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Quantification of Local and Global Benefits from Air Pollution Control in Mexico City

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Complex sociopolitical, economic, and geographical realities cause the 20 million residents of Mexico City to suffer from some of the worst air pollution conditions in the world. Greenhouse gas emissions from the city are also substantial, and opportunities for joint local−global air pollution control are being sought. Although a plethora of measures to improve local air quality and reduce greenhouse gas emissions have been proposed for Mexico City, resources are not available for implementation of all proposed controls and thus prioritization must occur. Yet policy makers often do not conduct comprehensive quantitative analyses to inform these decisions. We reanalyze a subset of currently proposed control measures, and derive cost and health benefit estimates that are directly comparable. This study illustrates that improved quantitative analysis can change implementation prioritization for air pollution and greenhouse gas control measures in Mexico City.

1. Introduction

With nearly 20 million inhabitants, 3.5 million vehicles, and 35,000 industries, Mexico City consumes more than 40 million liters of fuel each day (*1*). Mexico City is also located in a closed basin at high-altitude (mean 2240 m)− geographic realities that precondition it for a severe air quality problem. Unfortunately, resources for public health and environmental protection are scarce, and only limited efforts to curb emissions have been possible. In 2002, Mexico City air quality exceeded local standards for ozone (110 ppb for 1 h) on 80% of the days of the year. Ambient levels of particulate matter (PM_{10}) are also high, and concentrations at most monitoring stations exceed the annual average standard of 50 $\mu g/m^3$ (the annual average for 2002 across monitoring stations was approximately 53 $\mu g/m^3$) (*2*). While it is not possible to determine the total public health impact of this poor air quality, Evans et al. (*3*) estimate that only a 10% reduction in PM_{10} would save 3,000 lives and 10,000 new cases of chronic bronchitis each year, and that a 10% O_3 reduction would save 300 lives and 2 million minor restricted activity days. Thus, the potential public health gains from air pollution mitigation are substantial.

Emissions in Mexico City are dominated by mobile sources. According to the latest inventory in 2000 (*4*), nearly 80% of $PM_{2.5}$ and NO_x, 45% of volatile organic compounds (VOCs), and 30% of SO_2 emissions come from mobile sources. Area sources (specifically the use of solvents and LPG) are a significant source of VOC emissions (over 45%), whereas point sources (dominated by chemical, textile, and paper industries) contribute 70% of SO_2 emissions.

Greenhouse gas (GHG) emissions from Mexico City are also significant. In 1998, Mexico ranked among the top 15 GHG-emitting nations, contributing nearly 2% of the world total. Mexico City emits approximately 13% of the national total (*5*). By 2010, Mexico City will emit approximately 70 million tons (Mton) of CO_2 and by 2020, nearly 100 Mton (assuming a 1996 base year of 45.6 Mton (*5*) and a 3.3% annual growth rate, based on GDP projections (*9*)). Mobile sources represent over 50% of all CO_2 emissions in the city, followed by 20% from the industrial sector, 15% from residential and 8% from electricity generation (when electricity generated outside of the city is considered, this share rises to over 20%) (*5*). As emissions of GHGs and local air pollutants are often generated from the same sources, opportunities may exist for their joint control. Although Mexico is not required to reduce its GHG emissions under the Kyoto Protocol, there is interest in understanding the potential for foreign investment (e.g., Clean Development Mechanism) to support GHG emissions reductions and in determining how to maximize local benefits if such investment were to occur.

In Mexico City, an intergovernmental commission, Comision Ambiental Metropolitana (CAM), brings together the city, state, and federal governments with jurisdictions in the Mexico City metropolitan area (MCMA) to address air quality issues. The CAM does not have legal authority to implement plans, but must build consensus for action between the three governments. The CAM is presently working toward the implementation of the third air quality management plan for Mexico City, PROAIRE 2002−2010. The first plan Programa Integral para el Control de la Contaminación Atmosférica (PICCA)−Comprehensive Program to Control Air Pollution) was initiated in 1990 and had several major accomplishments, including the introduction of two-way catalytic converters, the phase-out of leaded gasoline, and the establishment of vehicle emissions standards. The second program, PROAIRE 1995−2000 (Programa para Mejorar la Calidad del Aire en el Valle de México − Program to Improve Air Quality in the Valley of Mexico) achieved the introduction of methyl tertiary-butyl ether (MTBE) in gasoline to improve combustion efficiency, and implemented restrictions on the aromatic content of fuels and on the sulfur content in industrial fuel. While significant improvements in ambient air quality have been achieved through these programs, air pollution levels remain dangerously high, and the government has recently initiated PROAIRE 2002−2010.

PROAIRE 2002−2010 (1) includes 89 control measures targeting emissions reductions from mobile, point and area sources, and also proposes education and institutional strengthening measures to combat air pollution. While a few measures are being undertaken, it is unlikely that the full PROAIRE plan, with a total undiscounted investment cost for 2002−2010 of approximately $14 billion US (*1*), will ever

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be implemented. Prioritization must occur, yet the only quantitative bases available for prioritization are incomplete and do not allow for direct cost-to-benefit comparisons. In PROAIRE, costs are reported only as total undiscounted investment costs for 2002−2010, and local emissions reductions are reported only for the year 2010. Recently, the CAM has developed more complete cost analyses for several measures, but they are not working to improve emission reduction estimates or to include health benefits in their analysis. These analyses do not provide a basis from which cost-to-benefit comparisons can proceed, and only incomplete metrics for prioritization of measures can be derived. Comparisons of, for example, the total tons of local pollutants reduced in 2010 to the total undiscounted investment cost of a measure (*9*) implicitly assume that all air pollutants are equally toxic. Yet it is clear from the public health literature that not all air pollutants are equally damaging to human health. Such metrics are potentially seriously misleading in the decision making process.

Previous studies have considered the local and global benefits of air pollution control measures for Mexico City and other urban areas (*6*−*11*). For Mexico City, West et al. (*9*) compiled a large number of PROAIRE and GHG mitigation options and optimized for the least cost set of options for joint control. Although West et al. illustrate an interesting technique for joint local−global control analysis, the relevancy of the work to Mexico City decision making is limited because costs in the study cannot be directly compared to the local and global emission reductions since they are derived for different time frames (costs for 2002−2010, emissions reductions in 2010 alone, as in PROAIRE). Other studies have analyzed the health benefits of air pollution control in Mexico City on the basis of percent reductions in PM_{10} and O_3 concentrations. Cesar et al. (*12*) found that a 10% reduction would result in an annual public health benefit of over $2 billion US. While this is a valuable contribution to our understanding of the scope of the air quality problem and the potential benefits of its mitigation, it is not directly applicable to prioritization for the implementation of specific control measures.

In this study, we apply cost−benefit analysis methodology to analyze the tradeoffs between costs, public health benefits, and reductions of GHGs and local pollutants for a select set of Mexico City control measures. In contrast to previous works (*1*, *9*), we consider consistent time profiles of implementation and emissions reductions, extend the time horizon of consideration from 2010 to 2020, and estimate public health benefits. This study allows for direct cost-to-benefit comparisons for specific measures and includes GHG benefit estimates. Through this work, we show that although data are scarce and resources limited in Mexico, as in other developing countries, such analyses are feasible and can provide valuable information to the policy making process.

While conducting this analysis, we have worked with analysts and decision makers across the Mexico City government to build capacity for the application of a consistent cost−benefit methodology to future analyses of PROAIRE and GHG measures. To facilitate the step from costs and emission reductions to full cost-to-benefit comparisons, we have integrated the air quality, health impacts, and valuation modules of our analysis into a freely-available tool coded in Analytica software (http://www.ine.gob.mx/dgicurg/cclimatico/benlg.html). Once appropriate costs and emissions reductions estimates are determined, this "co-benefits model" allows for immediate estimation of PM_{10} and O_3 concentration reductions using reduced-form air quality models, determination of health impacts, and calculation of monetized benefits. Reduced-form air quality models are simplified model formulations, based on three-dimensional airshed models and observations, that allow rapid calculation of changes in ambient concentration due to changes in emissions. Their key benefit is that they eliminate the need for time-consuming three-dimensional air quality model runs. They provide reasonable estimates of concentration reductions, allowing for much-needed benefits calculations and rapid intercomparisons of control options. The co-benefits model calculates health impacts using concentration response methodology and allows the application of various valuation metrics. Finally, the model facilitates comparison of results, and it is user-friendly and flexible enough for direct use by policy makers as they review PROAIRE and make difficult implementation choices.

In the following sections, we summarize our analytical methodology and review the results for the five measures we have considered to date. We then compare prioritization metrics derived from our results reported as in PROAIRE to metrics from the full cost−benefit estimates. This comparison illustrates that if cost and benefit estimates are directly compared, decisions regarding Mexico City's air pollution and greenhouse gas emission challenges could change considerably.

2. Methodology

The analysis is organized in four modules: emission reductions and costs, exposure modeling, health impacts analysis, and valuation. In this section, we discuss methodology for each module and provide interim results. Complete methodological details and additional results are available as Supporting Information and in McKinley et al. (*10*).

2.1. Emission Reductions and Costs for Specific Control Measures. Using the final PROAIRE report (*1*) and supporting documentation provided by the CAM, previous greenhouse gas emission control studies (*5*, *13*), and other studies (*9*, *11*, *14*), we estimate the annual emission reductions for 2003−2020 of local pollutants (PM_{10}, SO_2, CO, NO_x, and HC) and global pollutants (CO_2, CH_4, and N_2O), and annual costs for five control measures. For each measure, we first estimate baseline emissions based on emission factors (EF) and activity levels (AL) for the relevant technology in use in Mexico City for each year from 2003 to 2020. The emissions impact of a control measure is then estimated based on changes to the EFs and/or the ALs that are projected to occur due to implementation of that control. Investment costs are estimated based on the capital expenditures required to implement the measure, and fuel savings due to new technologies are calculated. For consistency and political relevancy, we incorporate the implementation schedules, emissions factors, technology choices, and unit cost estimates from PROAIRE and other previous studies into this work as much as possible. However, when calculation errors or inconsistencies between assumptions are found, we make corrections. Greenhouse gas EFs are from the International Panel on Climate Change (*15*). We estimate emission reductions and costs for each year from 2003 to 2020 and base the benefits analysis on annualized results (using a 5% discount rate).

We choose five control options from PROAIRE and the greenhouse gas studies, outlined in Table 1 and discussed below, that address transportation, residential, and industrial emission sources to capture the breadth of options under consideration in Mexico City. Several of these options are currently relevant to implementation negotiations. We consider significantly fewer options than PROAIRE and others (*1*, *9*) because we fully reevaluate each option such that, for the first time, cost and benefit estimates can be directly compared.

Taxi Fleet Renovation. Approximately 110,000 taxis circulate the streets of the MCMA, with an average age of 9 years. Due to their age and the large number of vehicle kilometers traveled each day, emissions from taxis are quite high (3.6% of PM_{10}, 11.5% of SO_2, 10.7% of CO, 10.2% of NO_x,

TABLE 1. Control Measures

control measure	description
taxi fleet renovation	80% of old taxis replaced by 2007 fuel efficiency increases from 6.7 to 9 km/L compliance with Tier I standards in 1999 and newer models
Metro expansion	76 km of new construction by 2020 new ridership assumed to come from microbus transport recuperation value of capital included using a 30-year useful life 5 km will be constructed between 2003 and 2010, and 71 km between 2011 and 2020
hybrid buses	1029 hybrid buses brought into circulation, replacing diesel buses, by 2006 emissions factors are for Orion-LMCS VI hybrid diesel buses for New York City (*14*)
LPG leaks	stove maintenance (initial and follow-up) is performed in one million households to eliminate leaks combination of four measures that each address a specific part of LPG stove systems (*13*)
cogeneration	installation of 160 MW of capacity by 2010 heat/electricity (Q/E) = 3 recuperation value of capital included, using a 20-year useful life

TABLE 2. Emission Reductions and Direct Costs for 2003–2020[a]

	emission reductions (ton/yr)						investment costs and fuel savings (million USD/yr)		
	PM$_{10}$	SO$_2$	CO	NO$_x$	HC	CO$_2$ equivalent	public investment	private investment	fuel savings
taxi renovation	0	59	145,000	3,100	12,800	397,000	8.9	29.7	57.3
Metro expansion	9	65	28,800	1,270	2,650	164,000	44.1	0	0.02
hybrid buses	82	16	635	−134	307	60,700	30.0	0	10.2
LPG leaks	0	0	0	0	1,950	32,100	0.7	1.0	0.8
cogeneration	0	0	13	110	0	857,000	0	7.3	6.4

[a] Annualized, 5% discount rate.

and 14% of VOCs of mobile source emissions), despite the fact that they account for only 3.4% of Mexico City's vehicle fleet (*4*). In response to growing concerns about the emissions from taxis, an ambitious program has been designed to scrap 80,099 older taxis by 2007 in the federal district, and to replace them with newer, less polluting vehicles (*1*). With this measure, the government provides a direct subsidy of $1,500 US and other financial incentives to taxi owners once they prove that their old vehicle has been destroyed and that their new vehicle meets specified emission standards. Although implementation of this program has officially started, progress is slow. Completion of the entire, or even majority, of the plan is uncertain due to budget constraints and competing priorities within the Transportation Secretariat.

Metro Expansion. The Metro represents the cleanest and most efficient transportation mode in Mexico City. With over 200 km of train lines and 2,637 trains, the Metro transports approximately 5 million people each day (*16*). Although demand for transportation continues to rise with population growth, the percent share of trips in the Metro has decreased in recent years because the urban area has grown far beyond the Metro's coverage. On June 9, 2004, over 12,000 residents of communities outside the Metro's reach marched to advocate for its extension (*17*). Despite this demand, the Mexico City government has currently suspended plans to expand Metro service due to the enormous capital investment that would be required. Particularly where controversy exists, quantitative evaluation of costs and benefits is important. We analyze the PROAIRE proposal to add 76 km of new lines to the Metro with 5 km being constructed between 2003 and 2010, and 71 km between 2011 and 2020.

Hybrid Buses. Although high-capacity buses constitute a small fraction of total public transit vehicles in Mexico City, their diesel engines emit large amounts of particulate matter, NO$_x$ and VOCs. According to the 2000 emissions inventory, diesel buses account for 15% of total mobile emissions of particulate matter. Furthermore, passengers' exposure to particulate matter while traveling in these vehicles is high. The replacement of dirty diesel vehicles with cleaner technologies could result in significant benefits to local air quality and to the health of passengers. Previous research on hybrid vehicles for Mexico City consists of a study by Consultants to the World Bank (*18*) in which four bus technologies were compared to a diesel option. We meld this work with PROAIRE by using the implementation schedule for measure 22 (Introduction of Compressed Natural Gas Buses) (*1*) in which 257 buses are replaced each year for 4 years (2003–2006) (*9*).

LPG Leaks. The majority of Mexico City's four million households use liquid petroleum gas (LPG) for cooking and water heating. Blake and Rowland (*19*) reported that LPG usage is a significant source of hydrocarbon emissions and contributes significantly to ozone formation in the city, although more recent studies (*20*, *21*) have reported otherwise. Approximately 22,000 tons of VOCs are annually emitted from LPG stove leaks in Mexico City (*4*), and thus their maintenance may be a simple and inexpensive way to lower ozone levels. We estimate the impact of repairs to three specific stove parts (pictels, regulators, and connections) and elimination of the pilot flame in approximately 1 million homes between 2003 and 2010.

Cogeneration. Mexico City consumes over 20 million MW of electricity every year. Nearly 60% of this energy is consumed by medium and large industries. In 1995, the cogeneration potential of the industrial sector was estimated at 1,600 MW (*22*). We evaluate a scenario in which 10% of this potential is realized between 2004 and 2010. Emissions reductions and fuel savings derive from equivalent reductions in electricity production from nearby power plants.

In Table 2, estimated emissions reductions and costs are presented for each measure. CO$_2$ equivalent is calculated from CO$_2$, N$_2$O, and CH$_4$ by using the global warming potentials estimated by the IPCC (*15*).

Technological change, political shifts, enforcement challenges, and the unpredictability of the future behavior of 20

TABLE 3. Apportionment Fractions Relating Primary Pollutant Emissions to Observed PM_{10} (*23*)

pollutant	apportionment fraction
$F_{\text{PRIMARY\_GEOLOGIC}}$	0.45
$F_{\text{PRIMARY\_COMBUSTION}}$	0.25
F_{HC}	0.02
F_{NOX}	0.07
F_{SO2}	0.11

million people contribute to large uncertainty in these cost and emission reduction estimates. An exploration of the full range of uncertainty in these cost and emission estimates is beyond the scope of this project, although uncertainty is estimated for the other three modules. We base our cost and emission reduction estimates on conservative assumptions and provide realistic central estimates based on the best available information. Quantification of cost and emission reduction uncertainty is an important direction for future work.

2.2, Exposure Modeling. For the estimation of the impact of emission reductions on ambient concentrations and population exposures, we have developed reduced-form air quality modeling approaches that circumvent the need for repeated three-dimensional air quality model runs and that facilitate the rapid exploration of control options. Results from the source apportionment study of Chow et al. (*23*) are used to estimate changes in primary and secondary PM_{10}. Ozone isopleths derived from Multiscale Climate Chemistry Model (MCCM) runs from Salcido et al. (*24*) are used to estimate changes in 1-h maximum O_3 due to changes in hydrocarbon and NO_x emissions.

The chemical species of PM_{10} mass are attributed to primary pollutants based on source apportionment information for Mexico City. Fractional changes in the emissions inventories of primary pollutants are related to fractional reductions in the respective particulate matter concentration using eq 1:

$$\mathrm{RF}_{\mathrm{PM10}} = \sum_{i=1}^{n} F_i \cdot \mathrm{RF}_i \qquad (1)$$

where

$$\mathrm{RF}_i = \frac{\Delta E_i}{E_i}$$

where $\mathrm{RF}_{\mathrm{PM10}}$ is the reduction fraction of the total PM_{10} concentration, F_{i} is the fraction of PM mass due to a primary pollutant i ("apportionment fraction"), and RF_{i} is the fractional reduction of emissions of the primary pollutant, estimated by the change in emissions (ΔE, Table 2) over the total emissions (E) from the most recent inventory (*4*). Results of chemical analyses are averaged across six sampling sites used during the Investigación Sobre Materia Particulada y Deterioro Atmosférico (IMADA) − Aerosol and Visibility Evaluation Research campaign of March 1997 (*23*) to derive the mass fractions attributable to primary pollutants. These fractions are presented in Table 3. To attribute organic carbon to its primary and secondary sources, we follow Turpin et al. (*25*). Reductions of SO_2 may be overestimated with this model since we assume that all secondary sulfates are formed within the MCMA, while Chow et al. (*23*) concluded that two-thirds of sulfate aerosols are transported in from outside the Valley. However, since total emissions reductions of SO_2 are small (Table 2), we expect this to have minimal impact on results.

To determine the reduction in 1-h maximum O_3 concentrations, we use results from a series of runs of the MCCM (*24*) in which HC and NO_x emissions were varied in equal proportion from all sources and O_3 concentration changes were recorded. Fitting a polynomial regression to these results, we determine the reduction fraction for O_3 as a function of fractional reductions of hydrocarbons and NO_x emissions.

To account for the spatial relationship of population and pollution concentrations, as well as to account for annual exposures, we multiply reduction fractions by projected future baseline population-weighted concentrations to estimate annual reductions in future concentrations due to each control measure (*12*, *27*). Future concentrations are projected from baseline mean 1995−1999 observed, population-weighted concentrations (*12*) to 2010 using MCCM model runs with the 1998 emissions inventory and the 2010 emissions inventory projection (*1*, *24*). This projection is linearly extrapolated to 2020.

Reduced-form air quality modeling approaches are limited by their simplified nature and by the still large uncertainty about fundamental processes responsible for ozone and particulate matter formation in the MCMA (*11*). Further, these approaches have uncertainty due to the lack of spatial and temporal resolution, and imperfections in the modeling and measurement techniques on which the approaches are based. To estimate uncertainty bounds for particulate matter results, we compare our calculations to two alternative reduced form modeling techniques (Section S.1.1, Supporting Information), and follow the method of Hammitt et al. (*26*) who use multipliers of 1/5 and 5 for all PM intake fractions in their study of diesel particle filters for the MCMA. Cohen et al. (*8*) use intake fractions in their cost-effectiveness comparison of public bus technologies in the U.S. They estimate the ranges of uncertainty as multipliers of the central intake fraction estimate that vary between 1/5 for the lower bound to 6 for the upper bound. Considering these two studies and the alternative results, we use lower and upper bound multipliers on our central estimates for primary particulate matter concentration reductions of 1/3 and 3, respectively, and we use 1/5 and 5 multipliers for secondary particulate matter and maximum ozone concentration reductions.

2.3. Health Impacts Analysis. Results from epidemiological studies are used to estimate avoided cases of mortality and morbidity due to reductions in ambient concentrations of ozone and PM_{10} using a linear concentration response relationship. We analyze only these two pollutants given the evidence that the magnitude of their effects greatly outweighs those of other local pollutants (*27*). A set of 11 health outcomes, including premature mortality, chronic bronchitis, hospitalizations, and emergency room visits for cardiovascular and respiratory disease, and minor restricted activity days (MRAD) are considered.

Much uncertainty exists as to the correct concentration response values to use for estimating health impacts. It is not clear if concentration response functions derived from other countries can be applied to Mexico City, where socioeconomic and environmental factors may be quite different. We estimate concentration response functions and their associated uncertainty bounds based on literature derived in Mexico City where available, and also use international literature. By combining evidence from different studies, we try to capture the uncertainty associated with the true value of the concentration response functions, which is greater than the statistical uncertainty as reported in confidence intervals from epidemiological studies.

Since no cohort studies have been conducted in Mexico, we turn to the international literature to derive concentration response functions for premature mortality due to exposure to particulate matter. We use results from the American Cancer Society study (*28*), adjusting from $PM_{2.5}$ to PM_{10} assuming a ratio of 0.6 (3.6% increase per 10 $\mu g/m^3$ of PM_{10}) as the central estimate and evidence from the Six Cities study

TABLE 4. Annual Avoided Cases for Each Control Measure[a]

	taxi renovation	Metro expansion	hybrid buses	LPG leaks	cogeneration
premature mortality	40 (13:83)	18 (6:35)	13 (4:28)	11 (0:24)	0 (0:2)
chronic bronchitis	295 (147:474)	152 (83:241)	184 (75:336)	76 (22:155)	6 (2:12)
cardiovascular and respiratory hospital admissions	63 (18:137)	23 (7:49)	1 (0:3)	102 (26:212)	2 (0:4)
respiratory emergency room visits	632 (211:1,240)	232 (86:457)	19 (−4:49)	154 (53:303)	16 (5:31)
MRAD	297,000 (113,000:600,000)	119,000 (50,700:233,000)	48,600 (18,000:88,400)	73,400 (24,500:155,000)	7,190 (2,250:15,600)

[a] 90% CI in parentheses.

TABLE 5. WTP Estimates for Mexico

	value per statistical case (US$)		
health effect	lower estimate ($\epsilon = 2$)[a]	central estimate (*39*)	upper estimate ($\epsilon = 0.3$)
mortality	$81,120	$506,000	$2,600,000
chronic bronchitis	$4,394	$28,000	$140,980
MRAD	0	$20[b]	$30

[a] ϵ is the elasticity of VSL. [b] For a minor illness (cold).

(*29*) (8.3% increase per 10 μg/m^3 of PM$_{10}$) as the upper bound. For a lower estimate of premature mortality, we assume that there is no effect of long-term exposure to particulate matter and use evidence from Mexico City on the short-term effects of exposure to high levels of particulate matter from time series studies (*30*) (1.4% increase per 10 μg/m^3 of PM$_{10}$). Of the several time series studies conducted in Mexico, only one (*31*) identified ozone exposure as a predictor for premature mortality due to cardiovascular causes, but not for total mortality. For premature mortality due to ozone exposure, we use the concentration response values based on the meta-analysis by Levy et al. (*32*).

Two studies have linked chronic bronchitis to exposure to PM$_{10}$ in Mexico City (*33*, *34*); however, their results were not statistically significant (*11*). We rely on results from studies conducted in the United States for our estimate of chronic bronchitis incidence, specifically that of Abbey et al. (*35*) (10% per 10μg/m^3 of PM$_{10}$). For MRADs, we use the evidence from Ostro (*36*) and Ostro and Rothchild (*37*) for our estimates (4.3%, 95% CI: 3.1%, 5.6% per 10μg/m^3 of PM$_{10}$ and 0.5% 95% CI: 0%, 2% for 10μg/m^3 peak hour ozone). A full discussion of the concentration response functions considered, including hospitalizations and emergency room visits, is included in Supporting Information. Background data on mortality, hospitalization, and emergency room visit rates are derived from a study by the Mexican National Institute of Public Health (INSP) that occurred in conjunction with this project (*38*). Table 4 details results of cases avoided per year for the five measures analyzed.

2.4. Valuation. We apply monetary values to the estimated reductions in health outcomes using three methodologies: (1) direct health costs, (2) productivity loss, and (3) willingness to pay (WTP). Mortality, chronic bronchitis, and minor restricted activity days are evaluated using WTP only, whereas direct health costs and productivity loss are summed in the evaluation of hospitalizations and emergency room visits (*38*).

In Table 5, we report the WTP values used in this study. Our central WTP estimates are derived from the only study conducted in Mexico (*39*). Given the limited evidence from Mexico, we also use WTP values from the USEPA's analysis of "The Benefits and Costs of the Clean Air Act 1990 to 2010" (*27*), adjusted to Mexican income. We use the Mexican value for the value of a statistical life (VSL) as our central estimate and WTP estimates from the USEPA adjusted to Mexico using an income elasticity of 2 as a lower estimate and 0.3 as an upper estimate to provide a range of VSL. Recognizing the controversy between the use of the VSL or evaluating life years lost (*40*), we choose to limit our valuation of mortality benefits to the use of VSL for the purposes of our analysis.

Direct health costs are derived from Mexican Institute of Social Security (IMSS) costs for medical attention (*38*). Productivity loss was calculated based on the duration of the illness and average salary. Duration was derived from the IMSS disability database, whereas average salaries were calculated from the National Institute of Statistics and Geography's (INEGI) Survey of Household Salaries and Spending (ENIGH) for 2000. Values used for direct health costs and productivity loss for emergency room visits and hospitalizations can be found in Supporting Information.

As a preliminary estimate of the benefits from the reduction of GHG emissions, we adopt the analysis of Cohen et al. (*8*) where they estimated damages for 1 ton of CO$_2$ to range from $2 and $22 with a geometric mean of $7 as a central estimate.

3. Results

We find that implementation of these five measures will reduce PM$_{10}$ exposure by approximately 1% (0.6 μg/m^3), maximum ozone exposure by approximately 3% (4.8 μg/m^3), and CO$_2$ equivalent emissions by more than 1.5 Mton per year. Together, we estimate that these measures could save nearly 100 lives, 700 cases of chronic bronchitis, and over 500,000 cases of MRADs each year. Monetized local benefits are estimated to be over $150 million US and global benefits of approximately $10 million US per year for the combined five controls. Since we use linear models for the atmospheric modeling, health impacts analysis and valuation, the benefits found for each control measure are proportional to emissions reductions. Total annualized costs are approximately $120 million US, although this is substantially offset by a fuel savings of $75 million US. Each measure contributes uniquely to these results as summarized in Table 6.

Due to the size and age of the taxi fleet, the option to accelerate its turnover is appealing. Our analysis suggests that if current plans to implement the taxi fleet renovation measure are fulfilled, Mexico City would benefit from over $70 million US in reduced health impacts from air pollution each year on an annualized basis through 2020. Due to the increased efficiency of vehicles, fuel savings are also realized long after the implementation of the program is completed in 2010 and their sum is greater than the measure's

TABLE 6. Annualized (2003−2020, 5% Discount Rate) Concentration Reductions, Costs, Benefits, and Benefit-to-Cost Ratios for the Five Controls[a]

control measure	PM_{10} reduction ($\mu g/m^3$)	ozone reduction ($\mu g/m^3$)	investment cost (million USD/yr)	fuel savings (million USD/yr)	health benefit (million USD/yr)	CO_2 benefit (million USD/yr)	local benefit[b]/ cost	local + global benefit[c]/ cost
taxi renovation	0.24 (0.12:0.38)	3.02 (0.94:5.9)	38.6	57.3	72.0 (27.2:147)	2.8 (0.8:8.7)	3.3 (2.2:5.3)	3.4 (2.2:5.5)
Metro expansion	0.12 (0.07:0.18)	1.07 (0.33:2.1)	44.1	0.02	32.8 (12.9:60.0)	1.1 (0.3:3.6)	0.7 (0.3:1.4)	0.8 (0.3:1.4)
hybrid buses	0.15 (0.07:0.25)	−0.07 (−0.14:−0.02)	30.0	10.2	28.1 (8.5:62.2)	0.4 (0.1:1.3)	1.3 (0.6:2.4)	1.3 (0.6:2.5)
LPG leaks	0.06 (0.02:0.12)	0.74 (0.23:1.4)	1.7	0.8	18.2 (5.4:38.8)	0.2 (0.1:0.7)	11.0 (3.6:22.9)	11.1 (3.7:23.3)
cogeneration	0 (0:0.01)	0.08 (0.02:0.15)	7.3	6.4	1.6 (0.5:3.5)	6.0 (1.7:18)	1.1 (0.9:1.4)	1.9 (1.2:3.8)

[a] 90% CI in parentheses. [b] Local benefit = fuel savings + health benefit. [c] Local + global benefit = fuel savings + health benefit + CO_2 benefit.

investment cost. This results in a local benefit-to-cost ratio of over 3. This measure also reduces approximately 0.4 Mton of CO_2 equivalent emissions per year (Table 2).

Metro expansion involves significant capital investment, but the inclusion of the recuperation value for the Metro (30-year useful life) offsets a significant portion of these initial costs. We find that the local health benefits due to reduced use of on-road public bus transportation can also be large and compensate for much of the remaining costs. Approximately 20 lives could be saved per year, which, combined with other avoided health effects, results in over $30 million US in health benefits each year. Both the local and local + global benefit-to-cost ratios approach one for the Metro expansion. An increase in Metro length would require more electricity, and this will increase emissions from power plants. Although impacts of power plant emissions through long-range transport have been shown to be important (*41*, *42*), the evaluation of such impacts is beyond the scope of this analysis. We also do not evaluate the impact of emissions from additional electricity generation on populations outside the city, and this could reduce health benefit estimates. Also, public health and other benefits due to reduced congestion are not evaluated here, and they may significantly add to the health benefits of the measure.

The hybrid bus measure has relatively large upfront investment costs, but generates significant cost savings in the long term due to enhanced fuel efficiency. Health benefits are relatively large because of the reductions in primary particulate matter emissions that occur as new hybrid buses replace old diesel vehicles. Hybrid buses would provide a local benefit-to-cost ratio of 1.3, but relatively little GHG emissions reduction for its cost. We note that these results have a large source of unquantified uncertainty since the emissions factors used in this analysis are for the altitude, driving conditions, and fuel mix of New York City, not for Mexico City (*14*). Altitude has been shown (*43*) to significantly impact emissions behavior from heavy-duty vehicle technology, but it is not well-known how to adjust emissions factors for altitude and direct estimates do not yet exist for Mexico City. We recommend that a better understanding of these emissions factors be obtained and that the net benefits of other types of advanced technologies (*8*) also be considered.

The LPG leaks measure has low costs because of the low unit cost for each stove repair, and fuel savings compensate for approximately half of this cost. Health benefits are much larger than the costs because of the significant reduction in hydrocarbon emissions and thus both ozone and secondary organic particulate matter exposure. Both local and local + global benefits are more than an order of magnitude larger than the costs (Table 6).

For cogeneration, investment costs are relatively low, in part because of the inclusion of the recuperation value of the equipment at the end of the time horizon (20-year useful life). Fuel savings almost compensate for the net investment required. With cogeneration, on-site production of thermal and electrical energy replace off-site electricity generation. Only a small fraction (approximately 3.1%) of the electricity consumed in Mexico City is generated in the valley where the city is located, and thus on-site generation increases emissions of local pollutants within the city. Though cogeneration significantly reduces total emissions by increasing efficiency, the fact that it moves emissions of local pollutants into the valley makes its local benefits to the population of Mexico City quite small. However, the global benefits are significant, with over 0.8 Mton of CO_2 equivalent avoided each year (Table 2).

As discussed in the methodology section, no uncertainty is evaluated in the emission and costs module of this analysis. Uncertainty estimates, however, are included in the air quality, health impact, and valuation modules. We estimate the sensitivity of the overall results of the co-benefits model to uncertainty in individual variables by performing Monte Carlo runs of the model with uncertainty in only one variable and comparing the uncertainty in these results to that of results produced when uncertainty in all variables is used. We find that uncertainty in reduction fractions in the exposure modeling module accounts for 30% of model variability, mostly originating from the ozone and secondary particulate matter reduction fractions. In the health impacts analysis module, the uncertainty in the concentration response values contributes less than 10% of the total variability, and this is dominated by uncertainty in the coefficient for mortality from exposure to particulate matter. Finally, in the valuation module, VSL uncertainty accounts for nearly 40% of the total variability. Other uncertain parameters such as latency of the mortality effect, daily salaries, morbidity concentration response coefficients, and WTP values for chronic bronchitis and MRADs play a minimal role. Future research on air quality science and VSL quantification would be most effective in reducing uncertainty in this type of analysis.

4. Prioritization Metrics

The primary purpose of this paper is to provide improved quantitative analysis of a few measures and to demonstrate the potential effect of improved metrics on the decision making process. In this section, we consider the importance of a full cost−benefit analysis to the development of quantitative metrics for implementation prioritization. In Table 7, we compare prioritizations that can be derived from results reported in the same format as in PROAIRE to the prioritizations based on metrics using the variety of cost and benefits estimates now available for the five measures that we have analyzed in detail. We use only our results in these comparisons so that the impact of analysis methodology, as

TABLE 7. Implementation Rankings Based on Selected Quantitative Metrics, Most (1) to Least Optimal (5)[a]

ranking based on indicated metric	2010 local ton/total investment 2003−2010[b]	health benefit/cost	local benefit/cost	local + global benefit/cost
1	taxi renovation	LPG leaks	LPG leaks	LPG leaks
2	LPG leaks	taxi renovation	taxi renovation	taxi renovation
3	Metro expansion	hybrid buses	hybrid buses	cogeneration
4	hybrid buses	Metro expansion	cogeneration	hybrid buses
5	cogeneration	cogeneration	Metro expansion	Metro expansion

[a] Unless otherwise noted, rankings derive from central estimates and annualized results for 2003−2020 in Table 6. [b] This study (see Section S.7, Supporting Information), reported as in PROAIRE and West et al. (9).

opposed to the updates we have made to the cost and emissions reduction estimates for individual measures, are clear.

Ranking these five measures based on a metric that could be derived from PROAIRE results (total tons of local emissions reduction in 2010 over undiscounted investment costs for 2003−2010), we find the prioritization in the first column of Table 7. Taxi renovation ranks first. When health impacts are added to the consideration (second column), the rankings change. The LPG leak measure now ranks first since it provides the most health benefit for the cost due to its low costs and large hydrocarbon impacts, and at the same time Metro expansion drops to fourth place because its impacts on health-relevant emissions (PM_{10}, NO_x, and HC) are small (Table 2). When fuel savings are considered (third column), cogeneration, a fuel efficiency measure, ranks above Metro expansion. When global benefits are included in the benefit-to-cost ratio (fourth column), cogeneration again moves up in the ranking due to its large CO_2 reductions. Were the value of a ton of CO_2 greater, cogeneration could rank even higher.

These comparisons indicate that full cost−benefits analysis in Mexico City air pollution studies could change implementation prioritizations that derive from quantitative metrics. Policy discussions will be better informed when health benefits are quantified and when a variety of cost-to-benefit metrics are available. The cost-benefits model developed as part of this work can facilitate the further application of full cost−benefits analysis methodology to local and global air pollution problems in Mexico City.

5. Discussion

The five pollution control measures analyzed here have the potential to provide local benefits to Mexico City and at the same time to generate global benefits. Regardless of the metric used to compare controls, the LPG leak measure ranks high because it provides health benefits that are an order of magnitude larger than the costs of implementation. Investment costs for the LPG leak measure are also quite small in comparison to other measures, making its implementation more politically feasible. Taxi fleet renovation is also clearly a very promising control measure because it provides substantial fuel savings, significant local public health benefits, and relatively large GHG emission reductions. This is consistent with previous recognition (*44*) that the efficiency of transportation is key to joint local/global air pollution control. Cogeneration provides more than 50% of the GHG benefits from this set of measures, but only a very small local health benefit because it moves emissions of local pollutants into the valley where Mexico City sits. Were a similar study conducted at the national level and full consideration of the health impacts from power generation included, cogeneration may be found to be an even more promising option for joint local/global air pollution control.

Improved understanding of emissions factors from new and old vehicles under Mexico City driving conditions and altitude are needed. Benefits from reduced congestion due to Metro expansion, not quantified here, could be large. Uncertainty in cost and emission reduction estimation, air quality science, and VSL quantification needs to be addressed. Even without such improvements, we show that significantly improved understanding of opportunities for both local and joint local/global air pollution control in Mexico City can be achieved if full cost and benefit analyses are pursued. Cost-to-benefit comparisons are needed for additional PROAIRE and GHG measures. In-depth cost-benefit analysis can provide improved quantitative metrics for the full suite of control measures and better inform Mexico City's decision making process.

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Supporting Information Available

Extensive details regarding the five control measures and the analysis methodology. This material is available free of charge via the Internet at http://pubs.acs.org.

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