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Health Benefits of Air Quality Improvements in Mexico City: Emission Controls for Heavy Duty Vehicles

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Abstract

Due to the potential health impacts of diesel emissions to the atmosphere, we chose to conduct a cost-effectiveness analysis on emission reductions from diesel heavy-duty vehicles that circulate in Mexico City -adoption of emissions controls are also known as retrofit.

Our analysis shows that performing retrofit with Diesel Oxidation Catalysts (DOCs) or Diesel Particulate Filters (DPFs), can reduce particulate matter emissions, lead to improvements in air quality, and produce public health benefits among the inhabitants of the Mexico City Metropolitan Area (MCMA), at a cost that is acceptable relative to the health benefits.

We evaluate 1985 to 2014 model-year vehicles from ten vehicle classes and five model-year groups, that span the range of vehicle types, uses and model years in the heavy-duty fleet operating in Mexico City. Our analysis shows that a fully implemented program to retrofit every heavy-duty vehicle with the control which maximizes *expected* net benefits for that vehicle type and model-year group, has the potential to reduce annual emissions of primary fine particles by close to 950 metric tons; which would; cut the annual population-weighted mean concentration of $PM_{2.5}$ in Mexico City by slightly over 0.90 $\mu g/m^3$; reduce the annual number of deaths attributable to air pollution by over 80; and to generate expected health benefits of almost 250 million US$ per year. Also, it would have *expected* annual costs of close to 93 million US$ per year – consisting of 61 million US$ in 'amortization' of capital cost of retrofit devices; 19 million US$ in annual maintenance costs; and 11 million US$ in fuel use penalties. Net benefits, thus, would be in the order of 150 million US$ per year.

We close by noting that this one small step must be viewed from the wider perspective of many other programs -- such as the development of an integrated public transportation system, the promotion of the rational use of cars, the reduction of emissions from industrial sources and fires, and redesign of the MCMA area to reduce urban sprawl – that must be analyzed and implemented to make significant strides forward in the control of air pollution and its public health impacts.

Introduction

The objective of this analysis is to explore the cost-effectiveness of technologies to control emissions of primary fine particles from heavy-duty diesel-fueled vehicles circulating in Mexico City. The benefits of such controls are the expected improvements in ambient air quality and the associated reductions in mortality. The costs of control include capital costs and annual operating and maintenance costs.

Adverse health effects of short and long-term exposure to ambient fine particles (with an aerodynamic diameter of 2.5 µm or less, $PM_{2.5}$) have been documented profusely. Cohort studies have examined the association with long-term $PM_{2.5}$ exposures and annual premature mortality and have found positive associations with no discernible threshold. The health effects of $PM_{2.5}$ may be explained because their small size allows their penetration deep into the lungs, and because they absorb metals and other toxic agents.

Multiple emitting sources contribute to ambient $PM_{2.5}$ concentrations in urban settings, including emissions from vehicles. Among the most significant contributors to air pollution-associated public health impacts are diesel-fueled heavy-duty vehicles. For instance, among the risks posed by such emissions is lung cancer, in fact, the International Agency for Research on Cancer (IARC) has classified diesel engine exhaust as carcinogenic to humans (IARC, 2015).

Mexico City is located in a nearly closed basin. Trapped pollutants favor the exposure of around 20 million inhabitants, when considering the metropolitan surrounding area, with severe health implications. The adverse health effects of $PM_{2.5}$ concentrations, that exceed the national ambient air quality standards and the World Health Organization recommended limits, require efforts to analyze control strategies aiming at reducing particle emissions and protecting public health.

Methods

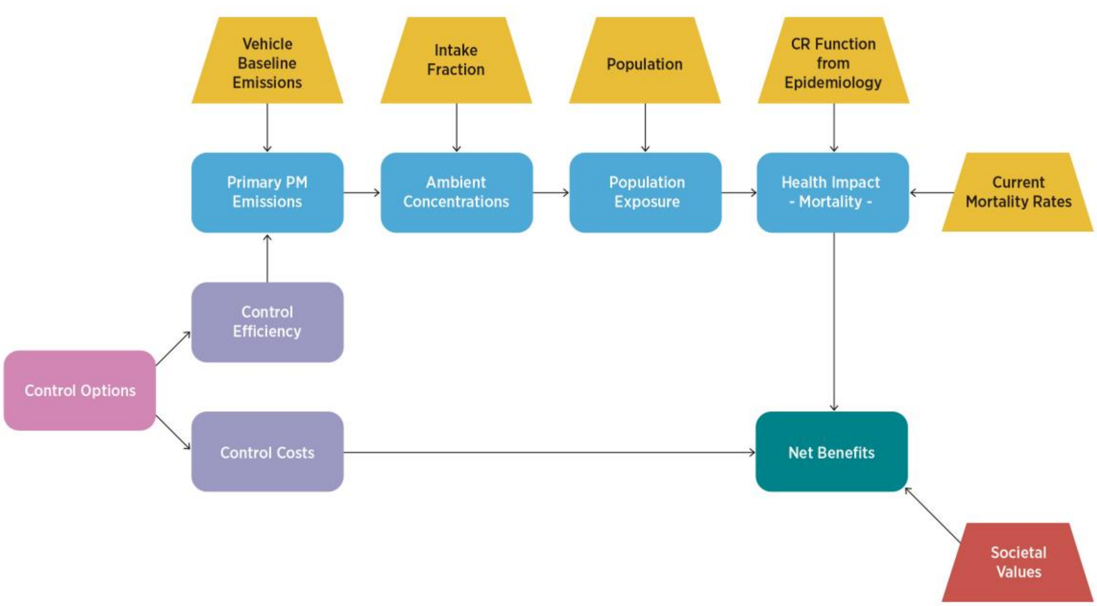
Our analysis, conducted using the software Analytica, involves five major elements: (i) analysis of the efficiency of each potential control for reducing emissions of primary fine particles; (ii) analysis of the costs of each potential control; (iii) characterization of the impacts of emissions reductions on ambient PM concentrations; (iv) analysis of the reductions in mortality expected to result from these improvements in ambient air quality; and (v) monetization of these health benefits and comparison of benefits and costs.

The unit of analysis is a single vehicle, and we included vehicles from model years 1985 to 2014. We evaluate representative vehicles from each of ten vehicle classes and five model-year groups – intended to span the range of vehicle types, uses and model years in the heavy-duty fleet operating in Mexico City, and included in Mexico's City latest emissions inventory with base-year 2014 (SEDEMA, 2016). The vehicle classes are: bus RTP public transportation – local plate; bus school and personnel – local plate; bus concession – local plate; Metrobús – local plate; bus tourism – federal plate; bus passenger – federal plate; truck – local plate; truck – federal plate; long-haul trailer – local plate; and long-haul trailer – federal plate. The model-year groups are: 1985-1993 (vehicles before emissions control regulations were in place (pre-control); 1994-1997 equivalent to US 1991 or Euro I standards (US 1991/EURO I); 1998-2006 (US 1994/Euro II); 2007-2010 (US 1889/Euro III); and 2011-2014 (US 2004/Euro IV).

Based on their model years, RTP public transportation buses and Metrobús vehicles were assigned to the corresponding model-year groups that were formed for the rest of the heavy-duty fleet. RTP buses belong to 1998-2006 and 2007-2010 model-year groups. The Metrobús System started operations in 2005, so vehicles were assigned to the three newest model-year groups: 1998-2006 (for model year vehicles 2005-2006), 2007-2010, and 2011-2014.

Figure 1 is a schematic representation of the model and its major elements, which relate emissions from vehicles, pollutant concentrations in the atmosphere, population exposures to air pollutants, health impacts, the benefits from control options (i.e., effect on emissions reductions), and their estimated societal values in monetary units.

Figure 1. Cost-Effectiveness Heavy-Duty Vehicle Retrofit Analysis Diagram



Activity and Emissions Per Vehicle

The analysis begins by characterizing each vehicle in terms of its nature (bus, truck, tractor trailer) and age (model-year group), its activity level (vehicle km travelled each year), its baseline emissions rates (g/km travelled) and fuel economy (km/L), and its remaining useful lifetime (yr.). Data on age, activity and baseline emissions rates come from the official emissions inventory for 2014 (SEDEMA, 2016). Data on fuel economy comes from U.S. Department of Energy (2015). Using this information, baseline annual emissions (g/yr) for primary PM are computed.

Table 1 provides information on the size and composition of the heavy-duty diesel fleet operating in Mexico City, by vehicle type and model-year group.

Table 1. Heavy-Duty Fleet by Vehicle Type and Model-Year Group

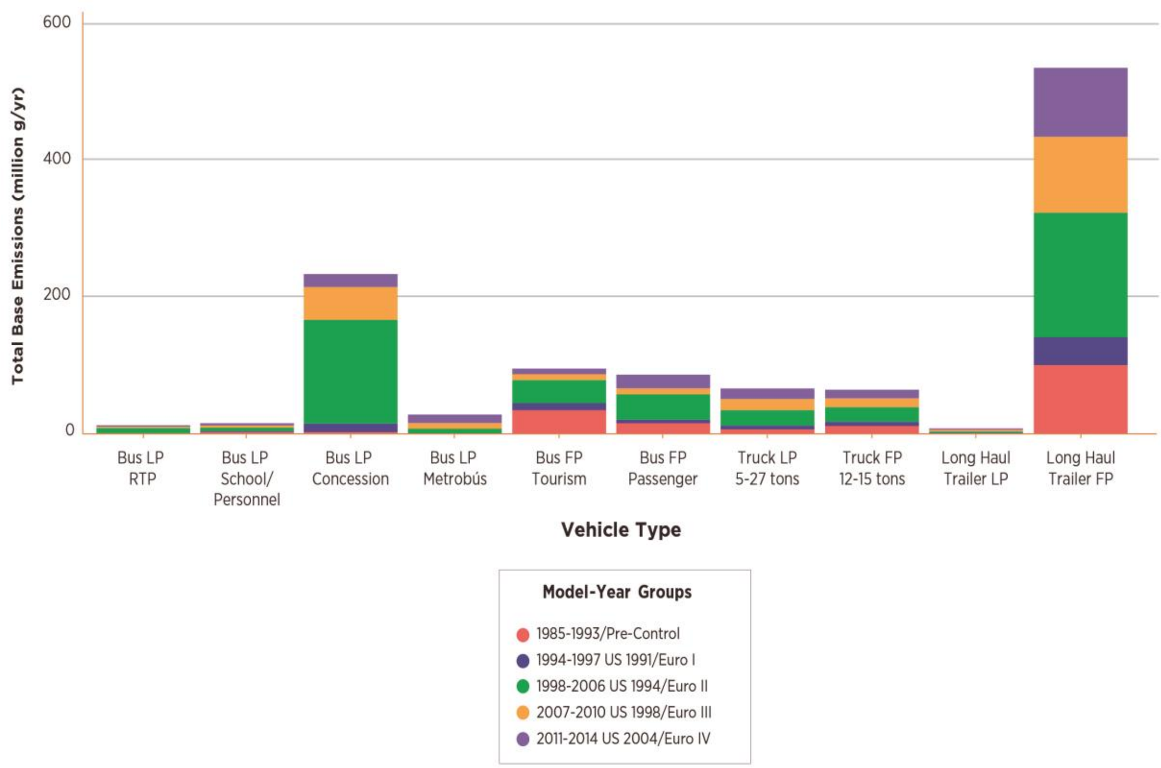
Vehicle Type		1985-93 Pre-Control	1994-97 US 1991/ EURO I	1998-06 US 1994/ EURO II	2007-10 US 1998/ EURO III	2011-14 US 2004/ EURO IV	All Model Years
Transportation Buses	RTP Public Transport Local Plate	0	0	949	250	0	1,199
	School & Personnel Local Plate	55	65	490	227	324	1,161
	Concession Local Plate	12	310	3,770	1,669	626	6,387
	Metrobús Local Plate	0	0	99	129	148	376
	Tourism Federal Plate	2,250	861	3,465	1,343	992	8,911
	Passenger Federal Plate	1,491	491	5,722	2,028	4,155	13,887
Delivery Trucks >3.8 tons	Trucks Local Plate	1,162	750	3,893	2,367	2,763	10,935
	Trucks Federal Plate	2,013	893	3,603	1,862	2,065	10,436
Long-Haul Tractor Trailers >27.2 tons	Trailers Local Plate	13	9	206	273	139	640
	Trailers Federal Plate	8,864	3,929	15,839	8,207	9,088	45,927
All Vehicle Types		15,860	7,308	38,036	18,355	20,300	99,859

Notes: Vehicles from model year 1984 and older are excluded from the cost-effectiveness analysis because the Emissions Inventory, 2014 groups them in one category, which results in aggregate emissions for a wide range of technologies. Also excluded are vehicles that have been retrofitted under a voluntary program from the government of Mexico City (*Autorregulación* Program): 16 RTP buses, 2 school and personnel buses, 24 trucks with local plates, and 3 trucks with federal plates. RTP buses belong to only two model-year groups, 1998-2006 and 2007-2010, and Metrobús System vehicles to only three model-year groups, 1998-2006, 2007-2010, and 2011-2014. Delivery Trucks > 3.8 tons with local plates weigh between 4.6 and 27.2 tons, those with federal plates weigh from 11.8 to 14.9 tons.

There are roughly 100,000 heavy-duty diesel trucks and buses from model years 1985 to 2014 that are still in operation. Long-haul tractor trailers make up almost half of the fleet, with virtually all having federal plates. Buses account for about one third of the fleet, with two thirds of these having federal plates serving as tourism or passenger buses. Trucks, split equally between those with local plates and federal plates, account for the remaining 20% of the fleet. The heavy-duty diesel fleet is relatively old. Roughly 60% of the vehicles are more than 10 years old, with two thirds of these more than 20 years old. Only 20% of vehicles are in the most recent model-year group – between 3 and 7 years old.

Figure 2 shows estimated annual emissions of primary particles by each type of vehicle and model-year group. Note that of the estimated total annual emissions of primary particles of ~ 1000 metric tons, more than 50% is due to long-haul trailers with federal plates, another 25% is due to concession buses with local plates. The remaining 20-25% of primary particle emissions is roughly equally split between buses (both tourism and passenger) with federal plates, and trucks (with both local and federal plates). Two categories of vehicles – school & personnel buses with local plates, and long-haul trailers with local plates make inconsequential contributions to primary particle emissions.

Figure 2. Annual Emissions of Primary Particles by Vehicle Type and Model-Year Group



Among the two vehicle types which dominate emissions of primary particles, 1998-2006 EPA 1994/Euro II model year vehicles contribute most substantially, followed by 2007-2010 EPA 1998/Euro III model year vehicles, and then, almost equally, by 1985-1993 pre-control model year vehicles, and 2011-2014 US 2004/Euro IV.

Controls: Efficiency and Cost

Once the vehicle is characterized, attention turns to determining which controls are potentially applicable and then to estimating their costs. Our analysis considers four possible controls: (i) oxidation catalyst, (ii) diesel particulate filter, active regeneration, (iii) diesel particulate filter, catalyzed, and (iv) an ideal control, one which is 100% efficient in reducing emissions of primary PM and which has no cost. The ideal control provides an upper bound on the net benefits of any possible emission-control technology.

Diesel particulate filters (DPF) trap particulate matter and must undergo a process called "filter regeneration" to burn it off (releasing carbon dioxide and water). This process cleans the trap and avoids clogging, which would result in high back-pressure affecting the engine performance. Catalyzed DPFs are not compatible with pre-1994 Mexican diesel technologies, also, they require ultra-low sulfur (ULS) fuel for reliable regeneration and optimal function. ULS diesel (≤ 15 ppm) has been available in Mexico City since 2009 but is not yet available in a large portion of the country, which restrains the use of DPFs with catalytic regeneration for vehicles that drive outside of the city, ie., vehicles that hold federal plates.

Information on the efficiency of each control for reducing primary PM emissions came from CARB Diesel Certification & Verification Procedure, and technology-specific corresponding Executive Orders (CARB, 2013, 2014, 2015a and 2015b). We have assumed that since ultra-low sulfur fuel is the only type of diesel fuel available in Mexico City that the introduction of retrofit technology has no impact on SO_2 emissions. Similarly, we assume that oxidation catalysts and diesel particulate have no impact on NOx emissions.

Estimates of the capital costs are taken from recent SEDEMA bids for diesel retrofit devices (SEDEMA, 2017b).[1] Annual maintenance costs are from a SEDEMA quote from HUG Engineering (SEDEMA,2017), and estimates of the fuel use penalties for each control device

[1] The bids submitted to SEDEMA were for retrofit equipment that combined diesel particulate filters with oxidation catalysts. We subtracted the median estimate of the cost of an oxidation catalyst, $1000, from each bid to estimate the cost of diesel particulate filters for application in Mexico City.

came from MECA (1999) in Stevens et al. (2005). The costs and efficiency of the control devices considered are summarized in Table 2.

The equivalent annual control cost for each device was computed by converting the capital cost to an equivalent annual cost stream using the capital recovery factor and adding the result to the annual maintenance cost and any additional cost related to the decreased fuel economy of vehicles equipped with DPFs. The discount rate used in our analysis was 3% per year. The cost of (ultra-low sulfur) fuel used to compute the fuel use penalty was taken as 1.01 US$ per Liter (INPC, 2017).

$$EAC = C * crf + M + CIFU$$

where EAC is the equivalent annual cost (US$/veh-y); C is the capital cost (US$/veh); crf is the capital recovery factor which depends on the lifetime of the equipment, L (y), and the discount rate, r (fraction/y); M is the annual maintenance cost (US$/veh-yr); and CIFU is the cost of increased fuel use (US$/veh-yr).

Table 2. Costs and Efficiency of Control Retrofit Technologies for Heavy-Duty Diesel Vehicles

		Diesel Oxidation Catalyst	Diesel Particulate Filter Active Regeneration	Diesel Particulate Filter Catalyzed	Hypothetical Perfect Control
Capital Cost (1000 US$/veh)		0.5 – 1.5	7.0 – 9.0	6.0 – 8.0	--
Lifetime of Equipment (y)		10(9)	10	10	--
Annual Maintenance Cost (US$/veh-y)		--	220	220	--
Fuel Use Penalty (fractional)		--	0.02	0.004	--
Control Efficiency (fractional)	PM	0.20 - 0.26	0.8 - 0.9	0.8 - 0.9	1.00

The capital recovery factor is given by:

$$crf = \frac{r*(1+r)^L}{(1+r)^L - 1}$$

The cost of increased fuel use is given by:

$$CIFU = P * F * A/E$$

where P is the price (US$/L) of fuel; F is the fuel use penalty (fractional increase); A is the activity level (km/veh-y); and E is the baseline fuel economy (km/L).

The emissions $E_{i,j,k}$ (g/y) of the j^{th} pollutant from the i^{th} vehicle type expected after implementation of the k^{th} control are given by:

$$E_{i,j,k} = (1 - \varepsilon_{j,k}) * Eo_{i,j}$$

Where $\varepsilon_{j,k}$ is the control efficiency (fractional) of the k^{th} control for the j^{th} pollutant, and $Eo_{i,j}$ (g/y) represents the uncontrolled emissions of the j^{th} pollutant from the i^{th} vehicle type.

Population Exposure: Intake Fraction and Primary Particle Concentrations

Once the uncontrolled emissions, and the emissions with the implementation of each control device, are known, the vehicle's contribution to population exposure may be estimated using the concept of intake fraction.

Intake fraction, which is the simplest measure of the relationship between emissions and exposure, is defined as the ratio of the population intake of a pollutant (g/yr) divided by the emissions (g/yr) of the pollutant or a precursor. Intake fractions depend on all the factors which influence the relationship between emissions and exposure. These include the nature and location of the source (whether it is ground level or elevated; whether it is located in a densely populated city or in a rural area); the pollutant (whether it is conservative – i.e., has a low deposition velocity, does not react chemically with other pollutants – or reactive – i.e., has a short atmospheric half-life) and the atmosphere to which it is emitted (e.g., the wind speed, the mixing height); and the receptors (for example, the population density).

Intake fractions may be estimated using atmospheric fate and transport models or by combining results from source-receptor analysis with information from emissions inventories. Because our emission controls do not affect NOx or SO_2 we only care about the primary $PM_{2.5}$ intake fractions. Intake fractions may be greater for emissions within the city than for emissions outside of the city – especially for primary $PM_{2.5}$ emitted by vehicles.

Our estimates of intake fraction for primary $PM_{2.5}$ used for exposures within the MCMA rely on the intake fraction estimates of Stevens et al. (2007) which are consistent with a recent effort to estimate iF for hundreds of cities globally (Apte et al., 2012). These estimates reflect the entire MCMA population of 18 million and use a nominal breathing rate of 20 m^3/day.

Stevens and coauthors applied four approaches (a static box model, a dynamic box model, a regression approach, and a source apportionment method) that gave iF estimates varying from 26 (regression) to 120 per million (box and source apportionment), geometrically centered at 60 per million, with an approximate factor of two uncertainty. Our analysis relies on a triangular distribution with a mode of 60 per million, a minimum of 30 and a maximum of 120 per million to reflect their results.

Using these estimates of intake fraction and the emissions estimates discussed previously, the city-wide average annual concentration change, $\Delta C_{i,j}$ ($\mu g/m^3$), due to the emissions, $E_{i,j}$, of the pollutant from the i^{th} vehicle type under the j^{th} control are given by:

$$\Delta C_{i,j} = iF_j * E_{i,j} / (P * B * 365)$$

where iF is the intake fraction, P is the population (persons), B is the nominal breathing rate (m^3/person-day) and 365 is the constant needed to convert the daily breathing rate to an annual breathing rate.

Health Impact: Concentration-Response Function

The impact on mortality of the incremental air pollution exposure caused by emissions from a representative vehicle is computed using the integrated exposure response functions (IER) developed to support the 2010 and 2013 Global Burden of Disease analysis (Lim et al., 2012; Burnett et al., 2014 Forouzanfar et al., 2015).

Current evidence suggests that, among adults, mortality rates from four causes of disease – Ischemic Heart disease (IHD), Cerebrovascular Stroke (STK), Chronic Obstructive Pulmonary Disease (COPD), and Trachea, Bronchus and Lung Cancers (LC) – are elevated by chronic exposure to airborne $PM_{2.5}$. In addition, among young children, mortality rates from Acute Lower Respiratory Infections (ALRI) are elevated among those with chronic $PM_{2.5}$ exposure. The IER has the form:

$$for\ C \geq Xo, \qquad RR = 1 + \alpha * (1 - \exp\left(-\beta * (C - Xo)^{\delta}\right))$$

where α is the asymptotic limit of RR as $PM_{2.5}$ approaches infinity, β indicates the rate of increase per unit increase in $PM_{2.5}$, Xo is the counterfactual (the $PM_{2.5}$ concentration below which there is no known increase in risk), δ (dimensionless) is the power, and C is the annual average concentration ($\mu g/m^3$) of $PM_{2.5}$.

Values of the parameters α, β, Xo, and δ for COPD and for LC have been estimated for persons 25 or more years of age, and for ALRI for children younger than 5 years of age; for IHD and for STK, parameters have been estimated for each of 12 five-year-age groups from 25 to ≥ 80 years (Burnett et al., 2014). Burnett and coauthors have analyzed the uncertainty in the parameters and provided a set of 1000 equally-likely sets of parameter values for each disease.

Our analysis relies on a linear approximation to the IER. We assume that for small increments or decrements in $PM_{2.5}$ the change in relative risk can be approximated well by the product of the slope of the tangent to the IER evaluated at current levels of $PM_{2.5}$ in Mexico City. The annual average $PM_{2.5}$ level in Mexico City in 2014 was 22.8 μg/m^3 (SEDEMA, 2015). We probabilistically characterized the slope (% increase in RR per μg/m^3) of the IER for each of the five diseases of interest at 20 μg/m^3. This was done numerically by evaluating:

$$\text{Slope of RR @ Co} = [\text{RR (Co + 1)} - \text{RR (Co)}] / [(\text{Co} + 1) - (\text{Co})]$$

Summary slopes for application in Mexico City and in the MCMA excluding Mexico City (minus CDMX) were then computed by weighting the disease-and-age-specific slopes obtained above by the disease-and-age-specific mortality rates in Mexico City and in the MCMA (minus CDMX). Fifteen parameters (min, 1%, 2.5%, 5%, 10%, 25%, 33%, 50%, 67%, 75%, 90%, 95%, 97.5%, 99% and max) of each of these distributions were used to probabilistically characterize the summary slopes for Mexico City and MCMA (minus CDMX) in our calculations.

Table 3 provides probabilistic characterizations of 5 out of 15 retrieved parameters of the distribution (median, 25% and 75%, 2.5% and 97.5%) of the disease-and age-weighted relative risk (RR) of mortality and slope of the function, across all diseases and age groups of interest, for Mexico City and MCMA (minus CDMX) given by the integrated exposure-response function at an ambient $PM_{2.5}$ concentration of 20 μg/m^3. Table 4 provides the mortality rates used in computing the summary slope.

Table 3. Relative Risk of Mortality and Slope of the Integrated Exposure-Response Function in Mexico City and in the MCMA (minus CDMX) at 20 μg/m^3

Parameter	RR @ 20 μg/m^3		Slope @ 20 μg/m^3 (% increase in RR per μg/m^3 $PM_{2.5}$)	
	CDMX	MCMA (minus CDMX)	CDMX	MCMA (minus CDMX)
2.5%	1.209	1.218	0.753	0.678
25%	1.229	1.236	0.880	0.792
50%	1.239	1.247	0.962	0.880
75%	1.250	1.257	1.042	0.974
97.5%	1.274	1.278	1.234	1.182

Table 4. Mortality Rates for $PM_{2.5}$ Related Causes in Mexico City and MCMA (minus CDMX), 2014

Disease	Mortality Rate in 2014 (deaths / year)	
	CDMX	MCMA (minus CDMX)
Ischemic Heart Disease	9,851	6,376
Cerebrovascular Stroke	1,195	1,069
Chronic Obstructive Pulmonary Disease	2,012	1,953
Trachea, Bronchus and Lung Cancers	667	491
Acute Lower Respiratory Infections	168	258
All Diseases of Interest	13,893	24,045

Finally, we introduced a *cessation lag* in our benefit calculation, which refers to the reductions over time in the risks of mortality that are expected after the exposure to ambient $PM_{2.5}$ is reduced (HES, 2004). The reduction of risk may start immediately after the emissions are reduced and may continue for some time. In practice, the $PM_{2.5}$ *cessation lag* effect is estimated by assigning a fraction of avoided deaths attributable to the $PM_{2.5}$ exposure (i.e., the benefits) every year after cessation (or reduction) of the exposure. In our analysis, the lag structure allocates benefits over 20 years: 20% of the benefits in the first year, 50% equally divided in the following four years, and an even distribution of the remaining 30% in the following 15 years (HES, 2004).

Economic Impact: Monetization of Health Impact

The monetary value of the reduction in mortality risk is calculated by multiplying the population risk reduction (i.e., the reduction in deaths attributed to PM) times the rate at which mortality risk is valued, the Value per Statistical Life (VSL). We estimate VSL following recommendations developed for conducting benefit-cost analysis (BCA) in low- and middle-income countries supported by the Gates Foundation. Robinson, Hammitt and O'Keefe (2018) suggest that, when high-quality direct estimates of VSL are not available, analysts should extrapolate from values estimated for the United States, adjusting for the difference in average income between the US and the target country. They recommend (i) using purchasing-power-parity (PPP) rather than market exchange rates to compare incomes; (ii) to use one of two values of income elasticity (1.0 or 1.5), chosen based on the ratio of incomes; and to extrapolate from ratios of VSL to income of 160 and 100 (based on US and OECD values) or from a ratio of 160.

We apply these methods to both Mexico City and the MCMA outside of the city boundaries and assume the lowest and highest estimates for each region span an 80 percent credibility interval.

The extrapolated ratios are calculated as follows:

$$VSL_M/y_M = (y_M/y_{US})^{h-1}\ VSL_{US}/y_{US}$$

Where y is income, and h is the income elasticity.

For income, we use GDP per capita in Mexico City itself and in the MCMA outside of the city proper. We adjust to US dollars using PPP and obtain US $37,500 for Mexico City and US $14,600 and in the MCMA outside of the city proper (INEGI, 2017).

For Mexico City we characterize VSL using a lognormal distribution with a median of 4.7 million US$ and a geometric standard deviation of 1.4 (implying a mean of 5.1 million US$) (Table 10). For the area in the MCMA outside of the city proper, we characterize VSL using a lognormal distribution with a median of 1.7 million US$ and a geometric standard deviation of 1.7 (implying a mean of 1.9 million US$). The population weighted mean VSL for the entire MCMA is 3.3 million US$.

For comparison, the only study estimating VSL in Mexico of which we are aware is Hammitt and Ibarrarán (2006). They estimated VSL in Mexico as $230,000 and $310,000 for an average income of $4100. Table 10 summarizes the estimates of the VSL used to monetize mortality impacts.

Results

Emissions within CDMX lead to exposures and health risks in the City and throughout the metropolitan area, so our results consider the benefits in the MCMA. For each type of vehicle and model-year group results include the emissions reductions (kg/veh-yr), the attributable deaths avoided (#/1000 veh-yr), the monetized benefits of the avoided deaths (1000 US$/veh-yr), the control costs (1000 US$/veh-yr), and the net benefits (1000 US$/veh-yr) for the *Ideal Control*, each of the three control technologies, and an ideal control.

Illustrative results for the two most important categories of vehicles in terms of emissions (bus concession – local plate –and long-haul trailer – federal plate) for one model-year group (1998-2006 EU 1994/Euro II) will be discussed. The complete set of results for all vehicle types and model-year groups is not shown.

For the approximately 4 thousand concession buses with local plates, the largest *expected* net benefits are generated by choosing to retrofit with a catalyzed DPF (Table 5). These vehicles are heavily used, each traveling roughly 70 thousand km per year. The catalyzed DPF retrofit is expected to reduce emissions by 35.6 kg per vehicle-year; and to reduce premature deaths attributable to air pollution by about 3 per 1000 vehicle-year; with benefits of US$ 9.2 thousand and costs of only 1.4 thousand US$ per vehicle-year. The catalyzed DPF is an option because these buses are driven only locally, where ultra-low sulfur fuel is available. The expected net benefits of this strategy (health benefits minus control costs) are almost 8 thousand US$ per vehicle year.

Table 5. Results for Bus Concession – Local Plate
Model Years 1998 to 2006 US 1994/Euro II

	Emissions Reduction (kg/veh-yr)	Deaths Avoided (#/1000 veh-yr)	Benefits (1000 USD/veh-yr)	Control Cost (1000 USD/veh-yr)	Net Benefits (1000 USD/veh-yr
Status Quo	0.00	0.00	0.00	0.00	0.00
DOC	9.35	0.83	2.41	0.14	2.27
DPF -- Active	35.56	3.14	9.17	2.42	6.75
DPF -- Passive	35.56	3.14	9.17	1.43	7.74
Ideal Control	40.64	3.59	10.48	0.00	10.48

Notes: DOC stands for Diesel Oxidation Catalyst; DFP-p stands for Diesel Particulate Filter with catalyzed regeneration (passive), and DFP-a stands for Diesel Particulate Filter with active regeneration. Rows in green highlight the retrofit technology that maximizes the expected net benefits.

For the approximately 16 thousand long-haul trailers with federal plates the largest *expected* net benefits (almost 1.8 thousand US$ per veh-year) would be generated by choosing to retrofit with a catalyzed DPF (Table 6). This would be expected to reduce emissions by 10.2 kg per vehicle-year; and to reduce premature deaths attributable to air pollution by approximately 1 per 1000 vehicle-year; with benefits of over 2.6 thousand US$ and costs of less than 0.9 thousand US$ per vehicle-year. Unfortunately, the catalyzed DPF is not an option because these long-haul trailers, with federal plates, are driven both in Mexico City and outside of the city, where ultra-low sulfur fuel is not widely available. The use of these trailers *within the city* is on average only 14 thousand km per vehicle-year.

Of the remaining options, the largest *expected* net benefits of close to 1.6 thousand US$ per veh-year are generated by choosing to retrofit with an active regeneration DPF. This generates the same emissions reductions and health benefits as the catalyzed DPF but has costs which are roughly 20% higher due to the larger fuel penalty associated with active regeneration of the filter.

Table 6. Results for Long-Haul Tractor Trailer – Federal Plate
Model Years 1998 - 2006 EU 1994/Euro II

	Emissions Reduction (kg/veh-yr)	Deaths Avoided (#/1000 veh-yr)	Benefits (1000 USD/veh-yr)	Control Cost (1000 USD/veh-yr)	Net Benefits (1000 USD/veh-yr
Status Quo	0.00	0.00	0.00	0.00	0.00
DOC	2.68	0.24	0.69	0.09	0.60
DPF -- Active	10.18	0.90	2.63	1.06	1.56
DPF -- Passive	10.18	0.90	2.63	0.86	1.77
Ideal Control	11.64	1.03	3.00	0.00	3.00

Notes: DOC stands for Diesel Oxidation Catalyst; DPF-p stands for Diesel Particulate Filter with catalyzed regeneration (passive), and DPF-a stands for Diesel Particulate Filter with active regeneration. Rows in light gray highlight retrofit technologies that are not adequate for such vehicle type. Rows in green highlight the retrofit technology that maximizes the expected net benefits.

Following this approach and examining the cost-effectiveness and the applicability of available control technologies for each vehicle type and model-year group, control options that maximize expected net benefits were identified (Table 7).

For the two categories of vehicles, bus concession - local plate and long-haul trailer - federal plate, which are responsible for the greatest share of primary PM emissions, DPF retrofits are cost-effective – providing the maximum possible expected net benefits with expected emissions reductions between 80 and 90%. Comparable results are shown for the third largest primary PM emitter, bus tourism – federal plate, for which DPF retrofits are cost-effective for all year groups.

Our results indicate that for all categories and model years some retrofit is cost-effective. In some cases, for example trucks with local or federal plates, DPFs are not cost-effective for some model-year groups, but oxidation catalysts are, for which projected emissions reductions range between 20 and 26%. A similar result is found for bus passenger - federal plate –the fourth largest primary PM emitters--, either DPF or DOC are cost-effective for all model-year groups.

Our analysis indicates that the strategy consisting of retrofitting every vehicle with the control which maximizes *expected* net benefits for that vehicle type and model-year group, would have the potential to:

- Reduce annual emissions of primary fine particles by 950 metric tons; which would
- Cut the annual population-weighted mean concentration of $PM_{2.5}$ in the MCMA by close to 0.90 $\mu g/m^3$
- Reduce the annual number of deaths attributable to air pollution by over to 80; and to
- Generate expected health benefits on the order of 250 million US$ per year.

It has *expected* annual costs of less than 93 million US$ per year – consisting of 61 million US$ in 'amortization' of capital cost of retrofit devices; 19 million US$ in annual maintenance costs; and 11 million US$ in fuel use penalties. This results in close to 150 million US$ net benefits for a fully implemented strategy of retrofitting every vehicle.

Table 7. Maximized Expected Net Benefit Retrofit Control by Vehicle Type and Model-Year Group and Estimated Probability (%) of a Positive Net Benefit for Each Indicated Retrofit Control

Type of Vehicle & Plate		1985-93 Pre-Control	1994-97 US 1991/EURO I	1998-06 US 1994/EURO II	2007-10 US 1998/EURO III	2011-14 US 2004/EURO IV
Transportation Buses	RTP - Public Transport Local Plate	n.a.	n.a.	DPF-p 80	DOC 70	n.a.
	School & Personnel Local Plate	DPF-a 99	DPF-p 97	DPF-p 97	DPF-p 80	DPF-p 78
	Concession Local Plate	DPF-a 96	DPF-p 99	DPF-p 99	DPF-p 99	DPF-p 99
	Metrobús Local Plate	n.a.	n.a.	DPF-p 72	DPF-p 99	DPF-p 99
	Tourism Federal Plate	DPF-a 99	DPF-a 96	DPF-a 95	DPF-a 86	DPF-a 82
	Passenger Federal Plate	DPF-a 90	DPF-a 74	DPF-a 70	DOC 98	DOC 98
Delivery Trucks > 3.8 tons	Trucks Local Plate	DOC 99	DPF-p 80	DPF-p 80	DPF-p 80	DOC 96
	Trucks Federal Plate	DOC 99	DOC 99	DPF-a 65	DPF-a 74	DPF-a 58
Long-Haul Tractor Trailers > 27.2 tons	Trailers Local Plate	DOC 91	DOC 93	DPF-p 84	DPF-p 93	DPF-p 87
	Trailers Federal Plate	DPF-a 95	DPF-a 88	DPF-a 95	DPF-a 97	DPF-a 94

Notes: RTP public transportation and Metrobús vehicles have vehicles than belong to only two and three model-year groups, respectively. DOC stands for Diesel Oxidation Catalyst; DPF-p stands for Diesel Particulate Filter with catalyzed regeneration (passive), DPF-a stands for Diesel Particulate Filter with active regeneration, and n.a. stands for not applicable for vehicle categories and model-year groups for which there were no vehicles in the Emissions Inventory, 2014.

There is always uncertainty about the health benefits and costs of policies to reduce air pollution. Our analysis quantifies uncertainty about some of the most important inputs, including the relationship between emissions (in this case emission reductions) and population exposure (summarized by the intake fraction), the slope of the exposure-response functions relating mortality to air pollution, the monetary value of reductions in mortality risk (summarized by the value per statistical life), as well as the efficiency and cost of each control option.

By quantifying uncertainty about some of the most important parameters, we can estimate the probability that the net benefits of the identified retrofit program are positive, that is, that the benefits of the reduction in mortality risk exceed the cost of the specified retrofit technology. These probabilities are displayed in Table 13 for each vehicle type and model-year group. As shown there, for the vehicle type accounting for the largest share of emissions --long-haul trailers with federal plates--, the estimated probability that the value of the mortality-risk reduction associated with retrofit with active DPF exceeds the cost of the retrofit is between 88 percent and 97 percent depending on the specific model-year group. For the vehicle type accounting for the second largest share of emissions --concession buses with local plates--, the probability that retrofitting vehicles of model year 1994 or later with passive DPFs is cost effective is 99 percent and the probability that retrofitting older vehicles with active DPFs is cost effective is 96 percent.

Overall, for most vehicle type/model-year group categories, the probability that the identified retrofit option will yield benefits greater than its cost is about 80 percent or larger. The two exceptions are RTP buses with local plates, and delivery trucks with federal plates. For the first group, the probability that retrofitting 2007-2010 vehicles with oxidation catalysts yields net benefits is only 70 percent. For the second group, the probability that retrofitting newer vehicles (model years 1998 and after) with active DPF yields net benefits is estimated as 58 to 74 percent. However, this does not imply that these vehicles should not be controlled, because the probability that retrofitting these vehicles with oxidation catalysts --a less costly control technology--, yields positive net benefits is 99 percent.

In evaluating uncertainty about the net benefits of different control options, we find that uncertainty about the net benefits of DPFs is greater than about the net benefits of oxidation catalysts. This result because the DPFs reduce primary PM emissions substantially more than do DOCs, and hence uncertainty about the effect of emissions on mortality or about the monetary value of mortality risk have a larger effect on estimated benefits. Moreover, because oxidation catalysts are much less costly than DPFs, the range of benefits that is less than their costs are very small, and it is unlikely that benefits fall in this narrow range. It should be iterated that the net benefits of the passive DPF always exceed those of the active DPF, because they produce the same benefits but are less pricy, partly because the active DPFs impose a larger fuel-efficiency penalty.

Discussion

The cost-effectiveness analysis conducted for Mexico City heavy-duty vehicles clearly shows that performing retrofit with DOCs or DPFs can reduce particulate matter emissions, lead to improvements in air quality, and have public health benefits among the inhabitants of the MCMA.

Retrofit programs have been put in place in other countries and have been on the radar of policy makers in Mexico for decades. Their success comes from the fact that diesel retrofit technologies, such as DOCs and DPFs, that can reduce diesel particulate matter, are similar in control efficiency to emission control technologies from newer diesel vehicles (ICCT, 2017). In the US, CARB implemented a mandatory retrofit program for most in-use heavy-duty diesel vehicles, and EPA, in turn, established a voluntary retrofit program. EPA's benefit-cost analysis of the program for the years 2009 to 2013 shows an estimate of 1,700 fewer deaths attributed to the reduction in pollutant emissions, with a total present value of up to $11 billion in monetized health benefits over the lifetime of the affected engines (ICCT, 2017).

Over ten years ago (2005-2006), a pilot retrofit project was conducted in Mexico City, by EMBARQ in partnership with EPA, and Mexican environmental federal and local authorities (EMBARQ-WRI, 2007). DOCs and DPFs-catalyzed were installed in 20 urban passenger buses and followed-up for 11 months; DOCs were installed in model year 1991 buses, and DPFs in model year 2001 buses. Emission reduction efficiencies were as expected; primary $PM_{2.5}$ reductions were on the order of 20 to 30% for DOCs, and 80 to 90% for DPFs. Two fundamental lessons were learned. One key to the success of the program was selecting appropriate buses for retrofitting through previous careful testing. A second essential element for success was training operators on how the emissions control devices worked, how they were installed, and driving techniques for best performance of the equipment. More recently, Mexico City's Environmental authorities put in place a voluntary program (*Autorregulación* Program) which has succeeded in having retrofit devices installed in 27 heavy-duty trucks and 18 RTP buses.

Our current analysis seeks to determine whether expanding retrofit programs to a wide variety of diesel-fueled heavy-duty vehicles might be cost-effective. In Mexico City, there are over 100,000 heavy-duty vehicles that are used intensively, that stay on the road for long periods of time, and that are significant sources of particle emissions.

Our study indicates that one attractive target for retrofit might be concession buses-local plates for the model-year group 1994-97 (US 1991/EURO I). If these buses were retrofitted with catalyzed DPFs, emissions reductions would be on the order of 38 kg per vehicle-year. Such a reduction would be expected to reduce the annual number of deaths attributable to ambient particulate matter by 3.5 per 1000 vehicle-year, leading to health benefits of US$ 6 thousand per vehicle year, with costs of less than 1.5 thousand US$ per vehicle-year, and net benefits of over 4.5 thousand $US per vehicle-year.

The benefits of controlling concession bus emissions are not limited to the 1994-97 model-year group. Positive net benefits are generated by retrofitting concession buses from all model-year groups (from pre-control (1985-93) to Euro III (2011-2014) and would yield more benefits than any other vehicle type in the heavy-duty diesel fleet.

Long-haul trailers -- federal plate are also important targets for retrofit, especially those for the model-year group 2007-10 (US 1998/EURO III). If retrofitted with the most cost-effective and adequate technology –DPF-active regeneration--, emissions would be reduced by 12 kg per vehicle-year. Such a reduction would be expected to decrease the annual number of deaths attributable to ambient particulate matter by 1.1 per 1000 vehicle-year, leading to health benefits of more than US$ 3 thousand per vehicle-year. The costs would be only approximately of 1 thousand US$ per vehicle-year. This would yield net benefits of over 2 thousand US$ per vehicle-year.

Retrofitting the heavy-duty diesel vehicle fleet would represent a small, but important step towards further improvement of air quality in Mexico City. In addition to reducing emissions from heavy-duty vehicles, many other programs -- such as the development of an integrated public transportation system, the reduction of emissions from industrial sources and fires, and redesign of the MCMA area to reduce urban sprawl -- must be analyzed and implemented to make significant strides forward in the control of air pollution and its public health impacts.

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