Mortality Benefits and Control Costs of Improving Air Quality in Mexico City: The Case of Heavy Duty Diesel Vehicles

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Diesel vehicles are significant contributors to air pollution in Mexico City. We estimate the costs and mortality benefits of retrofitting heavy-duty vehicles with particulate filters and oxidation catalysts. The feasibility and cost-effectiveness of controls differ by vehicle model-year and type. We evaluate 1985 to 2014 model-year vehicles from 10 vehicle classes and five model-year groups. Our analysis shows that retrofitting all vehicles with the control that maximizes expected net benefits for that vehicle type and model-year group has the potential to reduce emissions of primary fine particles (PM$_{2.5}$) by 950 metric tons/year; cut the population-weighted annual mean concentration of PM$_{2.5}$ in Mexico City by 0.90 µg/m$^3$; reduce the annual number of deaths attributable to air pollution by over 80; and generate expected annual health benefits of close to 250 million US$. These benefits outweigh expected costs of 92 million US$ per year. Diesel retrofits are but one step that should viewed in the context of other efforts—such as development of an integrated public transportation system, promotion of the rational use of cars, reduction of emissions from industrial sources and fires, and redesign of the Mexico City Metropolitan Area to reduce urban sprawl—that must be analyzed and implemented to substantially control air pollution and protect public health. Even if considering other potential public health interventions, which would offer greater benefits at the same or lower costs, only by conducting, promoting, and publishing this sort of analyses, we can make strides to improve public health cost-effectively.

KEY WORDS: Air pollution; health benefits; heavy-duty vehicles; particulate matter; retrofit technologies

1. INTRODUCTION

The objective of this analysis is to explore the benefits and costs of technologies to control emissions of primary fine particles from heavy-duty diesel-fueled vehicles circulating in Mexico City. The main benefits of controlling fine particle diesel emissions are the expected improvements in ambient air quality in terms of fine particles (PM$_{2.5}$) and the associated reductions in attributable mortality. The costs of control technologies include capital, operating, and maintenance costs.

Ambient PM$_{2.5}$ is the main focus of this analysis as fine particulate matter has been judged to be responsible for the largest share of all environmental contributors to the global burden of disease, and shown consistent and statistically significant adverse associations with all-cause, cardiopulmonary, ...
and lung cancer mortality from key epidemiological evidence (International Agency for Research on Cancer, 2012; Pope, Coleman, Ponda, & Burnett, 2020; Stanaway et al., 2018).

Adverse health effects of short- and long-term exposure to ambient particles have been widely documented. Time-series epidemiological studies have been conducted in hundreds of cities, including Mexico City, and results of the associations between daily fine-particle concentrations and mortality have been consistent (Atkinson, Kang, Anderson, Mills, & Walton, 2014; Borja-Aburto, Loomis, Bangdiwala, Shy, & Rascon-Pacheco, 1997; Borja-Aburto, Castillejos, Gold, Bierzwinski, & Loomis, 1998; Castillejos, Borja-Aburto, Dockery, Gold, & Loomis, 2000; Liu et al., 2019; Romieu et al., 2012). Cohort studies, conducted mostly in the United States and Europe, have found an association between long-term PM$_{2.5}$ exposures and annual mortality (Beelen et al., 2008; Cesaroni et al., 2013; Chen et al., 2005; Crouse et al., 2012; Dockery et al., 1993; Krewski et al., 2000; Lepere, Laden, Dockery, & Schwartz, 2012; Pope et al., 1995; Pope et al., 2002; Pope et al., 2019; Pope et al., 2020; Puett et al., 2009; Tseng et al., 2015). The toxicity of ambient particles and diesel exhaust, and their widespread population exposures have aroused public health concerns, which have triggered interest in evaluating policies to mitigate emissions, decrease ambient concentrations, and reduce public health risks.

Multiple emission sources contribute to ambient PM$_{2.5}$ concentrations in urban settings. As stated by the latest official emissions inventory developed by the Secretary of Environment of Mexico City, among the most significant sources are diesel-fueled heavy-duty vehicles (HDVs), which mainly emit primary particles and nitrogen oxides (that contribute to secondary particle formation). In Mexico City, HDV accounts for 75% of the 33% share of mobile sources to total PM$_{2.5}$ emissions (Secretaria del Medio Ambiente [SEDEMA], 2016). The estimated contribution of HDV to annual PM$_{2.5}$ concentrations in Mexico City ranges between 10% and 14%, centered within the range of some of the world’s major cities’ (3–26%), and close to those for Mexico’s second and third largest cities (6% and 11% for Monterrey and Guadalajara) (Anenberg, Miller, Henze, & Minjares, 2019; Pineda et al., 2018). Despite documented air quality improvements, annual average PM$_{2.5}$ concentrations (22.8 µg/m$^3$ in 2014) still exceed Mexico’s standard (12 µg/m$^3$) and the World Health Organization recommended limit (10 µg/m$^3$), and have exceeded these standards since official PM$_{2.5}$ monitoring started in 2004 (SEDEMA, 2015).

The Mexico City Metropolitan Area (MCMA) spreads over the valley of Mexico in a nearly closed basin inhabited by over 20 million people, of whom almost 9 million live in Mexico City proper and 11.5 million live in the metropolitan area excluding Mexico City (hereafter referred to as the metropolitan area).

This analysis was commissioned by Mexico City environmental authorities as part of a collaborative project to examine the link between air pollution reductions observed in the city over the past 25 years and the public health benefits, with a complementary quantitative benefit–cost analysis (BCA) of control measures to further improve air quality.

We chose to estimate the health benefits and costs of retrofitting in-use HDV to inform decision making. In response to regulatory programs in the United States, Europe, and other developed countries, extremely efficient diesel engine emission control technologies have been developed. These technologies (such as diesel particulate filters) are needed to comply with the US EPA 2010 (henceforth US 2010) standard or the Euro VI standard for new diesel engines and vehicles. They have also been used to retrofit earlier diesel engine models as exhaust after-treatment devices. Such controls, in combination with ultra-low sulfur (ULS) diesel (sulfur at or below 15 ppb), result in emissions with extraordinarily low concentrations of particulate matter relative to those emitted from engines without controls (McClellan, Hesterberg, & Wall, 2012).

2. METHODS

We evaluate the costs and risk reduction is identified with retrofitting PM$_{2.5}$ pollution control equipment on heavy-duty diesel vehicles that circulate in Mexico City. Because emissions in Mexico City also affect air quality in the metropolitan area, we evaluate the air quality and health effects for residents of Mexico City and the adjacent metropolitan area.

As illustrated in Fig. 1, our analysis of the benefits of retrofitting diesel HDV follows a conventional damage-function approach, in which changes in emissions are linked to changes in atmospheric concentrations, population exposure, mortality rates, and economic valuation (Levy, Hammitt, Yanagisawa, & Spengler, 1999). These estimated benefits are compared with the estimated costs, which include capital, maintenance, and operating costs. The unit of
The feasibility, costs, and effectiveness of emission controls vary by vehicle type and model year. We evaluate representative vehicles from each of 10 vehicle classes and five model-year groups (from 1985 to 2014) intended to span the range of vehicle types, uses, and model years in the fleet (we took mid values for emissions and activity rates per model-year group and vehicle type, and average fuel economy by vehicle type). Vehicles operating in Mexico City may be licensed by the city (local plate, LP) or the federal government (federal plate, FP), depending on whether they operate only within the city or travel more widely. We adopt the following vehicle classes: bus from public passenger transport network (henceforth “RTP bus-LP”); school and personnel bus-LP; concession bus-LP; rapid transport lanes’ bus (henceforth “Metrobús-LP”); tourism bus-FP; passenger bus-FP; truck-LP; truck-FP; long-haul tractor trailer-LP; and long-haul tractor trailer-FP. The model-year groups are as follows (Table I): 1985–1993 (vehicles before emission control regulations were in place [precontrol]); 1994–1997 (similar to new heavy-duty diesel engines and vehicles emission standards from the US Environmental Protection Agency’s [US-EPA] US 1991 or from the European Union EURO I [US 1991/EURO I]; 1998–2006 (US 1994/Euro II); 2007–2010 (US 1998/Euro III); and 2011–2014 (US 2004/Euro IV).

2.1. Activity and Emissions per Vehicle

We characterize each vehicle by type (bus, truck, and tractor trailer), age (model-year group), activity rate (kilometers traveled per vehicle per year [km/veh-yr]), baseline emission rates (gram/km traveled [g/km]), and fuel economy (km/liter [km/L]).

1Trucks with local plates weigh between 4.6 and 27.2 tons, those with federal plates weigh from 11.8 to 14.9 tons.

2Emissions for all model-year vehicles from Mexico City’s Emissions Inventory were compared to US-EPA and to the European Union emission limits, for standards for heavy-duty compression-ignition engines, to frame our model-year groups with their closest standard equivalencies (DieselNet, 2017a, DieselNet, 2017b).
### Table I. Mexico City’s in Use Heavy-Duty Fleet by Vehicle Type and Model-Year Group

| Vehicle Type                      | 1985–1993 Precontrol | 1994–1997 US 1991/EURO | 1998–2006 US 1994/EURO | 2007–2010 US 1998/EURO | 2011–2014 US 2004/EURO | All model years |
|-----------------------------------|----------------------|------------------------|------------------------|------------------------|------------------------|-----------------|
| Transportation buses              |                      |                        |                        |                        |                        |                 |
| RTP Public 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                          | 2,250                | 861                    | 3,465                  | 1,343                  | 992                    | 8,911           |
| Federal Plate Passenger           | 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                  | 37,087                 | 18,105                 | 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 & personnel buses, 24 trucks-LP, and 3 trucks-FP. RTP buses belong to only two model-year groups, 1998–2006 and 2007–2010, and Metrobús vehicles to only three model-year groups, 1998–2006, 2007–2010, and 2011–2014. 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. Elaborated by authors with data from Mexico City’s Emissions Inventory, 2014 (SEDEMA, 2016).

Data on type, age, activity, and baseline emission rates come from Mexico City’s 2014 official emissions inventory, which includes vehicles that circulate within Mexico City (SEDEMA, 2016). Data on fuel economy come from the US Department of Energy (2015).

Roughly, 100,000 heavy-duty diesel trucks and buses from model years 1985 to 2014 are in operation (Table I). 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 and 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 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 (2011–2014).

Fig. 2 shows estimated baseline annual emissions (g/yr) of primary particles by each vehicle type and model-year group. Estimated total annual emissions of primary particles are approximately 1,000 metric tons, of which more than 50% is due to tractor trailers-FP with another 25% due to concession buses-LP. 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 vehicle...
categories—school & personnel buses-LP, and tractor trailers-LP—make inconsequential contributions to primary particle emissions.

Among the two vehicle types that dominate primary particle emissions, 1998–2006 (US 1994/Euro II) model-year vehicles contribute most substantially, followed by 2007–2010 (US 1998/Euro III) model-year vehicles, and then, almost equally, 1985–1993 precontrol model-year vehicles and 2011–2014 (US 2004/Euro IV).

2.2. Controls: Efficiency and Cost

The primary technologies available for retrofit to reduce particle emissions are diesel oxidation catalysts (DOCs) and diesel particulate filters, either active regeneration (DPF-active) or catalyzed (DPF-passive). We analyze these three technologies plus a hypothetical ideal control, which is 100% efficient in eliminating primary PM emissions and has no cost. The ideal control provides an upper bound on the net benefits of any possible technology for controlling primary PM emissions.

Information on the efficiency of each control for reducing primary PM emissions came from the California Air Resource Board’s Diesel Certification & Verification Procedure, and technology-specific corresponding Executive Orders (California Air Resource Board [CARB], 2013, 2014, 2015a, 2015b, 2017), and from the US-EPA (2017).

Both DPFs and DOCs remove primary particulate matter from the exhaust with little or no effect on NOx emissions. DPFs are more effective in removing primary PM (about 90%) than DOCs (at most 26%) but are substantially more expensive (Table II).

DPFs trap particulate matter and must undergo “filter regeneration” to burn it off (releasing carbon dioxide and water). Catalyzed DPFs burn the material using exhaust heat, while active DPFs use an additional diesel or electric burner to actively regenerate the filter. Catalyzed DPFs are not compatible with pre-1994 Mexican diesel technologies and require ULS fuel to avoid poisoning the catalyst and to ensure reliable regeneration of the filter. ULS diesel (≤15 ppm) has been available in Mexico City since 2009 but is not yet available in some portions of the country, which prevents the use of DPFs with
catalytic regeneration for vehicles that drive outside the city, that is, vehicles with federal plates. In contrast, actively regenerating DPFs can be used on older vehicles and do not require ULS fuel; however, they decrease fuel efficiency by a few percent. DOCs function by oxidizing the soluble organic fraction of the particulate matter. They are less expensive than DPFs and can be used on all vehicle types. We assume that since ULS fuel is the only type of diesel fuel available in Mexico City, the introduction of catalyzed DPFs that require ULS fuel has no impact on SO2 emissions.

Estimates of the capital costs are taken from recent SEDEMA bids for diesel retrofit devices (Personal correspondence, Quotes of retrofit diesel particulate filters from manufacturers/distributors to SEDEMA, 2017).6 Annual maintenance costs are from a quote from HUG Engineering (Personal correspondence, SEDEMA, 2017), and estimates of the fuel use penalties for each control device came from the Manufacturers of Emission Controls Association (1999) as reported by Stevens, Wilson, and Hammitt (2005). The costs and efficiency of the control devices considered are summarized in Table II.

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 (with an annual discount rate of 3%) 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 cost of ULS fuel used to compute the fuel use penalty was taken as 1.01 US$ per liter (Índice Nacional de Precios al Consumidor, 2017).

\[
EAC = C \times crf + M + CIFU,
\]

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

The capital recovery factor is the share of the capital cost that if incurred as an equivalent annual cost over the equipment lifetime has the same present value as the capital cost. It is given by:

\[
crf = \frac{r \times (1 + r)^L}{(1 + r)^L - 1}.
\]

The cost of increased fuel use is given by:

\[
CIFU = P \times F \times \frac{A}{E},
\]

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

The emission reduction \(\Delta E_{i,j}\) (g/yr) from the ith vehicle type expected after implementation of the jth control is given by:

\[
\Delta E_{i,j} = \varepsilon_j \times Eo_i,
\]

where \(\varepsilon_j\) is the control efficiency (fractional) of the jth control, and \(Eo_i\) (g/yr) represents the uncontrolled emissions from the ith vehicle type.

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

|                         | Diesel Oxidation Catalyst | DPF – Active Regeneration | DPF – Passive Regeneration | Ideal Control |
|-------------------------|---------------------------|--------------------------|---------------------------|--------------|
| Capital cost (1000 US$/veh) | 0.5 - 1.5                | 7.0 - 9.0                | 6.0 - 8.0                 | –            |
| Lifetime of equipment (yr) | 10                       | 10                       | 10                        | –            |
| Annual maintenance cost (US$/veh-yr) | –                        | 220                      | 220                       | –            |
| Fuel-use penalty (fractional) | –                        | 0.02                     | 0.004                     | –            |
| Emissions control efficiency (fractional) | 0.20 - 0.26             | 0.8 - 0.9                | 0.8 - 0.9                 | 1.00         |

6 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, $1,000, from each bid to estimate the cost of diesel particulate filters for application in Mexico City.

#### 2.3. Population Exposure: Intake Fraction and Primary Particle Concentrations

The effect of an emission reduction on population exposure is estimated using the concept of intake fraction (\(IF\)) (Bennett et al., 2002; Evans, Wolff, Phonboon, Levy, & Smith, 2002).

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 that 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, whether it is chemically reactive—i.e., has a short atmospheric half-life) and the atmosphere to which it is emitted (e.g., wind speed and mixing height); and the receptors (e.g., population density).

Intake fractions may be estimated using atmospheric fate and transport models or by combining results from source-receptor analysis with information from emission inventories. Because the focus of our analysis is PM$_{2.5}$ and because our emission controls do not affect NO$_x$ or SO$_2$, we only care about the primary PM$_{2.5}$ $iF$ (PM$_{2.5}$ intake divided by primary PM emissions).

Our estimates rely on the $iF$ estimates of Stevens, de Foy, West, and Levy (2007), which are consistent with a recent effort to estimate $iF$ for 3,646 cities with more than 100,000 inhabitants, which includes Mexico City (Apte, Bombrun, Marshall, & Nazaroff, 2012). These estimates reflect the entire MCMA population of close to 20 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 $iF$ and the emission estimates discussed previously, the MCMA-wide average annual concentration change, $\Delta C_{i,j}$ (µg/m$^3$), due to the emissions reduction, $\Delta E_{i,j}$, of the pollutant from the $i$th vehicle type under the $j$th control is given by:

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

where $iF$ is the intake fraction, $P$ is the population (persons), $B$ is the nominal breathing rate (20 m$^3$/person-day), and 365 is the constant needed to convert the daily breathing rate to an annual breathing rate.

Our analysis relied on intake fractions computed as described above, which ignore possible differences in the relationship between emissions and ambient concentration/population exposure in Mexico City itself and in the MCMA outside of the City proper. We conducted Supplementary Analyses (not reported here) based on the recent atmospheric dispersion modeling effort of the International Council on Clean Transportation’s work (Pineda et al., 2018), which suggested that the intake fraction for fine particles emitted at ground level in the city was 56, consisting of 27 within the city and 29 outside of the city. This value is well within the rather broad uncertainty interval for intake fraction used in our analysis.

### 2.4. 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 (IER) functions developed to support the 2010 and 2013 Global Burden of Disease analyses (Burnett et al., 2014; Forouzanfar et al., 2015; Lim et al., 2012).

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 (ALRIs) are elevated among those with chronic PM$_{2.5}$ exposure. The IER has the form:

$$RR = \frac{1 + \alpha \ast \left(1 - \exp \left(-\beta \ast (C - X_0)^\delta\right)\right)}{1},$$

where $\alpha$ is the asymptotic limit of relative risk (RR) as PM$_{2.5}$ approaches infinity, $\beta$ indicates the rate of increase per unit increase in PM$_{2.5}$, $X_0$ is the counterfactual (the PM$_{2.5}$ concentration below which there is no increase in risk), $\delta$ (dimensionless) is an exponent, and $C$ is the annual average concentration (µg/m$^3$) of PM$_{2.5}$.

Values of the parameters $\alpha$, $\beta$, $X_0$, and $\delta$ for COPD and 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 STK, parameters have been estimated for each of the 12 five-year-age groups from 25 to $\geq$ 80 years (Burnett et al., 2014). Our approach relies on the data resources...
from the GBD study (Institute for Health Metrics and Evaluation, 2017), including Burnett and coauthors’ set of 1,000 equally likely sets of parameter values for each disease that resulted from their analysis of uncertainty in the parameters.

Inherent in this approach are the following assumptions:

• Associations between PM$_{2.5}$ and mortality seen in the Six Cities Study, the ACS Study, and the other studies underlying the IER are causal.
• Particle mass, without regard to chemical composition, is an adequate proxy for the toxicity of ambient PM$_{2.5}$.
• Findings of epidemiological studies conducted largely in the United States and Western Europe are relevant for predicting mortality risks in Mexico.

There are, of course, questions about the validity of each of these assumptions (Evans, 2016; McClellan, 2016). McClellan provides a particularly clear and well-reasoned presentation of these concerns. Note, however, that while the issue of causality is contentious, the Global Burden of Disease consortium—which includes in its analyses only risk factors which it has deemed to reflect causal relationships—has included PM$_{2.5}$ for over two decades. Furthermore, in his most recent review of the literature, Pope et al. (2020) have argued compellingly for a causal interpretation of the evidence.

On the question of differential toxicity, we agree entirely with the sentiment expressed by McClellan (2016). As illustrated by the elicitation of European experts in epidemiology, many experts would argue that diesel particles are more toxic on a mass basis than the ambient mix (Cooke et al., 2007). If this is true, our use of the IER would underestimate mortality risks in Mexico City—perhaps substantially.

On the final point, we share McClellan’s (2016) concern for the relevance of results from the United States and Western Europe for application in Mexico. However, we note that this concern is mitigated by the recent findings of GEMM—which included results from a larger number of studies conducted in a greater variety of countries (including China) and found risks at high exposure about three times larger than those suggested by the IER (Burnett et al., 2018). Further evidence of the relevance of these estimates to Mexico is provided by the recent analysis of Dockery and colleagues, which found strong relationships between exposure to PM$_{2.5}$ and ozone and reductions in life expectancy in Mexico City (Dockery et al., 2018).

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 RR 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 Co = 20 µg/m$^3$. This was done numerically by evaluating:

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

Summary slopes for application in Mexico City and in the metropolitan area outside of the city were 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).  

Table III provides the median, 25% and 75%, 2.5% and 97.5% of the disease-and-age-weighted RR of mortality and slope of the function, across all diseases and age groups of interest, for Mexico City and the metropolitan area. Table IV provides the number of deaths used in computing the summary slope.

Finally, we introduced a cessation lag in our benefit calculation, which refers to the time between reductions in exposure and mortality risk (Health Effects Subcommittee [HES], 2004; Science Advisory Board, 2004; Walton, 2010; US-EPA, 2011). 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 assumes that 30% of the risk reduction occurs in the first year following the reduction, 50% is divided equally over years two through five, and 20% is divided equally over years six through 20 (HES, 2004; US-EPA, 2011; Walton, 2010).

7Mortality counts for specific causes of death by sex and quinquennial age-group were obtained from the Secretary of Health of the Government of Mexico City and from Mexico’s National Institute of Statistics and Geography (Instituto Nacional de Estadística y Geografía [INEGI], 2016).
### Table III. Relative Risk of Mortality and Slope of the Integrated Exposure-Response Function in Mexico City (CDMX) and in the metropolitan area excluding Mexico City (MCMA minus CDMX) at 20 μg/m³ (Evans et al., 2018)

| Parameter | Mexico City (CDMX) | Mexico City Metropolitan Area (minus CDMX) | Slope @ 20 μg/m³ (% increase in RR per μg/m³ PM$_{2.5}$) |
|-----------|-------------------|------------------------------------------|-----------------------------------------------|
| 2.5%      | 1.209             | 1.218                                    | 0.753                                          |
| 25%       | 1.229             | 1.236                                    | 0.88                                           |
| 50%       | 1.239             | 1.247                                    | 0.962                                          |
| 75%       | 1.25              | 1.257                                    | 1.042                                          |
| 97.5%     | 1.274             | 1.278                                    | 1.234                                          |

### Table IV. Mortality for PM$_{2.5}$ Related Causes in Mexico City (CDMX) and in the metropolitan area excluding Mexico City (MCMA minus CDMX), 2014 (INEGI, 2016)

| Disease                              | Mexico City (CDMX) | Mexico City Metropolitan Area (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                                   |

### 2.5. Economic Valuation: 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) by the rate at which mortality risk is valued, the value per statistical life (VSL). We estimate VSL following recommendations developed for conducting BCA in low- and middle-income countries supported by the Gates Foundation (Robinson et al., 2019). Robinson, O’Keeffe et al. (2019) and Robinson et al. (2019); Robinson, Hammitt, & O’Keeffe, 2019; Robinson, Hammitt, Jamison, & Walker, 2019 suggest that, when high-quality direct estimates of VSL are not available (as happens for Mexico City), analysts should extrapolate from values estimated for higher-income countries, adjusting for the difference in average income measured as gross national income per capita and converted using purchasing-power-parity. They recommend three alternative values obtained by extrapolating from ratios of VSL to income of 160 and 100 (based on U.S. and OECD values) using an income elasticity of 1.0 and from a ratio of 160 using an income elasticity of 1.5. Formally,

$$VSL_{M}/\text{y}_M=(\text{y}_M/\text{y}_US)^{h^{-1}}VSL_{US}/\text{y}_US,$$

where $y$ is income, $h$ is the income elasticity, and the subscripts $M$ and $US$ denote Mexico City (CDMX or MCMA excluding CDMX) and the United States (or other high-income country).

Conversion from GDP per capita in Mexican pesos using PPP, from Mexico’s National Institute of Statistics and Geography (Instituto Nacional de Estadística y Geografía [INEGI], 2017), yields income values of US $37,500 for Mexico City and US $14,600 for the metropolitan area outside of the city proper. The extrapolated values of VSL (US $ million) are 6.0, 3.8, and 4.9 for Mexico City and 2.3, 1.5, and 1.1 for the metropolitan area.
Table V. Results for Bus Concession—Local Plate, Model Years 1998–2006 (US 1994/Euro II)

|                      | Emissions Reduction (kg/veh-yr) | Deaths Avoided (#/1,000 veh-yr) | Benefits (1,000 US$/veh-yr) | Control Cost (1,000 US$/veh-yr) | Net Benefits (1,000 US$/veh-yr) |
|----------------------|--------------------------------|---------------------------------|-----------------------------|---------------------------------|---------------------------------|
| 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; DPF–passive stands for diesel particulate filter with catalyzed (passive) regeneration, and DPF–active stands for diesel particulate filter with active regeneration. The row in dark gray highlights the retrofit technology that maximizes the expected net benefits and that is adequate for this model-year and vehicle type.

Table VI. Results for Long-Haul Tractor Trailer—Federal Plate, Model Years 1998–2006 (US 1994/Euro II)

|                      | Emissions Reduction (kg/veh-yr) | Deaths Avoided (#/1,000 veh-yr) | Benefits (1,000 US$/veh-yr) | Control Cost (1,000 US$/veh-yr) | Net Benefits (1,000 US$/veh-yr) |
|----------------------|--------------------------------|---------------------------------|-----------------------------|---------------------------------|---------------------------------|
| 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–passive stands for diesel particulate filter with catalyzed (passive) regeneration, and DPF–active stands for diesel particulate filter with active regeneration. The rows highlighted in gray (dark and light) correspond to retrofit technologies that maximize the expected net benefits; however, the dark gray row presents the retrofit technology that is adequate for this model-year and vehicle type.

1.2 for the metropolitan area. We represent uncertainty about VSL as a lognormal distribution and assume the smallest extrapolated value is the tenth percentile and the largest is the 90th percentile. For Mexico City, this implies a median of 4.7 million US$ and a geometric standard deviation of 1.4 (with a mean of 5.1 million US$ and a 95% confidence interval between 2.3 million US$ and 9.7 million US$). For the metropolitan area, it implies a median of 1.7 million US$ and a geometric standard deviation of 1.7 (with a mean of 1.9 million US$ and a 95% confidence interval between 0.6 million US$ and 4.7 million US$). The population weighted mean VSL for the entire MCMA is 3.3 million US$.

3. RESULTS

Emissions within Mexico City lead to exposures and health risks in the City and throughout the metropolitan area, so our results include the benefits in the entire MCMA. For each type of vehicle and model-year group, results include the emission reduction (kg/veh-yr), the attributable deaths avoided (#/1,000 veh-yr), the monetized benefits of the risk reduction (1,000 US$/veh-yr), the control costs (1,000 US$/veh-yr), and the net benefits (1,000 US$/veh-yr) for each of the three control technologies and the ideal control.

Illustrative results for the two most important categories of vehicles in terms of emissions (bus concession-LP and tractor trailer-FP) for one model-year group (1998–2006) are presented in Tables V and VI. A summary of control options that maximize expected net benefits is presented in Table VII, and results for other vehicle types and model-year groups are shown in Supplementary Materials.

For the approximately 4,000 concession buses with local plates, the largest expected net benefits are generated by choosing to retrofit with a catalyzed DPF (Table V). These vehicles are heavily used, each traveling roughly 70 thousand km per year. The catalyzed DPF retrofit is expected to reduce emissions by 36 kg per vehicle-year and to reduce premature deaths attributable to air pollution by about 3 per 1,000 vehicle-year with benefits of US$ 9.2 thousand. The expected costs are only 1.4 thousand US$ per vehicle-year, producing expected net benefits (health benefits minus control costs) of almost 8 thousand US$ per vehicle year. The catalyzed DPF is an option because these buses are driven only locally, where ULS fuel is available.

For the approximately 16 thousand tractor trailers with federal plates, catalyzed DPFs are not an
### Table VII. 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 (In Brackets)

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

**Notes:** RTP Public Transport and Metrobús vehicles belong to only two and three model-year groups, respectively. Color coded in terms of retrofit technology – DOC stands for Diesel Oxidation Catalyst (light green); DPF-p stands for Diesel Particulate Filter with passive (catalyzed) regeneration (mid-tone green); DPF-a stands for Diesel Particulate Filter with active regeneration (dark green). There were no vehicles in “n.a.” cells.

Option because these vehicles circulate outside Mexico City where ULS fuel is not widely available. Although these vehicles see heavy use, their activity within Mexico City is on average only 14 thousand km per vehicle year. Among the remaining options, the active regeneration DPF offers the largest expected net benefits (more than 1.5 thousand US$ per veh-year) (Table VI). This option is expected to reduce emissions by 10 kg per vehicle-year and to reduce premature deaths attributable to ambient fine particles by approximately 1 per 1,000 vehicle-year with benefits of over 2.6 thousand US$ and costs of less than 1.1 thousand US$ per vehicle-year. Active regeneration DPFs generate the same emission reductions and health benefits as catalyzed DPFs but have costs, which are roughly 20% higher due to the larger fuel penalty. Note that, because our analysis considers only the impacts of emission reductions within the city, the true public health benefits of controlling these vehicles are underestimated.

Following this approach and examining the benefits, costs, 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 VII).
For the two categories of vehicles, bus concession-LP and tractor trailer-FP, 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 emission reductions between 80% and 90%. Comparable results are found for the third largest primary PM emitter, bus tourism-FP, for which DPF-active retrofits are cost-effective for all model-year groups.

Our results indicate that, for all vehicle categories and model-year groups, retrofit with some technology is cost-beneficial. 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. Similarly, for bus passenger-FP, either DPF-active or DOC are cost-effective for all model-year groups.

Estimates of the health benefits and costs of policies to reduce air pollution are inherently uncertain. Our analysis quantifies uncertainty about some of the most important inputs to our analysis, including the relationship between changes in emissions and population exposure (summarized by the intake fraction), the slope of the concentration-response functions relating mortality to ambient PM$_{2.5}$, the monetary value of reductions in mortality risk (summarized by the VSL), 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 controls are positive (i.e., the benefits associated with the reduction in mortality risk exceed the cost of the specified retrofit technology). These probabilities are displayed in Table VII for each vehicle type and model-year group.

As shown there, for the vehicle type accounting for the largest share of emissions (tractor trailers-FP), the estimated probability that the value of the mortality-risk reduction associated with the DPF-active retrofit technology exceeds the cost is between 88% and 97% depending on the specific model-year group. For the vehicle type accounting for the second largest share of emissions (concession buses-LP), the probability that retrofitting vehicles of model year 1994 or later with passive DPFs is cost-effective is 99%, and for older vehicles, the probability that retrofitting with active DPFs is cost-effective is 96%. Even among the vehicle classes and model years that contribute relatively insignificantly to total emissions, the probability of achieving positive net bene-

### Table VIII. Annual Benefits and Costs of a Strategy to Retrofit All in Use Heavy-Duty Vehicles with the Control that Maximizes Expected Net Benefits

| Benefits                                      | Costs (million US$/yr) |
|-----------------------------------------------|------------------------|
| PM$_{2.5}$ emissions reduction (metric tons/yr) | 951                    | Capital costs retrofit devices | 61 |
| PM$_{2.5}$ concentration reduction (µg/m$^3$)   | 0.91                   | Maintenance costs              | 19 |
| Attributable deaths reduction (deaths/yr)      | 84                     | Fuel use penalties             | 11 |
| Monetized health benefits (million US$/yr)     | 246                    | Total                          | 92 |
| Net benefits (million US$/yr)                 | 153                    |                                 |    |

Note: Values may not sum because of rounding.

fits for most vehicle classes and model years is 80% or greater.

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

- Reduce annual emissions of primary fine particles by 950 metric tons
- Cut the annual population-weighted mean concentration of PM$_{2.5}$ in the MCMA by approximately 0.90 µg/m$^3$
- Reduce the expected number of deaths attributable to air pollution each year by about 85
- Generate expected health benefits on the order of 250 million US$ per year

This strategy 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. We estimate benefits to outweigh the costs of a fully implemented strategy of retrofitting every vehicle, that is, the net benefits, by over 150 million US$.

4. DISCUSSION

The BCA conducted for Mexico City HDV suggests that performing retrofit with DOCs or DPFs can reduce particulate matter emissions, lead to improvements in air quality, and produce public health benefits for the inhabitants of the MCMA that are substantially larger than their costs.
Retrofit programs have been adopted 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, can substantially reduce diesel particulate matter emissions to levels like those of newer diesel vehicles (The International Council on Clean Transportation [ICCT], 2017). In the United States, CARB implemented a mandatory retrofit program for most in-use heavy-duty diesel vehicles and US-EPA established a voluntary retrofit program (CARB, 2017). US-EPA’s BCA of the program for the years 2009–2013 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).

More than 10 years ago (2005–2006), a pilot retrofit project was conducted in Mexico City by the World Resource Institute in partnership with US-EPA and Mexican federal and local authorities (World Resource Institute [WRI], 2007). Retrofitted urban passenger buses were followed-up for 11 months; DOCs were installed in eight model-year 1991 buses, and DPF-passive in 12 model-year 2001 buses. Emission reduction efficiencies were as expected: primary PM$_{2.5}$ reductions were on the order of 20–30% for DOCs and 80–90% for DPFs. Two fundamental lessons were learned. First, that a key to the success of the program was selecting buses appropriate for retrofitting through careful testing. Second, that training operators about how the emission control devices worked, how they were installed, and driving techniques for best performance of the equipment was needed. More recently, Mexico City’s environmental authorities established a voluntary program (Autorregulación Program), which has succeeded in having retrofit devices installed in 27 heavy-duty trucks and 18 RTP buses (Comunicación Social Ciudad de México, 2016).

Other studies that have assessed the public health benefits of reducing HDV emissions in Mexico City have found large benefits. Greco, Belova, and Huang (2016), in their assessment of 42 global cities, estimated that a hypothetical 100-metric-ton reduction in PM emissions would reduce attributable deaths in Mexico City by about 50, valued at close to 100 million USD. Stevens et al. (2005) estimated that retrofitting each of the different classes of HDV operating in Mexico City with either DOCs or DPFs produced positive net benefits. McKinley et al. (2005) estimated that replacing diesel buses with hybrid buses produced health benefits comparable to investment costs; including fuel cost savings, the net benefits were positive.

Our analysis seeks to determine whether expanding retrofit programs to a wide variety of heavy-duty diesel vehicles might be cost-effective. In Mexico City, there are over 100,000 diesel-fueled HDVs. These are used intensively and are significant sources of particle emissions. For instance, positive net benefits are generated by retrofitting concession buses-LP from all model-year groups, from precontrol (1985–1993) to Euro III (2011–2014). Retrofitting these buses would yield more benefits per vehicle than any other vehicle type in the heavy-duty diesel fleet.

Tractor trailers-FP are also important targets for retrofit. If model-year group 2007–2010 (US 1998/EURO III) were to be retrofitted with the most cost-effective appropriate technology, DPF-active emissions would be reduced by 12 kg/veh-yr. Such a reduction would be expected to decrease the annual number of deaths attributable to ambient particulate matter by 1.1 per 1,000 veh-yr, leading to health benefits of more than US$ 3 thousand/veh-yr. The costs would be approximately of US$ 1 thousand/veh-yr. This would yield net benefits of over US$ 2 thousand/veh-yr.

Our study has several weaknesses, including the following:

- Relies on official emissions inventory’s vehicular activity rates and emission factors to estimate the baseline emissions from each class and model-year group of vehicles.
- Relies on intake fractions, rather than project-specific modeling of atmospheric fate and transport, to characterize the relationship between emissions and ambient concentrations.
- Assumes equitoxicity (by mass) of fine particles regardless of their source.
- Uses estimates of the efficiencies of diesel retrofit from studies conducted largely in the United States.
- Estimates VSL by extrapolating from the United States, rather than from a local study conducted in Mexico.

On the other hand, our study has many strengths, which include:

- Relies on the individual vehicle as the unit of analysis.
• Considers separately each of 10 classes and five model-year-groups of vehicles.
• Includes a hypothetical “ideal control”—with 100% efficiency and no cost—to bound the analysis.
• Relies on the most widely used and vetted available concentration-response function of PM health effects—that is, the IER function from the GBD.
• Applies this function to PM2.5 concentrations in the vicinity of 20 µg/m³, which is quite near the center of the ranges of PM concentrations studied in many of the underlying epidemiological studies.
• Characterizes the uncertainty in the relationships between emissions and concentrations, concentrations and mortality, and mortality and societal benefits, and it carries these uncertainties through the integrated benefit–cost model at the heart of the analysis.
• Uses the results of the uncertainty analysis to characterize the uncertainty in estimates of the net benefits available from each control strategy and the confidence that a decisionmaker relying on these results can have that net benefits will be positive (Table VII).

We have attempted to provide an unbiased and fair interpretation of the evidence and to account for major uncertainties underlying the analyses. Nevertheless, arguments could be made that benefits have been overestimated—due to questions about interpretation of the epidemiological results as causal—or that they have been underestimated—due to failure to consider the potential differential (and higher) toxicity of primary carbonaceous particles, and potential differential effects (also higher) in Mexican population with a greater share and lower socioeconomic status (Stevens, Dias, & Ezzati, 2008).

Our analysis is framed using the conventions of welfare economics and asks whether, at the margin, the monetized health benefits generated by each proposed control exceed the costs of implementing that control. Strategies that generate positive net benefits are recommended for consideration.

Some might argue that, in an absolute sense, the magnitude of the health benefits generated by implementation of these strategies is small or that there might be other potential public health interventions, which would offer greater benefits at the same or lower costs (McClellan, 2016).

We would not disagree with either of these suggestions, but believe that only by conducting, promoting, and publishing analyses of this kind will we make progress toward cost-effective improvement of public health. In the meantime, every effort should be taken to pursue environmental strategies, which are thought to generate positive net benefits.

Since the analysis was conducted, Mexico has updated the heavy-duty emissions standard. The disposition in Mexico’s Federal Register is that all new HDVs and engines will require advanced pollution control technologies, DPFs, and selective catalytic reduction systems, in line with the United States (US 2010) and the European Union (EURO VI) standards starting in January 1, 2022 (Diario Oficial de la Federación [DOF], 2018; DOF, 2020). These systems require ULS diesel, which is now available in more than 80% of Mexico’s service stations (Instituto Nacional de Ecología y Cambio Climático, 2019; Onexpo, 2020). Meeting these standards should reduce PM and NOx emissions from new vehicles between 90% and 99%, which will in turn benefit air quality and protect human health. However, because heavy-duty diesel vehicles are durable and long-lived, the rate at which older vehicles will be replaced by new, lower-emitting vehicles is slow. Retrofitting the existing and intensively used heavy-duty diesel vehicle fleet would represent an important additional step toward further improvement of air quality in Mexico City.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1. 1985–1993 Precontrol Model-Year Group
Table S2. Model-Year Group 1994–1997 (US 1991/EURO I)
Table S3. Model-Year Group 1998–2006 (US 1994/EURO II)
Table S4. Model-Year Group 2007–2010 (US 1998/EURO III)
Table S5. Model-Year Group 2011–2014 (US 2004/EURO IV)