implicit assumption is that this elasticity will remain the same between 2010 and 2044, despite the fact that income per capita in Bangladesh is projected to grow. That is, we assume that individual preferences in Bangladesh will not change over the project life. This assumption may or may not be true, and could thus bias our projected VSL estimates for Bangladesh.

2.4.3 Mortality Lag Adjustment

There is uncertainty about the portion of the mortality effects due to changes in long-term $PM_{2.5}$ exposure that occurs in a single year versus subsequent years. The air pollution evidence suggests that, although there are greater impacts in the first year, some of the mortality effects are experienced in subsequent years (SAB, 2004). Following SAB recommendations, EPA assumes that the premature mortality effects due to changes in long-term $PM_{2.5}$ exposure are distributed over time. Specifically, EPA uses a 20-year lag structure, with 30 percent of the total estimated mortality effects in the first year, 50 percent of the effects distributed evenly among years 2 through 5, and the remaining 20 percent distributed evenly among years 6 through 20 (U.S. EPA, 2011). We have followed EPA's assumption of a 20-year mortality lag in developing our benefit estimates.

The mortality lag adjustment is important in the context of valuing cases of premature mortality avoided because the benefits occurring in the future should be discounted. In the present analysis, we estimate the cases of premature mortality avoided for each year of the project analysis period 2014–2044. Existence of a lag implies that the premature deaths avoided due to emission reductions in 2019, for example, will be experienced in 2019-2039. Similarly, deaths avoided due to emission reductions in 2044 will be experienced in 2044-2064. This implies a much longer discounting time frame, which substantially decreases the present discounted value (PDV) of mortality benefits associated with long-term $PM_{2.5}$ exposure reductions for individuals over age 30.

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be different from that associated with injuries. Furthermore, the WTP may vary with age. For example, older people may be more risk averse than young people, and therefore may have a higher WTP for reducing mortality risks.

3. Inputs

This section contains the inputs to the relevant models. The general approach was described in the previous section.

3.1 Change in Emissions

The change in emissions from the BRT line is a function of the change in vehicle-kilometers traveled (VKT) and the emissions factors of the vehicle types. We obtained information to help estimate the VKT for vehicle classes from the BRT project preparation report, "Preparing the Greater Dhaka Sustainable Urban Transport Corridor," submitted to ADB in May 2011 by Advanced Logistics Group, BETS Consulting Services Limited, and Transports Metropolitans de Barcelona.

3.1.1 Vehicle-Kilometers Traveled

We estimated the VKT for three vehicle classes: articulated CNG buses, diesel buses, and diesel minibuses. In the "with BRT" project scenario, we assumed that all three types will travel on the BRT lane, but that only the diesel buses and minibuses will travel on the non-BRT lanes. The "without BRT" project scenario includes only diesel buses and minibuses. For the articulated CNG buses, occupancy was assumed to be 70 passengers. For the large diesel buses, it was assumed to be 40 passengers. It was assumed that the number of minibuses would decrease with the BRT project.

The changes proposed in the existing bus route structure (including for large buses and minibuses) due to the BRT were described in some detail in Chapter 11 of the project preparation report. Maps of the affected routes were also provided in this chapter. Data on the number of buses presently operating on each route and the number of round trips per bus per day were provided in Chapter 9. Using these data, we constructed tables showing the number of diesel buses and minibuses on each bus route that would traverse each of the six corridor segments in both the "with BRT" and "without BRT" scenarios in 2014. The results are plotted in Exhibit 3-1 for large buses and in Exhibit 3-2 for minibuses. Overall, construction of the BRT would have relatively little effect on the numbers of large buses traversing the corridor, but would reduce the numbers of minibuses by approximately 50 percent.

Exhibit 3-1: Effect of BRT on VKT by Diesel Large Buses by Corridor Segment in 2014

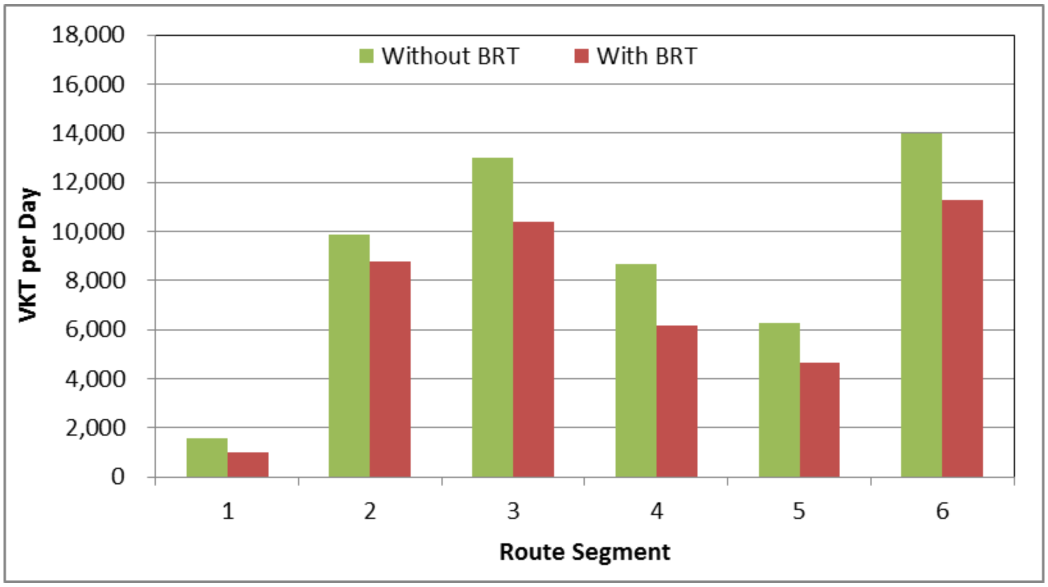
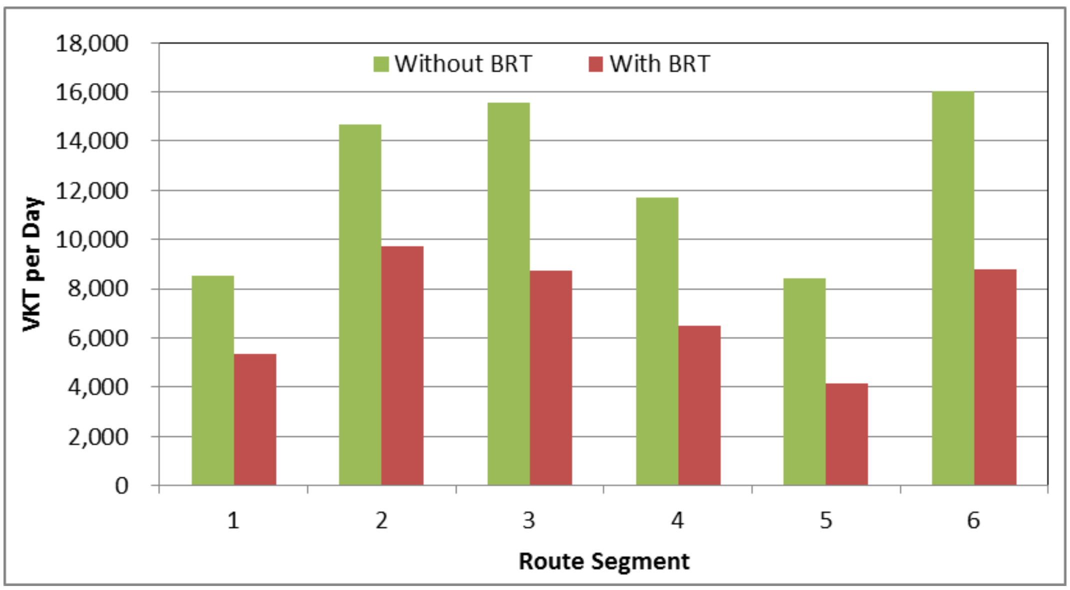


Exhibit 3-2: Effect of BRT on VKT by Diesel Minibuses by Corridor Segment in 2014



Vehicle-kilometers traveled by the articulated CNG BRT buses were calculated using the estimates for the "enhance elevated" scenario given in Chapter 15 of the project preparation report. Those data included estimates of BRT and non-BRT bus passengers per day in the corridor for the years 2014, 2019, 2024, 2034, and 2044. We estimated the number of trips for the BRT buses by assuming an average occupancy of 70 passengers per bus trip, or 50 percent occupancy.

For the diesel buses not traveling on the BRT lane (non-BRT buses), we estimated baseline 2014 VKT as discussed earlier. This baseline value included a large number of buses on intercity trips, or otherwise not included in the route structure. For years after 2014, we assumed that the growth in the number of estimated non-BRT bus passengers would result in a corresponding increase in the number of large bus trips through the corridor, with an increase of 40 passengers per day resulting in one additional large bus trip. The resulting estimates are shown in Exhibit 3-3. To calculate additional VKT, each additional large bus trip was assumed to extend the length of the corridor.

Exhibit 3-3: Additional Bus and BRT Passengers and Bus Trips

	Passengers/Day in "with BRT" Project[a]			Additional "with BRT" Project[b]			Additional "without BRT" Project[c]	
Year	Diesel Large and Mini-buses	Articu-lated CNG	Total	Large Diesel Pax[d]	Large Diesel Trips[e]	Articu-lated CNG Trips[f]	Large Diesel Pax[d]	Bus Trips[e]
2014	372,644	114,300	486,944	0	0	1,633	0	0
2019	423,135	277,535	700,670	50,491	1,262	3,965	213,726	5,343
2024	469,345	325,730	795,075	96,701	2,418	4,653	308,131	7,703
2034	525,987	372,591	898,578	153,343	3,834	5,323	411,634	10,291
2044	610,179	415,939	1,026,118	237,535	5,938	5,942	539,174	13,479

Notes:

[a] Includes articulated CNG buses, diesel large buses, and diesel minibuses.

[b] Includes large diesel buses and articulated CNG buses (diesel minibuses are not expected to grow).

[c] Assumes that total capacity of "with BRT" project estimates will be handled by diesel large buses.

[d] Pax = passengers.

[e] Assuming 40 passengers per bus trip.

[f] Assuming 70 passengers per bus trip.

While it is not possible to directly compare the number of buses calculated with the VKT approach, the project preparation report estimated that 34 articulated CNG buses would be introduced in the first decade of the BRT project, 46 in the second decade, and 62 in the third decade (Section 13.2 of the project preparation report, Scenario C).

3.1.2 Emission Factors

Since the VKT estimates addressed only the change in VKT by minibuses and large buses, the emission factors required to estimate the air quality impact are limited to those two vehicle types. The Government of Bangladesh is encouraging the conversion of diesel buses and minibuses in Dhaka and Chittagong to CNG, and information suggests that many transit buses currently operating in Dhaka use CNG. (See, for example, presentation by Roychowdhury, 2011.) The new articulated buses for the BRT project were assumed to use only CNG fuel. For the non-BRT buses, however, it was unclear whether the reduction in VKT in the corridor would affect CNG buses, or if the buses to be withdrawn would be the remaining diesels. We assumed the latter. If instead only CNG buses would be withdrawn, there would be negligible impact on $PM_{2.5}$ emissions.

The project preparation report referred to an articulated CNG bus design produced in China as representative of the buses that could be expected in the BRT project. This bus had an engine meeting Euro 3 standards. In a study in Mexico City, a very similar articulated bus was subjected to emission testing under simulated BRT operating conditions (Weaver and Balam-Almanza, 2006). These measurements included both methane and non-methane hydrocarbons (HC). The data from that study were averaged to produce the CNG bus emission factors shown in Exhibit 3-4. For the articulated CNG bus, one of three tests with methane and non-methane HC data showed much higher emissions than the other two. This was likely the result of occasional misfiring due to maladjusted air-fuel ratio. Since such problems are unlikely to be prevalent in actual operation, we weighted this test at only 5 percent when calculating the averages.

Extensive data are available on emissions from diesel buses in the United States and Europe, but the bus characteristics and bus engine technologies used do not correspond to those common in Bangladesh and other developing Asian countries. Emission testing conducted by the Thai Department of Environment (Hunt et al., 2000) did address emissions from in-use buses typical of those found in Bangladesh, as did another project in Mexico City (Balam-Almanza et al., 2006). In general, these two studies yielded similar results. We based the emission factors for diesel large buses and minibuses in Bangladesh on the Thai study results, which are the averages from tests of 15 pre-emission control diesel buses operating in Bangkok, also shown in Exhibit 3-4.

Exhibit 3-4: Estimated Emission Factors for Buses in the BRT Corridor

	Emissions - g/km						
Vehicle Class	**$PM_{2.5}$**	**NO_x**	**SO_2**	**CO**	**CO_2**	**Methane**	**NMHC**
Articulated CNG bus (BRT)	0.02	11.9	0.00	2.6	1,212	7.6	0.32
Diesel large bus (BRT and non-BRT)	1.80	17.6	4.36	9.9	1,363	0.2	3.15
Minibus diesel (BRT and non-BRT)	0.90	8.78	2.18	4.95	682	0.1	1.57

Though not presented above, Balam-Almanza et al. (2006) also evaluated emissions factors for CNG minibuses and large CNG buses. The $PM_{2.5}$-related emissions factors for these types of vehicles were similar to those for the articulated CNG buses, except that the NO_x emission factor for the articulated CNG buses was twice as high as those of the other CNG buses. For GHG-related emissions, the methane emission factor for large CNG buses was approximately 30 percent higher than those for articulated CNG buses.

3.2 Reductions in Ambient $PM_{2.5}$

There are three main inputs required for the ATMoS model. The first input to the ATMoS model is the extent and resolution of the domain. As described in Section 3.3.3, we used population data from the Gridded Population of the World (GPW) dataset developed by Socioeconomic Data and Applications Center (SEDAC) of Columbia University.[7] The dataset provides population by 2.5 arc-minute grid cells. We chose a subset of the GPW grid as our modeling domain. Specifically, we created a domain with a resolution of 1.00032 x 0.87528 decimal degrees, or approximately 100 square kilometers. This domain consisted of a 24-cell by 21-cell grid, with each cell having a resolution of 0.04168 x 0.04168 decimal degrees. We centered our domain around the location of the BRT line, based on ADB's GIS shape file containing information on the catchment area. Exhibit 3-5 shows our modeling domain and the BRT line.

The second input, reductions in emissions, came from our emissions estimates for each corridor segment (described in Section 3.1). We matched the route segments to the domain grid cells as shown in Exhibit 3-5.

The third input is meteorological data for the area modeled. We obtained 2006 meteorological data from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis Data.[8] The data included six hourly precipitation values, mixing height, and wind vector values for each day in 2006.

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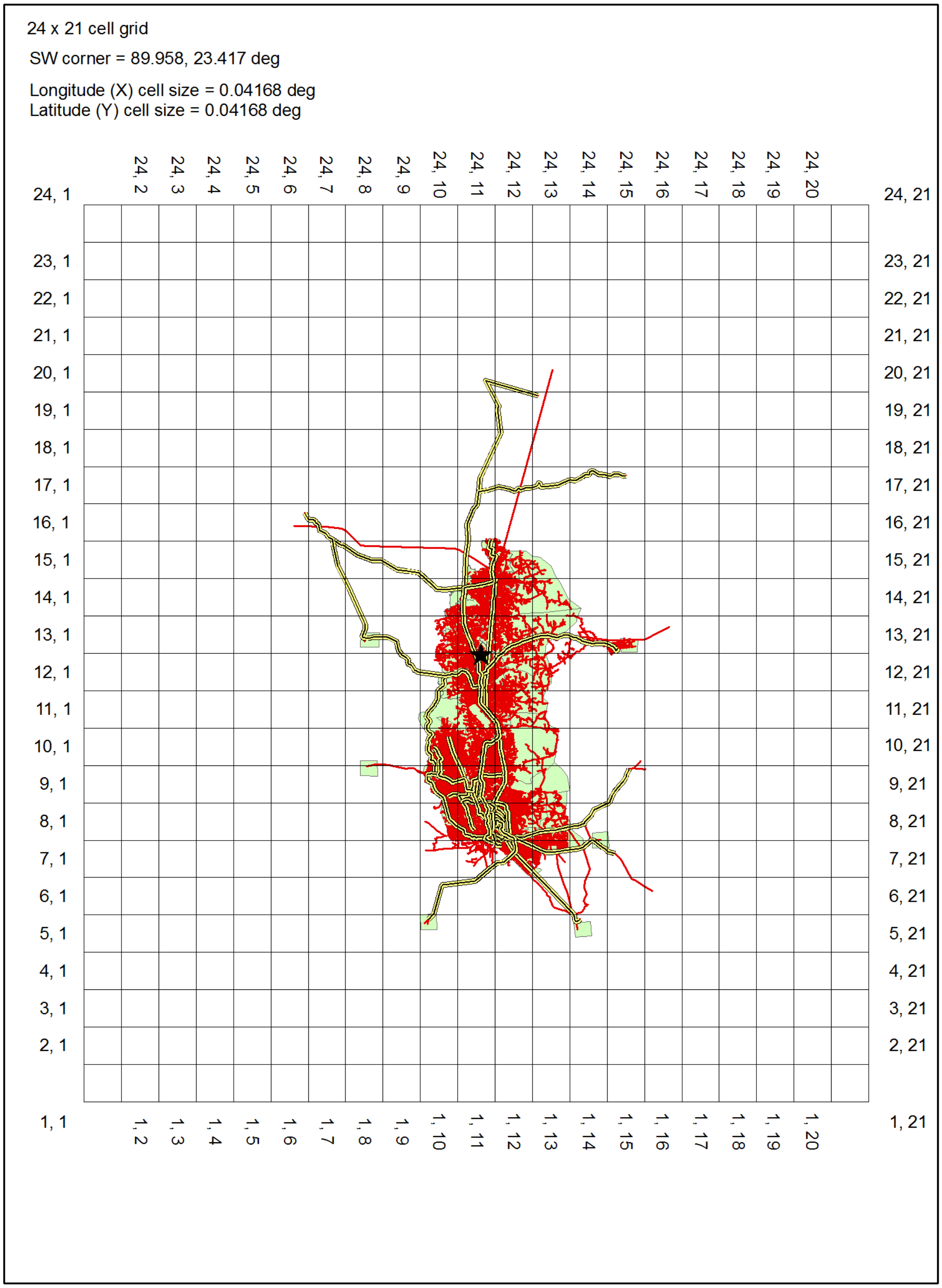
[7] See http://sedac.ciesin.columbia.edu/gpw/index.jsp.

[8] NCEP Reanalysis Data are at http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml.

Exhibit 3-5: The Atmospheric Modeling Domain



3.3 Improvements in Health Outcomes

3.3.1 Selection of Health Outcomes and C-R Functions

Given the substantial number of health endpoints and studies addressing $PM_{2.5}$ effects, we included in this analysis only the better-understood (in terms of health consequences) health endpoint categories for which the weight of the scientific evidence supports the inference of a likely causal relationship between $PM_{2.5}$ and the effect category.

Regarding mortality, the evidence suggests that the short-term exposure studies capture only a small portion of the overall health effects of long-term, repeated exposure to PM. Adverse health effects are dependent on both exposure concentrations and length of exposure, and long-term exposures have larger, more persistent cumulative effects than short-term exposures (HEI, 2010). Cohort studies, which examine long-term exposure effects, are not available for Asia. Following the approach suggested by Ostro (2004), we made adjustments to the U.S.-based C-R functions in order to derive relevant estimates of exposure effects for Bangladesh (see Section 2.3).

In this analysis, we selected two cohort studies for use in estimating adult mortality, Laden et al. (2006) and Krewski et al. (2009). Laden et al. (2006) estimated a relative risk (1.16) and 95 percent confidence interval (1.07–1.26) associated with a $PM_{2.5}$ change in annual mean exposure of 10 $\mu g/m^3$. Krewski et al. (2009) reported a relative risk (1.06) and 95 percent confidence interval (1.04–1.08) for a 10 $\mu g/m^3$ increase in the average of $PM_{2.5}$ exposure level. As Laden's estimates are larger than Krewski's, we used the former as our main estimate, but conducted a sensitivity analysis of the latter. To apply Laden and Krewski's estimates to the study area of this analysis, we made adjustments using Ostro (2004) as described in Section 2.3. Specifically, Ostro (2004) reported adjusted coefficients for mortality C-R function using the results of Pope et al. (2002). (See Table 3 in Ostro, 2004.) We then calculated the ratio of the unadjusted estimate from Laden to the unadjusted estimate from Pope et al. (2002). Finally, we multiplied the ratio by the adjusted Pope coefficient to obtain the adjusted coefficient for Laden's estimates.[9] We made similar adjustments to the Krewski estimate.

For child mortality, cohort studies are not available. Meanwhile, daily time-series studies in several cities of developing countries have demonstrated associations between PM_{10} and mortality for those under 5 years old. Ostro (2004) summarized five such studies (see Table 2 of Ostro, 2004) and conducted a meta-analysis to derive the overall effect of PM_{10} on child mortality. Ostro's meta-analysis reported that a 10 $\mu g/m^3$ increase in ambient PM_{10} concentration would result in a 1.66 percent (95 percent CI=0.34–3.0 percent) mean increase in daily respiratory mortality in children 0–4 years of age. As we focused on $PM_{2.5}$ in the current analysis, we converted the estimated coefficient to a $PM_{2.5}$ coefficient using a ratio of $PM_{2.5}$ to PM_{10} of 0.5, as suggested for developing countries by Ostro (2004).

As for acute morbidity, epidemiological studies in China reported contradictory findings for the relationship between hospital admission and exposure to $PM_{2.5}$ (HEI, 2010, p. 106, Figure 45). Thus, we have not included acute morbidity in this analysis.

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[9] We have proved that the relationship between the unadjusted and adjusted coefficients is linear.

For chronic morbidity, HEI (2010) reviewed a large number of studies (see Section VI in HEI, 2010), and concluded: “Overall, the available studies provide evidence that long-term exposure to ambient air pollution in Asia is associated with chronic respiratory illness, reduced lung function, lung cancer, and adverse reproductive outcomes” (HEI, 2010, p. 173). In this Dhaka analysis, we have included chronic bronchitis as illustrative of this chronic morbidity effect. Although we could not find an epidemiological study on chronic bronchitis in Bangladesh, we identified one published Chinese study, Jin et al. (2000), which reported an odds ratio of 1.06 (95 percent CI 1.01–1.08) associated with a 10 μg/m^3 increase in PM_{10}. Similar to respiratory mortality, we converted the estimated coefficient to $PM_{2.5}$ using a ratio of $PM_{2.5}$ to PM_{10} of 0.5.

Exhibit 3-6 summarizes the selected epidemiological studies, health endpoints, and C-R functions – including the estimated coefficient (“beta”) of $PM_{2.5}$ in the function and the standard error of the estimate, the location(s), and age range covered.

3.3.2 Baseline Incidence Rates

The data source for all-cause mortality is the Bangladesh Bureau of Statistics (http://www.bbs.gov.bd). We first downloaded the age-specific life table for the year 2007[10] and calculated age-specific mortality rates.

$$ {}_{n}M_x = \frac{{}_{n}q_x}{n - {}_{n}q_x(1 - {}_{n}a_x)} \qquad 3\text{-}1 $$

where ${}_{n}M_x$ is the age-specific morality rate; ${}_{n}q_x$ is the probability of dying at age x in a time interval with width n; and ${}_{n}a_x$ is the average proportion of the year lived by those who die.[11]

To obtain the all-cause mortality rate for adults, we used population distributions by age group from the Bangladesh Bureau of Statistics. For example,

$$ M_{25+} = \frac{M_{25-29} \cdot A_{25-29} + M_{30-34} \cdot A_{30-35} + \cdots + M_{80+} \cdot A_{80+}}{A_{25-29} + \cdots + A_{80+}} \qquad 3\text{-}2 $$

where M_{25+} is the mortality rate for age 25+; A_{25-29} represents the population in the 25-29 age group.

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10 The most recent available data are for the year 2008, but there are obvious errors in the 2008 data.

11 Usually, it is assumed that death occurs uniformly across time and that on average people will live 0.5 of the interval before death. However, there are some cases where we know that death does not occur uniformly across time within age groups. For example, for those aged under 1 we assume that the average proportion of the year lived by those who die is 0.1.

Exhibit 3-6: Summary of $PM_{2.5}$ Concentration-Response Functions and Baseline Incidence Rates

Health Endpoint	Study Upon Which Beta is Based	Study Location	Study Age Range	Share of Bangladesh Population in Age Range[c]	Relative Risk / Odds Ratio Function[d]	Beta	Std. Err.	Baseline Incidence Rate (per 1000)
Mortality, All Cause (long-term exposure)	Laden et al. (2006)[a]	6 U.S. cities	30+	35.71%	$RR = \left(\frac{x_0 + 1}{x_1 + 1}\right)^{\beta}$	0.26510	0.07113	17.3[c]
	Krewski et al. (2009)[a]	116 U.S. cities	25+	43.29%		0.10408	0.01642	12.3[c]
Mortality, Respiratory (short-term exposure)	Ostro (2004)[b] – Meta-analysis	Brazil, Mexico, Thailand	< 5	11.09%	$RR = e^{\beta \cdot (x_0 - x_1)}$	0.00332 per µg/m^3	0.00136 per µg/m^3	3.9[c]
Chronic Bronchitis	Jin et al. (2000)[b]	Benxi, China	25+	43.29%	$OR = e^{\beta \cdot (x_0 - x_1)}$	0.00900 per µg/m^3	0.00320 per µg/m^3	5.6[e]

[a] These studies were conducted in the United States. The betas reported in the table are adjusted as described in Section 2.3 and Section 3.3.
[b] Note that these studies measured PM_{10}, and that we converted the concentration-response functions to $PM_{2.5}$ using a $PM_{2.5}$ to PM_{10} ratio of 0.5, as suggested for developing countries by Ostro (2004).
[c] Bangladesh Bureau of Statistics, 2008 data.
[d] x_0 denotes the baseline ("without BRT") $PM_{2.5}$ concentration, and x_1 denotes the control ("with BRT") $PM_{2.5}$ concentration. The data for x_0 were obtained from monitoring data reported in Begum et al. (2010). We also estimated the change in air quality using air quality modeling. With the baseline and change in air quality, we then calculated the control air quality (i.e., x_1).
[e] Estimated from Xu and Wang (1993, p. 1519) and Huang and Li (2001)

For respiratory mortality, we identified Adjuik et al. (2006), which reported the respiratory mortality rate for children under 5 years old in Matlab, Bangladesh. As the Matlab area has been involved in Health and Demographic Surveillance System (HDSS) programs for years, we were concerned that the incidence rates in Matlab were not representative of the general population. Instead of using the Matlab incidence rates directly, we calculated the ratio of Matlab respiratory mortality rate in children to Matlab all-cause mortality rate in children and multiplied this ratio with the all-cause mortality rate in children obtained from the Bangladesh Bureau of Statistics. As expected, our estimated respiratory child mortality (0.0039) is higher than that in the Matlab area (0.0030).

For chronic bronchitis, the incidence rate in Bangladesh is not available. We approximated the annual incidence of chronic bronchitis by dividing the prevalence rate by the average duration of the illness (World Bank, 2007).

$$\textit{Incidence rate} = \textit{Prevalence rate} \,/\, \textit{Duration of illness} \qquad \text{3-3}$$

As we could not find the prevalence rate of chronic bronchitis in Bangladesh, we used the prevalence rate in other developing countries. Xu and Wang (1993, p. 1519) reported a prevalence rate for chronic bronchitis of 13 percent in their random sample from three districts in Beijing. Menezes et al. (1994) reported a prevalence of 12.7 percent from a survey of 1,053 adults over 40 years old in Brazil. These estimates are consistent and may be representative of the chronic bronchitis prevalence rate in developing countries. In this analysis, we have used the average of the above two estimates for Bangladesh (i.e., 12.85 percent).

We also needed the duration of chronic bronchitis to estimate the incidence rate. The World Bank (2007) used 23 years as the average duration. Huang and Li (2001) reported a range of 17–35 years in China. Using equation 3-3 and duration estimates of 17–35 years, we obtained an upper and lower bound estimate of incidence rates of 7.6 and 3.7 per 1,000 people. In our analysis, we employed the average, or 5.6 per 1,000 people.

3.3.3 Population

We obtained population estimates in each cell of the modeling domain from the GPW dataset developed by SEDAC of Columbia University.[12] The dataset provides population by 2.5 arc-minute grid cells and includes projections for 2010 and 2015. The data are based on collections of census data at the sub-national level from countries mainly during 1990–2000. Population data for Bangladesh come from the 1991 and 2001 Census. We used SEDAC's short-term future projection for 2015 in our analysis.[13] The 2015 gridded populations were used as the baseline, from which gridded population projections were generated for 2014–2044. To be consistent with ADB's project preparation report, we used an annual compound growth rate of 3 percent for population projections.

[12] See http://sedac.ciesin.columbia.edu/gpw/index.jsp.

[13] This projection is based on applying the same growth rate that occurred between the last two censuses in each country (i.e., these projections do not account for complexities such as urban-rural migrations, etc.).

3.4 Value of Avoided Premature Mortality and Chronic Bronchitis

The approach for estimating the benefits of avoided premature mortality and chronic bronchitis for Bangladesh is discussed in Section 2.4. This section summarizes the benefit transfer results for the VSL and the WTP for chronic bronchitis cases avoided. Exhibit 3-7 shows the data sources used in developing the estimates.

Exhibit 3-7: Data Sources Used in Valuation Estimates

Variables	Data Source
Gross national income (GNI) adjusted for purchasing power parity (PPP)	World Development Indicators Database, The World Bank
U.S. VSL estimate FY 1990	U.S. EPA, 1999
Income elasticity to VSL and chronic diseases for U.S.	U.S. EPA, 1999
Annual compound growth rate for real per capita gross domestic product (GDP)	World Economic Outlook Database, September 2011, International Monetary Fund (IMF)
Income elasticity of WTP for mortality and morbidity risk reductions in Bangladesh	Hammitt and Robinson (2011)
Value per case of chronic bronchitis in the United States	U.S. EPA, 2010
Forecasted per capita real income growth rate in Bangladesh	ADB project preparation report projects a 5% real GDP growth and a 3% population growth rates from 2010

For the current analysis, the choice of income elasticity of VSL was important since it affected both the magnitude of the transferred value and the rate of change in this value over time as the real per capita income changes during the project evaluation period. For benefit transfers, Robinson and Hammitt (2009) proposed using the following values for income elasticity of WTP for mortality and morbidity risk reductions: 1, 1.5, and 2. This estimate was based on the theoretical observation that WTP estimates are a smaller fraction of income for poorer household heads, implying risk reduction to be a luxury good. In our analysis, we used an elasticity of 1.5 to transfer values from the United States to Bangladesh.

3.4.1 Extrapolation of the U.S. Values

Aside from the income elasticity of WTP, benefit transfer requires two additional components: the relative per capita income and the U.S. value to be used in a transfer. A description of how these components were developed is provided below.

The ratio of Bangladesh's per capita income to that of the United States in 2010, 0.0382, was developed using the per capita gross national income (GNI) expressed as purchasing power parity (PPP). The GNI at PPP for 2010 was derived from the World Bank's World Development Indicators Database. Note that we use GNI PPP instead of market exchange rates because it has the same purchasing power, and unlike market rates it is not volatile based on economic and political factors.

U.S. EPA (1999) reports the VSL estimate (for a 1 in 10,000 risk change) for the United States to be $4.8 million (1990 U.S. dollars) using 1990 per capita income. To update the U.S. VSL estimate from 1990 to 2010, we needed to adjust the 1990 year estimate for the rate of growth in real per capita income, income elasticity of VSL, and inflation from 1990 to 2010. First, we updated the 1990 estimate to 2010 U.S. dollars using the U.S. Bureau of Labor Statistics, Consumer Price Index (CPI) adjustment factor. The annual compound growth rate of real per capita income for the United States using the IMF World Economic Outlook Database (September 2011) is estimated to be 1.38 percent from 1990 to 2010. U.S. EPA (1999) reports the central estimate of income elasticity for willingness to pay for changes in mortality risks for U.S. residents to be 0.4. The resulting annual compound growth rate in VSL from 1990 to 2010 is 0.55 percent. The VSL adjusted for 2010 U.S. per capita income is estimated to be $8.67 million (2010 U.S. dollars). This value when transferred to Bangladesh results in $65,000 (2010 U.S. dollars).

The willingness to pay per case of chronic bronchitis in the United States (U.S. EPA, 1999) is $0.26 million (in 1990 U.S. dollars and 1990 income level). To adjust this figure from 1990 level of income to that of year 2010, we used the income elasticity to WTP value per case of chronic bronchitis of 0.45 (U.S. EPA, 1999) and the per capita real income growth rate between 1990 and 2010, resulting in an annual growth rate of 0.62 percent in the WTP value per case of chronic bronchitis. The updated WTP per case of chronic bronchitis in the United States is thus estimated to be $0.48 million (in 2010 U.S. dollars). This value after transfer results in $3,555 (2010 U.S. dollars) for Bangladesh.

The $65,000 for the VSL and $3,555 for WTP per case of chronic bronchitis in Bangladesh in 2010 were used as starting points to project the estimates for the project evaluation period.[14]

3.4.2 Projecting Values for the Project Time Frame

Derived values of the VSL ($65,000) and the WTP per case of chronic bronchitis estimates ($3,555) for Bangladesh in 2010 were projected using the annual compound income per capita growth rate for Bangladesh of 1.94 percent[15] and an income elasticity of 1.5.

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14 Theoretically, VSL should be greater than or equal to the present discounted value of future consumption. This is because the WTP for a change in the probability of death in a given year should be greater than or equal to the value of the gain in utility associated with living from that year onwards. We followed the approach of Hammitt and Robinson (2011) to estimate the present value of future consumption in Bangladesh using publicly available data, and then compared it to our VSL estimates. Following Hammitt and Robinson (2011), we determined the current age in Bangladesh as half of the life expectancy at birth (Global Health Observatory Data Repository, 2009. World Health Organization), or 33 years of age. We used the estimate of life expectancy conditional on reaching the midpoint age (i.e., 33 years), which is 40 years (using Life Tables, Global Health Observatory Data Repository, 2009. WHO). Thus, we assumed with certainty that individuals will live for 40 years. Annual consumption was estimated to be equal to per capita GNI (in 2010 $PPP). Thus, we assumed that consumption is constant and is equivalent to the average income. We then estimated the present value at a 12 percent discount rate to be almost $15,000 (2010 $PPP), which is lower than our estimated VSL.

15 This value was derived based on the information supplied by ADB on the annual income growth of 5 percent and the annual population growth of 3 percent. We assumed that these values represented the annual compound growth rate from 2010 onwards.

Exhibit 3-8 presents the series of projected VSL and the WTP that were developed for this analysis.

Exhibit 3-8: Estimated Unit Values for Bangladesh in Select Years (2010 U.S. Dollars)

Select Years	VSL	WTP per Case of Chronic Bronchitis
2014	73,000	4,000
2019	84,000	5,000
2024	97,000	6,000
2034	130,000	8,000
2044	173,000	10,000
2064	307,000	--

Note: Only premature mortality benefits required projected values for 2014–2064 due to the mortality lag adjustment.

4. Results

Results are presented separately by analytical step: change in emissions, reductions in ambient $PM_{2.5}$, improvements in health outcomes, and the value of avoided premature mortality and chronic bronchitis.

4.1 Change in Emissions

Using the VKT and emissions factor estimates, we calculated the reduction in primary $PM_{2.5}$ and in NO_x and SO_2 that could lead to secondary $PM_{2.5}$ resulting from the BRT project. We also estimated the change in select GHG emissions, as well as in CO and NMHC. Although there are potential health benefits associated with reductions in all of these pollutants, we limited our benefits estimates to $PM_{2.5}$ since these benefits have been found to be the largest in previous benefits analyses.

4.1.1 Change in Direct and Precursor Particulate Matter Emissions

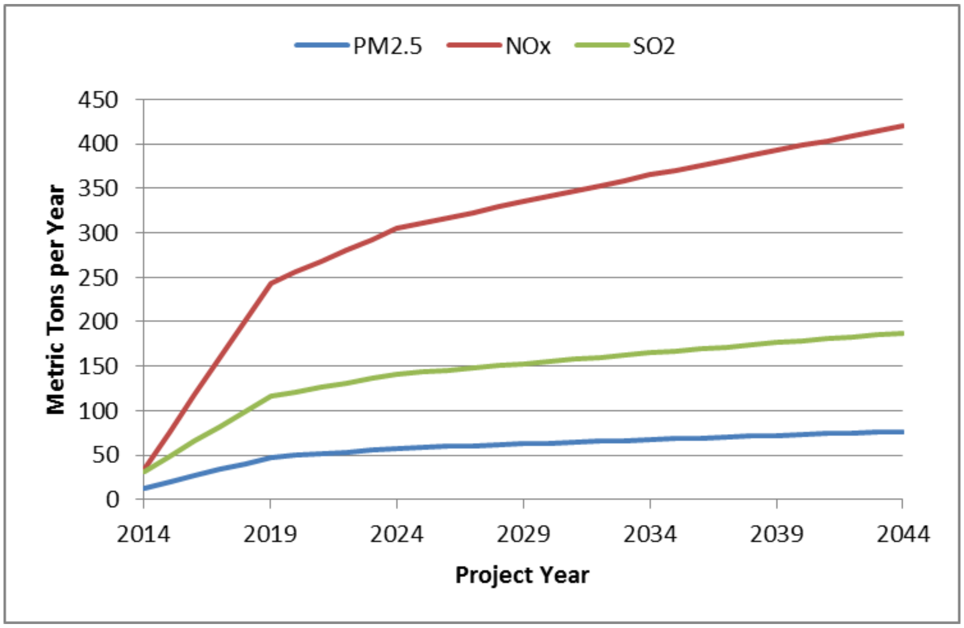
The primary and secondary $PM_{2.5}$ reductions are driven mainly by replacing a fraction of the existing diesel large buses and minibuses with articulated CNG buses. In total, the largest emissions reductions were seen for the pollutant NO_x, followed by SO_2, and primary $PM_{2.5}$. (See Exhibit 4-1 for emissions for select years and Exhibit 4-2 for emissions for all years). To understand the factors driving these pollutant reductions, compared to the diesel buses and minibuses, articulated CNG buses have lower emission factors for primary $PM_{2.5}$. For NO_x, while minibus diesel vehicles have the lowest emission factors, articulated CNG buses still have lower emission factors than large diesel buses. Since the fuel is sulfur-free, articulated CNG buses emit virtually no SO_2.

Exhibit 4-1: Reductions in Direct $PM_{2.5}$, NO_x, and SO_2 Emissions Due to BRT (Overall and for Select Years)

	Reduction in Pollutant for Select Years (metric tons)					
Pollutant	**2014**	**2019**	**2024**	**2034**	**2044**	**Total (metric tons)**
$PM_{2.5}$	13	47	57	67	77	1,801
NO_x	35	243	305	365	420	9,567
SO_2	31	116	141	165	187	4,410

Note: Results for five individual years (2014, 2019, 2024, 2034, 2044) are shown in the exhibit. The total includes reductions for all years 2014 through 2044.

Exhibit 4-2: Estimated Annual Reductions in Direct $PM_{2.5}$, NO_x, and SO_2 Emissions Due to BRT



4.1.2 Change in GHG Emissions

Using the VKT and emissions factor estimates, we calculated the changes in carbon dioxide and methane emissions resulting from the BRT project. We present the estimates for the change in GHG emissions in Exhibit 4-3 and Exhibit 4-4. For the project evaluation period, we estimated a reduction in CO_2 emissions by approximately 541,000 metric tons. However, increases are seen for methane (approximately 5,000 metric tons) because articulated CNG buses have the highest methane emission factors of the vehicle classes we examined. Since methane is a more potent GHG than CO_2, 5,000 metric tons of methane corresponds to approximately 107,000 metric tons of CO_2 equivalents.[16] Overall, we estimated a reduction in GHG emissions of 434,000 metric tons (in CO_2 equivalents) for the entire project evaluation period.

Again, these changes are driven mainly by replacing a fraction of the large diesel bus and diesel minibuses with articulated CNG buses. Methane emission factors are higher for articulated CNG buses compared to diesel vehicles. However for CO_2, diesel minibuses have the lowest emission factors, followed by articulated CNG buses, followed by large diesel buses.

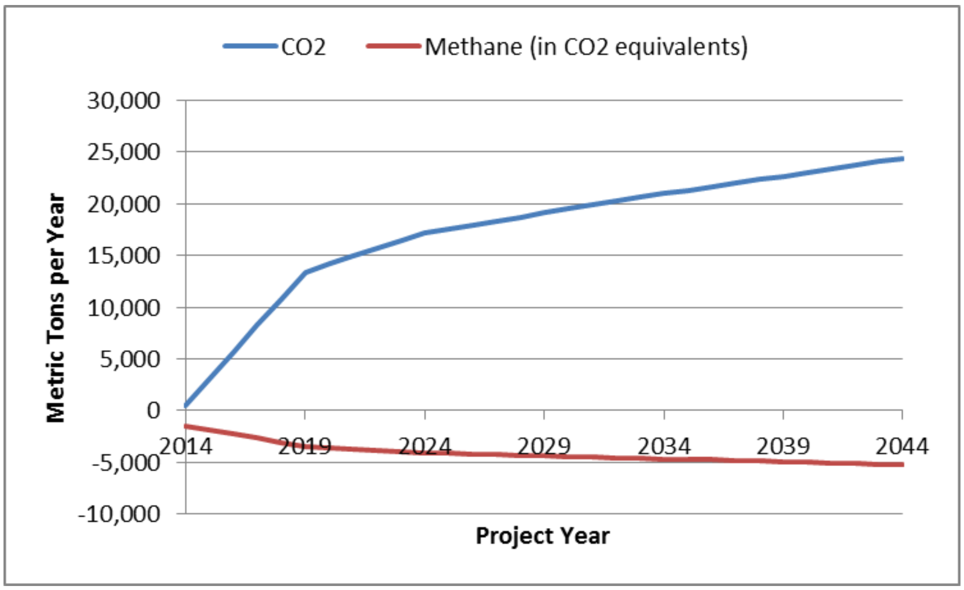
[16] See http://www.epa.gov/cleanenergy/energy-resources/calculator.html.

Exhibit 4-3: Changes in Greenhouse Gas Emissions Due to BRT (Overall and for Select Years)

Pollutant	Changes in Emissions for Select Years (metric tons)					Total (metric tons)
	2014	2019	2024	2034	2044	
CO_2	438	13,404	17,234	20,958	24,402	541,378
Methane	-58	-139	-163	-186	-208	-5,095
Methane (in CO_2 equivalents)	-1,214	-2,918	-3,421	-3,911	-4,363	-106,994
Total CO_2 equivalents	**-775**	**10,486**	**13,813**	**17,047**	**20,039**	**434,384**

Note: Results for five individual years (2014, 2019, 2024, 2034, 2044) are shown in the exhibit.
The total includes reductions for all years 2014 through 2044.

Exhibit 4-4: Estimated Annual Reductions in GHG Emissions Due to BRT



4.1.3 Change in Non-Methane Hydrocarbon (NMHC) and CO Emissions

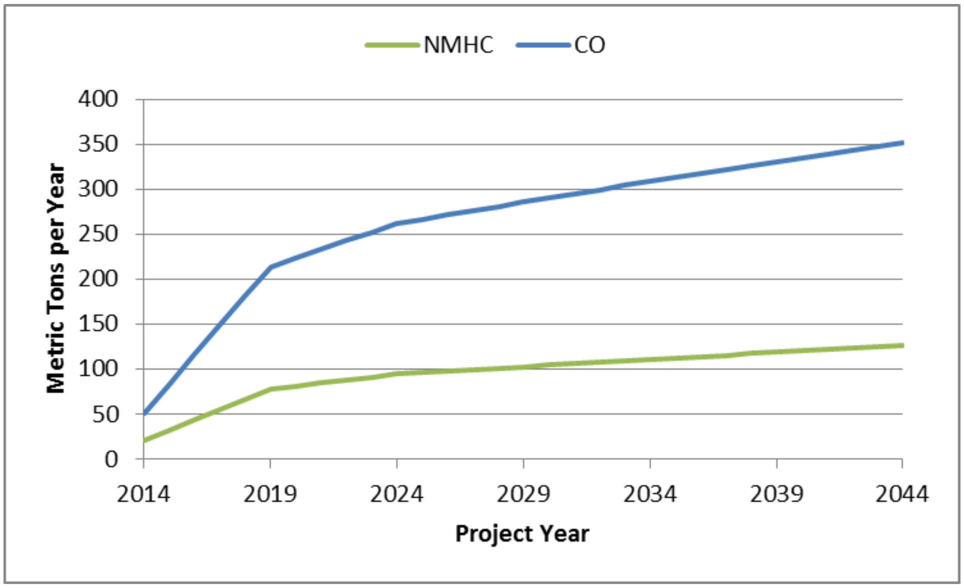
Exhibit 4-5 and Exhibit 4-6 show the estimated reductions in NMHC and CO emissions. We estimated reductions in NMHC and CO emissions of approximately 3,000 metric tons and 8,000 metric tons, respectively, over the project evaluation period. Compared to diesel vehicles, articulated CNG buses have the lowest emission factors for non-methane hydrocarbons. Articulated CNG buses also have lower emission factors for primary CO.

Exhibit 4-5: Reductions in NMHC and CO Emissions Due to BRT (Overall and for Select Years)

Pollutant	Reduction in Pollutant for Select Years (metric tons) 2014	2019	2024	2034	2044	Total (metric tons)
NMHC	20	78	95	111	126	2,966
CO	51	214	262	309	352	8,220

Note: Results for five individual years (2014, 2019, 2024, 2034, 2044) are shown in the exhibit. The total includes reductions for all years 2014 through 2044.

Exhibit 4-6: Estimated Annual Reductions in NMHC and CO Emissions Due to BRT



4.2 Reductions in Ambient $PM_{2.5}$

Mobile sources contribute to $PM_{2.5}$ pollution by direct emissions (primary $PM_{2.5}$) as well as emissions of precursor pollutants such as sulfur dioxide and nitrogen oxides (leading to secondary $PM_{2.5}$). As mentioned in Sections 2.2 and 3.2, we used our estimates of changes in estimated annual $PM_{2.5}$, SO_2, and NO_x emissions in the ATMoS model to estimate changes in $PM_{2.5}$ ambient concentrations for 2014–2044.

Exhibit 4-7 summarizes the effects of reducing primary $PM_{2.5}$, SO_2, and NO_x emissions by 1 metric ton on the ambient $PM_{2.5}$ concentrations. We found that a 1 metric ton reduction in $PM_{2.5}$ emissions would result in an approximately 0.042 $\mu g/m^3$ reduction in average annual primary ambient $PM_{2.5}$ concentrations in 2014. Likewise, a 1 metric ton reduction in SO_2 and NO_x would result in roughly 0.013 $\mu g/m^3$ and 0.003 $\mu g/m^3$ reduction in average annual secondary ambient $PM_{2.5}$ concentrations. The values are fairly stable across the years because the same year's meteorology data (2006) were used. Also, while emissions might increase over time, so would the concentration impact, thus keeping the ratio fairly constant. For reference, the baseline measured annual average $PM_{2.5}$ concentration in 2006 was 76.72 $\mu g/m^3$.[17]

Exhibit 4-7: Effects of Reductions in $PM_{2.5}$, SO_2, and NO_x Emissions on Primary and Secondary Ambient Concentrations of $PM_{2.5}$ ($\mu g/m^3$) for Select Years

	Select Years				
	2014	2019	2024	2034	2044
Primary $PM_{2.5}$ Effects					
Reduction in ambient $PM_{2.5}$ ($\mu g/m^3$) per 1 metric ton of $PM_{2.5}$ reduced	0.0423	0.0437	0.0438	0.0439	0.0440
Secondary PM2.5 Effects					
Reduction in ambient $PM_{2.5}$ ($\mu g/m^3$) per 1 metric ton of SO_2 reduced	0.0128	0.0132	0.0132	0.0132	0.0132
Reduction in ambient $PM_{2.5}$ ($\mu g/m^3$) per 1 metric ton of NO_x reduced	0.0029	0.0033	0.0033	0.0033	0.0033

Exhibit 4-8 presents the spread of reductions in ambient $PM_{2.5}$ concentrations in grid cells for select years. The impact of the BRT project is modest, with a maximum impact of 1.01 $\mu g/m^3$ expected in 2044 using our modeling assumptions. The minimum grid cell reduction was 1.29E-05 $\mu g/m^3$ in 2014. On average, the grid cell reductions varied between 2.07E-03 $\mu g/m^3$ (in 2014) and 1.44E-02 $\mu g/m^3$ (in 2044).

Exhibit 4-8: Variability in Estimated $PM_{2.5}$ Reductions across the Grids on the Study Domain

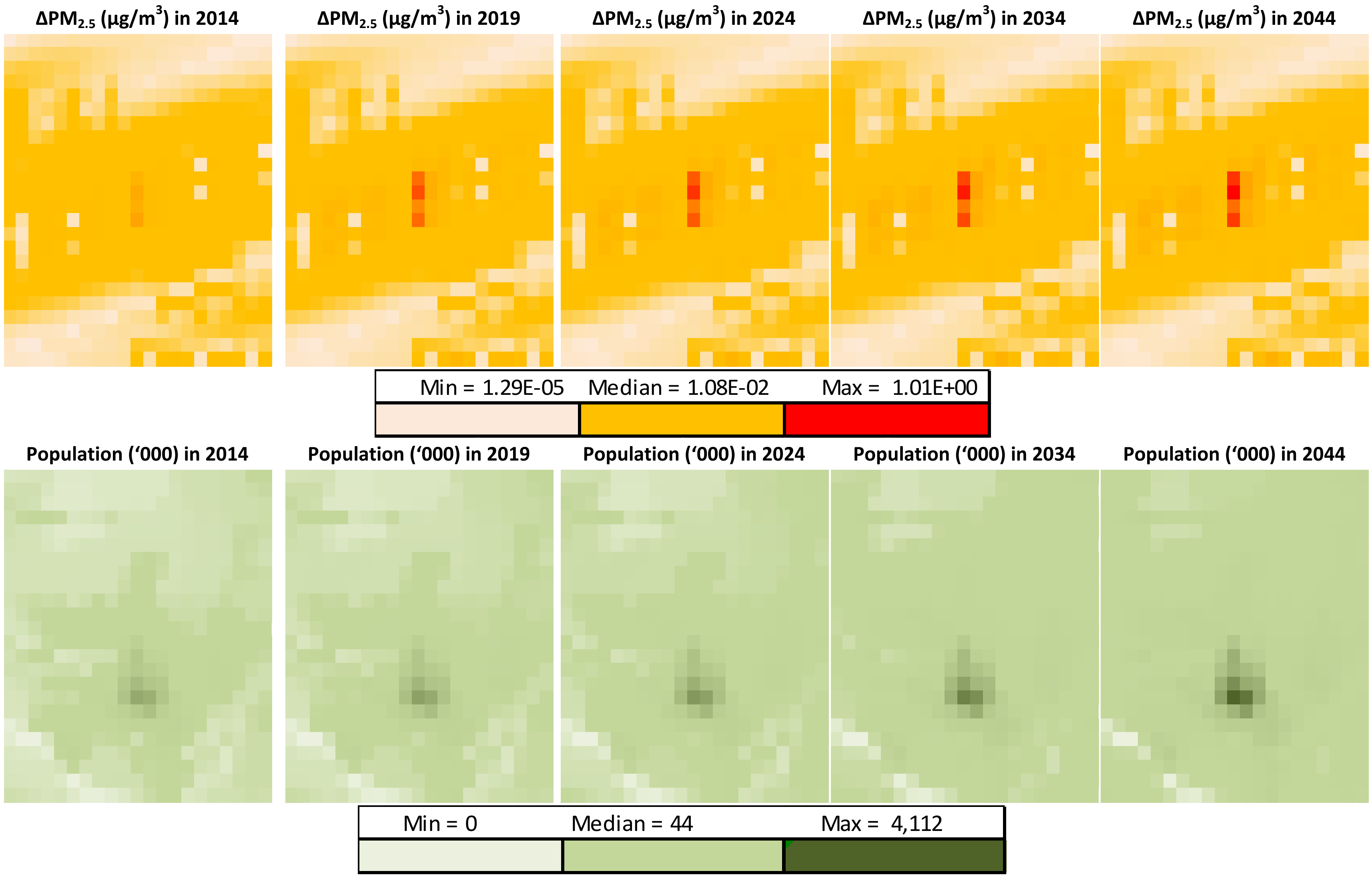
Reduction in $PM_{2.5}$ ($\mu g/m^3$)	Select Years				
	2014	2019	2024	2034	2044
Minimum	1.29E-05	5.52E-05	6.77E-05	7.98E-05	9.10E-05
Average	2.07E-03	8.72E-04	1.07E-02	1.26E-02	1.44E-02
Population-weighted Average	5.22E-03	8.72E-03	2.21E-02	2.59E-02	2.93E-02
Maximum	1.50E-01	6.02E-01	7.45E-01	8.84E-01	1.01E+00

[17] This measurement was obtained by Begum et al. (2010) for the Tongi area.

To estimate the health benefits, we must combine the grid-cell $PM_{2.5}$ reductions with the grid-cell population projections. In Exhibit 4-8 we also report the population-weighted average reductions in $PM_{2.5}$. They varied between 5.22E-03 $\mu g/m^3$ (in 2014) and 2.93E-02 $\mu g/m^3$ (in 2044) and were higher than the corresponding non-weighted $PM_{2.5}$ averages. This implies that relatively larger reductions occurred in areas that are more densely populated. This observation is also confirmed by looking at Exhibit 4-9, which displays the spatial patterns of populations and reductions of $PM_{2.5}$ for grid cells in the modeling domain.

Exhibit 4-9 also enables another observation: over time, both emission reductions and population projections are expected to increase. Therefore, the health benefits will increase over time not only because of the magnitude of emission reductions, but also because there will be more people experiencing the improvements in air quality due to these emission reductions.

Exhibit 4-9: Spatial Patterns of Estimated Reductions in $PM_{2.5}$ ($\mu g/m^3$) and Population in the Study Domain for Select Years



4.3 Improvements in Health Outcomes

Exhibit 4-10 and Exhibit 4-11 present our estimates of the number of premature mortality cases and chronic bronchitis cases avoided each year of the project evaluation period, respectively. The number of adverse health effects avoided increases over time, which is expected because emission reductions and populations benefitting from these reductions are expected to grow over the period 2014–2044.

As mentioned in Section 3.3, the adult mortality functions included in this analysis are associated with long-term exposure, and the child mortality function is associated with short-term exposure. As the short-term exposure studies capture only a small portion of the overall health effects of long-term, repeated exposure to particulate matter, the child mortality reported here may underestimate the real effects. If any long-term concentration-response functions become available for child mortality, they should be included in this analysis to better capture the health effects in children.

Another item that may have underestimated the $PM_{2.5}$ mortality benefits in our analysis is our inability to capture mortality estimates for people aged 5–30 due to unavailability of appropriate C-R functions. In Bangladesh, this is a significant portion of the population: approximately 53 percent are between the ages of 5 and 30. Chronic bronchitis was selected as a morbidity endpoint because available evidence allowed its estimation. Being able to account for other morbidity endpoints would likely increase the benefits.

Exhibit 4-10: Estimated Number of Premature Deaths Avoided during 2014–2044

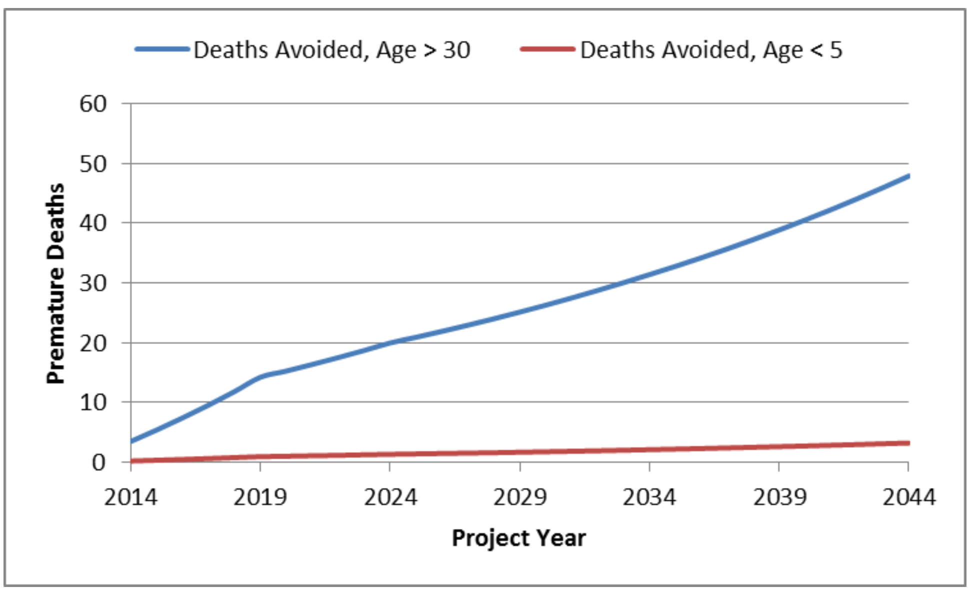
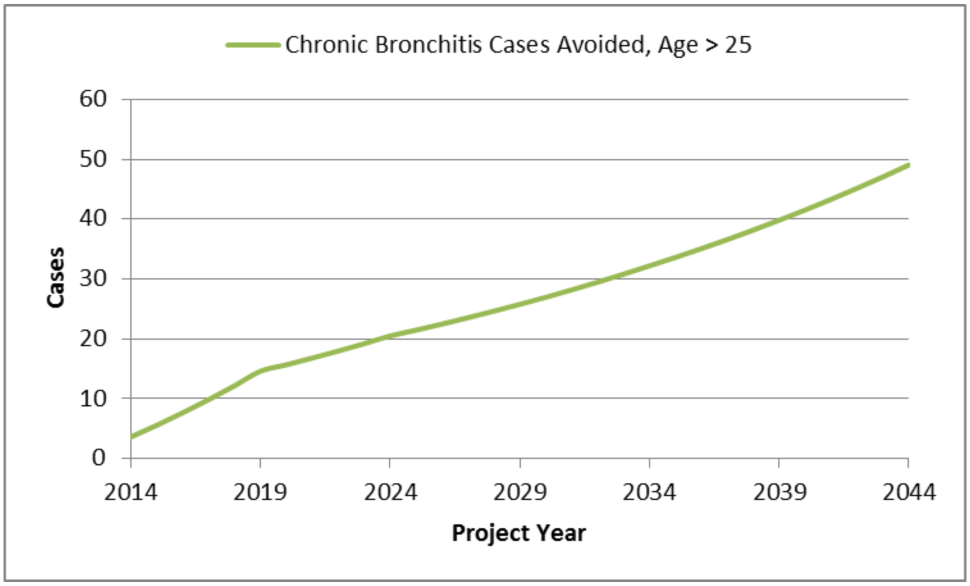


Exhibit 4-11: Estimated Number of Cases of Chronic Bronchitis Avoided during 2014–2044



4.4 Value of Avoided Premature Mortality and Chronic Bronchitis

Exhibit 4-12 reports the main results of our analysis: the number of avoided premature deaths for adults over 30 years old and children under 5 years old, the number of avoided chronic bronchitis cases in adults over 25 years old, and the monetary value of these health endpoints. We report the benefit estimates for the entire project evaluation period as well as those for 10-year intervals. As expected, the health benefits that we have focused on in this analysis increase over time. Overall, we estimated 798 premature deaths avoided for adults aged over 30; 55 premature deaths avoided for children aged under 5; and 819 new cases of chronic bronchitis avoided for adults over 25. The undiscounted value of health benefits is approximately $116 million (2010 U.S. dollars). When the stream of benefits was discounted to 2010 using a 12 percent discount rate (DR), the present discounted value of quantified benefits came to approximately $9.5 million (2010 U.S. dollars).[18] Using a lower discount rate would have increased the PDV benefits.

[18] The discount rate of 12 percent was used to be consistent with the project preparation report. Note that U.S. EPA typically uses much lower discount rates (3 percent and 7 percent) for health benefits assessments (U.S. EPA, 2011).

Exhibit 4-12: Summary of the Estimated Benefits Associated with Avoided Premature Mortality and Chronic Bronchitis due to the BRT project in Greater Dhaka, Bangladesh (2010 U.S. Dollars)

	Deaths Avoided (Age > 30)		Deaths Avoided (Age < 5)		Chronic Bronchitis Cases Avoided (Age > 25)	
	No.	Value $2010	No.	Value $2010	No.	Value $2010
10-Year Intervals						
2014–2023	120	$10,286,000	9	$700,000	123	$580,000
2024–2033	247	$27,685,000	17	$1,882,000	254	$1,560,000
2034–2044	431	$65,370,000	29	$4,442,000	442	$3,681,000
Total for 2014–2044	798	$103,341,000	55	$7,024,000	819	$5,821,000
PDV @ 12% DR		$8,127,000		$705,000		$574,000
Total Health Benefits, $2010						**$116,186,000**
PDV @ 12% DR						**$9,406,000**

Exhibit 4-13 presents the results of two sensitivity analyses of the estimated benefits of avoided premature mortality for adults aged over 30. In our Baseline Analysis, we used a C-R function derived from Laden et al. (2006). Sensitivity Analysis I shows the resulting benefits if the C-R function were derived from Krewski et al. (2009). Had we used this relationship, benefits in this category would have been 66 percent lower because the estimated number of deaths avoided would have been 271 (rather than 798).

Furthermore, for our Baseline Analysis we used a 20-year mortality lag adjustment. As described in Section 2.4, this reduces the benefits of avoiding the long-term $PM_{2.5}$ exposure-related premature mortality (for adults aged over 30), because this implies a much longer discounting timeline. Not surprisingly, Exhibit 4-13 shows that our present discounted value of avoiding premature mortality would have been 28 percent higher if the 20-year mortality lag had not been used (Sensitivity Analysis II).

Exhibit 4-13: Sensitivity of the Estimated Benefits of Avoided Premature Mortality for Adults Aged over 30 to Key Assumptions (2010 U.S. Dollars)

Assumptions			Total Mortality Benefits for Adults Aged > 30, 2014–2044		
Analysis	**C-R Function**	**Discounting**	**Cases**	**PDV @ 12%DR $2010**	**Difference from Baseline**
Baseline	Laden et al. (2006)[a]	Mortality Lag-adjusted	798	$8,127,000	--
Sensitivity I	Krewski et al. (2009)[a]	Mortality Lag-adjusted	271	$2,751,000	-66%
Sensitivity II	Laden et al. (2006)[a]	Unadjusted for Mortality Lag	798	$10,365,000	28%

a. Adjusted for use in developing countries following Ostro, 2004.

5. Discussion

In examining the potential benefits of the BRT project in Dhaka, ADB had previously focused on reductions in vehicle operating costs, shorter journey times, and increased land values. The present analysis is the first attempt to quantify potential public health benefits as a result of reductions in particulate matter and greenhouse gases. This analysis estimated that reductions in primary $PM_{2.5}$ and in SO_2 and NO_x that could lead to secondary $PM_{2.5}$ would result from the BRT project. It also estimated change in emissions of GHG as a result of the project: reductions in CO_2 and increases in methane, resulting in an overall reduction in CO_2 equivalents. This analysis demonstrated reductions in the ambient concentration of $PM_{2.5}$ resulting from reductions in emissions of primary $PM_{2.5}$, SO_2, and NO_x. It went on to estimate benefits of avoiding premature deaths for adults (over 30 years old) and for children (under 5 years old) as well as cases of chronic bronchitis (for adults over 25 years old). Thus, the BRT project will lead to public health and GHG benefits, in addition to the non-public health benefits already studied.

In terms of the magnitude of the benefits, the number of avoided cases and the valuation of these avoided cases is less than the previously studied non-public health benefits. For example, ADB's initial baseline scenario for the BRT project estimated NPV benefits (accounting for vehicle operating costs, journey time, and land values) of approximately $71 million. The present analysis estimates the PDV of benefits of approximately $9.5 million for the project evaluation period.

Several items might have increased or decreased our public health benefits estimate. We could not estimate all possible types of health benefits for all pollutants because epidemiological information on the relevant relationships in Bangladesh is lacking, and accounting for more health benefits (e.g., acute effects of CO reductions, morbidity endpoints in addition to chronic bronchitis for $PM_{2.5}$ reductions) would have increased our public health benefits. While we did account for premature mortality which is typically the largest benefit health endpoint in fine particulate matter air quality assessments, we were not able to estimate it in those aged 5–30 since epidemiological evidence is lacking in this age group. This age group comprises more than 50 percent of the Bangladeshi population, so accounting for this age group would be expected to increase the public health benefits. We assumed that the buses removed from circulation as a result of the BRT project (and replaced by articulated CNG buses) were large diesel buses and diesel minibuses. This assumption results in larger $PM_{2.5}$ improvements and subsequent public health benefits than if CNG buses and CNG minibuses would be removed from circulation as a result of the BRT project (and replaced by articulated CNG buses).

Our characterization of "with BRT" and "without BRT" emissions scenarios was limited by the data available in the project preparation report and supplemental files provided by ADB and their consultants. Having information on average vehicle speeds in the corridor as a result of the BRT project would have been helpful and would have refined our estimates, though it is impossible to speculate whether this information would have increased or decreased the public health benefits. Characterizing the inspection and maintenance component of the BRT project would likely have increased the public health benefits associated with the BRT project, though there was not sufficient detail to be able to do so.

To put our concentration modeling results in context, we calculated an intake fraction (iF) for primary $PM_{2.5}$. The iF is defined as the fraction of a pollutant emitted from a source that is inhaled by a specified population (Bennett et al., 2002). Researchers have calculated the iF for a variety of sources and contexts. Recently, a project to estimate the iF for a large number of urban areas using a dynamic box model determined an iF for primary $PM_{2.5}$ for Dhaka of 260 ppm (Apte et al., 2011). This was among the highest for the areas examined, driven largely by the high population density in Dhaka. Combining the results of our concentration modeling with our population estimates, and normalizing by our estimated reduction in $PM_{2.5}$ emissions, we calculated an iF for primary $PM_{2.5}$ of 44 ppm (in 2014) rising to 94 ppm (in 2044). The rise in our iF estimate is driven by the anticipated population growth in the greater Dhaka area over that time period. In any case, our iF estimates are lower than those estimated by Apte et al. These differences are likely a result of the differences in the definition of the study area. The study area used in Apte et al. (2011) covered Dhaka, which has the highest population density in Bangladesh. On the other hand, our study area covered greater Dhaka, which included slightly less densely populated areas as well. The modeling approaches were also different: Apte et al. (2011) used a dynamic box model, while we used the ATMoS model to estimate concentrations. Finally, the source and year of the meteorology data were different. Had our estimates resulted in an iF similar to Apte et al., our benefits would be three to six times higher.

Clearly, our findings are dependent upon how we defined the emissions in the "with BRT" and "without BRT" project scenarios, as well as all the other assumptions we made in our approach. We presented our best estimate and conducted a limited sensitivity analysis examining the impact of using different assumptions for the C-R function and the discounting procedure. Basing our analysis on a different C-R function for adult mortality (Krewski et al. (2009) versus Laden et al. (2006)) resulted in 66 percent lower benefits. Because the Krewski et al. and Laden et al. studies were conducted in the United States, we adjusted their RRs for use in developing countries by using a log-linear function of exposure (versus a linear function of exposure). Had the results from these two studies been used directly, the public benefits would have been larger.

We found no primary studies that have developed WTP estimates for avoided premature mortality and chronic bronchitis in Bangladesh that could be used for the present study. Therefore, we relied on the benefit transfer approach proposed by Hammitt and Robinson (2011) to extrapolate for Bangladesh using U.S. VSL estimates under the assumption that WTP is a luxury good in low-income countries (i.e., income elasticity greater than one). Hammitt and Robinson (2011) point out that if income elasticity values lower than one are used (i.e., risk reductions are a normal good), unrealistically high VSL values will be obtained through the benefit transfer method. However, given the paucity of WTP studies in developing countries, there is no strong empirical evidence that risk reduction is a luxury good in developing countries. OECD (2001) used an income elasticity of 0.5 to estimate the impacts of clearing air in India. Similarly, Alberini et al. (1997) used a contingent valuation survey in Taiwan and estimated the income elasticity of WTP to avoid acute respiratory illness in Taiwan to be 0.45. Bhattacharya et al. (2007) used a contingent valuation survey to estimate the WTP for reduced traffic-related mortality risk in Delhi, India. The study reported the estimated VSL to be $150,000 (in $PPP). However, Bhattacharya et al. (2007) note that this value is lower than the value that would be estimated using a benefit transfer from the U.S. Department of Transportation VSL at an income elasticity of one, implying that traffic-related risk reductions may be a luxury good in India.

Following U.S. EPA methods, we assumed a 20-year mortality lag structure for mortality benefits associated with long-term $PM_{2.5}$ exposure reductions for individuals over age 30 (U.S. EPA, 2011). This implied a much longer discounting time frame, which substantially affected the present discounted value (PDV) of these mortality benefits. A sensitivity analysis indicated that these benefits could have been 28 percent higher, had we not used the mortality lag structure.

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