Air quality and health benefits of improved fuel and vehicle emissions standards in Mexico

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Summary

At the North American Leaders Summit (NALS) in June 2016, the heads of the governments of Canada, Mexico, and the United States agreed to "commit to reduce air pollutant emissions by aligning air pollutant emission standards for light- and heavy-duty vehicles and corresponding ultralow-sulfur fuel standards by 2018." (The White House, 2016). To support regulatory efforts in Mexico that are necessary to achieve this goal, the International Council on Clean Transportation (ICCT) coordinated the efforts of several organizations working to model the emissions, air-quality, and public-health benefits of aligning fuel and vehicle emission standards in Mexico with the rest of North America.

The study investigated the impacts of updating three standards in Mexico to align with the international best practices employed in the rest of North America: gasoline and diesel sulfur standards, passenger vehicle emissions standards, and truck and bus emissions standards. The study partners include Eastern Research Group (ERG), University of Tennessee (UT), and Mexico's National Institute of Ecology and Climate Change (Instituto Nacional de Ecología y Cambio Climático, INECC).

KEY FINDINGS

- Implementation of just three key fuel and vehicle standards in Mexico will result in important reductions in premature mortality. The modeling suggests that approximately 9,000 deaths can be avoided in 2035 alone, with approximately 80% of the benefits coming from reductions in fine particle concentrations and the rest from ozone reductions. Considering just the premature deaths avoided in that year, the monetized benefits are valued at over $20.8 billion (2010 USD). This analysis does not capture the cumulative health benefits that will accrue leading up to 2035 and will extend over the following years. Other health benefits not quantified in this analysis include reductions in asthma, chronic bronchitis, and lost work days.
- These standards will result in dramatic reductions in emissions in Mexico. As a share of the 2035 on-road transport sector emissions, nitrogen oxides (NO_x) are reduced by 66%, volatile organic compounds (VOC) by 53%, and fine particulate matter ($PM_{2.5}$) by more than 90%, including an 84% drop in black carbon. As a share of total economy-wide emissions, NO_x and VOC—the two key precursors in ozone production—are reduced by 43% and 31%, respectively.
- The emissions reductions translate into important air-quality benefits at both the local and national levels, especially in densely populated areas. $PM_{2.5}$ concentrations were reduced by 18% nationwide and 20% in the Mexico City metropolitan area. During the peak season, maximum ozone concentrations were reduced by 12% and 14%, respectively. These reductions

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would be a significant step toward reducing air-pollution incidents.

POLICY RECOMMENDATIONS

To achieve the air quality and health improvements demonstrated in this analysis, several policy actions are needed. In December 2017 the government is in the final stages of approval and publication of an updated NOM-044, which regulates emissions from heavy-duty diesel vehicles and will achieve harmonization with U.S. 2010 and Euro VI standards (SEMARNAT, 2017). This policy will provide tremendous health and air quality benefits and is responsible for 69% of the health and economic benefits in this analysis.

There are two other key policies responsible for the other 31% of the benefits, for which action is still needed:

- NOM-042, which regulates emissions from new light-duty vehicles, should be updated to adopt much more stringent limits for exhaust and evaporative emissions. Standards should immediately align with U.S. Tier 2 standards and Euro 6 for tailpipe emissions, but all vehicles should be required to meet the much more stringent U.S.-based standards for control of evaporative emissions. U.S. Tier 3 standards will bring significantly more health and air quality benefits and will be necessary to ensure that emissions continue to decline even as the fleet continues to grow.
- NOM-016, which regulates fuel quality, should be updated to reduce sulfur levels in gasoline to 10 parts per million (ppm). In addition, waivers to increase Reid vapor pressure (RVP), which would contribute to higher VOC emissions, should not be allowed in major polluted cities or municipalities.

Introduction

The goal of this study was to investigate the impacts of revising three federal standards in Mexico: gasoline and diesel sulfur standards (NOM-016-CRE-2016), passenger vehicle emissions standards (NOM-042-SEMARNAT-2005), and truck and bus emissions standards (NOM-044-SEMARNAT-2006). The study considered the then current standards as the baseline, and measured the reductions of air pollutants that could occur and premature deaths that could be avoided through adoption of best practice standards currently employed throughout the rest of North America.

The study partners include Eastern Research Group (ERG), University of Tennessee (UT), and Mexico's National Institute of Ecology and Climate Change (Instituto Nacional de Ecología y Cambio Climático, INECC). ERG used policy scenarios defined by the International Council on Clean Transportation (ICCT) to generate inputs to MOVES-Mexico, an adaptation of the U.S. Environmental Protection Agency (U.S. EPA) Motor Vehicle Emission Simulator (MOVES) to the Mexican context (ERG, 2016a). UT researchers used the MOVES-Mexico results as an input to model the air-quality impacts of the best practice policy scenario, using the open-source Community Multi-Scale Air Quality (CMAQ) model. Finally, INECC and ICCT derived an estimate of the reduction in premature deaths attributable to $PM_{2.5}$ and ozone pollution under the policy scenario, using U.S. EPA's Benefits Mapping and Analysis Program (BenMAP) tool.

The following sections lay out the policy context, the study methodology, results, areas of uncertainty and further study, and conclusions.

FUEL QUALITY

Fuel quality is both a direct driver of emissions reductions and also an essential element to allow the introduction of cleaner vehicles. Regulations for vehicle emissions fall under the purview of the environment ministry, whereas fuel quality is now considered part of the energy sector.

In 2013, the Mexican Congress enacted a package of energy sector reforms that, among many other changes, opens refined fuels to a competitive market, including deregulating fuel prices and allowing private companies to produce and import refined fuels and own and operate fueling stations, ending the monopoly of the nationally owned oil company Petróleos Mexicanos (PEMEX).

As part of the reform, the jurisdiction of fuel quality standards was moved from an authority shared by the Secretariat of the Environment and Natural Resources (Secretaría de Medio Ambiente y Recursos Naturales, SEMARNAT) and the Secretariat of Energy (Secretaría de Energía, SENER) to the Energy Regulatory Commission (Comisión Reguladora de Energía, CRE). The fuel types relevant to this analysis are gasoline and diesel intended for use in on-road vehicles.

Background

In 1994, NOM-086-ECOL-1994 was published, regulating liquid and gaseous fossil fuels for both fixed and mobile sources (INE, 1994). This standard was replaced by NOM-086-SEMARNAT-SENER-SCFI-2005 (NOM-086), which required both gasoline and diesel to meet very low sulfur levels starting in 2009 (SEMARNAT & SENER, 2006). Full compliance with the NOM-086 gasoline and diesel sulfur limits was never achieved by PEMEX, which was the sole provider of refined fuels in the country prior to energy sector reform.[1]

Upon transfer of authority to CRE, the agency passed a 6-month emergency standard, NOM-EM-005-CRE-2015 (NOM-EM-005), which was then extended another 6 months (CRE, 2015a, 2015b). The emergency standard was replaced by a permanent standard, NOM-016-CRE-2016 (NOM-016), in August 2016 (CRE, 2016).

Current regulations

NOM-016 sets specifications for fuels used in on-road and other types of vehicles and uses. It sets nationwide standards, in some cases requiring more stringent standards for priority regions. Compliance is measured along the full chain of distribution for locally refined and imported fuels.

NOM-016 requires all gasoline sold in Mexico to meet a 30 ppm sulfur average, with an 80 ppm maximum. Diesel is required to meet the 15 ppm sulfur limit initially in the northern border region,[2] along a network of 11 major freight corridors, in the metropolitan areas of Guadalajara, Monterrey, and Mexico City, and for all fuel imports. Beginning on December 31, 2018, all diesel sold throughout Mexico is required to meet the 15 ppm sulfur limit.

Of the fuel quality specifications, those most critical to air quality are sulfur content and Reid vapor pressure (RVP).

Table 1. NOM-016 sulfur specifications for diesel and gasoline.

Fuel	Current sulfur limit	Sulfur limit starting on December 31, 2018
Diesel	500 ppm maximum: rest of the country 15 ppm maximum: border region, three major metropolitan areas, 11 freight corridors, and all fuel imports	15 ppm maximum
Gasoline	30 ppm average 80 ppm maximum	

- Sulfur content is the limiting factor for introduction of new vehicle technologies and thus is closely linked to the enforcement of new vehicle standards. Lowering the sulfur content also has an immediate impact on particle emissions from all existing diesel vehicles and NO_x emissions from all gasoline vehicles equipped with catalytic converters (the majority of vehicles on the roads today).
- RVP pertains only to gasoline and affects the rate of evaporation of gasoline during refueling, parking, and vehicle use. Although RVP does not affect tailpipe emissions of volatile organic compounds (VOCs), it is one of the most important factors in levels of evaporative VOC emissions. RVP levels vary by region and season, with specifications set considering altitude, latitude, average temperatures, and formation of secondary pollutants.

Sulfur limit values for fuels in Mexico derived from NOM-016 are summarized in Table 1.

Although NOM-016 did not contemplate any changes to RVP, the standard has since been adjusted to allow for higher RVP, corresponding to the relaxed limit for the use of ethanol (CRE, 2017). Ethanol is an oxygenate typically used in U.S. gasoline at 10% by volume. NOM-016 originally established a maximum content of 5.8% by volume of ethanol levels in gasoline. In June 2017, this parameter was modified to allow ethanol to be added up to 10% by volume for all regions except for the metropolitan areas of Guadalajara, Monterrey, and Mexico City. As ethanol has a higher RVP, gasoline with 9-10% ethanol is also allowed to have higher RVP than the specifications require.

This study did not account for any changes in ethanol content or RVP. Higher RVP will increase evaporative emissions, and higher levels of ethanol also may be associated with higher evaporative emissions, especially in older vehicles. We also did not consider the slight reductions in other tailpipe pollutants that have been associated with ethanol. Although the critical metropolitan areas are not allowed to use ethanol as an oxygenate, there is a need for further studies to assess the emissions impact of higher ethanol mixtures and higher RVP on the existing Mexican fleet and in the typical climate and altitudes of Mexico. INECC is carrying out some analyses to address this concern.

Comparison with best practices

In terms of sulfur, fuel quality in Mexico continues to lag behind fuel quality in the United States and Europe, both of which have established ultralow-sulfur limits for diesel and gasoline (see Figure 1).

1 NOM-086 required diesel to meet a 15 ppm sulfur limit and gasoline to meet a 30 ppm average with a maximum of 80 ppm by 2009. While PEMEX complied with diesel limits in certain regions and met the gasoline limits for premium fuel, full compliance with NOM-086 sulfur standards for either gasoline or diesel was never achieved on a nationwide basis. See Alcántar González and Gómez Cruz (2011) for more information.

2 Including parts of the states of Baja California, Sonora, Chihuahua, Coahuila, Nuevo León, and Tamaulipas

	Region	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Gasoline	European Union	10 ppm maximum														
	United States	30 ppm average (80 ppm maximum)							10 ppm average (80 ppm maximum)							
	Mexico	30 ppm average / 300 ppm maximum					30 ppm average (80 ppm maximum)									
Diesel	EuropeanUnion	10 ppm maximum														
	United States	15 ppm maximum														
	Mexico	15 / 500 ppm maximum														

Figure 1. Gasoline and diesel sulfur limits in the European Union, United States and Mexico.

CRE has initiated a process to review the newly adopted NOM-016, with a focus on gasoline and diesel specifications, and it is possible that this process will result in further updates to harmonize Mexico's sulfur levels with global best practices. The emission-control scenario for this analysis was based on the original NOM-EM-005, which set full implementation of 15 ppm diesel for 2018. A further step to 10 ppm sulfur gasoline was also assumed to be feasible for implementation in 2020, allowing with harmonization of global best practices.

VEHICLE EMISSIONS

SEMARNAT has the authority to regulate pollutant emissions from vehicles. Currently, vehicle emissions standards are based on European and U.S. regulations and typically allow for compliance with either regulatory program. Vehicle standards are set for light-duty vehicles (LDVs; less than or equal to 3,857 kg of gross vehicle weight) and heavy-duty vehicles (HDVs; greater than 3,857 kg of gross vehicle weight).

Background

Emissions of new vehicles sold in Mexico were first regulated by NOM-044-ECOL-1993 (INE, 1993a) for HDVs and NOM-042-ECOL-1993 (INE, 1993b) for LDVs. Beginning in 1995, HDVs fueled by gasoline, natural gas, or liquefied petroleum gas were separately regulated by NOM-076-ECOL-1995 (SEMARNAT, 1995). Each of these standards received further updates, with the latest SEMARNAT revisions adopted in 2005 as NOM-042-SEMARNAT-2003 (NOM-042) (SEMARNAT, 2005), in 2006 as NOM-044-SEMARNAT-2006 (NOM-044) (SEMARNAT, 2006), and in 2012 as NOM-076-SEMARNAT-2012 (NOM-076) (SEMARNAT, 2012), respectively. A proposal for modification of NOM-044 was published in the official federal diary in December 2014 (SEMARNAT, 2014), with an updated proposal released September 2017 (SEMARNAT, 2017).

Current regulations

Heavy-duty vehicles

NOM-044 applies only to emissions from diesel engines and HDVs with diesel engines. The standard currently gives manufacturers the option of complying with either U.S. 2004 or Euro IV regulations. Because there is a high technology cost difference between these two standards, approximately 90% of new vehicles are supplied with engines meeting the lower cost U.S. 2004 standards (Blumberg, Posada, & Miller, 2014). The 2014 proposal for modification of NOM-044 intended to harmonize with U.S. 2010 or Euro VI standards in 2018 (ICCT, 2014). The update moves the date of full harmonization with U.S. 2010 or Euro VI standards out to January 1, 2021 (SEMARNAT, 2017).

NOM-076 requires engines run with non-diesel fuels, and vehicles powered by such engines, to comply with U.S. EPA regulations, increasing the stringency based on the fuel-quality timeline. Standard A, comparable to EPA 2004 standards, was effective immediately upon enactment of NOM-076. Standard B, equivalent to U.S. 2010 standards, was set to come into force 18 months after gasoline with an average sulfur concentration of 30 ppm (80 ppm maximum) would become widely available throughout the country. NOM-EM-005 mandated full availability throughout the entire country of gasoline with the latter sulfur content on January 31, 2016, but it is not clear whether Standard B will come into force based on the timeline of the emergency standard (NOM-EM-005) or the final standard (NOM-016).

Light-duty vehicles

NOM-042 sets tailpipe and evaporative emissions standards for new LDVs, allowing for compliance with either U.S.-based or Euro tailpipe standards and setting evaporative emissions limits based on the European program. Three levels of standards were set, to be phased in on a timeline governed by the sulfur content of the fuel. Standard A was mostly harmonized with U.S. Tier 1. The limit values currently being enforced pertain to Standard B, which was fully phased in by 2009. Under a European pathway, Standard B sets Euro 3 limits for diesel vehicles and slightly better than Euro 3 for gasoline-fueled vehicles. Under the U.S.-based pathway, compliance is measured using the U.S. federal test procedures, although the limit values are not actually harmonized with U.S.

Region	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
European Union	Euro V				Euro VI										
United States	U.S. 2010														
Mexico	Euro IV / U.S. 2004									Euro V / U.S. 2007		Euro VI / U.S. 2010			

Figure 2. HDV standards in the European Union, United States and Mexico.

Region	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
European Union	Euro 5a / b				Euro 6										
United States	Tier 2							Tier 3							
Mexico	Euro 3 / Tier 1+										Euro 4 / Tier 1+				

Figure 3. LDV standards in the European Union, United States and Mexico.

standards. The limits set in Standard B vary by pollutant, comprising limit values taken from Tier 1 and the temporary bins included in Tier 2, with weaker evaporative emissions limits and weaker useful life requirements (Miller et al., 2016).

Standard C is to be phased in over 4 years, starting 18 months after the full availability of low-sulfur fuel is established (defined in the regulation as 30 ppm average and 80 ppm maximum for gasoline and 10 ppm maximum for diesel). Under the European pathway, Standard C requires vehicles to meet Euro 4 standards. Under the U.S. pathway, Standard C again sets variable limits, mostly ranging from bin 7 to the temporary bin 10, under the U.S. Tier 2 program.[3] Important reductions in stringency compared to the U.S. program include the following: (1) For diesel vehicles, Standards B and C limits for particulate matter are based on Tier 1 standards and do not require particulate filters, despite the availability of ultralow-sulfur diesel; (2) evaporative emissions limits are equivalent to the European standard levels, which are significantly weaker than Tier 2 standards;[4] and (3) durability requirements are limited to 80,000 km rather than 190,000 km.

Although emissions will be reduced in all vehicles using lower sulfur fuels, neither of the options for Standard C actually requires the ultralow-sulfur diesel or gasoline to achieve the emissions limits or to enable any technology required to meet those limits. Given the delays in implementation of fuel-quality standards, full compliance with Standard C would not be expected prior to 2020. Although less than 2% of the new vehicles are diesels, the standard requires that both gasoline and diesel sulfur content limits are met to establish the implementation of Standard C.

Comparison with best practices

Heavy-duty vehicles

Figure 2 shows the timeline of the recently published NOM-044 update along with the adoption timelines of regulations in the European Union and the United States. While standards in Mexico do harmonize with global best practices, implementation is delayed by 7-11 years compared with the European Union and the United States.

The emissions-control scenario of this analysis was based on the original NOM-044 proposal, which set a direct path to U.S. 2010 or Euro VI standards in 2018, with no intermediate steps. While 2021 timeline would reduce expected 2035 benefits, additional programs to accelerate fleet renovation could compensate for the delay.

Light-duty vehicles

Although LDV standards are also seriously lagging behind the European Union and U.S., as demonstrated in Figure 3, no proposed modification of NOM-042 has been published, nor has any official working group been initiated.

While there was no official government proposal to frame our analysis, based on the original NOM-EM-005 timeline for fuels this study modeled a reasonable and achievable route to achieve harmonization with the rest of North America. In our emissions-control scenario, Mexico would meet Tier 2 or Euro 6 tailpipe emissions standards, with U.S.-based evaporative requirements (onboard refueling vapor recovery [ORVR]) starting in 2018, followed by a phase in of Tier 3 standards.

Methodology

The ICCT coordinated this project to determine the air quality and health

3 U.S. Tier 2 standards require manufacturers to meet a fleet average for NO_x emissions equivalent to bin 5, out of the 8 permanent certification bins available. Under the program, vehicles can be certified to bins with higher or lower emissions limits, as long as the manufacturer meets the bin 5 NO_x limit on a sales-weighted average.

4 U.S. emissions standards require control of evaporative emissions during refueling, known as onboard refueling vapor recovery (ORVR), which also results in much lower evaporation during vehicle use and while parked.

benefits in Mexico of improving national fuel and emission standards for on-road vehicles.

The analysis involved the following steps:

1. The ICCT defined a baseline scenario (Base) and an emissions-control scenario (Control). The analysis extends out to the year 2035, a year in which most of the vehicle fleet in circulation would be expected to meet improved standards (ERG, 2016b).
2. Eastern Research Group (ERG) ran these scenarios using MOVES-Mexico, an adapted version of the U.S. EPA's Motor Vehicle Emission Simulator (MOVES) (ERG, 2016a), providing detailed forecasts for the Base and Control scenarios. Less detailed modeling runs were also completed for several alternative cases to provide understanding of the impact of each policy step and to consider alternate policy approaches.
3. Researchers at the University of Tennessee (UT) used the Community Multi-Scale Air Quality (CMAQ) model to forecast the resulting air pollution concentrations under the Base and Control scenarios at the county (*municipio*) level for 2035.
4. Finally, INECC and ICCT used U.S. EPA's BenMAP model to forecast the reduced number of premature deaths attributable to $PM_{2.5}$ and ozone pollution under the Control scenario and computed the economic benefits in that year.

SCENARIOS

ICCT defined two primary modeling scenarios. The Base case was determined by the unchanged status quo conditions of 2015, and the Control case assumed the adoption and implementation of best practice standards for fuels and vehicles. Additionally, the ICCT defined sensitivity scenarios to assess the effects of stronger inspection and maintenance programs (I/M) nationwide and less stringent LDV and gasoline standards.

Table 2 summarizes the main characteristics and assumptions of the analyzed scenarios, all of which are described in more detail below.

Base case

The Base case scenario modeled status quo fuel quality prior to enactment of NOM-EM-005. Ultralow-sulfur diesel (15 ppm) and low-sulfur gasoline (30 ppm) were available in priority regions (northern border and metropolitan areas). Low-sulfur gasoline availability outside metropolitan areas was restricted to 15%, with the remaining 85% containing up to 300 ppm sulfur. The only diesel considered available outside the northern border states and metropolitan areas was 500 ppm sulfur.

For the Base case, regulatory standards for LDVs (NOM-042) and HDVs (NOM-044 and NOM-076) remained unchanged throughout the timeframe of the analysis. Based on analysis of remote sensing roadside emissions data measured in Mexico, the Base case for LDV exhaust emissions account for overcompliance with NOM-042 due to sales of vehicles certified to more stringent U.S. and European standards. More details can be found in ERG (2016b).

Control case

The emissions-control scenario was defined by the implementation of best practice standards as characterized by the president's commitment in the North American Leaders Summit (NALS) in June 2016. This scenario was supported either by policy proposals in place, policy discussions with SEMARNAT and CRE, or expert judgement of the most ambitious but feasible implementation timeline.

Table 2. Description of Base, Control, and Alternative scenarios for fuels sulfur content and vehicle emission standards.

Fuels / Vehicles	Base case	Control case	Alternative cases
Gasoline sulfur	Metropolitan areas: • 30 ppm Rest of country: • 85% 300 ppm • 15% 30 ppm	2016: • 150 ppm 2017–2019: • 30 ppm 2020+: • 10 ppm	1. Gasoline and LDVs remain unchanged after 2018: • Gasoline remains 30 ppm • LDVs remain U.S. Tier 2 2. Base case with I/M • Nationwide I/M only, no control case policies 3. Control case with I/M • Nationwide I/M, in addition to control case policies
Light-duty vehicles	PM: • U.S. Tier 1 NO_x: • U.S. Tier 2 bin 7	2018–2020: • U.S. Tier 2 or Euro 6 plus ORVR 2021: • U.S. Tier 3, fully phased in by 2025	
Diesel sulfur	Metropolitan areas & northern border: • 15 ppm Rest of the country: • 500 ppm	2016–2017: • 500 ppm 2018–2019: • 15 ppm 2020+: • 10 ppm	
Heavy-duty vehicles	Nationwide: • U.S. 2004 / Euro IV	2018+: • U.S. 2010 / Euro VI	

The emissions-control scenario assumed full compliance with 30 ppm sulfur gasoline in 2017 and 15 ppm sulfur diesel in 2018. To this scenario was added an additional step to 10 ppm sulfur fuels in 2020.

For LDVs, the scenario shifted toward a U.S.-based regulatory approach[5] with standards moving to full U.S. Tier 2 compliance or Euro 6 with the addition of U.S. ORVR requirements for control of evaporative emissions in 2018. U.S. Tier 3 standards are phased in starting in 2021, achieving full harmonization with U.S. fleet average standards by 2025. For HDVs, the scenario followed SEMARNAT's 2014 proposal for modification of NOM-044, with implementation of Euro VI or U.S. 2010 standards in 2018.

Alternative cases

To assess the effect of specific controls on the overall result, emissions in alternative cases were modeled at the aggregate national level. Each alternative case was investigated separately, allowing assessment of the relative benefits of: 1) the importance of the final regulatory step for LDVs, including 10 ppm average sulfur content in gasoline and Tier 3 vehicles; 2) the relative importance of inspection and maintenance programs, as compared to fuel and new vehicle standards; and 3) the importance of inspection and maintenance once stringent standards were in place.

To distinguish the effects of Tier 2 and Tier 3 standards, along 30 and 10 ppm sulfur gasoline, a relaxed version of the Control scenario was included to allow the benefits associated with each phase of the LDV standards to be distinguished. To this end, sulfur standards for gasoline were not improved beyond 30 ppm, eliminating the additional step to 10 ppm sulfur gasoline. Evaporative and exhaust standards for cars and light-duty trucks were also not improved beyond U.S. Tier 2 or Euro 6+ORVR, eliminating any regulatory progress beyond 2018.

To describe the potential effects of a nationwide I/M program for both primary scenarios, all deterioration rates were set to meet the lower levels encountered in the United States.

VEHICLE EMISSIONS MODELING

ERG had previously adapted the U.S. EPA's MOVES simulator to meet Mexico conditions and developed MOVES-Mexico (ERG, 2016a). MOVES takes into account the types of vehicles and fuels, roads, pollutants, geographical regions, and vehicle operating processes, and it can be run at a national level or for smaller scope at a county or project level (U.S. EPA, 2015). The default databases that ERG built for MOVES-Mexico included vehicle fleet and activity data, allocation of vehicle population by county, local meteorology conditions data, fuel specifications, and I/M programs (ERG, 2016a, 2016b).

The Base case used the default configuration built for MOVES-Mexico, while the Control case required further modifications of various inputs. The model was run at the municipality level to support photochemical air quality modeling and at an aggregate national level to assess overall emission reductions and alternative cases. This also helped to reduce the computing time of the runs for the different scenarios.

From MOVES-Mexico, ERG obtained a Mexico-specific database of emission rates by vehicle type, regulatory class, fuel type, model year, and operating mode. Remote-sensing device (RSD) data in Mexico was used to calibrate the emissions factors for nitrogen oxides (NO_x), carbon monoxide (CO), and exhaust hydrocarbons (HC) of LDVs, enabling emissions to more closely reflect real-world operating conditions in Mexico. RSD data showed that emissions deteriorate in Mexico at a higher rate than in the U.S., possibly as a result of high-sulfur fuels (reducing the effectiveness of catalytic convertors) and poor I/M programs and practices. To better model real-world conditions, both the Base and Control cases assume higher deterioration rates for LDV emissions in Mexico compared to the U.S. baseline values and deterioration rates. The rates are varied based on whether a given area has an I/M program in place, leading to geographically specific emission rates.

RSD data also showed that many newer vehicles over comply with NOM-042 limits because they are certified to more stringent standards. Other emission rates for vehicle classes or pollutants, where direct data was not available, were updated by mapping U.S. technologies to Mexico technologies by model year and adjusted based on the implementation of NOM-042, NOM-044, and NOM-076 standards (Table 2).

MOVES-Mexico considers two types of emissions:

- *Exhaust emissions* are produced as a result of fuel combustion during operation of the vehicle. These were modeled based on ratios between U.S. and Mexican standards.
- *Evaporative emissions* occur when fuel vapors escape from

5 U.S. light-duty standards currently represent global best practice. The U.S. Tier 3 emissions limits are notably more stringent than Euro 6 standards and are expected to result in significantly lower real-world NO_x emissions from diesel vehicles and evaporative hydrocarbon emissions from gasoline vehicles.

the vehicle's fuel system and can be the result of fuel permeation through the fuel tank and fuel lines or leaks. Evaporative emissions can occur through different processes, such as vapor vented during refueling, parking events (cold soak), vehicle operation (running loss), or immediately after engine shut-off (hot soak). In the modeling process, all evaporative emission rates were adopted from the corresponding U.S. standards and mapped to years in MOVES-Mexico. Due to less stringent NOM-042 evaporative controls, the U.S. "pre-enhanced" standards were used for the Base case from model year (MY) 1978 forward. For the Control case, U.S. Tier 2 was implemented from MY 2018–2024 and U.S. Tier 3 from MY 2025 forward.

To support the detailed spatial and temporal resolution required for photochemical air-quality modeling, MOVES-Mexico ran the Base and Control cases for all the 2,457 counties in Mexico, for typical weekdays and weekend days for each month of the year. The Base case was run for 2008 and 2035, while the Control scenario was run for 2035. Roughly 1 year of computing time is required to develop this level of detail; hence, the model was run in a cloud-computing configuration established by ERG, greatly reducing the clock time required to complete the model runs.

To understand how the Base, Control, and alternative cases would impact total emissions, the model was also run at the national and annual aggregate level where all inputs were reduced to single national averages. National emissions were calculated in 2008 and in 5-year intervals between 2015 and 2035, with one additional long-term forecast in 2050.

Around 160 pollutants were considered for the air-quality modeling runs, while just VOC, CO, NO_X, and $PM_{2.5}$ were reported for the national runs. Aggregating emissions data at the national level essentially allows insight into the relative effects of different regulatory scenarios. The county-level data were intended for modeling of air quality with a high level of geographic detail.

AIR-QUALITY MODELING

UT used the open source CMAQ model, developed and maintained by U.S. EPA, to estimate the air quality impacts of the Base and Control cases.

The first step was to run the CMAQ model by comparing results to a modeling year in which observational data was available. The 2008 Base run was used to complete this step. UT researchers used their own regridding algorithm to assign vehicle emissions in each county to grid cells at 50 km x 50 km resolution. For the year 2008, non-traffic emissions were based on the European Commission's Database for Global Atmospheric Research (EDGAR). For 2035, non-vehicle emissions came from the baseline scenario of the Evaluating the Climate and Air Quality Impacts of Short Lived Pollutants (ECLIPSE) modeling project. The Model of Emissions of Gases and Aerosols from Nature (MEGAN) supplied the biogenic emissions. The Weather Research Forecasting Model (WRF) was used to test against observational data of major meteorological parameters to develop optimized physics options for meteorological simulations in Mexico. In addition, CMAQ outputs were compared to local measurements of ozone and $PM_{2.5}$ in 2008 to ensure that model outputs were within benchmark modeling goals. Non-traffic emissions were held constant under each scenario modeled.

The air-quality modeling process was performed with and without transportation emissions, to estimate the impacts due specifically to transportation sources. Several sensitivity runs were done to see how PM and ozone concentrations changed as a result of greater of less control of each individual pollutant. Using a simplified approach to model the concentrations nationally, runs were done with emissions reductions from just light- or heavy-duty standards and assuming full emissions controls for all the other pollutants while holding each individual pollutant constant at base-case levels.

HEALTH IMPACTS ESTIMATION

INECC and ICCT carried out the estimation of health benefits from the Control scenario using the U.S. EPA's BenMAP tool (U.S. EPA, 2017) at the municipal level, which estimated the number of deaths related to the changes in air-quality levels of ozone and $PM_{2.5.}$

The CMAQ output grid of air pollutant concentrations was input into BenMAP to determine the health impact in each county. Demographic information at the municipal level, along with other information, is required to perform this assessment.

INECC used the annual population estimates from the National Council on Population (Consejo Nacional de Población, CONAPO) to project the population at the municipal level in 2035 for age groups: 0–14, 15–64, ≥65 years. Using the change rate of these groups over the period of years evaluated, the impacted population for age groups >30 and <1 was determined. Disease incidence rates at the municipal level were obtained from the National Institute of Statistics and Geography (Instituto Nacional de Estadística y Geografía, INEGI) for the year 2014, the most recent year available. These were projected to 2035 by the average historical rate of change from the past 16 years of data published by INEGI. For those municipalities that had no information, an average of all municipalities' disease incidence was used to populate missing values which would otherwise lead to an underestimation of the results.

Relative risk parameters of the health impact function were applied for the whole country and considered the following diseases: respiratory (J00-J99), cardiovascular (I10-I99), and lung cancer (C33-C34). The relative risk for those diseases were obtained from U.S. studies including Krewski (2009) for $PM_{2.5}$-related cardiovascular mortality in adults; Woodruff, Grillo, and Schoendorf (1997) for $PM_{2.5}$-related respiratory mortality from infants; and Jerrett et al. (2009) for ozone-related respiratory mortality from adults. A two-pollutant approach allowed for each pollutant impact to be treated separately (Anenberg, 2017).

In the case of ozone, 1-hour maximum daily ozone outputs from CMAQ were used to compute a 6-month mean value. The months considered were March to August, the ozone season in Mexico. The approach helps to reduce variability within months and provides a better estimation for the ozone season (Anenberg, 2017; Jerrett et al., 2009).

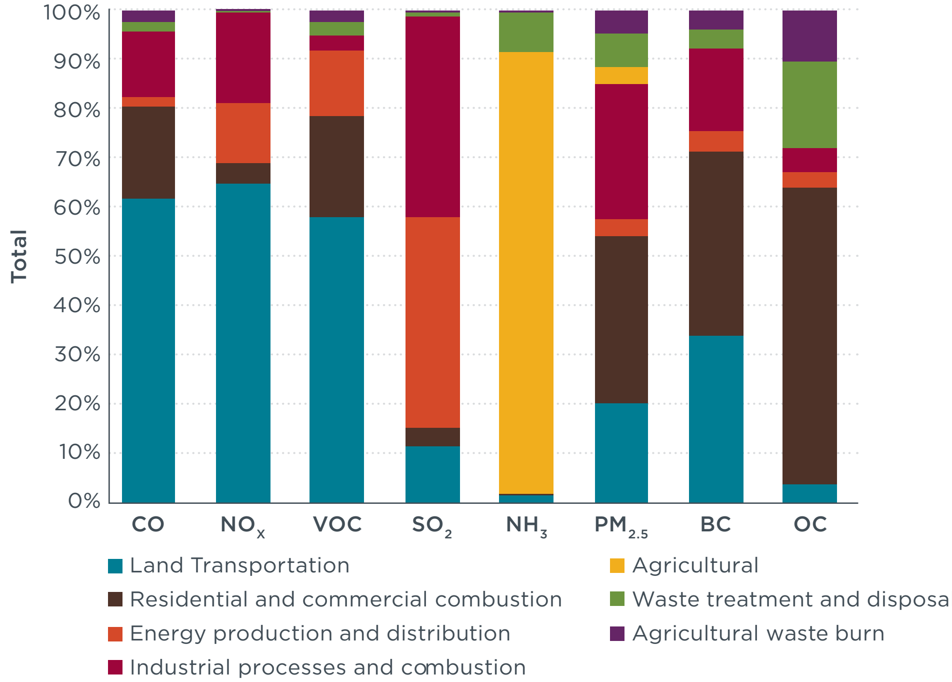

Figure 4: 2035 sectoral emissions by pollutant under the Base case.

Monetization of health benefits

Once BenMAP yielded the mortality results from the primary scenarios, the monetization of the health benefits was computed using the value of a statistical life (VSL) and a "benefit transfer" approach. This methodology has been applied in other ICCT's studies for Mexico, and we refer to these documents for further detail (see Miller, Blumberg & Sharpe [2014] and Minjares et al. [2014]).

The VSL reflects the economic value to the society or willingness to pay of each individual of reducing the statistical incidence of premature mortality (He & Wang, 2010). Thus, the 2035 VSL value calculated for this study is $3.9 million (2010 USD). Finally, to discount the benefits to current year 2017, a 3% rate was used.

Results

TAILPIPE EMISSIONS REDUCTIONS

Sectoral emissions impact

The emission projections shown in this section only account for on-road transportation, leaving aside other major pollutant sources, such as marine vessels, which have a tremendous impact especially on $PM_{2.5}$ emissions.[6]

In the year 2035, the on-road transportation sector contributes to more than half of NO_x, VOC, and CO emissions in the Base case. Transportation contributions also account for more than a third of black carbon (BC) and 20% of primary fine particles (see Figure 4).

6 According to the 2013 National Marine Inventory, ships within 200 nautical miles of the Mexican coastline account for more than double the total $PM_{2.5}$ mobile emissions in Mexico (Corbert, Comer, & Silberman, 2014).

Under the Control case, the transportation sector share of total emissions is reduced significantly, bringing contributions of CO, NO_x, and VOC down to below 50%. The transportation share of $PM_{2.5}$ and BC particles are reduced dramatically, a benefit of diesel particulate filter technology (Figure 5).

Figure 6 shows the level of emissions reductions achieved through the Control case, in terms of both the impact on overall transport sector and all sectors.

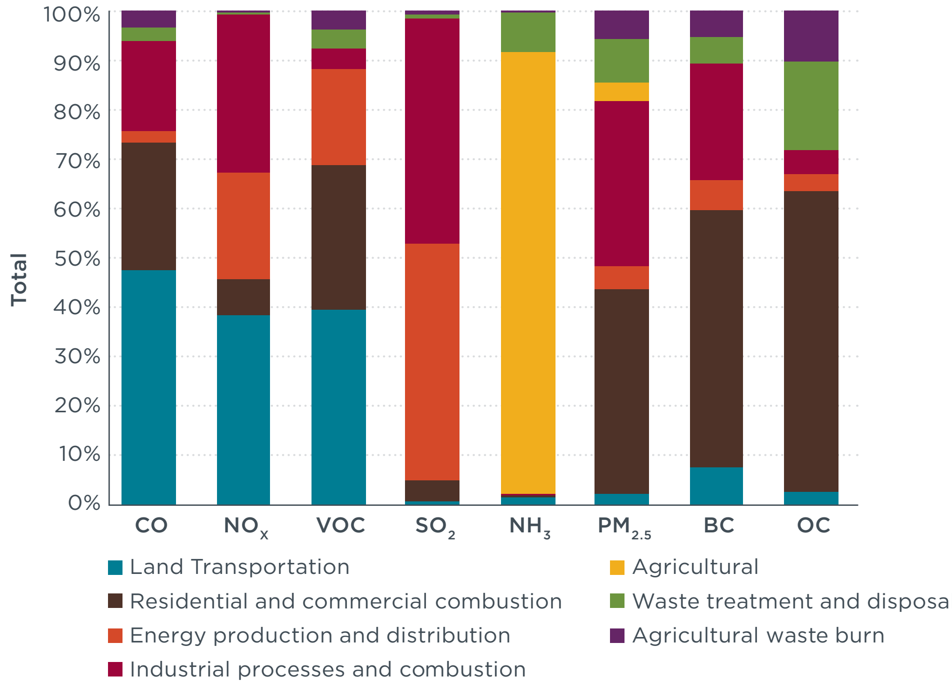

Figure 5: 2035 sectoral emissions by pollutant under the Control case.

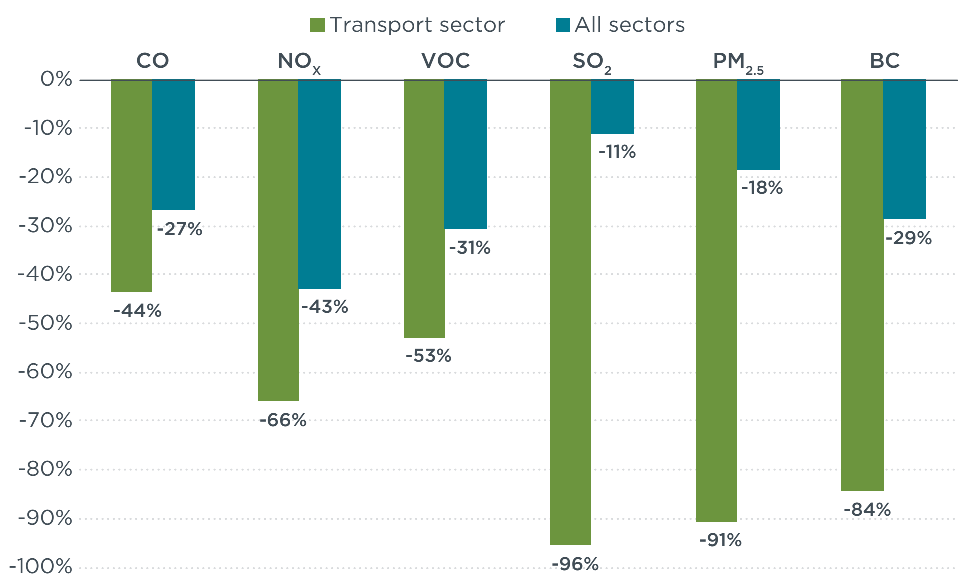

Figure 6: Control case emission reductions for transport only and all sectors in 2035.

Emission results by pollutant

The results of MOVES-Mexico runs show the reduction of transportation emissions in each pollutant class for each scenario modeled. The following graphs show the contribution of each measure included in Table 2 to transport sector emissions reductions in the Control case.

Nitrogen Oxides (NO_x)

Nitrogen oxides (NO_x), including both nitrogen oxide (NO) and nitrogen dioxide (NO_2), function as precursors for pollutant formation in the atmosphere, essential for production of ozone and also a very effective secondary PM precursor. NO_2 is also a direct respiratory irritant (Gamble, Jones, & Minshall, 1987).

Figure 7 shows that the potential reductions in NO_x emissions are fairly evenly split between HDV and LDV standards. The alternative cases demonstrate that improved I/M could have a near-term impact on emissions, while new vehicle standards would more than double the near-term potential and are necessary to enable longer-term reductions.

Evidence from the main diesel vehicle markets around the world, including Mexico, show that real-world NO_x emissions from diesel vehicles are, in most cases, significantly higher than certification limits (Anenberg et al., 2017). Only Euro VI and U.S. 2010 standards largely solve this issue for HDVs, giving even more importance to speeding the implementation of new vehicle standards to control these emissions. For LDVs, only Tier 3 standards offer a solution. MOVES-Mexico likely underestimates the poor compliance of the current fleet of HDVs, suggesting that the estimated NO_x reductions associated with the Control case may be conservative.

The alternative cases show that the harmonization of LDV and gasoline standards with U.S. Tier 2 is responsible for approximately 30% of the total reduction potential in 2035. From considering 2020 emissions in Figure 7, it becomes apparent that reducing fuel sulfur slightly more to 10 ppm would provide an immediate and additional 10% reduction of NO_x from the existing fleet, given that improved standards would have negligible impact in those initial years (ERG, 2016b). Tier 3 standards plus 10 ppm sulfur fuel represent 20% of the reduction potential and are the only way to continue to reduce NO_x emissions in the long term, given continued fleet growth.

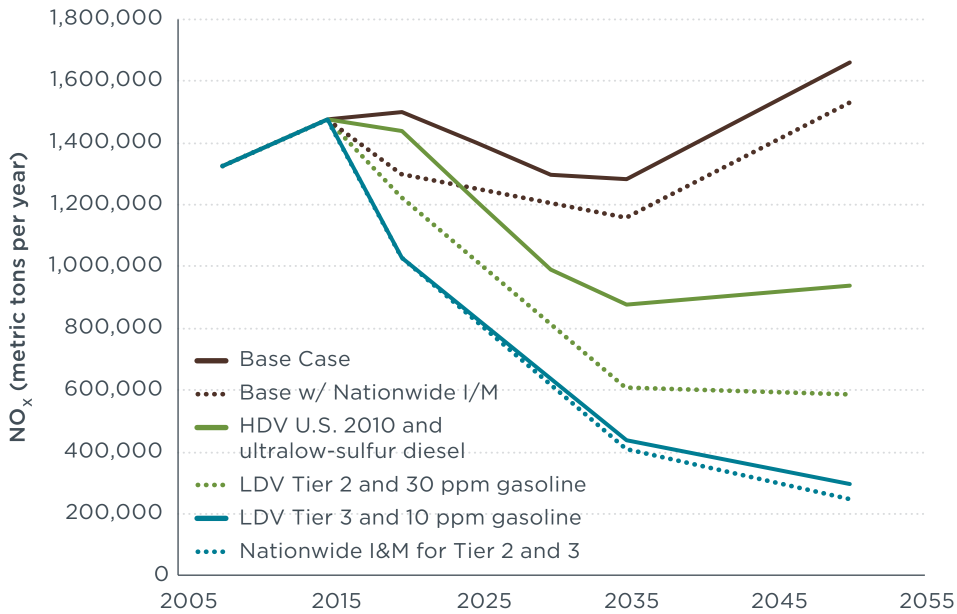

Figure 7: NO_x emissions under various regulatory scenarios.

Volatile Organic Compounds (VOCs)

Resulting primarily from evaporative emissions and incomplete combustion in gasoline vehicles, VOCs include many different species of hydrocarbon, many of which are toxic or carcinogenic. VOCs are essential ozone precursors and are especially critical in some of the major cities of Mexico where ozone production can be sometimes limited by the amount of VOC available. VOCs can also function as secondary particle precursors but appear to be significantly less important than NO_x as a precursor and are dependent on the other pollutant species available in the atmosphere, as well as climate and meteorological conditions.

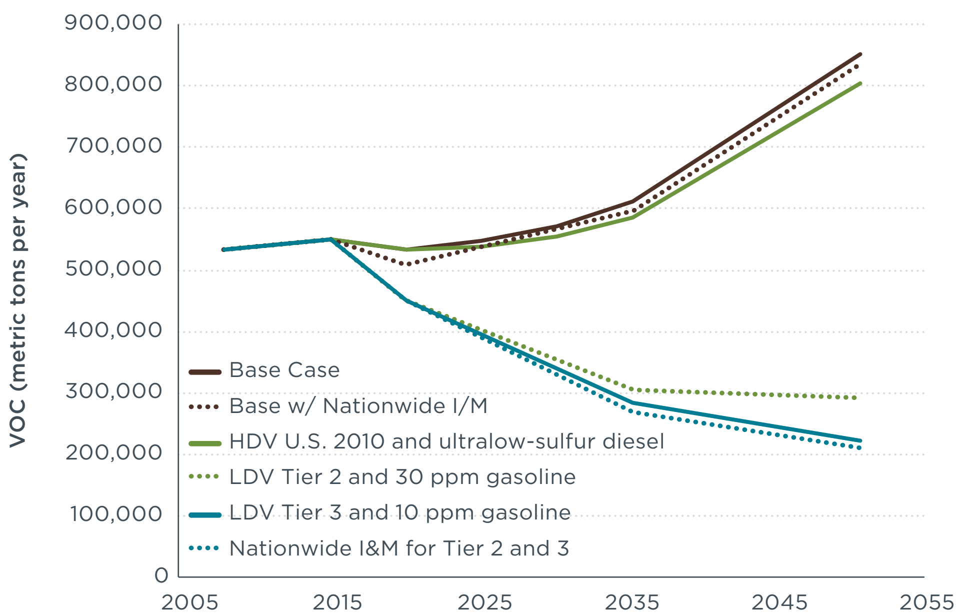

Figure 8: VOC emissions under various regulatory scenarios.

LDV and gasoline standards were responsible for the bulk of VOC reductions, which are expected to increase significantly in the absence of improved standards. Tier 3 standards were less critical for this pollutant than for NO_x but are required to reduce emissions in the long run (Figure 8). No changes to RVP were modeled, although allowances for higher RVP limits and noncompliance with RVP standards could substantially increase VOC emissions (Kirchstetter, Singer, Harley, Kendall, & Traverse, 1999).

The alternative cases show that Tier 3 and 10 ppm sulfur gasoline will not yield significant benefits in the near term compared to Tier 2 and 30 ppm sulfur gasoline as a result of the advanced controls in evaporative emissions adopted at this stage. Early adopted I/M programs show some impact in the short term, but these programs are not expected to result in significantly reduced VOC emissions over time.

Fine particulate matter ($PM_{2.5}$)

Fine particulate matter ($PM_{2.5}$) includes all particles of 2.5 micrometers in diameter and smaller. Diesel vehicles are the primary transportation-related source of primary particle emissions. While the MOVES-Mexico modeling only captures primary particle emissions, $PM_{2.5}$ can also be formed in the atmosphere from precursor emissions, including NO_x, sulfur oxides (SO_x), and VOCs. Secondary particle formation is captured in the CMAQ modeling process. $PM_{2.5}$ is associated with a number of health impacts ranging from pulmonary and cardiovascular disease to chronic bronchitis and premature death (Blumberg, Walsh, & Pera, 2003).

The Control case demonstrates that primary $PM_{2.5}$ emissions can be reduced by over 90% from HDV emissions standards and fuels (Figure 9). Ultralow-sulfur diesel allows for the adoption of cleaner technologies, especially diesel particle filters (DPFs), which dramatically cut primary $PM_{2.5}$ emissions. Although reductions are not expected from LDVs and fuels in primary particle emissions, these vehicles and cleaner fuels will have an important impact on secondary particulate matter, which in this study accounted for about 44% of total $PM_{2.5}$ reductions.

Carbon monoxide (CO)

Carbon monoxide impairs the blood's oxygen-carrying capacities, and elevated concentrations in the air are dangerous for individuals with cardiovascular disease (Blumberg, Walsh, & Pera, 2003). It should be noted that regardless of the relative size of the achievable reduction in CO emissions, this pollutant is no longer a main source of health-relevant pollution in Mexico, and therefore its reduction is a secondary concern (INECC, 2015). CO emissions observed in Figure 10 show similar trends as those of other pollutants, with a 41% reduction under the Control case by 2035. For this pollutant, LDV and sulfur standards together were responsible for most the improvements.

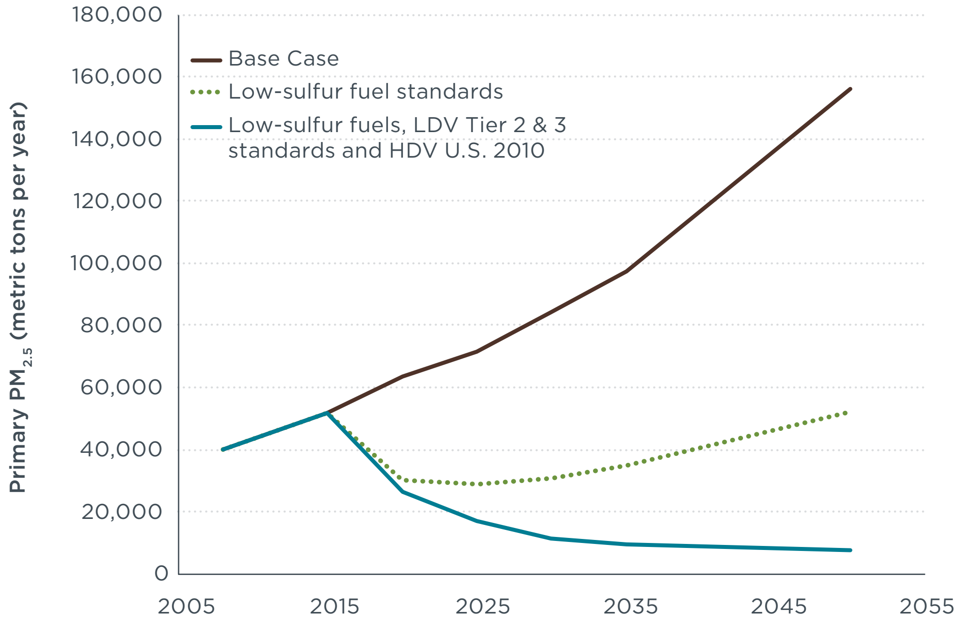

Figure 9: $PM_{2.5}$ emissions under various regulatory scenarios.

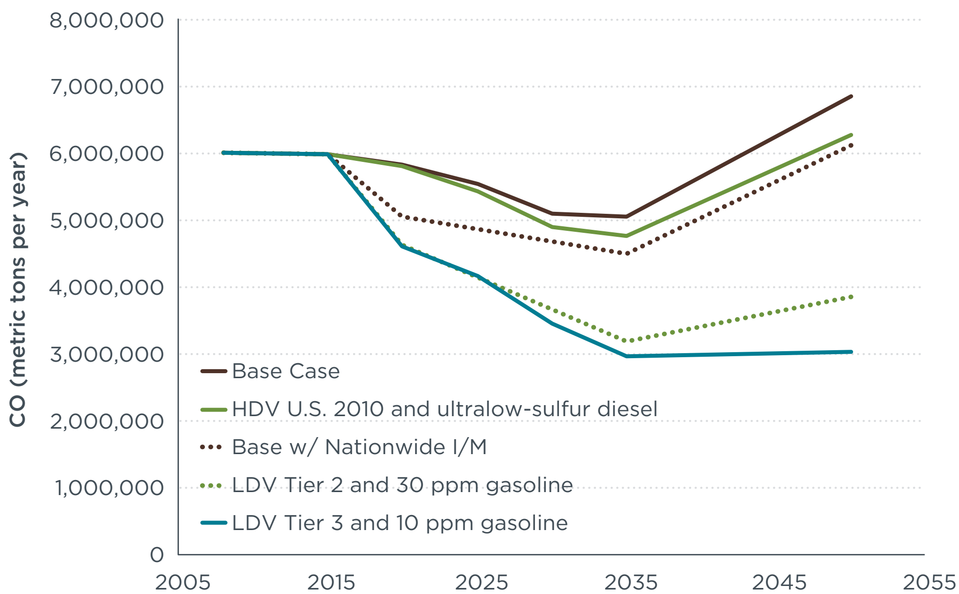

Figure 10: CO emissions under various regulatory scenarios.

Figure 11 shows the share of the reduction potential for LDVs and HDVs. CO and VOC reductions are mainly attributed to passenger vehicles technologies improvements and the use of low-sulfur gasoline. $PM_{2.5}$ reductions are almost entirely attributable to use of ultralow-sulfur diesel and emissions standards that require DPFs for HDVs. NO_x emission-reduction potential is almost evenly split between LDVs and HDVs.

AIR-QUALITY IMPACTS

The substantial reduction in primary and precursor emissions results in a significant decline in atmospheric concentrations of ozone and particulate matter, the two pollutants of most concern.

Ozone exposure is associated with a number of short- and long-term health effects, including cardiopulmonary and cardiovascular diseases, respiratory problems, and premature death (Turner et al., 2016). Particulate matter also increases the risk of cardiovascular and pulmonary diseases and premature death, as well as increases the risks of infant respiratory morbidity and mortality and lung cancer (Pope & Dockery, 2006).

Concentrations of $PM_{2.5}$ were reduced by 18% at the national level and 20% in Mexico City area, with up to 28% reductions in the winter months when concentrations are highest. The CMAQ modeling suggests that 44% of the $PM_{2.5}$ emissions reductions were from reductions in secondary particle formation, although it appears that the CMAQ model underestimates secondary particle formation, in some cases quite significantly (Park et al., 2006).

Ozone levels were also reduced for different metrics regarding 8-hour, 1-hour, and 1-hour-spring maximum values. Ozone concentrations are highest in the spring and early summer, before the rainy season begins. Considering just this season, the 1-hour ozone peaks were reduced by 12% throughout the country and 14% in Mexico City. Table 3 shows ozone and fine particle reductions derived from the Control scenario.

The maps in Figure 12 and Figure 13 show the location of the air-quality benefits, illustrating that the largest reductions (Base minus Control scenario) for both pollutants are located in regions with the highest population concentration, typically the metropolitan areas of Guadalajara, Monterrey, and Mexico City. In these figures, the deepest red color shows the greatest level of air pollution

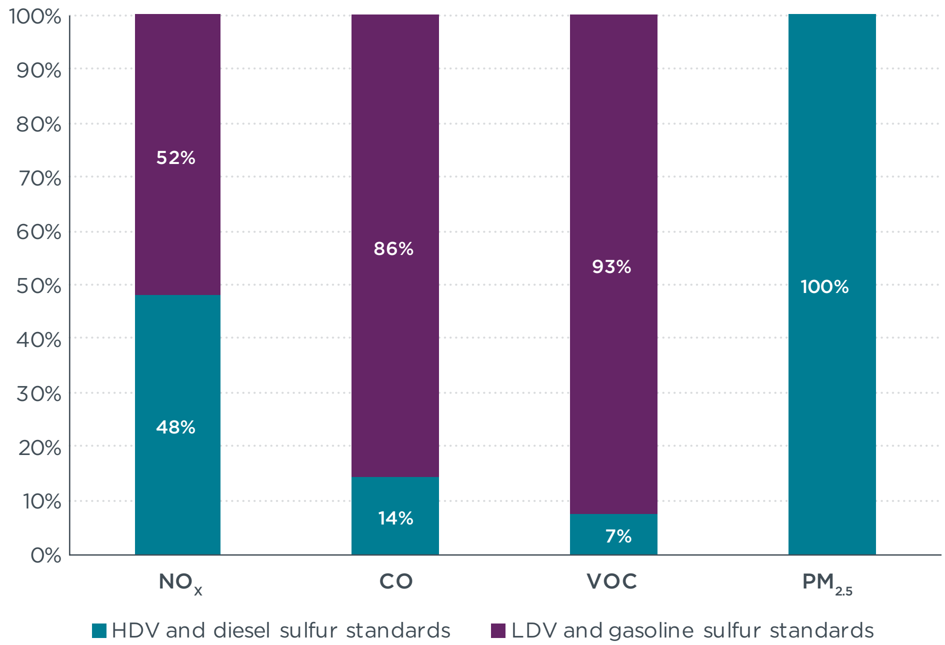

Figure 11. Contribution to the 2035 emissions reductions under the Control case.

Table 3. Population-weighted reductions in particulate matter and ozone concentrations.

Air quality indicator (population-weighted)	Nationwide	Mexico City
Annual mean $PM_{2.5}$	-18%	-20%
8-hour maximum ozone	-8%	-5%
1-hour maximum ozone (spring mean)	-12%	-14%

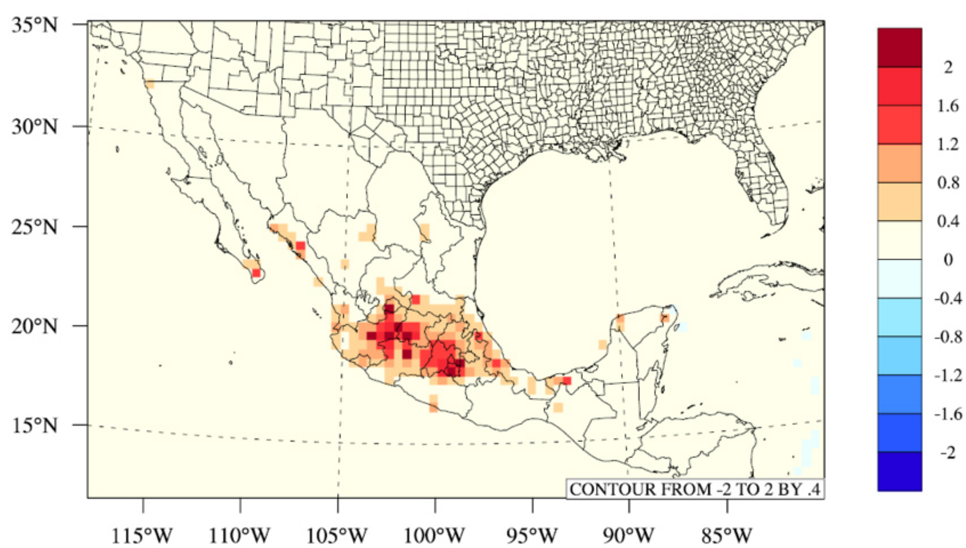

Figure 12. Nationwide reduction in $PM_{2.5}$ annual mean (µg/m3).

reductions between the Base and Control scenarios.

It is evident from these figures that the central region plays an important role in defining key policy measures to reduce both pollutants. This central region includes the *Megalópolis*—a region with 35 million inhabitants—comprised by six states: Mexico, Hidalgo, Puebla, Morelos, Tlaxcala, and Mexico City.[7] The Environmental Commission of the Megalopolis (CAMe) works jointly with the six governments toward improving air quality in the region, which is in non-attainment for ozone and $PM_{2.5}$ ambient quality standards. In the just-published air-quality program (ProAire), the CAMe acknowledges the impact of the transportation sector in the local emissions and proposes development of an emissions reduction plan for LDVs and HDVs (SEMARNAT, 2017). Other important urban regions that require urgent attention are Guadalajara and Monterrey, especially for ozone formation.

The Control scenario results in significant reductions in 1-hour-spring peak ozone concentrations—12% at the national level and 14% in the Mexico City metropolitan region—and an even more dramatic drop in fine particle concentrations—18% in the national average and 20% in the Mexico City metropolitan region.

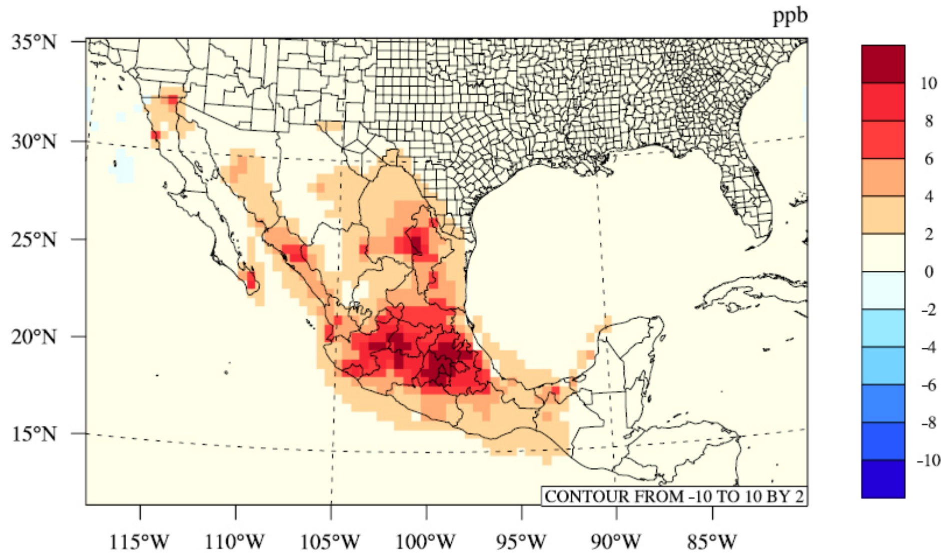

Figure 13. Nationwide reduction in 1-hour-spring ozone mean (ppb).

Table 4. Mortality reductions in year 2035 by pollutant and vehicle type, with monetary value in 2017.

Pollutant / Vehicle type	HDV	LDV	LDV Tier 3 increment	Total	Share	2017 valuation (billion 2010 USD)
Ozone	900	1,100	400	2,000	22%	$4.6
Secondary PM	1,400	1,700	500	3,100	34%	$7.2
Primary PM	3,900	0	0	3,900	43%	$9
Total PM	5,300	1,700	500	7,000	78%	$16.2
Total	6,200	2,800	900	9,000	100%	$20.8
Share	69%	31%	10%	100%		
2017 valuation (billion 2010 USD)	$14.3	$6.5	$2.1	$20.8		

HEALTH IMPACTS

This study found approximately 9,000 deaths avoided in the year 2035. We typically like to consider the impacts of vehicle standards at a point when the fleet will have fully turned over and almost all older vehicles will have been replaced with new technology. Because of the long lifetime of many HDVs and because the Tier 3 standards are not fully phased in under the Control scenario until 2025, this analysis will not be able to fully account for the impacts of the program.

In the Control case, ozone concentration reductions would allow for an estimated 2,000 premature deaths from respiratory diseases to be avoided. $PM_{2.5}$ concentration reductions allowed for 7,000 premature deaths to be avoided, mainly including cardiovascular mortality in adults and respiratory mortality in infants less than 1 year old. A detailed breakup of mortality reduction by pollutant is found in Table 4.

The concentration reductions mirror the regions of greatest population density in the country. Health impacts consequently closely track population density as well. The most populous state, México, was the location of approximately one fifth of all avoided ozone-related deaths and one quarter of all avoided PM-related deaths in Mexico.

The geographic distributions of mortality reductions due to each pollutant are displayed in Figure 14 and Figure 15. Each bubble represents the mortality in each state due to a specific pollutant, and the size of the bubble reflects the number of deaths—the bigger the bubble, the greater the number of deaths in that specific state.

7 The state of Querétaro was just announced to join the Megalópolis.

As shown in the figures, the areas with more population density have higher mortality levels; in both cases, the state of México is the region with the highest mortality and largest population.

Allocation to transportation standards considered

To allocate the air-quality and health impacts to the different policies, we used sensitivity runs conducted by the CMAQ modeling team. These sensitivity runs suggested that the contribution of NO_x to secondary particle and ozone formation was larger than that of any other pollutant. The results showed that VOC had a larger impact on ozone production in the Mexico City region, while nationally ozone production appeared to be largely NO_x limited. For secondary particle production, SO_x clearly have an important impact but, due to the much smaller amount of the primary pollutant reduced, is not as important as NO_x. Because of the nonlinearity of formation of both types of pollutants in the atmosphere, it was difficult to precisely quantify the impact of each pollutant.

Other studies suggest that the production of both ozone and secondary PM from their precursors could be more evenly distributed between VOCs and NO_x (as supported by Song et al. [2010] and Hodan and Barnard [2004] for ozone and secondary particles, respectively). However, the differences between weighted values produced through use of the sensitivity runs and giving even weighting to NO_x and VOC are not that great, with a variety of weighting factors reaching similar conclusions primarily as a result of the relatively even distribution of NO_x reduction potential for LDVs and HDVs and the much higher total amount of NO_x reduced compared to the other pollutants.

The present value of health savings from the Control scenario reductions

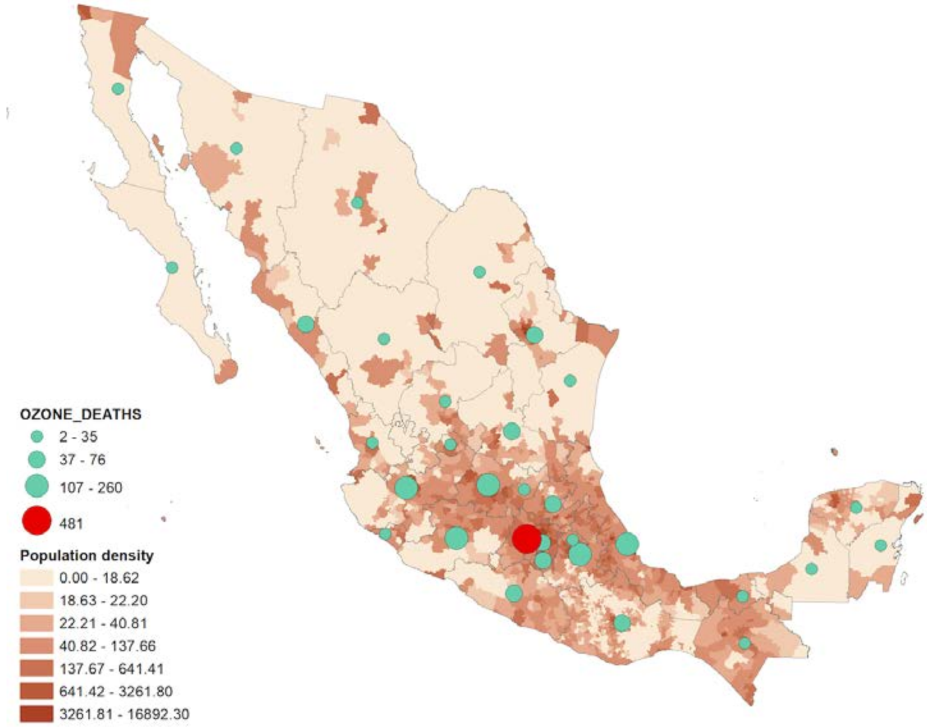

Figure 14: Geographic distribution of deaths avoided in 2035 due to ozone reductions.

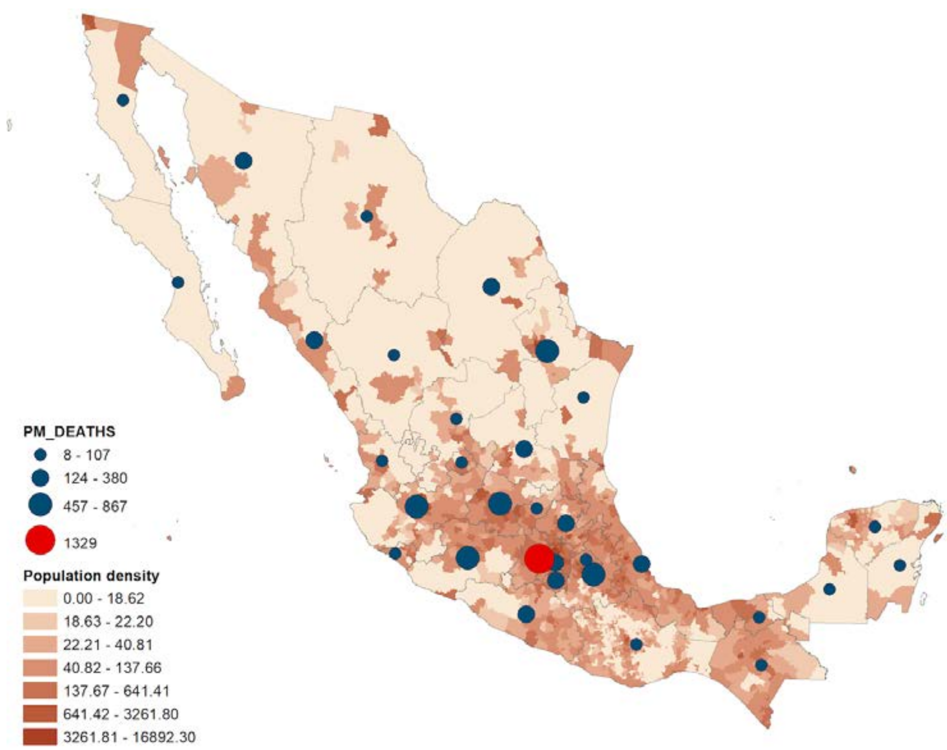

Figure 15. Geographic distribution of deaths avoided in 2035 due to $PM_{2.5}$ reductions.

of premature mortality in 2035 correspond to $20.8 billion (2010 USD). The emissions and health benefits breakdown in 2035 is shown in Table 4, highlighting the significant contribution of each set of standards to the total gain.

Uncertainties and areas of further study

There are many areas of uncertainty in this analysis, the most important of which are discussed here. While there is certainly further investigation warranted on many topics, overall we find the assessment to be conservative, likely underestimating the impacts of these critical regulations.

One of the key ways in which the study undervalues the benefits of these best practice policy scenarios (Control case) is that it only considers health benefits due to mortality reductions related to ozone and fine particles in the year 2035. The cumulative benefits over the prior and future years of the regulations are not considered, nor are the many other benefits to health and wellness, such as reductions in asthma, chronic bronchitis, cardiopulmonary diseases, lost work and school days, longer duration of colds, and other well documented but not necessarily lethal impacts of these pollutants.

The methodologies and models used in this study follow the latest findings; each module in the assessment has specific assumptions and an uncertainty associated with it, as follows:

- In the case of MOVES-Mexico, there are still significant uncertainties in the numbers of vehicles in existing fleet, the rate fleet renewal, the reduction in emissions deterioration available within Mexico due to the application of new vehicle standards, and even the emissions factors of the new and existing vehicles in the real world.
- For the air-quality modeling, different inventories were used for the non-transportation sectors in 2008, the year in which model correlation was conducted, and in 2035. Both data sets were the result of efforts conducted at the global level, lacking the detail that would be available through a strong local inventory. As a result, it appeared that $PM_{2.5}$, SO_2, and NO_X were all significantly underestimated by the modeling, with the largest differences seen for $PM_{2.5}$. Ozone levels were somewhat overestimated on the low end, but because we chose to use the peak ozone impacts to estimate health outcomes, this overestimation should not have an impact on the results.
- For the health-impact modeling, there were some data gaps that had to be estimated. For example, missing incidence rates at the municipal level were populated with the average of all municipalities, reducing the underestimation accounted for the missing values. Ozone mortality appears to be higher than expected (in relation to the overall mortality impact); however, that could have been caused by lower than expected PM-related health benefits because of CMAQ's underestimation of PM concentrations.

The Global Burden of Disease (GBD) visualization from the Institute for Health Metrics and Evaluation (IHME) reports that total ozone related mortality in Mexico in 2015 was 1,859, and PM-related mortality accounted for 28,991 in the same year (IHME, 2016). Ozone mortalities in our results account for 22% of total avoided deaths; in the case of IHME estimates, ozone represents the 6% of air quality-related deaths. As suggested above, this may have more to do with an underestimation of PM concentrations, but it also could relate to the more important impact that on-road transportation has on peak ozone levels.

Our biggest concern in the modeling, and the result that will have the most impact on the findings, is the significant underestimation of $PM_{2.5}$ concentrations at the national and local level, with average $PM_{2.5}$ concentrations at a quarter to half of the monitored levels. Some studies have suggested that CMAQ significantly underestimates the secondary organic formation of particles in the atmosphere, especially that portion of secondary particles formed from the highly volatile organic hydrocarbon precursors found in gasoline (von Stackelberg, Buonocore, Bhave, & Schwartz, 2013). This could be a significant factor, especially in this study. There may also be significant gaps in the inventory. For example, our inventory does not account for marine emissions. According to the 2013 National Marine Inventory, ships within 200 nautical miles of the Mexican coastline account for more than double the total $PM_{2.5}$ mobile emissions, as well as double sector-wide emissions of NO_X (Corbert et al., 2014). While it is not certain that increases in the inventory would also result in higher impacts in this study, it is likely that there would be some increase in the secondary particle formation due to higher overall pollution levels.

Finally, additional changes in fuel quality beyond sulfur limits were not considered here. While other changes in fuel specifications could have an impact on emissions, air quality, and health endpoints, sulfur levels have the highest overall impact. Nonetheless, other fuel specifications, such as RVP, deserve special attention and should be studied in the extreme conditions of Mexico (high altitude and low latitude) and with the existing fleet of older vehicles still in circulation.

Conclusion

The results of this detailed modeling assessment demonstrate the tremendous benefits to Mexico available through harmonization with three important on-road fuel and vehicle standards in place in the rest of North America. While the air-quality challenges implicit in Mexico City's geography and size will continue, these standards will reduce peak ozone levels by 14%, reducing the number of serious air pollution alerts triggered and the restrictions that result. In addition, they will reduce $PM_{2.5}$ concentrations by 20%, a tremendous reduction in the deadliest, but often unseen, pollution in urban areas.

The reductions in concentrations of ozone and $PM_{2.5}$ from the implementation of these standards will allow Mexico to avoid 9,000 premature deaths in 2035 alone. This analysis did not assess the number of avoided deaths that will continue to accrue beyond 2035 nor those that accumulate up until that date. This study was also not able to quantify other health benefits; however, we know that the cleaner air will reduce asthma episodes, chronic bronchitis, the severity and duration of colds, the toll that sickness takes on productivity in work and school, as well as a host of more severe cardiopulmonary and respiratory diseases. The monetized benefits for the assessed benefits in the year 2035 translate into $20.8 billion (2010 USD) today. The total benefits of this suite of standards would be many times more.

The most important emissions reductions were the direct reductions of $PM_{2.5}$ from the diesel truck regulations that require DPFs. These filters virtually eliminate primary particle emissions, and in 2035, after years of fleet growth but few of the current trucks still operating, the reduction in $PM_{2.5}$ from the sector is 91%, corresponding to a 18% reduction economy wide. The 30%–40% economy-wide reductions in NO_x and VOC are also critical, less because of their direct health impacts than because of what they can catalyze and turn into in the atmosphere. The NO_x and VOC are the two key ingredients necessary (along with sunlight) for ozone production. But they both also contribute to production of secondary $PM_{2.5}$, particles which are formed in the atmosphere and catalyzed by the complex mixture of pollutants already there.

SO_2 also forms secondary particles in the atmosphere; however, the most important result of sulfur reduction in the fuel is in the reduction of other pollutants. In diesel, lower sulfur fuel reduces emissions of primary particles from all diesel vehicles, even the oldest and most polluting vehicles on the road, while also enabling the use of filters to virtually eliminate these particles from the newer vehicles. In gasoline, lower sulfur fuel allows the catalysts that are on almost all passenger cars in Mexico to operate more efficiently, offering better control of NO_x, VOC, and CO. The 10 ppm sulfur fuel alone offers an immediate 10% reduction in NO_x from current vehicles. Like ultralow-sulfur diesel, 10 ppm sulfur gasoline also enables adoption of the best practice Tier 3 standards, which offer 20% of the total NO_x reduction potential available from these standards and 10% of the quantified health benefits.

10 ppm sulfur fuel is also important for VOC emissions, yet these impacts are hidden by the tremendous reductions available through the adoption of stringent evaporative emissions standards. The vehicle standards are critical for reducing fuel evaporation in Mexico's high altitude and sunny, hot climate, but fuel specifications also play an important role. Although in this study we did not assess the impact of noncompliance with RVP standards for fuels or the impact of higher ethanol content on emissions from the older vehicle fleet, these are important considerations for Mexico to study and consider.

The study showed the benefits, especially in the near term, of strong I/M programs, suggesting that strengthening these programs and adopting them in all urban areas that are noncompliant with air-quality standards would accelerate the benefits of these measures. Nonetheless, without a transition to cleaner vehicle standards, these programs alone cannot reduce emissions as the vehicle fleet continues to grow.

For the three key standards considered, timing and stringency are critical to achieve the benefits demonstrated. The final NOM-044 emissions standard for HDVs vehicles has now been approved, although the final standard introduces a three-year delay in achieving full harmonization with U.S. 2010 and Euro VI standards compared to the initial proposal. The following are the other critical policy measures that need to be enacted to realize the air-quality and health improvements quantified:

- Update and publish the NOM-042 emissions standard for LDVs to align with international best practices for control of both exhaust and evaporative emissions. The immediate policy goal would be harmonization with U.S. Tier 2 standards. Euro 6 standards should be allowed only with the addition of U.S.-style advanced evaporative emission control. A move to U.S. Tier 3 standards is necessary to keep up with a growing vehicle fleet. These standards have no current analog under the Euro system.
- Update NOM-016 to move from 30 ppm to 10 ppm sulfur for gasoline and enforce the 15 ppm sulfur diesel standard. RVP specifications should also be enforced, with special attention to and no waivers available for regions that are noncompliant with air-quality standards. While reducing diesel sulfur from 15 ppm to 10 ppm would be preferable, this will have a significantly smaller overall impact on emissions, air quality, and health than moving to 10 ppm gasoline.

List of Abbreviations and Acronyms

BenMAP	Environmental Benefits Mapping and Analysis Program
CMAQ	Community Multiscale Air Quality
CRE	*Comisión Reguladora de Energía* (Energy Regulatory Commission)
EDGAR	Emissions Database for Global Atmospheric Research
ERG	Eastern Research Group
HDV	Heavy-duty vehicle
ICCT	International Council on Clean Transportation
IHME	Institute for Health Metrics and Evaluation
I/M	Inspection and maintenance
INECC	*Instituto Nacional de Ecología y Cambio Climático* (National Institute of Ecology and Climate Change)
LDV	Light-duty vehicle
MOVES	Motor vehicle emission simulator
NALS	North American Leaders Summit
NOM-016	NOM-016-CRE-2016
NOM-042	NOM-042-SEMARNAT-2003
NOM-044	NOM-044-SEMARNAT-2006
NOM-076	NOM-076-SEMARNAT-2012
NOM-086	NOM-086-SEMARNAT-SENER-SCFI-2005
NOM-EM-005	NOM-EM-005-CRE-2015
ORVR	On-board refueling vapor recovery
PEMEX	Petróleos Mexicanos
ppm	Parts per million
RSD	Remote-sensing device
RVP	Reid vapor pressure
SEMARNAT	*Secretaría de Medio Ambiente y Recursos Naturales* (Secretariat of the Environment and Natural Resources)
SENER	*Secretaría de Energía* (Secretariat of Energy)
USD	U.S. Dollar(s)
U.S. EPA	U.S. Environmental Protection Agency
UT	University of Tennessee
VOC	Volatile organic compound

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