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EVALUATION OF NEXT-PHASE GREENHOUSE GAS REGULATIONS FOR PASSENGER VEHICLES IN MEXICO

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EXECUTIVE SUMMARY

Mexico's national record of 1.6 million new cars and light trucks sold in 2016 is a boost to the industry and economy, but only increases the challenge of meeting Mexico's climate and energy goals (Iliff, 2017). As part of the Paris Agreement adopted at the 21st session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC), Mexico has committed to an ambitious 18% reduction in carbon dioxide (CO_2) emissions from the transport sector, specifically citing the need to "standardize environmental norms and regulations of the North American Free Trade Agreement for existing and new vehicles…" (México, 2015). Mexico's President Peña Nieto further clarified the government's intentions at the 2016 North American Leaders' Summit by committing Mexico to align greenhouse gas (GHG) standards with those of the United States and Canada out to 2025 (*Declaración*, 2016).

Mexico's Secretary of Environment and Natural Resources (SEMARNAT) is now working to develop the next phase of passenger vehicle standards, building off the current program aligned with U.S. standards. In 2013, SEMARNAT adopted NOM-163-SEMARNAT-ENER-SCFI-2013 (NOM-163), which set mandatory manufacturer fleet-average limits of CO_2 emissions from new light-duty vehicles for years 2014 through 2016. These standards were based on the 2012–2016 fuel economy standards developed by the U.S. Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA). In 2016, an agreement extended the 2016 standard to model year 2017.

To support the adoption of a strong regulatory package in Mexico, this report evaluates the costs and benefits of extending Mexico's program to 2025 by fully aligning with U.S. standards. EPA's Optimization Model for Reducing Emissions of Greenhouse Gases from Automobiles (OMEGA) was adapted to evaluate the cost of technology needed to meet these standards, taking into account the characteristics of Mexico's existing new light-duty vehicle fleet. This assessment goes further than EPA's technology assessment developed in support of the midterm evaluation of the second phase (2022 through 2025) of light-duty vehicle GHG standards by including a second technology package and cost dataset that encompasses even more recent research on emerging technologies, including cylinder deactivation, hybridization, lightweighting, and electric vehicles. This second dataset, developed by the ICCT, fully captures the falling compliance costs associated with emerging non-electric technologies that are expanding the internal combustion engine efficiency frontier.

Scenarios for adoption of EPA 2021 and EPA 2025 standards were based on full harmonization with EPA standards, including all credit provisions. For comparison, the costs and benefits of adoption of a 2021 standard proposed by the Association of the Mexican Automotive Industry (AMIA) were also evaluated, including full adoption of the proposed credit provisions.[1] This comparison clearly demonstrates the importance of regulatory design, especially concerning manufacturer flexibilities in the form of credits. Well-designed credits should offer the automakers flexibility to choose the lowest-cost option to comply with the standards while still producing real GHG reductions. The

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[1] EPA scenarios were evaluated using both technology packages and both cost assumptions: the high-cost case based on EPA's original technology packages and costs (EPA 2021 H and EPA 2025 L) and the low-cost case based on ICCT's update (EPA 2021 L and EPA 2025 L). The AMIA scenario was evaluated using only EPA's original technology packages and costs.

EPA program allows automakers credit for the adoption of technologies that will result in real GHG savings (and, in many cases, fuel economy savings) that are not apparent on the official test cycle. Credit programs that are poorly designed simply weaken the standards without achieving real GHG or fuel economy benefits.

The most stringent scenario, adoption of the full EPA regulatory program out to 2025, would achieve a model year 2025 fleet-average test cycle fuel economy of 22 km/liter and emissions of 108 gCO_2/km, with fleet-average costs per vehicle between $1,153 and $1,821, similar to the anticipated costs in the rest of the North American market. Adoption of 2025 standards could reduce fleet-average energy consumption on the test cycle by 28% from 2016 levels. Considering the additional improvements made to reduce emissions off the test cycle and to reduce GHG gases from air conditioning refrigerants, this would represent a 38% reduction in fleet-average GHG emissions with respect to 2016.

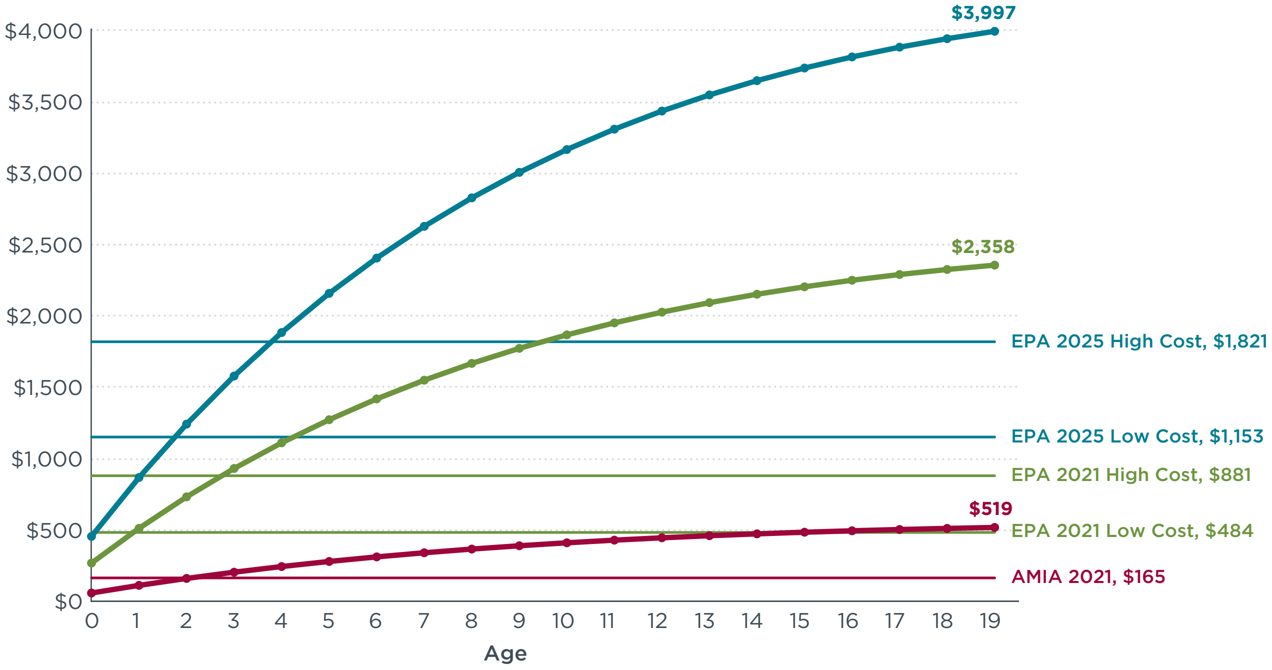

Figure ES1. Consumer payback of potential 2021 and 2025 standards.

As seen in Figure ES1, the average new vehicle sold in 2025 would save consumers $4,000 (72,000 MXN) over 20 years, equivalent to 2.2 to 3.5 times the cost of additional vehicle technology, with net savings of $2,000 to $3,000.[2] And even more substantial benefits to society are possible. Accounting for both the fuel savings and the climate benefits, the savings to society for a single model year (2025) would be 6 billion to 11 billion USD, with cumulative benefits from model years 2018 through 2025 on the order of 25 billion to 50 billion USD.

The technology projections show that the technology changes needed to reach the most ambitious targets will depend largely on improvements to the internal combustion engine—including the adoption of turbocharged and downsized GDI (gasoline

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[2] Considering a fuel price of 0.83 USD/liter (14.9 MXN/liter at an exchange rate of 18 MXN = 1 USD) and a discount rate of 7%, and accounting for the ~20% gap between real-world and test-cycle fuel economy.

direct injection) engines and high-compression Atkinson-cycle engines, with further improvement of technologies such as cylinder deactivation—as well as more efficient transmissions. Even under the most stringent scenario considered, only minimal amounts of electrification of the powertrain would be needed. Looking out to 2025, full harmonization with EPA standards would require full electrification of 1% to 3% of the Mexican fleet, involving only a few vehicle segments. While start-stop systems and mild hybrids have very low penetration rates across most scenarios, the highly congested traffic of Mexico City might drive higher rates of deployment for these options than are forecast in this analysis.

Stringent standards for passenger vehicle GHG emissions will help meet Mexico's climate goals and increase energy security, and will have tremendous benefits for consumers and society alike. Aligning standards with the rest of North America builds off the well-integrated vehicle market and the shared elements of regulatory design already in place. As the rapid pace of technology improvement brings costs down, it is clear that Mexico will benefit from the adoption of long-term, stringent standards, which should also enable the Mexican auto industry to remain competitive in other regulated or fuel price–sensitive markets. This analysis demonstrates the potential to dramatically reduce fuel consumption and GHG emissions from the light-duty vehicle fleet in Mexico, with clear and substantial savings for consumers and benefits to society. Careful regulatory design is critical to ensure that regulatory goals are achieved and consumer benefits are realized.

TABLE OF CONTENTS

Executive summary i

Introduction 1

1. Mexico’s passenger vehicle market 3

- Data sources 3
- Mexican fleet overview, model year 2012 3
- Comparison of Mexican and U.S. passenger vehicle fleets 5

2. Scenarios analyzed 10

- Compliance flexibilities 12
- Accounting for unproductive credits 16

3. Methods for OMEGA modeling and payback analysis 19

- OMEGA model structure 19
- OMEGA model applied to Mexico’s fleet 24
- Methods for payback analysis 26

4. Results of OMEGA modeling and payback analysis 32

- Technology deployment 32
- Cost per vehicle in 2021 and 2025 36
- Fleet-average costs and benefits of all scenarios 40
- Results of payback analysis 42

5. Conclusions 47

Acronyms and abbreviations 49

References 51

Annex A: Technologies projected by OMEGA 53

Annex B: Example technology packages 55

LIST OF TABLES

Table 1. Mexican fleet sales data, model year 2012 vehicles sold in calendar years 2011 to 2014. 4

Table 2. Mexico and U.S. light-duty vehicle (PV and LT) fleet characteristics, model year 2012 (EPA, 2015a; INECC, 2015) 6

Table 3. Scenarios and years evaluated with OMEGA. 10

Table 4. Credits applied under different scenarios. 17

Table 5. List of technologies to be adopted for reaching GHG/FE targets. 22

Table 6. EPA cost/benefit estimates for type 2 compact car, I4 DOHC/SOHC 4v 23

Table 7. CO_2 emission targets used for OMEGA modeling of NOM-163 target scenarios 25

Table 8. Impact of discount rate, mileage, and fuel price assumptions on consumer payback period. 29

Table 9. Social cost of carbon values in 2016 USD 31

Table 10. Weight reductions by scenario: cars, light trucks, and fleet. 36

Table 11. Cost to meet AMIA 2021 targets compared with NOM-163 2016 (2016 USD). 37

Table 12. Costs to meet proposed EPA 2021 targets in Mexico with respect to 2016 targets—high costs (2016 USD). 38

Table 13. Costs to meet proposed EPA 2021 targets in Mexico with respect to 2016 targets—low costs (2016 USD). 39

Table 14. Costs to meet proposed EPA 2025 targets in Mexico compared to 2021 targets—high costs (2016 USD). 40

Table 15. Costs to meet proposed EPA 2025 targets in Mexico compared to 2021 targets—low costs (2016 USD). 40

Table 16. Technology penetration and costs to meet potential 2021 standards 41

Table 17. Technology penetration and costs to meet potential 2025 standards 42

Table 18. Sensitivity of net benefits to climate and discounting assumptions for a single model year's fleet. 45

Table 19. Range of net benefits for a single model year (2021 and 2025) considering different regulatory targets. 46

LIST OF FIGURES

Figure 1. Fleet-average fuel economy and sales by manufacturer, model year 2012 vehicles sold in calendar years 2011 to 2014. 5

Figure 2. Fleet-average passenger vehicle fuel economy by manufacturer in Mexico and the United States, model year 2012. 6

Figure 3. Fleet-average light truck fuel economy by manufacturer in Mexico and the United States, model year 2012. 7

Figure 4. Passenger vehicle market share by manufacturer and for the overall fleet, model year 2012. 8

Figure 5. Fuel economy and vehicle footprint for models sold in Mexico but not in the United States or Canada, grouped by manufacturer 9

Figure 6. CO_2 emission targets for passenger cars. 12

Figure 7. CO_2 emission targets for light-duty trucks (SUVs and pickups). 12

Figure 8. Potential fleet-average test cycle CO_2 for the Mexican fleet under the current Mexican standard for model year 2017, EPA and NHTSA standards for model year 2017, and AMIA proposal for model year 2018 14

Figure 9. Modeled use of credits, including both productive credits (with real GHG benefits) and unproductive credits. 18

Figure 10. OMEGA model general structure and information flow. 20

Figure 11. Average annual distance traveled by vehicle age. 27

Figure 12. Current and projected gasoline price in the United States and Mexico 28

Figure 13. Technology penetration by scenario for the car, truck, and total fleet in Mexico. 32

Figure 14. Market share of turbocharged and downsized GDI engines by vehicle segment 33

Figure 15. Market share of advanced powertrain technologies (hybrids and EVs) by segment 35

Figure 16. Consumer payback of potential 2021 and 2025 standards 43

Figure 17. Net benefits to society of regulatory targets for model year 2021 and 2025 vehicles (2016 USD). 44

INTRODUCTION

This report is intended to help the Secretary of Environment and Natural Resources (SEMARNAT) analyze the next steps for passenger vehicle CO_2 emissions and efficiency standards for Mexico. NOM-163-SEMARNAT-ENER-SCFI-2013 set mandatory manufacturer fleet-average emission limits for CO_2 from new light-duty vehicles for model years 2014 through 2016 (DOF, 2013). In 2016, SEMARNAT published a notice extending the 2016 limits to also cover model year 2017 (DOF, 2016).

The NOM-163 regulation was built upon the U.S. fuel economy and greenhouse gas (GHG) standards adopted by the Environmental Protection Agency (EPA) and the Department of Transportation's National Highway Traffic Safety Administration (NHTSA). As that program draws to a close, SEMARNAT is working to develop the next phase of the regulatory program.

SEMARNAT expects to build off the current program and to continue to use U.S. standards as the regulatory model, including adoption of the U.S. regulatory test cycles and size-based regulatory design. To more fully align with the United States, the new standards would regulate CO_2-equivalent emissions, accounting for nitrous oxide (N_2O), methane (CH_4), and hydrofluorocarbons and other gases used as air conditioning refrigerants. Greater alignment is also expected around the regulatory time scale (U.S. standards extend to 2025), credit banking and trading, standard curves, and credit design.

The U.S. standards included a provision for a midterm review of the 2022–2025 standards to ensure that the stringency matched the updated understanding of technology potential and costs. In the Draft Technical Assessment Report, a joint report published by EPA, NHTSA, and the California Air Resources Board in July 2016, the agencies found that the pace of technology innovation is far more rapid than expected and that standards can be met at a lower cost than anticipated in the 2012 Regulatory Impact Assessment (EPA/NHTSA/CARB, 2016a). On the basis of these findings, EPA moved quickly to finalize the regulations for model years 2022 through 2025 as they had been originally proposed, issuing a Final Determination on standards in January 2017. The new administration has pledged to revisit this decision, with the intention to meet the original deadline of April 2018 for issuance of the final determination of model year 2022–2025 standards by EPA and final adoption by NHTSA.[3]

This analysis uses and adapts the latest version of the Optimization Model for Reducing Emissions of Greenhouse Gases from Automobiles (OMEGA) version 1.4.56, updated most recently to support the technical assessment for the midterm review (U.S. EPA, 2016). OMEGA was developed by EPA to evaluate the costs and benefits of and set appropriate stringency for GHG standards for passenger vehicles. OMEGA evaluates the relative costs and effectiveness (CO_2 emission reduction) of vehicle technologies and applies them to a defined vehicle fleet to meet a specified CO_2 emissions target. To support SEMARNAT's regulatory program, the ICCT adapted OMEGA for use in Mexico and applied the model to evaluate options for the next phase of GHG standards.[4]

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[3] See EPA's overview of all regulatory documents and steps covering the Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas (GHG) Emissions Standards for Model Years 2022–2025 at www.epa.gov/regulations-emissions-vehicles-and-engines/midterm-evaluation-light-duty-vehicle-greenhouse-gas-ghg.

[4] NHTSA uses the CAFE Compliance and Effects Modeling System, also known as the Volpe model, to calculate the costs and benefits of U.S. passenger vehicle fuel economy standards. The ICCT chose to use OMEGA rather than the Volpe model because of its ability to more fully integrate GHG credits and a CO_2-equivalent approach.

However, EPA's technology assumptions used as inputs in OMEGA version 1.4.56 did not include all the latest developments in this fast-changing market. To help inform the next phase of fuel economy standards in the United States, the ICCT had undertaken a study of emerging vehicle efficiency technologies and their emission benefits and costs in the 2025–2030 time frame (Lutsey et al., 2017). The analysis was focused on providing an update to the U.S. midterm evaluation regulatory analysis for new 2025 vehicles, as well as estimating the potential and cost of continued improvements through 2030. The analysis builds on the OMEGA technology inputs, updating technology costs and benefits according to the latest research on emerging technologies, including cylinder deactivation, hybridization, lightweighting, and electric vehicles. These updates draw upon peer-reviewed literature, simulation modeling, and auto industry developments.

The ICCT's analysis indicates that 8% to 10% greater efficiency improvement in internal combustion engines is available and will be cost-effective for vehicles by 2025, relative to the improvements reflected in OMEGA's technology data (Lutsey et al., 2017). Continual improvement of technologies such as cylinder deactivation, high-compression Atkinson-cycle engines, lightweighting, and mild hybridization will allow internal combustion to dominate automakers' strategies for complying with adopted 2025 standards. At the same time, technology costs continue to decrease, demonstrating that previous estimates—including those made by EPA—have been too conservative. State-of-the-art engineering studies and emerging supplier technology developments indicate that by 2025, costs for lightweighting, direct injection, and cooled exhaust gas recirculation will be reduced by hundreds of dollars per vehicle, and electric vehicle costs will drop by thousands of dollars per vehicle. Including these latest efficiency developments, the ICCT estimates that compliance costs for the adopted U.S. 2025 standards will be 34% to 40% lower than projected in the latest U.S. midterm evaluation regulatory analysis (Lutsey et al., 2017).

This report assesses the costs and benefits of harmonization with EPA standards for 2021 and 2025 using the original technology cost curves incorporated into EPA's OMEGA model as well as the cost curves developed by the ICCT that incorporate the accelerate pace of technology development currently under way in the automotive industry. By way of comparison, we also assess the costs and benefits of a proposal by the Mexican automakers' association.

This report describes in detail how this assessment was done, starting with the CO_2 performance and fleet characteristics of the 2012 passenger vehicle fleet in Mexico (the most recent complete database available when this analysis was begun). The report is structured as follows: Section 1 provides an overview of Mexico's new passenger vehicle fleet in 2012; section 2 explains the scenarios for consideration using the OMEGA model; section 3 presents the methodologies for adapting the OMEGA model to Mexico's fleet and calculating the costs, benefits, and payback of next-phase standards; section 4 presents the results of the OMEGA modeling and payback analysis; and section 5 interprets the implications of this analysis for the next phase of passenger vehicle GHG standards in Mexico.

1. MEXICO'S PASSENGER VEHICLE MARKET

To evaluate the costs and benefits of GHG standards in the Mexican passenger vehicle market, an understanding of the baseline vehicle fleet is required. The first phase of this project was to fully develop the passenger vehicle database with all the inputs required to run OMEGA and evaluate the results. The original database, developed in conjunction with the National Institute of Ecology and Climate Change (INECC), contained basic vehicle characteristics by model version, such as engine displacement, number of cylinders, and fuel type, along with the most critical inputs to OMEGA: the vehicle size or footprint (length x width), the technologies already installed on the baseline fleet, rated power and vehicle weight used to calculate power-to-weight ratios, and the CO_2 emissions and/or fuel consumption values from laboratory testing. The ICCT worked with the 2012 calendar year database because it was the most complete set of sales information available when the work began.

DATA SOURCES

The light-duty vehicle database used for the OMEGA analysis of NOM-163 was built from a basic vehicle database for calendar year 2012 provided by INECC for this analysis. The basic calendar year 2012 database contained information on vehicle features (model name, number of cylinders, transmission, etc.), fuel economy information (km/liter and CO_2 emissions), and sales data. The ICCT improved this basic database by adding information on fuel efficiency technologies to each of the 767 model variants available on the basic database. In that step, the ICCT identified which models had already adopted fuel efficiency technologies such as gasoline direct injection (GDI), turbochargers, start-stop systems, and electrically operated power steering systems. This additional information on technology was required as an input for OMEGA analysis.

For the OMEGA analysis, we used only the model year 2012 vehicles reported to have been sold during calendar year 2012. These numbers are equivalent to about 90% of all model year 2012 sales, because model year 2012 vehicles were also sold in calendar years 2011, 2013, and 2014.

MEXICAN FLEET OVERVIEW, MODEL YEAR 2012

Table 1 presents an overview of the Mexican light-duty fleet and market share by brand for model year 2012, including data for model year 2012 drawn from calendar years 2011 to 2014. For model year 2012, the seven largest manufacturers by sales cover 95% of the Mexican market; all of them are also present in the U.S. market. Renault[5] and Peugeot, with market shares of 0.7% and 0.5%, respectively, are the only manufacturers listed that are not represented in the U.S. market. Moreover, many manufacturers that sell in both markets have individual brands (such as Volkswagen's SEAT brand) or major-selling models (such as Toyota's Avanza) that are not offered in the U.S. market.

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[5] Renault is in a strategic alliance with Nissan but maintains a separate ownership structure.

Table 1. Mexican fleet sales data, model year 2012 vehicles sold in calendar years 2011 to 2014.

Manufacturer	Sales, model year 2012	% Sales	% Cumulative share
Nissan	326,030	31.7%	31.7%
General Motors	167,820	16.3%	48.0%
Volkswagen	165,262	16.1%	64.1%
Ford	101,980	9.9%	74.0%
Fiat Chrysler	100,636	9.8%	83.8%
Toyota	63,493	6.2%	90.0%
Honda	54,158	5.3%	95.3%
Daimler	12,042	1.2%	96.4%
BMW	11,836	1.2%	97.6%
Suzuki	10,733	1.0%	98.6%
Renault	7,676	0.7%	99.4%
Peugeot	5,204	0.5%	99.9%
Jaguar Land Rover	1,044	0.1%	100.0%
Subaru	283	0.0%	100.0%
Total	**1,028,197**	**100%**	**100.0%**

The manufacturers that focus exclusively on luxury brands have a relatively low market share: BMW, Daimler (Mercedes-Benz), and Jaguar Land Rover.[6] However, the manufacturer with the third highest market share for model year 2012, Volkswagen, also markets many luxury brands, including Audi, Porsche, Bentley, and Lamborghini.

Figure 1 shows sales and fleet-average fuel economy (km/liter) for all manufacturers with more than 5,000 vehicles sold, accounting for 99.9% of the market. The three largest manufacturers (accounting for 64% of the market share) all have relatively strong fuel economy.

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[6] At 0.1% or less of the market, Jaguar Land Rover and Subaru are not included in the results by manufacturer but are accounted for in the fleet-average costs.

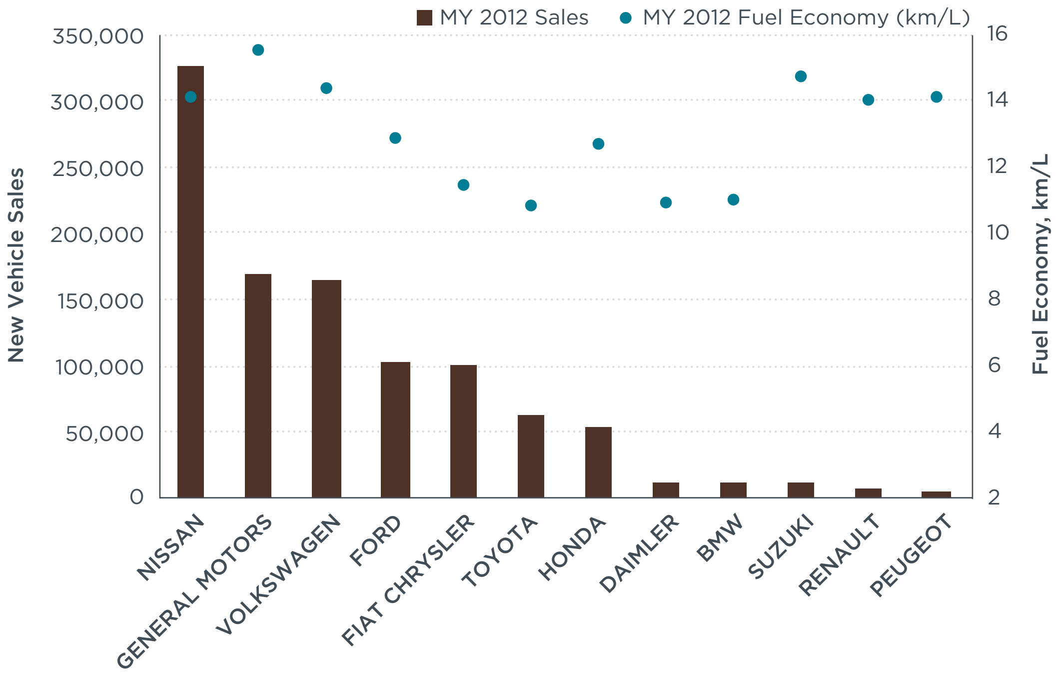

Figure 1. Fleet-average fuel economy and sales by manufacturer, model year 2012 vehicles sold in calendar years 2011 to 2014.

COMPARISON OF MEXICAN AND U.S. PASSENGER VEHICLE FLEETS

Given that one of the overall objectives of this project is to assess the costs and benefits of harmonizing the second phase of the Mexican NOM-163 regulation with the EPA vehicle GHG standards, a comparison between the fleet performances is relevant. This section compares the fuel economy for both fleets by manufacturer, the relative shares of cars and trucks in both markets, and basic fleet-average vehicle characteristics.

Table 2 shows an overview of the main vehicle characteristics of the Mexican passenger vehicle (PV) fleet compared to the U.S. fleet, with data taken from the EPA Trends Report (U.S. EPA, 2015a). As can be seen, the model year 2012 Mexican fleet was 24% lighter and 11% smaller on average than the U.S. fleet, with 30% lower engine power. The differences in weight, power, and size, however, are not fully reflected in terms of CO_2 emission reductions or fuel economy, which was only 5% better in Mexico. The extensive literature on the effect of vehicle mass and power on fuel consumption shows that a 20% reduction in mass alone would yield a fuel consumption decrease of about 7% under the same testing conditions; a 20% reduction in both mass and power would yield a fuel consumption decrease of 12% to 14% (NRC, 2011). The primary reason for such misalignment in the Mexican fleet is differences in vehicle technology; that is, the average new vehicle in Mexico lacks the fuel efficiency technology available to vehicles in the U.S. market.

Table 2. Mexico and U.S. light-duty vehicle (PV and LT) fleet characteristics, model year 2012 (EPA, 2015a; INECC, 2015).

Fleet	Diesel share	Market share	Fleet-average weight (kg)	Fleet-average power (kW)	Fleet-average size (m²)	Fleet-average CO_2 emissions (g/km)	Fleet-average fuel economy (km/liter)
U.S. PV	1.0%	64%	1595	143	4.2	160.1	14.6
Mexico PV	0.2%	67%	1195	100	3.7	150.8	15.5
Mexico–U.S. difference			**−25%**	**−30%**	**−12%**	**−6%**	**+6%**
U.S. LT	0.7%	36%	2181	212	5.1	229.1	10.2
Mexico LT	5%	33%	1730	154	4.5	221.5	10.5
Mexico–U.S. difference			**−21%**	**−27%**	**−12%**	**−3%**	**+3%**
U.S. total	0.9%		1804	169	4.5	184.0	12.7
Mexico total	1.8%		1375	119	4.0	174.4	13.4
Mexico–U.S. difference			**−24%**	**−30%**	**−11%**	**−5%**	**+5%**

Figures 2 and 3 show the model year 2012 fuel economy of passenger cars and light trucks in the United States and Mexico. Toyota and BMW stand out for having higher fuel-economy performance in the United States than in Mexico for both car and truck fleets. In the United States, Toyota and BMW may offer models with more fuel economy technology installed relative to the vehicles sold in Mexico. The OMEGA results described below consider the extent to which manufacturers will have to incorporate technologies to reduce GHG emissions. These differences between the two countries may also reflect different marketing strategies. Manufacturers could potentially lower compliance costs of future standards in Mexico by changing marketing and sales strategies; however, OMEGA is not able to predict or optimize costs with respect to specific manufacturers' marketing and fleet mix strategies. As a result, this analysis assumes that no changes are made in the models or types of vehicles offered.

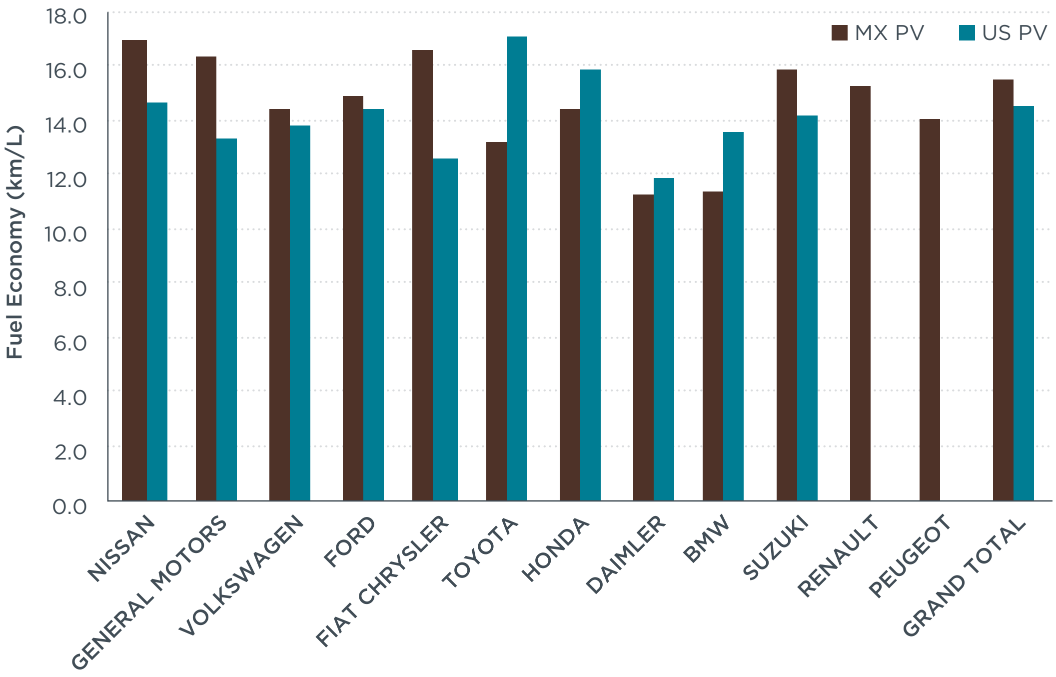

Figure 2. Fleet-average passenger vehicle fuel economy by manufacturer in Mexico and the United States, model year 2012.

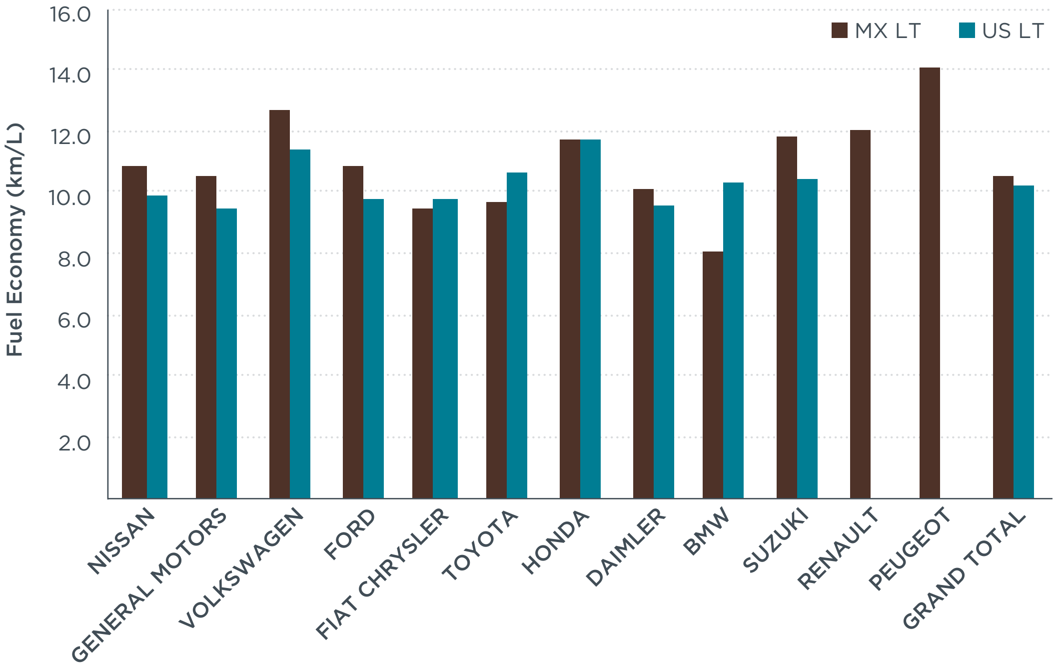

Figure 3. Fleet-average light truck fuel economy by manufacturer in Mexico and the United States, model year 2012.

The overall CO_2 fleet emissions depend on the market share of passenger cars versus light trucks (e.g., Ford F-150 or Chevrolet Silverado). Figure 4 shows a description of the fleet composition, focusing on the PV fleet share, for the United States and Mexico. It is evident that the Mexican and U.S. fleets are very similar with respect to the total share of passenger cars. Most manufacturers offer similar product lines and have a similar sales mix, although there is variation among manufacturers. Passenger vehicles make up nearly 90% of GM and BMW sales, a much higher proportion than their passenger vehicle sales mix in the United States; light trucks constitute more than 60% of Toyota and Honda sales, also a substantial difference from the U.S. sales mix for those companies. This should not be an important factor in the feasibility of manufacturer compliance with aligned standards in Mexico because the targets for light trucks are less stringent than for cars, as explained in detail below.

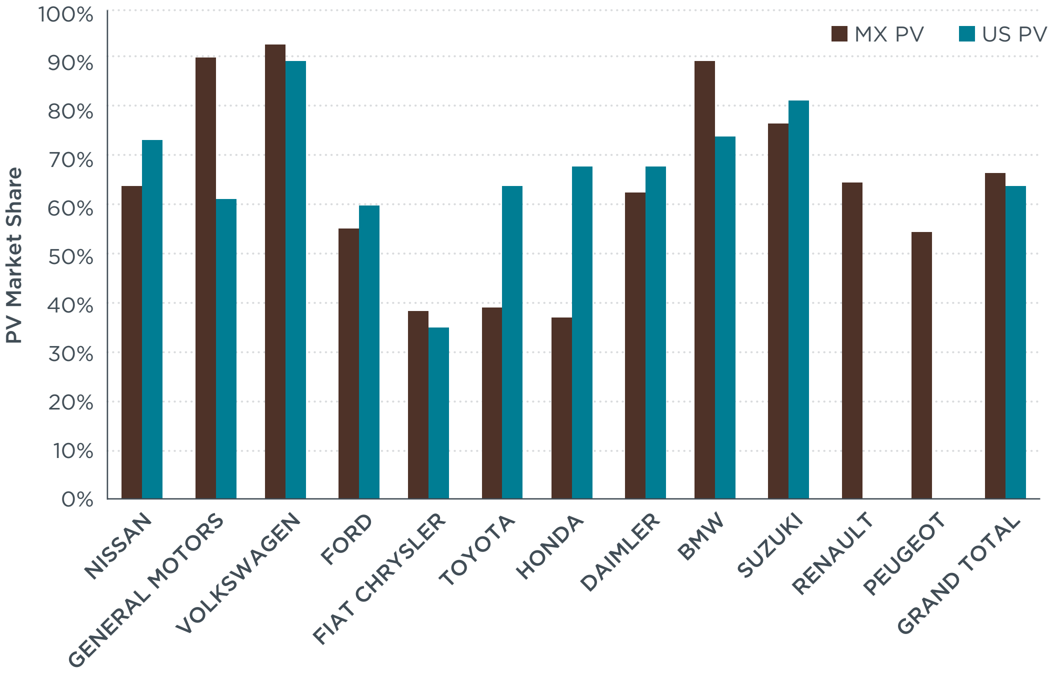

Figure 4. Passenger vehicle market share by manufacturer and for the overall fleet, model year 2012.

Although there are a few manufacturers and brands that are not sold in the U.S. market, several of the brands that are well-represented in the United States also supply specific vehicle models to Mexico that are not available in the U.S. market. Many models are branded differently in Mexico (for example, Nissan's Frontier is the NP300 in Mexico) and the version available in Mexico may contain less fuel efficiency technology and, potentially, less safety and emissions control technology. Nonetheless, as redesigns for comparable vehicle models sold in the United States will incorporate technologies required by the U.S. fuel economy and GHG standards, more efficient versions could easily be phased into the Mexican market as well. In addition, although the U.S. and European standards are designed differently, many of the more popular vehicles in the Mexican market that are not available in the United States will have to meet European CO_2 standards, which require a similar level of stringency. For manufacturers with models and brands not sold in the United States or Europe, more effort may be required to meet the standards, potentially including increasing the fuel economy of particular models, increasing sales of the most fuel-efficient models, or phasing out certain models from the Mexican market.

The ICCT's fleet analysis of vehicle models sold in Mexico in 2012 shows that 10% of the vehicles sold in Mexico during that year had no equivalent model in the U.S. or Canadian markets. Figure 5 shows the fuel economy and vehicle size of the models without U.S. or Canadian analogs, with each bubble representing a particular model and the bubble size representing sales in 2012.[7] In past years, this included small, efficient cars such as the Dodge i10 (branded as Hyundai in other markets); however, this big seller in Mexico is now being imported into the Canadian market as well. Some of the less efficient models, such as the Toyota HiLux, HiAce, and Avanza models, are intended specifically for Latin

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[7] The sales information is from 2012, but we compared this to 2016 fleets in the United States and Canada.

American and developing-world markets. Although more than one-quarter of both Volkswagen's and Toyota's sales were vehicle models not sold in the United States, these Toyota models stand out for their poor fuel economy and may help explain why Toyota's fleet-average fuel economy is so much better in the United States than in Mexico.

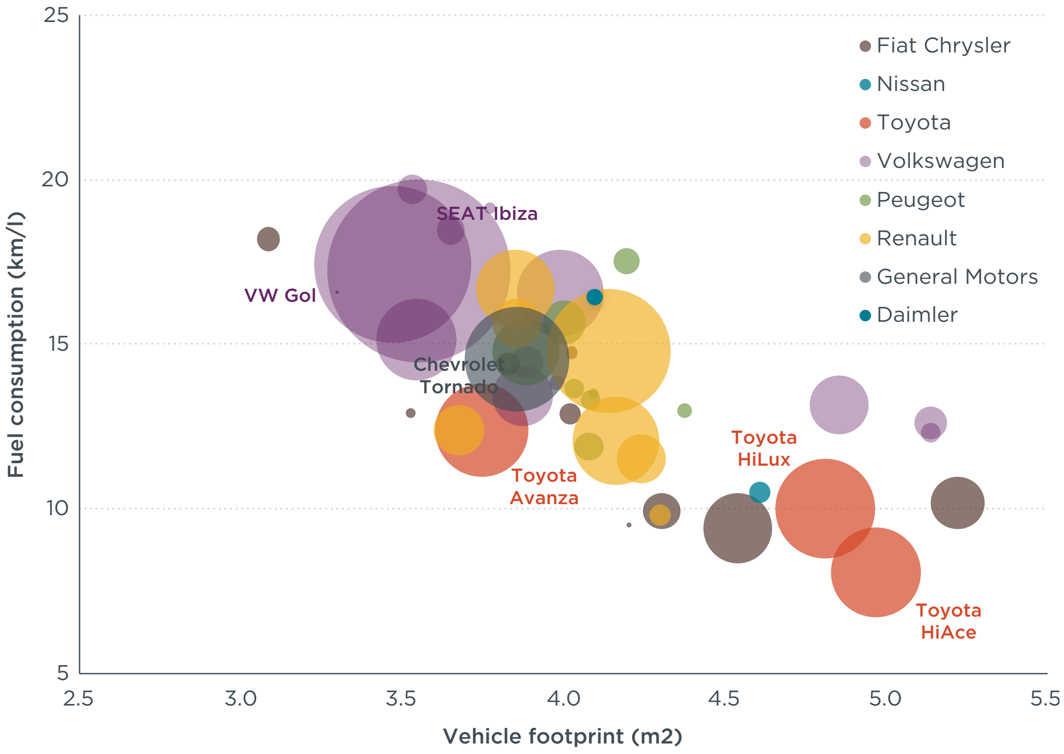

Figure 5. Fuel economy and vehicle footprint for models sold in Mexico but not in the United States or Canada, grouped by manufacturer. Circle diameter corresponds to relative sales volume during calendar year 2012.

2. SCENARIOS ANALYZED

The objective of applying OMEGA to the Mexican market was to gain a precise understanding of the vehicle technologies that would be required and the costs and benefits of different regulatory scenarios for the next phase of vehicle GHG standards in Mexico. The report compares two regulatory proposals, over two different time periods, with two different sets of cost and technology assumptions. In the end, five scenarios for future costs and benefits were considered: two different regulatory scenarios, one which was assessed with two cost scenarios, for meeting 2021 targets, and one regulatory scenario assessed with two cost scenarios for meeting 2025 targets (see Table 3).

The primary question concerned the costs and benefits of harmonization with U.S. standards. Two different technology packages and cost assumptions were used to assess the cost and impact of harmonization with EPA 2021 and 2025 GHG standards. The higher-cost results are based on EPA's original technology packages and costs (EPA 2021 H and EPA 2025 H); the lower-cost results are based on the ICCT's technology packages and costs update (EPA 2021 L and EPA 2025 L). As a point of comparison, we also assessed the costs and benefits that would accrue from adoption of a proposal made by the Mexican Association of the Automotive Industry (AMIA). As there was no longer-term proposal put forth, we assessed this proposal only for 2021, and because the costs were already so low, we considered only EPA's original technology and cost assumptions.

The EPA technology package and cost dataset was developed by EPA in 2016 and 2017 for the analysis supporting model year 2017 through 2025 light-duty vehicle GHG emissions and fuel economy standards development. The documentation was released in July 2016 in support of the Draft Technical Assessment Report and Proposed Determination, as part of the midterm evaluation of the second phase (2022 through 2025) of light-duty vehicle GHG standards (EPA/NHTSA/CARB, 2016a). The second technology package and cost dataset was the result of a 2017 update produced by the ICCT that incorporated new information on emerging technologies such as cylinder deactivation, hybridization, lightweighting, and electric vehicles (Lutsey et al., 2017). The updates included in ICCT's assessment were based on the research literature, simulation modeling, and auto industry developments.

EPA scenarios were based on full harmonization with EPA standards, including full credit provisions. The AMIA scenario included all credit provisions in the AMIA proposal. Our assumptions on credits are described in more detail below.

Table 3. Scenarios and years evaluated with OMEGA.

Scenarios analyzed from a baseline of NOM-163 implementation in 2016	Technology package and costs	Scenario	
AMIA proposal (2021 only)	EPA	AMIA 2021	—
Full harmonization with EPA standards (2021 and 2025)	EPA	EPA 2021 H	EPA 2025 H
	ICCT	EPA 2021 L	EPA 2025 L

OMEGA was used first to assess the cost and efficiency starting point of full implementation of NOM-163 in 2016. As the baseline, the costs associated with this scenario are subtracted from the 2021 scenario costs (AMIA 2021, EPA 2021 H, and EPA 2021 L). In this way, the baseline scenario represents the starting point for future regulations, and the costs and benefits of this scenario are not assessed further in this document. In the same way, evaluations of the cost associated with meeting EPA 2025 targets (EPA 2025 H and 2025 L) are referenced with respect to the corresponding EPA 2021 targets (EPA 2021 H and EPA 2021 L). This approach was followed by the EPA for the 2025-rule analysis, in that EPA assumed that in the absence of the model year 2021 GHG/FE standards, the fleets for model year 2021 would have fleetwide emissions no better than what is projected to be necessary to meet the model year 2016 GHG/FE targets; in the absence of model year 2025 GHG/FE standards, the model year 2025 fleet would have to meet model year 2021 targets.

The regulatory scenarios assessed include:

- **AMIA 2021**, a scenario based on the proposal developed by the Asociación Mexicana de la Industria Automotriz for GHG standards for model years 2018 through 2021, is analyzed for the year 2021. The AMIA proposal sets 2021 tailpipe targets similar to the NHTSA fuel economy targets for 2020 in the United States, but with stringency reduced by 1% for cars and 2% for light trucks, slight adjustments to the regulatory curves that further reduce stringency, and the addition of credits for air conditioning refrigerants and technologies outside of what is allowed and included in the NHTSA rule (AMIA, 2016). As discussed below, refrigerant credits incorporated into the AMIA proposal are specifically excluded in the NHTSA program because NHTSA only regulates fuel economy. EPA's program, based on GHG emissions, increased the stringency of the tailpipe targets to account for the added flexibility given with refrigerant credits.
- **EPA 2021 L and 2021 H** and **EPA 2025 L and 2025 H** are a set of scenarios based on full harmonization with EPA standards. For the full harmonization scenarios, the EPA 2021 and EPA 2025 standards are assumed here to be implemented in Mexico in the same year as in the United States. Note that adopting the numerical standard 1 or 2 years later would result in lower costs as technologies enjoy cost reductions due to manufacturing improvements and learning. Therefore, the costs could be considered representative, although conservative, if the standards were implemented at a later date. The EPA scenarios include all manufacturer flexibilities available through the EPA program, such as air conditioning (AC) efficiency and refrigerant credits, off-cycle credits, and incentive multiplier credits for electric-drive technologies. Multiplier credits for electric-drive technologies were eliminated after 2021, as under EPA's standards.

The CO_2 standard curves used for each of the scenarios, covering the baseline and proposed target scenarios, are shown in Figures 6 and 7 for cars and light trucks, respectively. Note that the figures contain only the CO_2 curves for emissions on regulatory test cycles and do not show manufacturer flexibilities. The credits available to manufacturers have an important impact on standard stringency. An indication of how the credits can influence standard stringency is shown in Figure 8.

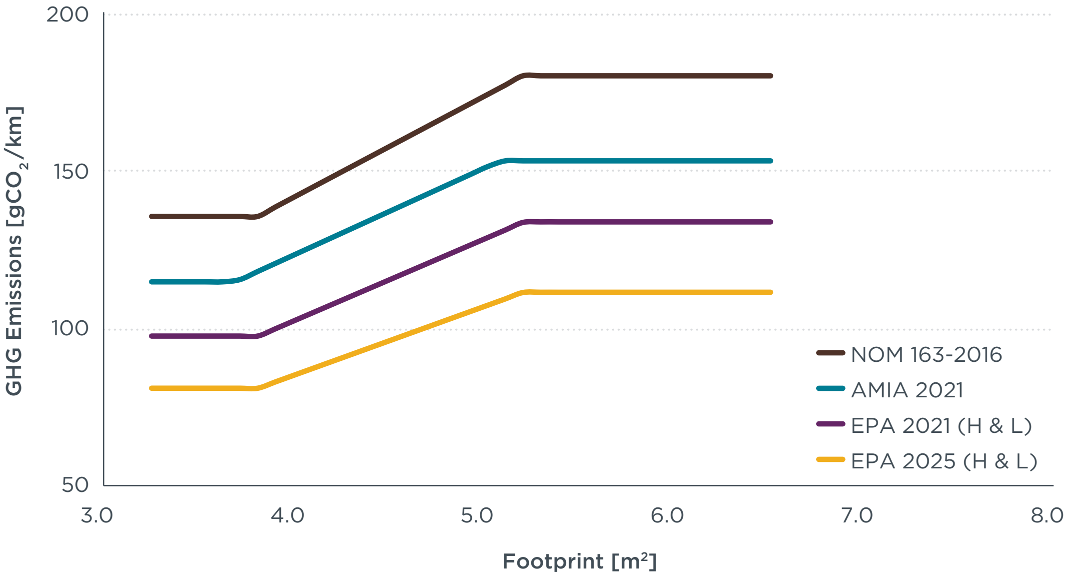

Figure 6. CO_2 emission targets for passenger cars.

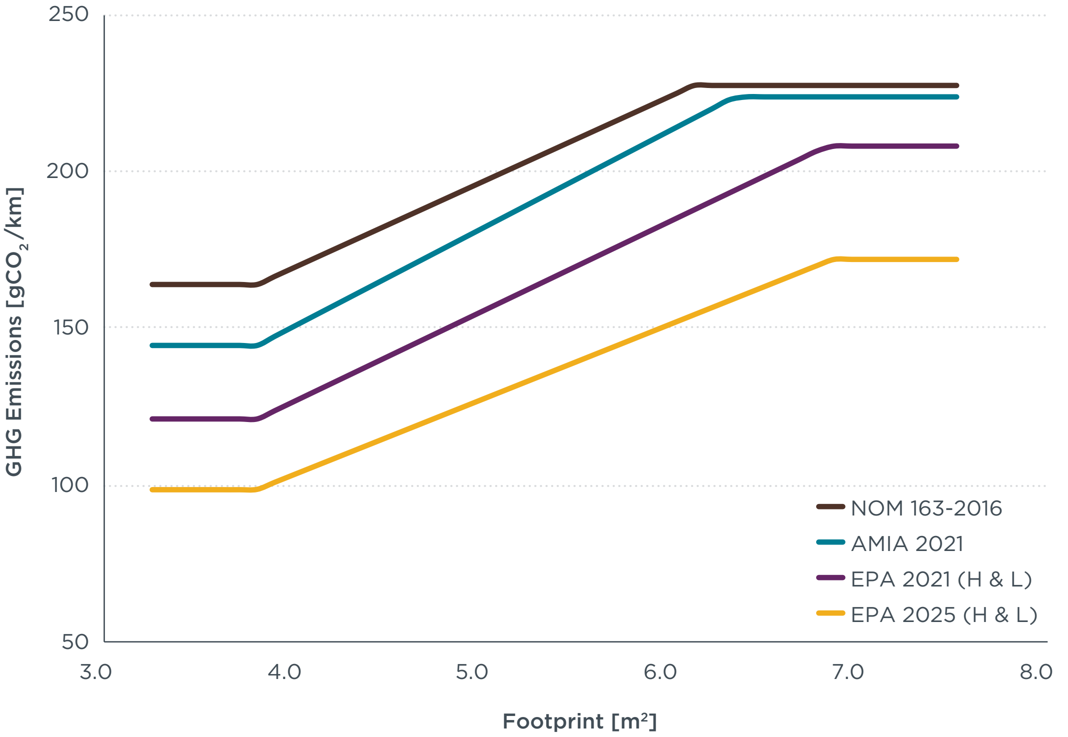

Figure 7. CO_2 emission targets for light-duty trucks (SUVs and pickups).

COMPLIANCE FLEXIBILITIES

The curves alone do not tell the whole story, however. Figure 8, which demonstrates how different standards and proposals would look in subsequent years (2016 and 2017), illustrates the importance of manufacturer flexibilities under different regulatory programs and proposals. In Figure 8, the test cycle limit value shows the fleet-average emissions on the regulatory test cycle required by the regulatory targets. If manufacturers were to use all the regulatory flexibilities offered, the CO_2 emissions allowed on the test cycle would be substantially higher. If credit flexibilities are well designed, using the credits will offer off-cycle GHG benefits that will reduce the real GHG emissions by approximately the same amount as the credits offered. And manufacturers will only make use of credits if the adoption of these technologies is cost-effective; in other words, the incorporation of an off-cycle technology and use of the credit will allow them to save money by not adopting a more costly technology that can reduce emissions on the test cycle. If credits are poorly designed, they reduce stringency without requiring additional technology investments and without achieving overall GHG benefits. We refer to these as unproductive credits.

As shown in Figure 8, only technology credits and a small amount of refrigerant credits are provided in the baseline scenario, NOM-163 2016, which was extended to also cover 2017 and is taken here as the 2017 baseline. Once credits are taken into account, it becomes clear that AMIA proposes a less stringent standard for 2018 than the regulatory standard in place for 2016 and 2017. Considering only the CO_2 standard curves, the AMIA proposal would result in a 5% reduction in fleet-average CO_2-equivalent emissions in 2018 relative to NOM-163. However, the greatly expanded credits proposed by AMIA would reduce the stringency to such a point that fleet-average CO_2-equivalent emissions would be allowed to increase by 5% from one year to the next. Although the standard curves are based on NHTSA (with a 1% to 2% reduction in stringency), AMIA proposes more generous and mostly unproductive technology credits as well as the addition of refrigerant credits. Refrigerant credits, which have an impact on GHG emissions but not fuel economy, are specifically avoided under the NHTSA program; instead, NHTSA matches the overall stringency of the EPA program by offering less restrictive standard curves.

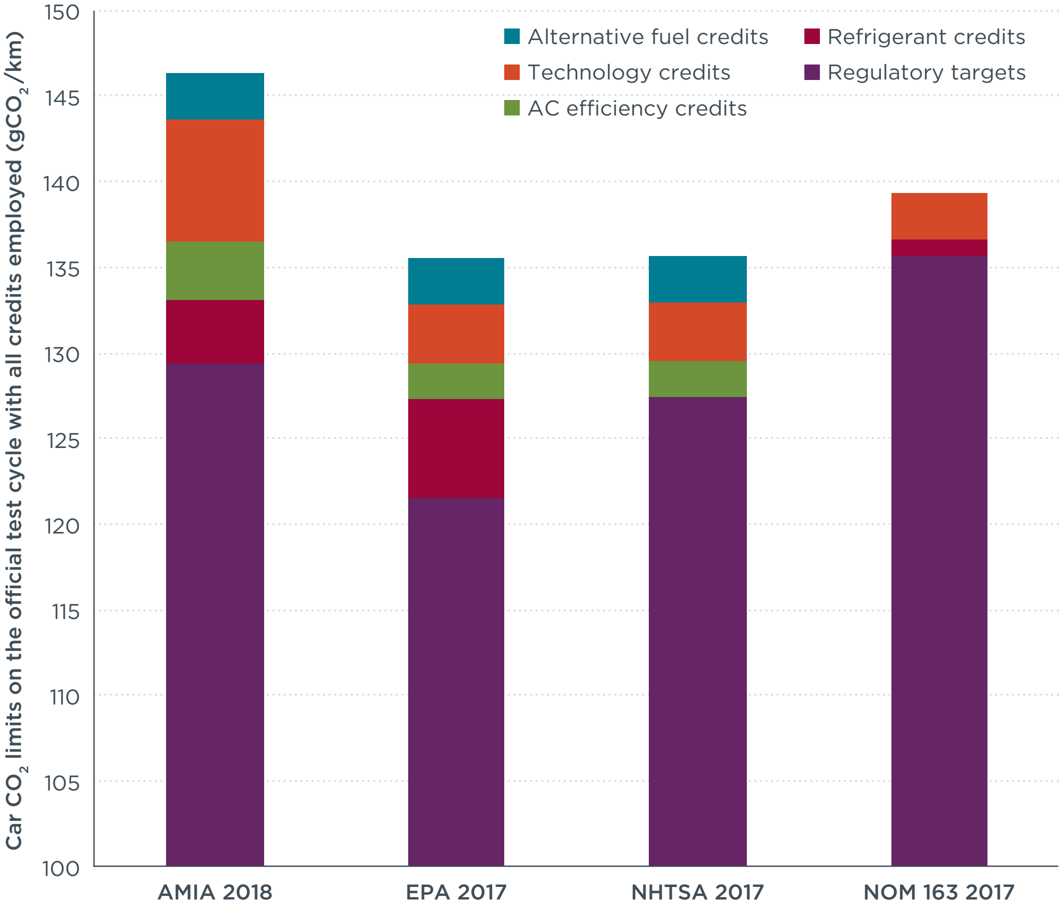

Figure 8. Potential fleet-average test cycle CO_2 for the Mexican fleet under the current Mexican standard for model year 2017, EPA and NHTSA standards for model year 2017, and AMIA proposal for model year 2018.

These flexibilities are intended to reduce the cost of compliance to manufacturers while still supporting actions to achieve the overall policy goal of GHG emission reductions. As some technologies will reduce GHG emissions in ways that cannot be fully captured by the official test cycle, credits are offered for incorporation of these technologies. Use of these credits reduces the need to reduce emissions on the regulatory test cycle but should leave overall GHG benefits unchanged. Productive credits are designed to have a neutral impact on overall fleet-average GHG emissions, while providing manufacturers flexibility in compliance pathways. Unfortunately, some of the credits proposed by AMIA do not provide any actual benefits and are essentially a direct reduction in stringency.

The types of credits applied in this analysis include refrigerant credits, AC efficiency credits, off-cycle credits, technology credits, advanced vehicle credits, and alternative fuel credits. These credits are primarily for technologies for which the full GHG benefits cannot be discerned on the official regulatory test cycles (the 2-cycle tests include a city and a highway drive cycle) but can be measured on the more comprehensive 5-cycle test procedures (which include aggressive driving, use of AC at high temperatures, and low-speed driving under cold conditions) or through other test procedures that would assess a real-world benefit of the technology. The types of credits are described below, with descriptions of how they were addressed in the modeling analysis.

Refrigerant credits include credits for use of refrigerants with substantially lower global warming potential (GWP) and credits for reducing leakage of refrigerants. The leading AC refrigerant in the market today, HFC-134a, is a potent GHG, and leakage can occur during vehicle operation and maintenance, making AC refrigerant an important component of the GHG emission reduction rule. Although HFC-134a is the default refrigerant sold in today's mobile air conditioning (MAC) systems, it will be banned in the United States starting in 2021.

As a clear example of an unproductive credit that does nothing to support the policy goal, AMIA's proposal offers credits for use of HFC-134a. AMIA's proposal and the other scenarios also include credits for lower-GWP refrigerants (such as HFC-1234yf or CO_2) and reduction of refrigerant leakage—two options that do offer substantial GHG benefits at a relatively low cost. Because HFC-134a will be banned for use in the United States starting in 2021, our modeling assumes that 100% of the market in Mexico will use the lower-GWP refrigerant, thus essentially phasing out this unproductive credit by 2021. Our Figure 8 assumptions were that 60% of the PV market share will use a lower-GWP refrigerant in 2017 (with a higher credit) and that the remainder will use the credit offered for the existing technology.

Air conditioning efficiency credits are for adoption of technologies that demand less energy, hence fuel, to operate with respect to conventional MAC systems. Such technologies include externally controlled variable- and fixed-displacement compressors, improved condensers, improved evaporators, improved blower controls, automatic recirculation systems, internal heat exchangers, and improved oil separators. The added efficiency benefits of more efficient AC systems, in terms of real-world CO_2 reductions, are not captured under official regulatory test cycles. Based on testing over a set of test cycles intended to measure the real-world impact of AC technologies, EPA and NHTSA offer credits based on per-vehicle adoption of specific technologies.

In applying the OMEGA model to the Mexican light-duty vehicle fleet, the AC credits adopted by EPA were also applied to the EPA-equivalent scenarios. In the case of the AMIA 2021 scenario, the AMIA proposal offers the maximum credit available for use of any single technology in the EPA technology menu. This approach overvalues the GHG benefits that would be expected under the AMIA proposal, as there would be no incentive for manufacturers to adopt multiple or more expensive technologies. Although based on the U.S. system, we consider the AC efficiency credits proposed by AMIA to be primarily unproductive credits.

Off-cycle credits are for adoption of technologies that can reduce GHG emissions of a vehicle in real-world driving but do not provide the same benefits in official 2-cycle compliance testing. Such technologies include more efficient lighting,[8] active or passive cabin ventilation, window glazing and paints that avoid heat build-up, engine idle start-stop systems, and active aerodynamics. EPA's standards provide a technology list, with varying per-vehicle credits provided for each type of technology that is adopted.

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[8] High-efficiency lighting offers a clear example of the need for off-cycle technology credits. The energy required for powering the vehicle lighting system, from headlamps to interior cabin lighting, comes from the electrical system that is powered by the alternator. This is powered by the rotation of the engine, which ultimately comes from combustion of the fuel in the tank. Fuel consumption can be reduced by improving the lighting efficiency, e.g., replacing halogen lights with LED technology. However, 2-cycle CAFE testing does not include turning on the vehicle lights during the test. This results in no measurable benefit during CAFE testing, although a benefit is expected under real-world driving, especially at night. Thus, additional testing and calculations are required to estimate the average fuel savings from such technology.

The credits are additive up to a maximum for the full fleet of 10 gCO_2/mile (6.21 gCO_2/km). For OMEGA modeling purposes, a GHG credit for start-stop technology and active aerodynamics improvements is included in the technology file.

Again, AMIA's proposal offers the maximum per-vehicle credit for use of any single technology on EPA's list, both eliminating any incentive to add additional efficient technologies and greatly overvaluing the GHG benefits adopted.

Technology credits. AMIA also proposes an additional technology penetration credit, which is another example of an unproductive credit, as the benefits of these technologies are measurable on the regulatory test cycles and as such are expected to be deployed to meet the standard in the first place, essentially allowing the manufacturers to double-count the GHG benefits provided by the technology.

Advanced vehicle credits are additional credits provided for plug-in hybrid, electric, and fuel-cell vehicles. As an added incentive to promote the adoption of these technologies, the electric portion for use of these vehicles is assigned 0 gCO_2/km, ignoring upstream emissions. And through 2021, there is an incentive multiplier for each vehicle deployed, also known as a super credit, which effectively counts a single vehicle as 1.3 to 2 vehicles. These are not captured in Figure 5 because they are unlikely to be used in the 2017 time frame.

The AMIA and EPA scenarios have virtually the same credit allowances for these vehicles, but it is highly unlikely that manufacturers would use these credits under the AMIA scenario, because OMEGA did not forecast the need for these vehicle types under AMIA's more lenient proposal. This analysis also did not account for the EPA credits for hybrid pickup trucks in the 2022–2025 time frame because of the difficulty in modeling this credit for the Mexican market. Although super credits and other examples of overvaluing the GHG benefits for crediting do serve a useful purpose in incentivizing emerging technologies (what EPA calls "game-changing" technologies), they do overvalue the GHG savings achieved and thus are included as unproductive credits in Table 4 and Figure 9.

Alternative fuel credits are credits for use of flex-fuel vehicles that can use ethanol. The AMIA proposal and EPA standards both include credits for these vehicles, but as they phase out by 2020, none of the modeling scenarios include these credits.

ACCOUNTING FOR UNPRODUCTIVE CREDITS

To accurately compare the scenarios, we needed to be able to account for which credits would add to the GHG benefits and which would simply reduce the standard stringency. Table 4 shows the actual credit values applied for all the modeled scenarios for both cars and light trucks and Figure 9 shows the share of productive and unproductive credits under each regulatory scenario. The "total modeled credits" row in Table 4 sums the credits applied to show how the fleet-average stringency was reduced in the OMEGA model. In order to calculate the GHG benefits of different scenarios, we also calculated the total GHG benefits estimated for each scenario, demonstrating the portion that can be considered unproductive credits. We consider much of the AMIA credits to be unproductive credits, in that manufacturers can gain access to the credits without using technologies that will achieve GHG benefits equivalent to the credit given.

The amount of credits used depends on technology deployment; our assumptions for credit use and technology deployment for all EPA scenarios were primarily taken from section 4.3.4 of the EPA Regulatory Impact Assessment Document (U.S. EPA, 2012). Although EPA assumptions are clearly conservative based on real-world technology deployment to date, this analysis leaves those assumptions unchanged, primarily because no solid cost data were available for many of the off-cycle technologies. These conservative assumptions result in conservative cost estimates, because deployment of these lower-cost alternatives and use of the credits is expected to be higher than estimated.

Under the AMIA program, we assumed full use of the credits. To estimate the GHG benefits associated with AMIA's proposal for off-cycle and air conditioning efficiency credits, we chose the lowest-cost technologies (solar reflective paint and oil separator, respectively) and used the EPA credit associated with that technology as the GHG benefit/productive portion of the credit. Any additional credit provided under the AMIA system was considered unproductive. Although this may underestimate the benefits that are actually achieved, it does provide a fair assessment of what manufacturers would do in the absence of other market factors. If more benefits accrue, we can safely say that this is a result of market integration with the United States and that any additional benefits are essentially free, enjoying the benefits without assuming the costs.

Other unproductive credits evaluated here are advanced technology credits proposed by AMIA, which double-count the benefits already measured during 2-cycle testing. We did not assess the light truck and SUV technology penetration credits offered by EPA, although we do consider them to be another example of unproductive credits due to double-counting of hybrid GHG/FE benefits. However, as a result of the sales minimums, it was too difficult to assess how they might be applied in Mexico.

Table 4. Credits applied under different scenarios.

	Cars			Light trucks		
Credits [gCO_2/km]	**AMIA 2021**	**EPA 2021**	**EPA 2025**	**AMIA 2021**	**EPA 2021**	**EPA 2025**
HFC-134a	2.1	Not applicable (NA)	NA	2.1	NA	NA
Advanced refrigerants	4.5	8.6	8.6	4.5	10.7	10.7
Efficient AC	3.4	3.1	3.1	3.4	4.5	4.5
Technology penetration	0.9	NA	NA	0.9	NA	NA
Off-cycle credits	6.3	0.5	0.9	6.3	0.9	2.7
Advanced vehicle credits (includes EVs)	0.0	0.1	0.2	0.0	0.0	0.0
Total modeled credits in OMEGA	15.1	12.2	12.7	15.1	16.1	17.8
Unproductive credits	10.0	0.1	0.2	9.8	0.0	0.0

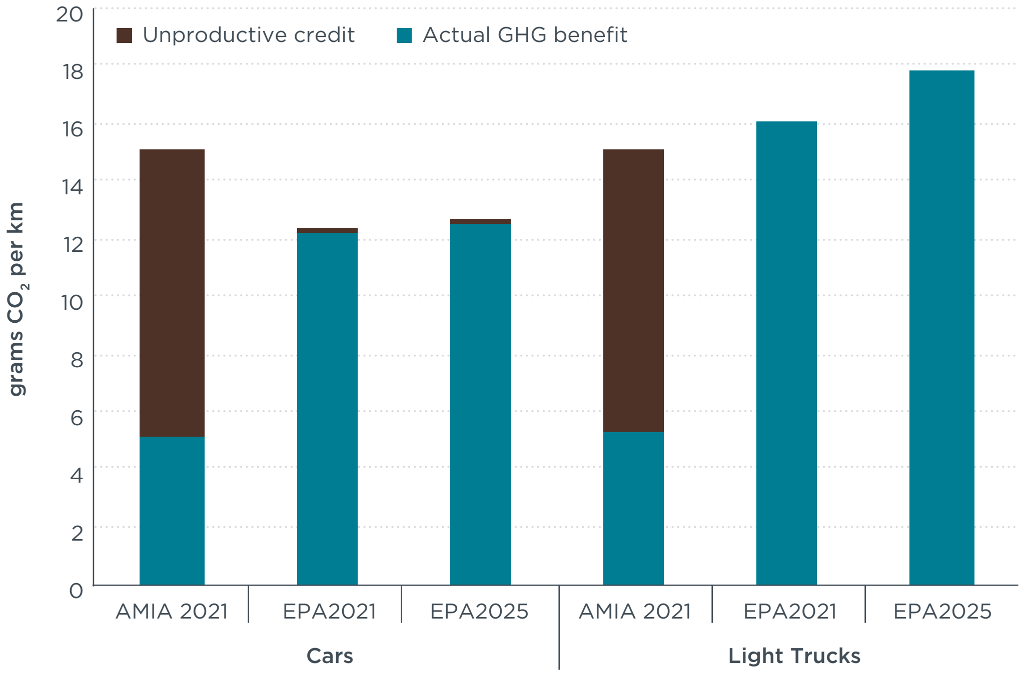

Figure 9. Modeled use of credits, including both productive credits (with real GHG benefits) and unproductive credits.

Although the scenarios incorporate and address technology credits, this analysis was not able to address credit banking and trading. Under the EPA program, manufacturers can trade between themselves and carry debits forward 3 years and credits for 5 years. This should reduce the costs further. As standards are phased in and become more stringent over time, the less stringent standards in the early years can increase the flexibility for manufacturers, while still requiring that they reach the overall goal for fleetwide efficiency.

3. METHODS FOR OMEGA MODELING AND PAYBACK ANALYSIS

This analysis applied EPA's OMEGA model to a Mexico baseline fleet to assess the costs and benefits of different regulatory scenarios. This section describes the methodology and model used in carrying out the analysis. OMEGA was developed by the EPA as a tool to evaluate the impact of the U.S. 2012–2016 GHG regulations for the light-duty vehicle fleet and was used again in the development and assessment of the 2017–2025 standards (U.S. EPA, 2012) and updated in 2016 for the midterm review analysis (U.S. EPA, 2016). We chose the OMEGA tool because SEMARNAT is committed to regulating GHG and not simply fuel economy. As such, the OMEGA tool has more flexibility and ability to incorporate refrigerant credits and other flexibilities than the NHTSA Volpe model, for example.

This analysis also took advantage of ICCT updates to the OMEGA model, which considered both emerging technologies and improvements in known technologies that yielded both reduced costs and improved GHG benefits.

Using both EPA and ICCT cost curves in the OMEGA model allows this analysis to capture a range of outlooks for vehicle and engine design under GHG standards in the 2017–2025 time frame consistent with EPA's original proposal. The two distinct technology cost curves include technologies that are applicable to various types of vehicles, along with the technologies' cost, effectiveness, and phase-in constraints. The OMEGA model uses this information to project how various manufacturers would apply the available technology to meet increasingly stringent CO_2 emission targets. The result is a description of the technologies that would need to be added to each vehicle platform, along with the resulting costs, to reach the CO_2 targets for various scenarios.

OMEGA is designed to apply technology in a manner similar to the way that a vehicle manufacturer might make such decisions (U.S. EPA, 2016). In general, the model considers these factors important to the manufacturer: the cost of the technology and the degree to which the technology moves the manufacturer toward achieving its fleetwide CO_2 emission target. OMEGA solves an optimization problem trying to find the lowest cost for each manufacturer while meeting the standard; this allows for some specific vehicle models to be overcompliant while others do not achieve the target, or cars may be overcompliant while trucks are undercompliant. As such, it is not necessarily useful to assess the outcomes by vehicle model. Instead, outputs should give a good understanding of the average costs by manufacturer or vehicle segment. OMEGA applies technology (subject to phase-in constraints, such as estimated hybrid and EV penetration rates) to vehicles until the sales- and activity-weighted emission average complies with the specified standard or until all the available technologies have been applied. Vehicle activity is used to balance total CO_2 for cars and trucks (and the corresponding CO_2 credit transfers).

OMEGA MODEL STRUCTURE

The overall structure of the OMEGA model is described in Figure 10 (EPA, 2016). OMEGA includes several components, including a number of preprocessors that assist the user in preparing a baseline vehicle database, creating and ranking technology packages, and calculating the degree to which technology is present on baseline vehicles. The OMEGA core model collates this information and produces estimates of changes in vehicle cost and CO_2 emission level. Based on the OMEGA core model output, the technology penetration and costs of the new vehicle mix are calculated via postprocessors.

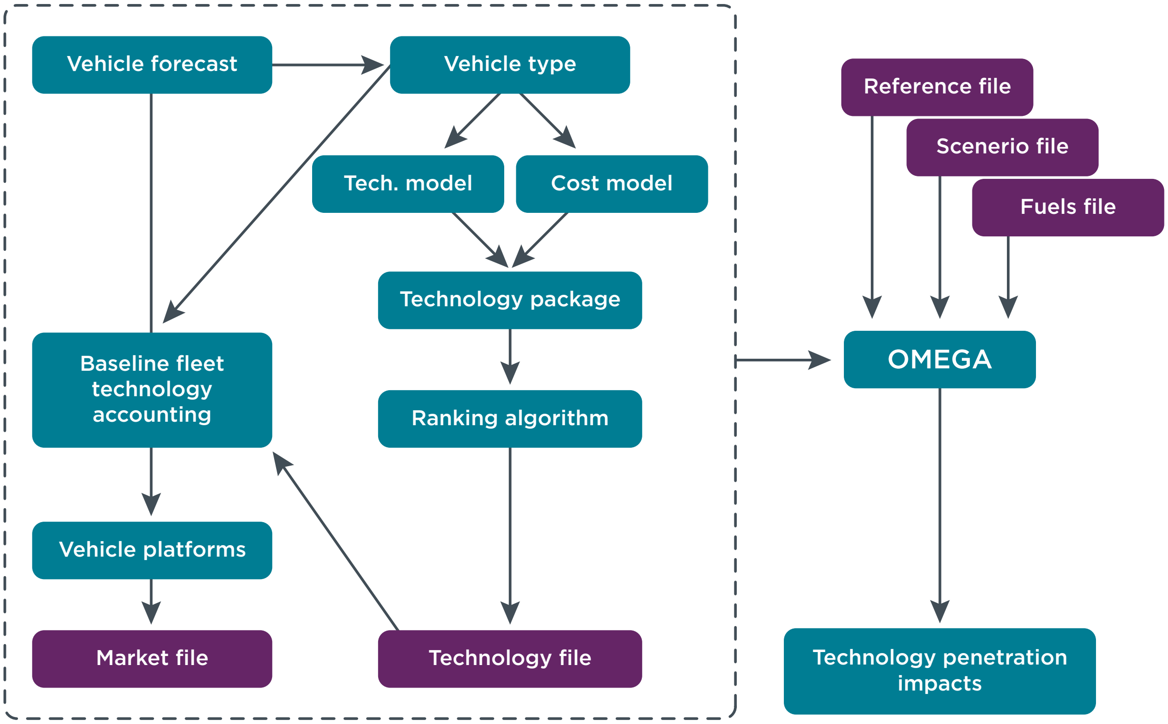

Figure 10. OMEGA model general structure and information flow.

OMEGA uses five basic sets of input data: the vehicle market file, the technology file, the fuels file, the scenario file, and the reference file. Below is a list of model input requirements that have been modified for use with the Mexican light-duty vehicle fleet.

1. Vehicle market fleet characterization file

OMEGA requires a detailed baseline fleet, including manufacturer, sales, base CO_2 emissions, footprint, and the extent to which efficiency technologies are already in use. This file is the input that describes the vehicle fleet composition used by the model to estimate costs. This file also contains information on future sales. The market data worksheet is composed, on a vehicle-by-vehicle basis, of:

a. Vehicle index number
b. Manufacturer
c. Model
d. Vehicle type number
e. EPA vehicle class
f. Baseline sales
g. Annual sales
h. Tailpipe emissions, gCO_2/mi
i. Footprint, ft^2

j. Fuel
k. Combined average electricity consumption (EC; kWh/mi) for hybrids
l. Refrigerant type (for air conditioners)
m. Refrigerant lifetime leakage (not used)
n. Efficient technology penetration

The last item, the efficient technology penetration input, contains information on all of the technologies that are already available in the vehicles being sold. This basic set of information allows the model to avoid adding technology to models that are already sold with the technology. As an example, if a vehicle model sold in 2012 already has turbocharging technology, then the cost of adding that specific technology is zero for that model.

1. The technology file

The technology file contains costs and efficiency values for each of the technology packages by vehicle type. Technology packages combine a number of individual technologies that reduce CO_2 emissions according to vehicle type. OMEGA uses 29 different vehicle types to assign technology packages (U.S. EPA, 2016). These vehicle types represent various vehicle categories including subcompact cars, midsize cars, crossovers, sport utilities (SUVs), and pickups as well as variants within these categories, such as luxury or sport models, with different performance characteristics. EPA defined a set of criteria to aggregate the application of many dozens of efficiency technologies across 29 different vehicle types that have differing engine technology, power, and weight characteristics.

EPA developed a list of 50 fuel efficiency technology packages that can be applied to each vehicle type. Technology packages and costs are also defined for each of three evaluation years: 2016, 2021, and 2025. In total, the technology file includes 1,099 technology package estimates of cost and fuel economy benefits (U.S. EPA, 2016). A detailed description of how these technology packages were defined is available in the appendix of EPA's draft technical assessment (EPA/NHTSA/CARB, 2016b).

The cost data for most of the technology packages were developed by EPA through vehicle tear-down studies (EPA/NHTSA/CARB, 2016b). Such studies involve disassembling vehicle systems and components to identify each component part (down to the level of individual nuts and bolts) and then estimating and aggregating the manufacturing costs associated with each individual component. A list of component parts was developed and costed using the best (and most credible) available information. This generally involves information obtained from parts suppliers and vehicle manufacturers. A detailed description on how individual technology costs were assessed are available in the appendix of EPA's draft technical assessment (EPA/NHTSA/CARB, 2016b). The individual technologies incorporated into OMEGA's technology packages are listed in Table 5.

Table 5. List of technologies to be adopted for reaching GHG/FE targets.

Abbreviation	Meaning
TDS 18/24/27	Turbocharging and downsizing at 18-, 24-, or 27-bar BMEP (brake mean effective pressure)
DI	Stoichiometric gasoline direct injection
AT6/8	Automatic transmission (six- or eight-speed)
DCT6/8	Dual-clutch transmission (six- or eight-speed)
DSL	Advanced diesel
SS	Stop-start technology with a 12-volt battery
MHEV	Mild hybrid electric vehicle
HEV	Hybrid electric vehicle
PHEV	Plug-in hybrid electric vehicle
EV	Full electric vehicle
LRRT	Low-rolling-resistance tires
HEG	High-efficiency gearbox
IACC	Improved accessories
EFR	Engine friction reduction
EGR	Cooled exhaust gas recirculation
AERO	Active aerodynamic technologies (e.g., grill shutters)
MWR	Mass weight reduction (limited to total reduction of 15% in 2021 and 20% in 2025)
DEAC	Cylinder deactivation
MC	Miller cycle + turbo
ATK	Atkinson cycle + high compression ratio

In addition to developing current cost estimates for fuel economy technologies, EPA also estimates learning factors (which are used to forecast future year costs from developed base year costs) and the current state of development for each potential fuel economy technology. Technologies that are in a more advanced stage of development are assumed to undergo relatively minor cost declines over time, whereas emerging technologies are subject to greater reductions, which are expected to accrue as manufacturers gain design and production experience. Thus, the same technology could have a lower cost in 2025 than in 2021.

The benefits were first determined at the individual technology level and later integrated into OMEGA as aggregate benefits under technology packages. Estimates of the fuel economy benefits of a given technology were based on detailed vehicle simulation modeling. Such estimates are necessary to define the specific benefits associated with both individual technologies and packages of multiple technologies (as required to determine “how much” technology is required to attain a specific standard). Simulation modeling is the state-of-the-science approach to evaluating the effects of a given technology on vehicle performance, relying on detailed physics-based algorithms and associated input data to represent the relationships between all systems that comprise a vehicle. Once defined, these relationships can be evaluated over the driving cycle to derive associated fuel economy estimates. Substituting alternative technologies for one or more of the vehicle components allows for associated fuel economy effects to be isolated. The development of the required physical models is quite demanding, but the resulting impact estimates are quite rigorous. When considered in conjunction with the general reusability of the developed component models, simulation modeling has become the industry standard alternative to the actual production and testing of a physical vehicle (during the early stages of vehicle design).

As an example, Table 6 presents a short list of technology packages for the second car type listed, the compact car with an I4 DOHC/SOHC 4v engine. The complete set of packages for this example vehicle type is shown in Annex B. Data for the other 28 types and evaluation years are of the same format. Acronyms for each technology are described at the end of the report. Although too voluminous to reproduce in this report, the complete dataset is publicly available (U.S. EPA, 2016).

Table 6. EPA cost/benefit estimates for type 2 compact car, I4 DOHC/SOHC 4v

Tech package number	Technology package components	Transmission	Cost in 2025 (2016 USD)	CO$_2$ reduction
0	Passenger car (auto) 4VDI4 with MPFI+4sp (baseline package)	4sp AT	$0	0.0%
1	Auto 4VDI4+X1+DCP+WR5	Auto, DCT, CVT; 6 speed	$395	21.78%
2	Auto 4VDI4+X1+DCP+WR5	Auto, DCT, CVT; 7, 8, 9 speed	$151	7.58%
3	Auto 4VDI4+X2+DCP+WR5	Auto, DCT, CVT; 7, 8, 9 speed	$53	2.26%
4	Auto 4VDI4+X1+DCP+WR5	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$392	12.72%
5	Auto 4VDI4+X2+DCP+WR10	Auto, DCT, CVT; 7, 8, 9 speed	$119	3.28%
6	Auto 4VDI4+X2+DCP+Deac+WR10	Auto, DCT, CVT; 7, 8, 9 speed	$109	2.76%
7	Auto 4VDI4+X3+DCP+WR10	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$341	8.00%
8	Auto 4VDI4+X4+DCP+Deac+WR10	Auto, DCT, CVT; 7, 8, 9 speed	$222	4.55%
9	Auto 4VDI4+X2+DCP+Deac+GDI+ATK2+EGR+WR10	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$981	16.01%
10	Auto 4VDI4+X3+DCP+Deac+GDI+ATK2+EGR+WR10	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$849	13.53%
..	...	...	...	...
..	...	...	...	...
48	Auto 4VDI4+X9+DCP+DVVL+GDI+HEV+SAX+ATK1+WR15	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$1,664	4.46%
49	Auto 4VDI4+X8+DCP+DVVL+GDI+ATK1+REEV20+WR20	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$7,275	41.64%
50	Auto 4VDI4+X5+DCP+Deac+GDI+MHEV48V+SAX+ATK2 +TURBM+EGR	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$95	0.39%

Note: X1=LUB+EFR1+LRRT1+IACC1+EPS+Aero1+LDB
X2=LUB+EFR1+LRRT2+IACC1+EPS+Aero1+LDB
X3=LUB+EFR1+LRRT1+IACC2+EPS+Aero2+LDB
X4=LUB+EFR1+LRRT2+IACC2+EPS+Aero2+LDB
X5=+EFR2+LRRT2+IACC2+EPS+Aero2+LDB
X8=+EFR2+LRRT2+IACC1+EPS+Aero2+LDB
X9=LUB+EFR1+LRRT2+IACC1+EPS+Aero2+LDB

2. The scenario file

This file defines regulatory scenarios and other economic parameters. In the scenario file, the user must specify the year, type of compliance target (CO$_2$ or MPG), type of compliance function (single-value target, S-shaped target, or piecewise linear), and the names of the other input files that describe the vehicle fleet, technology packages, and fuel properties as previously described.

3. The fuels file

This file defines physical properties and prices of fuel and energy sources. The fuels input file also contains annual price forecasts for up to 20 years. These data are used only in postprocessing and are not taken into account in the optimization process.

4. The reference file

This file describes vehicle survival rates and miles driven for both vehicle classes, cars and light-duty trucks. It is used to estimate total tons of CO_2 emitted by each vehicle class when calculating costs within the OMEGA framework.

OMEGA MODEL APPLIED TO MEXICO'S FLEET

Applying the OMEGA model to Mexico's light-duty vehicle fleet required the development of input files to properly reflect the current Mexican vehicle market and the technology installed on baseline vehicles in Mexico. Using the modified input files described below, the model was run for each of the scenarios. To determine the full compliance costs, the costs associated with AC refrigerant and efficiency changes were added back in to all future scenarios. Following EPA's estimate, the costs drop over time, from $79 per car and $95 per truck in 2021 to $69 per car and $84 per truck in 2025 (EPA, 2012).

Modifications to the input files for this project include:

1. The market file

The 2012 database initially lacked information on most of the technologies included in OMEGA modeling, and the first task was to update the missing fields. This detailed information for each of the 767 model versions was obtained from Mexican websites[9] and ICCT databases. The following technologies were manually added to the vehicle database for OMEGA input:

- Transmission type (manual, automatic, dual-clutch, continuously variable)
- Valve actuation systems (variable or fixed)
- Fuel systems (port fuel injection, direct injection)
- Air induction systems (turbochargers and superchargers)
- Hybrid systems
- Start/stop systems
- Cylinder deactivation systems

From this database, a market file was created for the Mexican fleet. The vehicle market fleet characterization is based on the model year 2012 vehicles contained in INECC's calendar year 2012 vehicle database. The technology penetration input was filled with information on all the technologies that were already available in the vehicles sold in Mexico in 2012. Future vehicle sales were based on INECC's sales fleet growth projections, estimated as part of the work conducted to develop Mexico's Intended Nationally Determined Contribution (INDC) submission to the UNFCCC.

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[9] Autocosmos vehicle Information website, www.autocosmos.com.mx.

2. The technology file

The technology files used in OMEGA modeling for Mexico made use of two different sources for cost and technology efficiency:

- The technology file originally developed to support the technical analysis for the LDG GHG 2022—2025 rule. No changes were made to the original technology file developed by EPA while applying it to Mexico's fleet OMEGA modeling. This assessment used the same technology file used by EPA in the midterm review.
- An update of the original technology file that incorporates the likely impact of recent emerging technology developments on EPA's estimated technology efficiency and cost. To incorporate the efficiency benefits and lower costs of emerging and rapidly evolving technologies, the ICCT modified the technology file to incorporate the latest research on emerging technologies, including cylinder deactivation, hybridization, lightweighting, and electric vehicles, based on the research literature, simulation modeling, and auto industry developments. See Lutsey et al. (2017) for further detail on these modifications.

The results associated with using EPA's original technology files are labeled as EPA 2021 H and EPA 2025 H (describing higher costs); the results from using the ICCT's updated technology files are labeled as EPA 2021 L and EPA 2025 L (describing lower costs).

3. The scenario file

The scenario file was updated to match the GHG target scenarios modeled for Mexico as described in section 2. This file incorporated the CO_2 emission targets for each scenario used for OMEGA, as shown in Table 3. The target values for OMEGA modeling applied to the Mexican vehicle fleet adjust the regulatory curves to incorporate the total credits provided for each scenario, as shown in Table 4. The values listed in Table 7 correspond to the inflection points in the curves presented in Figures 6 and 7 for cars and light trucks and include full benefits of credits due to AC efficiency, low-GWP AC refrigerants, and off-cycle credits.

Table 7. CO_2 emission targets used for OMEGA modeling of NOM-163 target scenarios

	Cars				Light trucks			
Target	Point A footprint (m^2)	Point A GHG (g/km)	Point B footprint (m^2)	Point B GHG (g/km)	Point A footprint (m^2)	Point A GHG (g/km)	Point B footprint (m^2)	Point B GHG (g/km)
NOM-163 2016	3.8	136	5.2	181	3.8	164	6.1	228
AMIA 2021	3.7	119	5.1	157	3.8	145	6.9	233
EPA 2021 (H & L)	3.8	110	5.2	146	3.8	138	6.9	225
EPA 2025 (H & L)	3.8	94	5.2	125	3.8	118	6.9	191

Point A represents the lower left inflection point in the target curve; Point B represents the upper right inflection point in the target curve.

4. The fuels file

Fuel properties for gasoline and diesel, such as energy density and carbon density, were taken from EPA's original files. Payback and return on investment was evaluated in postprocessing, as described in the next section. Because fuel pricing does not play a role in forecasting within the model, the fuels file did not need to be modified in any way.

5. The reference file

The reference input file was modified with respect to the original EPA input file to reflect vehicle activity in Mexico for cars and light-duty trucks. The lifetime vehicle activity of 232,038 km for cars and 281,360 km for light-duty trucks was developed by INECC for the Mexican national emissions inventory (INECC, 2014). Because of a lack of information on survival rates for Mexico, EPA's original survival rates were used; no substantial changes to per-vehicle costs due to deviations from typical Mexican survival rates are expected, and as vehicles are likely to last longer in Mexico, any impacts will be conservative.

METHODS FOR PAYBACK ANALYSIS

A key responsibility of regulatory agencies is to make sure that policies will have benefits that outweigh the costs to society. For fuel economy and GHG regulations, an additional criterion for decision-making is the extent to which fuel savings will pay back the cost of vehicle technology to buyers of more efficient vehicles.

This analysis considers three methods for consumer payback of next-phase GHG regulations for passenger vehicles in Mexico. The first two methods compare the cumulative discounted benefits (in the form of reduced fuel expenditures) with the incremental cost of vehicle technology, first for the buyer of an average vehicle and second for the new vehicle fleet in model year 2025. The benefits are counted over 20 years to reflect the relatively long average vehicle lifetime of Mexican vehicles. The third payback method reflects how many years it might take for buyers of an average new vehicle to recoup their investment (in terms of incremental technology cost), after which any fuel savings would represent a net gain when accounting for the value of time preference.

This section describes the methods for calculating payback according to each of these methods, including the inputs for discount rate, vehicle mileage, and fuel prices.

Discount rate

The discount rate represents the rate at which individuals or societies are willing to trade current consumption for future consumption. This rate is compounded over time to reflect preferences for near-term consumption as well as the opportunity cost of private investment. For investments made by consumers that yield private returns, the discount rate can be approximated by starting with the real rate of return on private investments (also called the real interest rate, equal to the nominal interest rate minus inflation) and adjusting for the impacts of risk, taxation, and imperfect operation of capital markets (U.S. EPA, 2010). For this reason, the actual rate at which individuals can trade current consumption for future consumption tends to be lower than the real interest rate if individuals are investing cash. If, on the other hand, individuals are borrowing to make a purchase (for example, taking out an auto loan to purchase a car), the consumer discount rate may be better approximated by the real interest rate on the loan.

In cases where investments have benefits to society at large, several factors can justify using a lower discount rate: (a) governments can typically borrow at a lower interest rate than individuals or businesses; and (b) investments with long-term social impacts (such as GHG mitigation) require a lower discount rate to appropriately value impacts on future generations (U.S. EPA, 2010). In this analysis, we seek to balance the valuation of future costs and benefits from a private and a social perspective, applying a discount rate of 7%.

Vehicle mileage

Annual distance traveled per vehicle is an important determinant of payback period: The farther that vehicles travel each year, the more fuel they save relative to baseline vehicle technology. Vehicle travel also tends to decline as vehicles age (Figure 11). These estimates of annual distance per vehicle by age were based on data developed by INECC for Mexico's National Emission Inventory (INECC, 2014), assuming an average of passenger cars and pickup trucks (based on cars accounting for 64% of sales and pickup trucks accounting for the remainder).

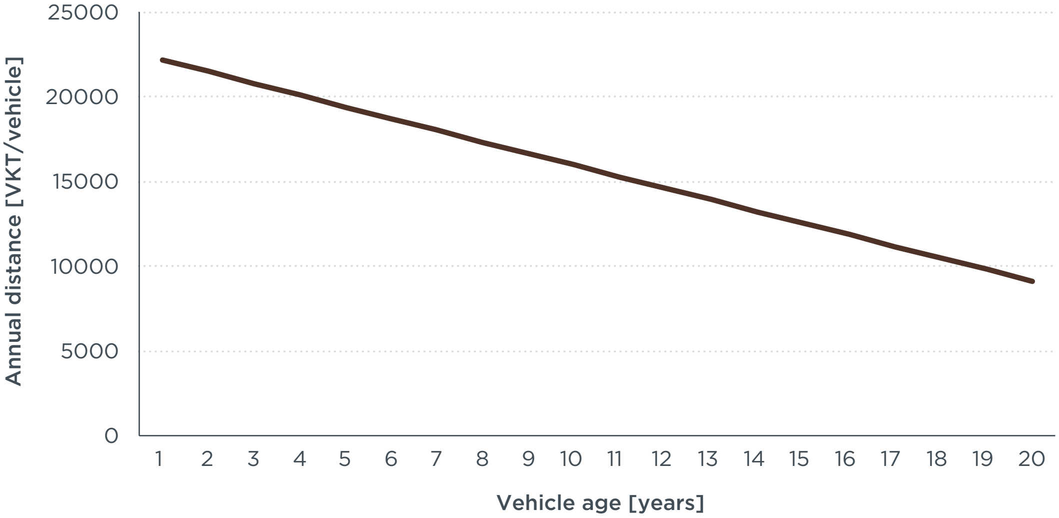


Figure 11. Average annual distance traveled by vehicle age.

Fuel prices

Released in April 2015, the U.S. Energy Information Administration's (EIA) Annual Energy Outlook (AEO) 2015 projected gasoline prices from 2016 to 2040. As shown in Figure 12, EIA's projected price for 2016 is very close to the actual price of regular ("magna") gasoline observed in Mexico in March 2016, 0.74 USD/liter (Nelson, 2016). As Mexico continues to liberalize its fuel market, fuel prices are expected to follow a pathway similar to that in the United States. For our payback analysis, the central fuel price in 2025 is based on EIA's reference case projection, plus the small differential between the present-day price of regular gasoline in Mexico and that in the United States. Although EIA projects under the reference case that fuel prices could continue to increase beyond 2025, we conservatively apply a single fuel price (in 2025) to estimate fuel savings over 20 years. Therefore, if fuel prices were to continue rising, we could expect the fuel savings to be greater—and the consumer payback periods shorter—than estimated here.

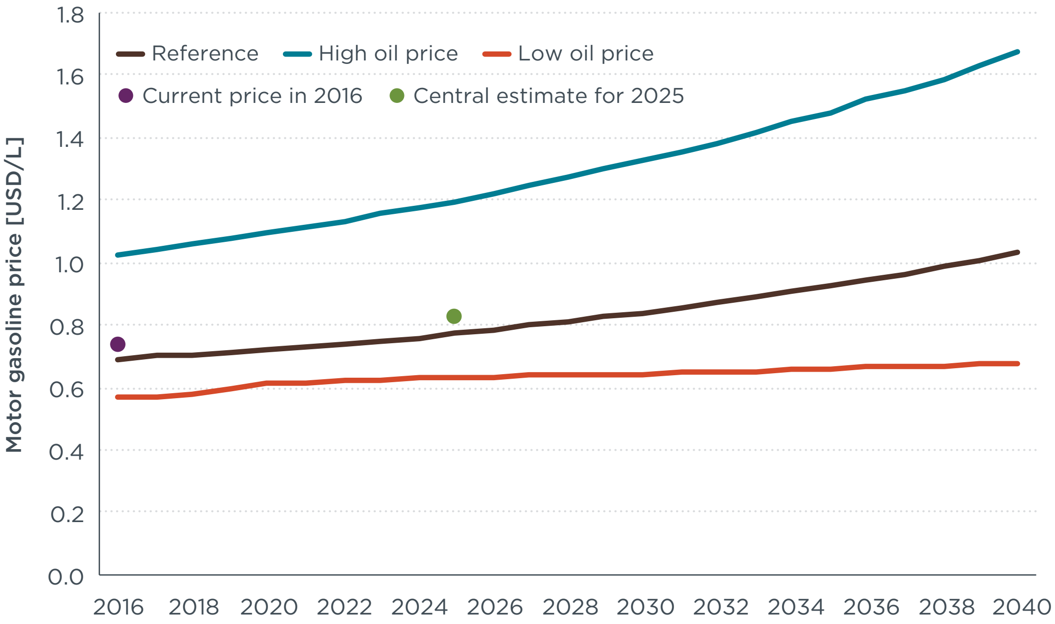


Figure 12. Current and projected gasoline price in the United States and Mexico (EIA, 2015).

Cumulative discounted fuel savings

For each of the three payback methods, the key benefit is the cumulative discounted value of fuel savings (reduction in fuel expenditures) over a specified time period (e.g., 20 years). The formula for the sum of discounted fuel savings is as follows:

$$S = \sum_{t=0}^{p} \left[(E_{base} - E_{final}) \times D_t \times F_t \times \frac{1}{(1+r)^t} \right]$$

where

S is the sum of discounted fuel savings (measured in USD)
p is the number of years over which savings are calculated
$t = 0$ is the time of the vehicle purchase
E_{base} is the energy efficiency of the baseline vehicle (MJ/km)
E_{final} is the energy efficiency of the more efficient vehicle (MJ/km)
D_t is the annual distance driven in each year (km)
F_t is the price of fuel per unit energy in a given year (USD/MJ)
r is the discount rate

Fuel savings are not discounted during the first year of travel (the same year as the vehicle purchase).

Per-vehicle fuel savings and technology costs over 20 years

This payback metric compares the sales-weighted average incremental technology cost for a model year 2025 vehicle with the cumulative discounted fuel savings over 20 years (as defined above), also averaged across vehicle models using a sales-weighted approach. The formula for sales-weighted incremental technology cost is as follows:

$$C_{avg} = \sum_{m=1}^{n} \left[(C_{final,m} - C_{base,m}) \times \frac{\text{Sales}_m}{\text{Total sales}} \right]$$

where

C_{avg} is the sales-weighted average incremental technology cost for a model year 2025 vehicle

C_{final} is the total cost of technology for a given vehicle model under the 2025 standards

C_{base} is the total cost of technology for a given vehicle model under the current (2016) standards

(C_{final} – C_{base} is defined as the incremental technology cost for a given vehicle model)

m represents a single vehicle model

n represents the total number of vehicle models

Sales_m represents the number of units sold for a given vehicle model in 2025

Total sales represents the total number of units sold for all vehicle models in 2025

New fleet fuel savings and technology costs over 20 years

This payback metric is the same as the previous per-vehicle estimate, except that it is not divided by total vehicle sales. Instead, it compares the technology costs and fuel savings over 20 years summed across all model year 2025 vehicles, the model year when the extended standards would be fully phased in for new vehicles. In other words, this metric captures the costs and benefits of the extended standards for the new vehicle fleet in 2025; somewhat smaller costs and benefits would be expected from model years 2017 to 2024, and larger costs and benefits for model years after 2025 if vehicle sales continue to grow. Subtracting the incremental costs of technology for model year 2025 vehicles from their expected fuel savings over 20 years can be termed the "net benefits" (over 20 years) of the standards for model year 2025 vehicles.

Consumer payback periods

The consumer payback period represents the number of years it takes for the sum of discounted fuel savings to exceed the incremental cost of efficient vehicle technology. After this point, any additional fuel savings can be considered a net gain to the vehicle owner. In addition to the incremental cost of vehicle technology and the efficiency improvement, the payback period is determined by the inputs shown in Table 8.

Table 8. Impact of discount rate, mileage, and fuel price assumptions on consumer payback period.

Factor	Assumption	Impact of higher value on payback period
Discount rate	7% (sensitivity at 3%, 5%)	Lengthen
Annual vehicle mileage	22,149 km the first year, decreasing ~3% to 5% each year	Shorten
Fuel price	0.83 USD/liter	Shorten

Payback periods were calculated for each vehicle model, then sales-weighted to come up with an average for the new vehicle fleet and each segment. The method for calculating the payback period of a given vehicle model is as follows:

$$\text{Find } p\text{, where } (C_{\text{final}} - C_{\text{base}}) = \sum_{t=0}^{p} \left[(E_{\text{base}} - E_{\text{final}}) \times D_t \times F_t \times \frac{1}{(1+r)^t} \right]$$

where

C_{final} is the total cost of technology for a given vehicle model under the 2025 standards
C_{base} is the total cost of technology for a given vehicle model under the current (2016) standards
($C_{\text{final}} - C_{\text{base}}$ is defined as the incremental technology cost for a given vehicle model)
p is the number of years over which fuel savings are calculated
$t = 0$ is the time of the vehicle purchase
E_{base} is the energy efficiency of the baseline vehicle (MJ/km)
E_{final} is the energy efficiency of the more efficient vehicle (MJ/km)
D_t is the annual distance driven in each year (km)
F_t is the price of fuel per unit energy in a given year (USD/MJ)
r is the discount rate

Valuation of climate benefits

EPA defines the social cost of carbon as “an estimate of the economic damages associated with a small increase in carbon dioxide (CO_2) emissions, conventionally one metric ton, in a given year. This dollar figure also represents the value of damages avoided for a small emission reduction” (U.S. EPA, 2015b). Because Mexico’s government has not recommended a value for the social cost of carbon, we used the range of scenarios given by EPA to evaluate the climate benefits of the modeled EPA 2025 standards in Mexico (Table 9). Values for 2025, 2030, 2035, and 2040 were taken directly from the EPA fact sheet on the social cost of carbon and converted from 2007 USD to 2016 USD using a multiplier of 1.16. Values for intermediate years were interpolated using annualized growth rates. The first three scenarios represent the average social cost of carbon from three integrated assessment models, applying a discount rate of 5%, 3%, and 2.5%, respectively. The fourth represents the social cost of carbon under a scenario with higher-than-expected climate impacts, also applying a 3% discount rate (U.S. EPA, 2015b). The 3% average discount rate is currently considered to be the best estimate for the social cost of carbon; however, as modeling currently suggests that climate impacts will be higher than previously expected (Hansen et al., 2016), the higher cost of carbon estimates may ultimately be more reasonable.

Table 9. Social cost of carbon values in 2016 USD (adapted from U.S. EPA, 2015b).

Year	Discount rate and social cost of carbon scenarios			
	5% average	3% average	2.5% average	3% 95th percentile
2025	16	53	79	160
2026	17	54	80	163
2027	17	55	81	166
2028	18	56	82	170
2029	18	57	83	173
2030	19	58	85	176
2031	19	59	86	180
2032	19	60	87	184
2033	20	61	88	187
2034	20	63	89	191
2035	21	64	90	195
2036	21	65	92	199
2037	22	66	93	203
2038	22	68	94	207
2039	23	69	95	211
2040	24	70	97	212

Real-world fuel economy adjustment

The fuel savings model includes adjustment factors to better reflect real-world fuel economy values. Adjustment factor values used in this analysis come from an EPA methodology that accounts for important factors that affect fuel economy in real-world operation, such as the use of air conditioning, aggressive acceleration, high-speed operation, and other factors not accounted for under CAFE 2-cycle testing. Generally, these factors range from 0.785 to 0.85, with the largest adjustments associated with model years after 2004 and the smallest adjustments associated with model years before 1990.

To convert 2-cycle fuel economy test data to real-world values for Mexico, we assume a constant 0.785 adjustment factor for all model years and scenarios, resulting in higher real-world fuel consumption estimates (i.e., lower fuel economy). However, because it applies to all scenarios, the real-world fuel savings of vehicle efficiency standards are actually higher than measured on the test cycle, because the absolute difference between scenarios is greater (although the percent difference is the same). EPA's report on fuel economy trends (U.S. EPA, 2015b) includes details of the methodology used to estimate this real-world fuel economy adjustment factor.

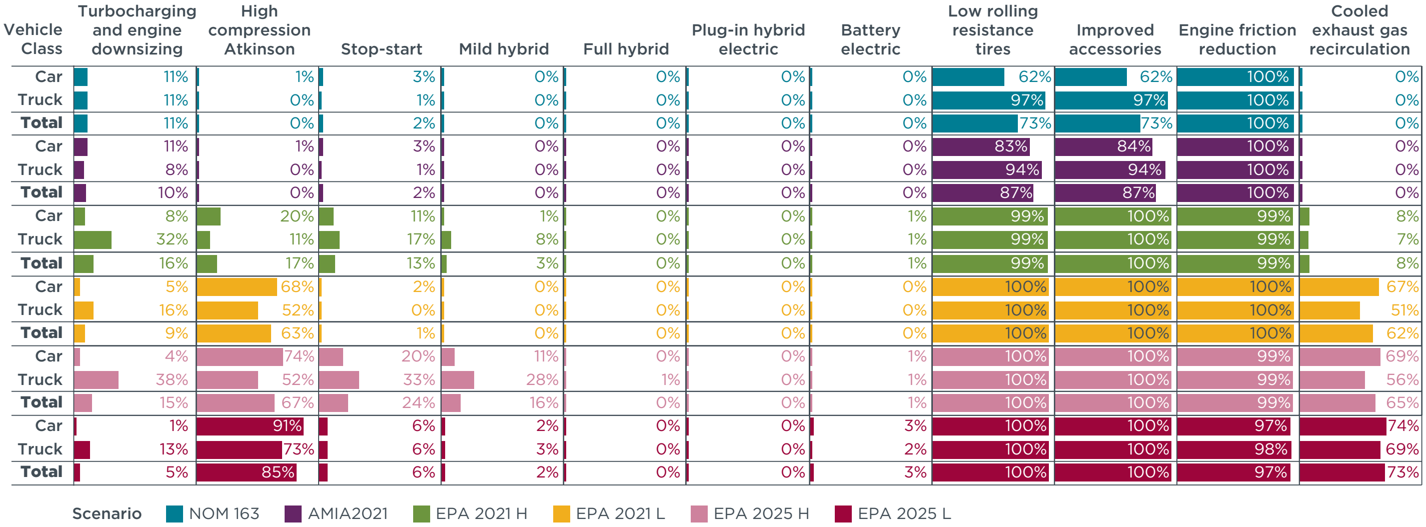
Although vehicles in Mexico and the United States are subjected to very different driving conditions and behaviors, we use the EPA-derived adjustment factor because there is currently no known adjustment factor available for the Mexican market. This would not have a substantial impact on the outcomes if the adjustment factor were constant over time. The more important uncertainty arises from a recent trend toward growth in the gap between real-world and test cycle fuel economy. However, as credits encourage incorporation of technologies that have real-world benefits, it is possible that this trend may reverse. Given that the uncertainty could go in either direction, we chose to keep the gap constant over time.

4. RESULTS OF OMEGA MODELING AND PAYBACK ANALYSIS

This section presents the projected technology adoption by the OMEGA model for the Mexican vehicle fleet, by car/truck class and by vehicle type, for each of the scenarios. The analysis shown here illustrates a potential technology pathway toward compliance; manufacturers may choose other pathways to compliance—including changes to vehicle types—depending on marketing strategies, local conditions and consumer preferences, and further technology development. See Annex A for a brief description of each of the technologies.

TECHNOLOGY DEPLOYMENT

Figure 13 shows the market adoption rates for each of the technologies for the total fleet and disaggregated by car and truck vehicle classes under the baseline and five scenarios considered in this study. In general, technology adoption rates increase as CO_2 targets become more challenging for manufacturers. However, as the H & L outcomes make clear, the cost and GHG benefits associated with different technologies also make a big difference in market uptake. The following sections describe the technology adoption by market segment for different technology groupings. The model predicts that for the average vehicle, most of the efficiency gains are expected to be realized by the least complex technologies, with very little market uptake for advanced powertrains (full hybrids and electric vehicles). In the 2025 time frame, EPA's technology pathways (EPA 2025 H) lead to more hybridization and less of a role for battery-electric technologies, whereas the ICCT update of those pathways (EPA 2025 L) results in little hybridization but an eventually increasing role for electrification, due primarily to the lower costs forecast for electrification.



Vehicle Class	Turbocharging and engine downsizing	High compression Atkinson	Stop-start	Mild hybrid	Full hybrid	Plug-in hybrid electric	Battery electric	Low rolling resistance tires	Improved accessories	Engine friction reduction	Cooled exhaust gas recirculation
Car	11%	1%	3%	0%	0%	0%	0%	62%	62%	100%	0%
Truck	11%	0%	1%	0%	0%	0%	0%	97%	97%	100%	0%
Total	11%	0%	2%	0%	0%	0%	0%	73%	73%	100%	0%
Car	11%	1%	3%	0%	0%	0%	0%	83%	84%	100%	0%
Truck	8%	0%	1%	0%	0%	0%	0%	94%	94%	100%	0%
Total	10%	0%	2%	0%	0%	0%	0%	87%	87%	100%	0%
Car	8%	20%	11%	1%	0%	0%	1%	99%	100%	99%	8%
Truck	32%	11%	17%	8%	0%	0%	1%	99%	100%	99%	7%
Total	16%	17%	13%	3%	0%	0%	1%	99%	100%	99%	8%
Car	5%	68%	2%	0%	0%	0%	0%	100%	100%	100%	67%
Truck	16%	52%	0%	0%	0%	0%	0%	100%	100%	100%	51%
Total	9%	63%	1%	0%	0%	0%	0%	100%	100%	100%	62%
Car	4%	74%	20%	11%	0%	0%	1%	100%	100%	99%	69%
Truck	38%	52%	33%	28%	1%	0%	1%	100%	100%	99%	56%
Total	15%	67%	24%	16%	0%	0%	1%	100%	100%	99%	65%
Car	1%	91%	6%	2%	0%	0%	3%	100%	100%	97%	74%
Truck	13%	73%	6%	3%	0%	0%	2%	100%	100%	98%	69%
Total	5%	85%	6%	2%	0%	0%	3%	100%	100%	97%	73%

Figure 13. Technology penetration by scenario for the car, truck, and total fleet in Mexico.

Turbocharged and downsized GDI engines and high-compression Atkinson-cycle engines

A look at the projected market share by vehicle segment (Figure 14) shows that naturally aspirated engines are projected to be replaced by high-compression Atkinson-cycle engines or by turbocharged and downsized GDI engines across most segments for compliance with 2025 targets. Under the original EPA technology pathway, naturally aspirated engines are forecast to retain a substantial market share for powering Mexican light-duty vehicles in 2021. Whereas in 2025 only the large pickup truck segment is predicted to be dominated by naturally aspirated engines.

High-compression Atkinson-cycle engines (e.g., Mazda's Skyactiv gasoline engine) are expected to gain a large market share across Mexican vehicle market segments meeting 2025 EPA targets, except for the large pickup segment under the high-cost scenario. Note that this type of engine technology is more predominant in the low-cost scenarios (EPA 2021 L and EPA 2025 L), as this relatively new technology is opening up a low-cost option to achieve higher efficiency without turbocharging. Lutsey et al. (2017) discuss how the costs and benefits of Atkinson-cycle engines are estimated.

GDI, turbocharging, and downsizing, primarily combined as a package, have already gained market share in some segments of the larger vehicle market (SUVs and small to medium pickups). Turbocharging improves vehicle performance in the high altitude and steep terrain of some regions of Mexico; by increasing air pressure in the intake manifold, turbocharging boost eliminates high-altitude performance degradation. At the same time, turbocharging provides more torque at a lower engine rpm, increasing performance during hill climbing. Although the OMEGA analysis shows turbocharged, downsized engine technologies being overtaken by the high-compression Atkinson-cycle engines that are quickly gaining market share, turbocharging may have sufficient additional advantages at the high altitudes found in Mexico to boost its share in the Mexican market. Figure 14 shows the forecast by segment from this analysis, compiling all the boost levels of turbocharging (from 18- to 27-bar pressure) into one category.

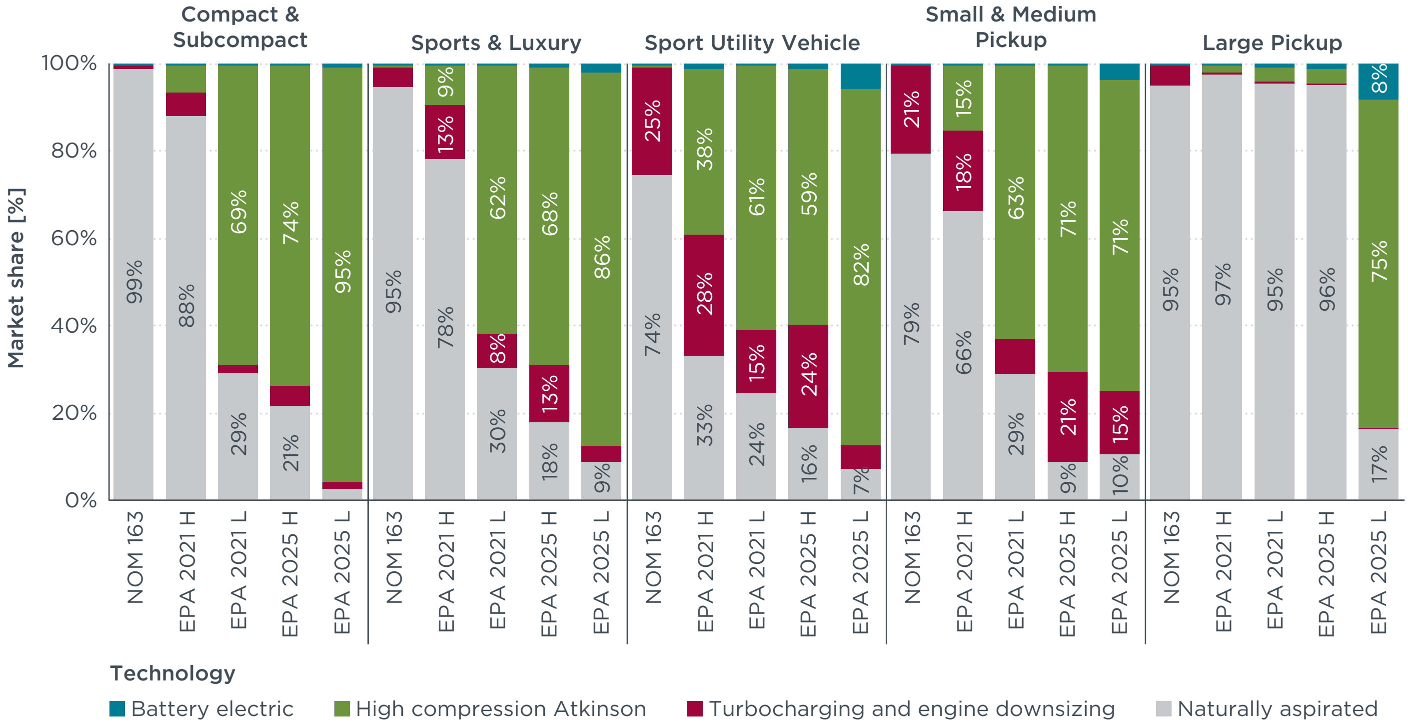


Figure 14. Market share of turbocharged and downsized GDI engines by vehicle segment. Baseline refers to naturally aspirated engines.

Hybrids and electric vehicle technologies

Under all technology pathways and scenarios considered, the OMEGA model predicts that the internal combustion engine is going to continue to be primary powertrain for the Mexican light-duty vehicle fleet. Figure 15 shows stop-start technology with a small market share in 2016 and, along with mild hybridization, gaining ground in future years. For some segments and scenarios, full electric and hybrid electric vehicles take the place that is currently captured by diesel technologies, and in general they gain only a slight foothold even under the most ambitious scenarios. According to OMEGA estimates, electric drive technologies would each be required on 1% to 3% of vehicles sold under the EPA 2025 target depending on technology and cost scenarios.

Among these more advanced powertrain technologies, the relatively low-cost mild-hybrid electric vehicle (MHEV) and start-stop technologies are dominant options, with projected increased market share under EPA's technology pathways, especially for high-end cars (luxury, sport, and SUVs) and smaller pickup trucks. These less expensive hybrid technologies are still projected to remain relatively low in many segments, especially the low-cost vehicle segments and the large pickup segment. However, adoption of hybrid technologies in Mexico could potentially provide greater benefits in terms of fuel consumption than can be achieved in U.S. markets. In a global study of traffic congestion, Mexico City is currently ranked as the most congested city in the world (TomTom, 2016). Start-stop and MHEV technologies can provide even greater benefits in highly congested conditions and therefore may find wider adoption in the Mexican market.

Hybrid (HEV) and plug-in hybrid (PHEV) market projections are expected to be less than 1% for the overall Mexican fleet in all scenarios and technology pathways. EVs are expected to gain a very small share to meet 2025 EPA equivalent targets in Mexico, typically below 2% in most segments. Interestingly, EV adoption in the luxury and sports car segments is projected to reach around 6% and 9% of sales in 2025 under the low-cost technology pathways, whereas market penetration stays around 1% over the full market under EPA's technology pathways. This increase is a result of rapidly falling costs for battery-electric technologies that have been incorporated in the low-cost technology pathway (EPA 2025 L).

Diesel technologies are projected to be required only for a small share of vehicles, focusing mainly on high-value vehicle segments (sports, luxury, and SUVs). Diesel market share could grow more than projected if emissions standards do not require higher-cost emissions controls that are included in this analysis. In such a case, substantial air quality impacts would be expected.

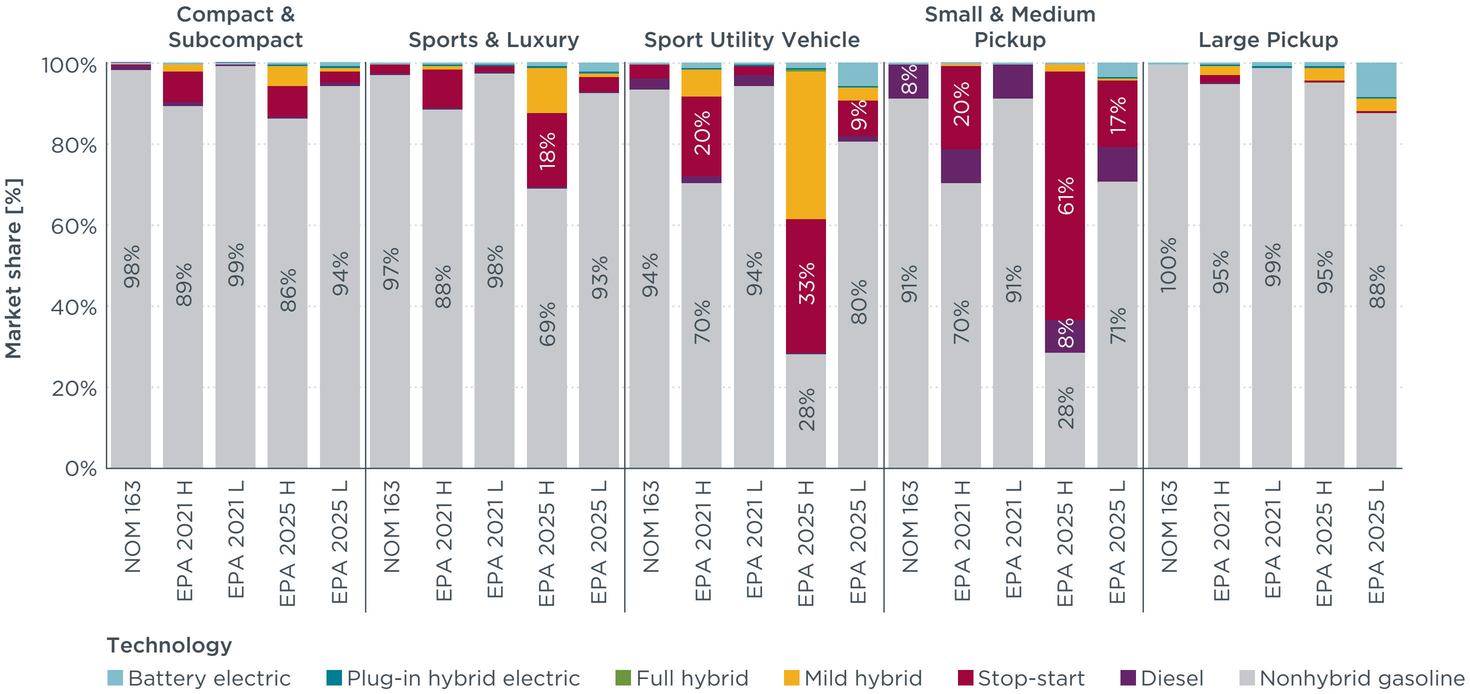


Figure 15. Market share of advanced powertrain technologies (hybrids and EVs) by segment.

Vehicle weight reduction

OMEGA predicts only slight weight reduction for the car segment that is stable over time and regardless of standard stringency. The reduction forecast for light trucks, on the other hand, is substantial and increasing over time and with standard stringency.

Table 10 shows the estimated mass reductions projected to meet each of the scenario targets. Weight reduction estimates in OMEGA include the mass changes due to lightweighting strategies to reduce the weight of the vehicle, as well as mass variations due to changes in technology (e.g., mass reduction by downsizing the engine from four to three cylinders, or mass increase by adding turbochargers). Note that lightweighting was modeled in OMEGA assuming per-vehicle available changes of 0%, 5%, 10%, 15%, and 20%; the maximum, 20%, was available as an option only for 2025 vehicles.

The overall average vehicle weight is expected to decline almost 5% under the EPA 2025 scenario. The impact of weight reduction is expected to be smaller in passenger cars, below 2% of the weight, and larger in trucks, where the strategy would reduce the weight by 8% to 9% for 2021 scenarios and reach up to 12% by 2025 scenarios. The costs of weight reduction strategies are accounted for in OMEGA's outputs.

Table 10. Weight reductions by scenario: cars, light trucks, and fleet.

Scenario	Car	Truck	Fleet
NOM-163 2016	–2%	–6%	–3%
EPA 2021 L	–2%	–8%	–4%
EPA 2021 H	–2%	–9%	–4%
EPA 2025 L	–2%	–10%	–5%
EPA 2025 H	–2%	–12%	–5%

Understanding the current market trends in lightweighting adoption provides an idea of how this strategy has become a key technical strategy toward meeting future fuel economy standards while improving performance. A number of lightweight materials are now used in vehicle production, including high-strength steels, aluminum alloys, magnesium, plastics, and composites.

Because manufacturers already produce vehicles with substantial mass reductions in both car and truck segments, the application of this technology may be underestimated by OMEGA. Examples from the car segment are the U.S. Chevrolet Cruze and the European Opel Astra, which show 7% and 12% weight reductions in the last model update, respectively (Isenstadt et al., 2016). The most noteworthy example of weight reduction in terms of magnitude and market adoption is the Ford F-150, where the 4-wheel drive lightweighted aluminum-body model is 14% lighter than the traditional steel-body model and, with a downsized engine to hold performance constant, achieves a 12% improvement in fuel economy (German, 2014).

Other fuel efficiency technologies

The remaining set of technologies, such as cooled EGR, engine friction reduction, low-rolling-resistance tires, and improved accessories, are expected to grow rapidly in market share, even under the least ambitious scenarios. Figure 13 shows the projected uptake to meet the targets. Low-rolling-resistance tires, improved accessories, and engine friction reduction technologies are expected to be nearly ubiquitous in all Mexican vehicle segments, both cars and light trucks. Cooled EGR is projected to be used by more than half the fleet. However, note that OMEGA does not model performance (sports car) or towing (pickup truck) requirements, both of which may suggest substantially higher incorporation of cooled EGR for these segments. With respect to aerodynamic improvements, OMEGA does not output that information.

COST PER VEHICLE IN 2021 AND 2025

This section presents the projected costs due to the adoption of technologies under different compliance scenarios in 2016, 2021, and 2025. Costs are given for the sales-weighted average vehicle representing the Mexican vehicle fleet and by car or truck class for each manufacturer. Unless otherwise noted, all costs are given in 2016 USD.

Note that in this analysis, OMEGA allows for credit transfer between cars and trucks. This means that cars are sometimes made to overcomply with the regulation to balance deficits from truck compliance. Credit transfers between vehicle classes (cars/trucks) are allowed by NOM-163 regulation and the EPA/NHTSA rule. A compliance option that could further lower costs is credit trading among manufacturers; however, this option was not included in this modeling exercise.

Evaluating the baseline (implementation of NOM-163 in 2016)

Relative to the 2012 fleet, OMEGA estimates that manufacturers needed to spend an average of $348 per vehicle to reach the adopted 2016 targets. Cars are estimated to incur lower average costs of $249, whereas the average costs for light trucks are estimated at $603. This difference in costs mostly matches the expected reductions needed to meet the 2016 targets: 8% for cars and 14% for light trucks, with 10% improvement over the full fleet. Note that these costs do not include credits or deficits that have been accumulated during the years of NOM-163 implementation.

The final costs and efficiency improvements for each of the studied scenarios, calculated using 2016 performance and costs as the baseline, are presented in the following sections.

AMIA 2021 costs with respect to NOM-163 2016 targets

Relative to a baseline of NOM-163 in 2016, OMEGA estimates that manufacturers would need to spend an average of $165 per vehicle to reach the 2021 targets in the AMIA proposal (Table 11). These relatively low costs reflect the small efficiency benefit, which averages 2% as a reduction in test cycle CO_2/km for AMIA's proposal for 2021 standards compared to NOM-163 in 2016.

Table 11. Cost to meet AMIA 2021 targets compared with NOM-163 2016 (2016 USD).

	Car	Truck	Fleet
BMW	$135	$162	$138
CHRYSLER	$87	$85	$86
DAIMLER	$133	$202	$153
FORD	$87	$55	$72
GENERAL MOTORS	$238	$105	$224
HONDA	$181	$105	$133
NISSAN	$239	$105	$196
PEUGEOT	$145	$105	$127
RENAULT	$224	$105	$182
SUZUKI	$228	$185	$218
TOYOTA	$87	-$21	$27
VOLKSWAGEN	$223	$220	$223
Total	$202	$86	$165

Average incremental cost

-$21 $239

	Car	Truck	Fleet
BMW	1%	1%	1%
CHRYSLER		-1%	0%
DAIMLER	1%	1%	1%
FORD		-2%	-1%
GENERAL MOTORS	4%		4%
HONDA	3%		1%
NISSAN	5%		3%
PEUGEOT	2%		1%
RENAULT	4%		2%
SUZUKI	4%	4%	4%
TOYOTA		-2%	-1%
VOLKSWAGEN	4%	3%	4%
Total	3%	-1%	2%

Average Reduction in Test Cycle CO_2/km

-2% 5%

EPA 2021 costs with respect to NOM-163 2016 targets

Tables 12 and 13 present the incremental costs for compliance with EPA 2021 numerical targets (high-cost and low-cost cases) with respect to the NOM-163 2016 baseline. OMEGA projects that under EPA technology cost estimates (high-cost case), the average cost of compliance to meet EPA 2021 targets by the Mexican fleet is $881 per vehicle, with very similar average costs for cars and light trucks. Among manufacturers, the high-cost case predicts a relatively large spread in costs for light trucks, with costs ranging from $500 per vehicle for Ford, which has a large share of truck sales, to $2,000 for Volkswagen, a manufacturer that focuses on the passenger car market.

OMEGA projects that with updated cost estimates (i.e., updated technology files), the average per-vehicle cost is reduced to $484, with slightly lower costs for light trucks and somewhat higher costs for cars. The overall benefits on the test cycle are slightly different for some manufacturers, as some technologies offer different levels of off-cycle credits (e.g., start-stop systems). The relative benefits for cars versus trucks change between the low-cost and high-cost cases, as some technologies that apply to one type of vehicle are cheaper under the low-cost case, driving OMEGA to overcomply on that vehicle type.

For Volkswagen, BMW, and Daimler, with a reasonably large share of luxury and performance vehicles, costs are substantially higher using EPA's original technology pathways. This is due to heavy vehicle weight and small footprint, which implies that the targets are more challenging. The lower cost of powertrain electrification under the low-cost case and the availability of conventional cheaper and efficient technologies, such as Atkinson-cycle engines, provide a substantial drop in cost for these manufacturers; this highlights the cost reductions that many advanced technologies are achieving and the rapidly increasing availability of newer technologies that are more cost-effective. The small variation across manufactures confirms that those low-cost technologies are available to achieve important CO_2 reductions, regardless of vehicle type and manufacturer fleet mix offering.

Table 12. Costs to meet proposed EPA 2021 targets in Mexico with respect to 2016 targets—high costs (2016 USD).

	Car	Truck	Fleet
BMW	$900	$1,589	$973
CHRYSLER	$648	$931	$826
DAIMLER	$957	$1,769	$1,197
FORD	$643	$500	$578
GENERAL MOTORS	$903	$846	$897
HONDA	$694	$648	$665
NISSAN	$864	$779	$837
PEUGEOT	$470	$699	$574
RENAULT	$911	$1,178	$1,006
SUZUKI	$879	$1,146	$942
TOYOTA	$845	$1,278	$1,088
VOLKSWAGEN	$1,048	$2,075	$1,125
Total	$880	$884	$881

Average incremental cost

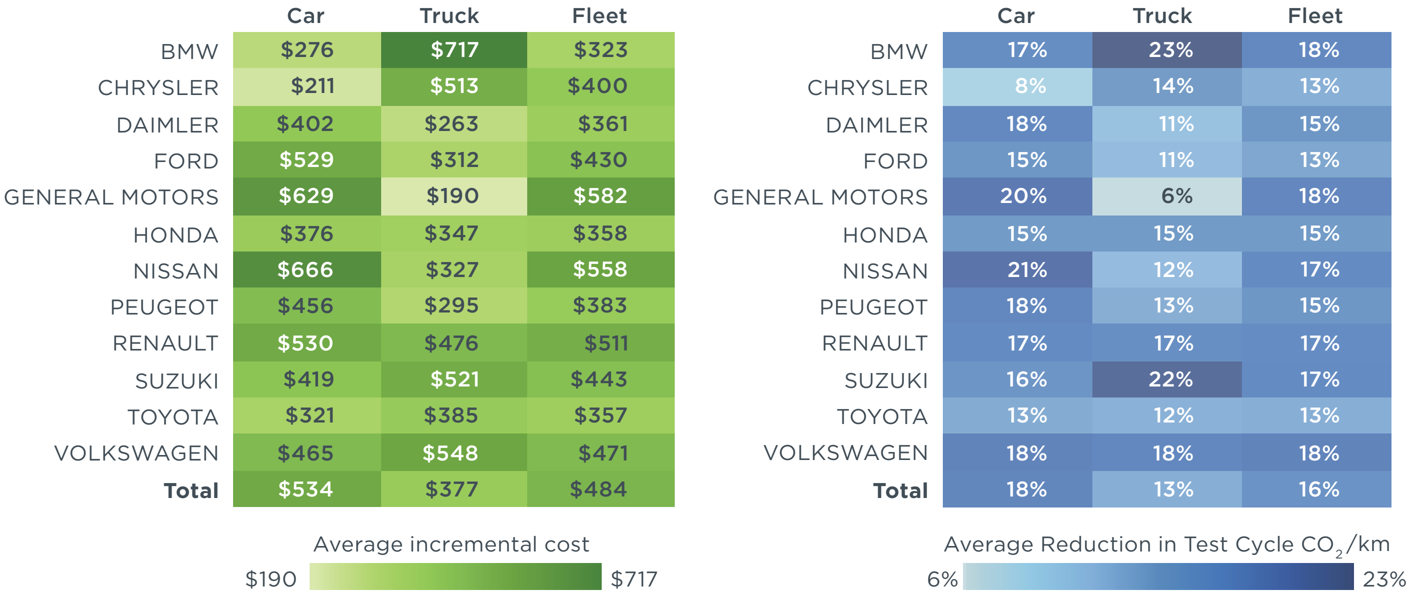
$470 — $2,075

	Car	Truck	Fleet
BMW	13%	11%	13%
CHRYSLER	12%	13%	13%
DAIMLER	11%	14%	12%
FORD	15%	12%	13%
GENERAL MOTORS	19%	13%	18%
HONDA	15%	14%	15%
NISSAN	19%	13%	17%
PEUGEOT	11%	20%	15%
RENAULT	18%	17%	17%
SUZUKI	17%	20%	18%
TOYOTA	13%	13%	13%
VOLKSWAGEN	18%	24%	19%
Total	17%	13%	16%

Average Reduction in Test Cycle CO_2/km

11% — 24%

Table 13. Costs to meet proposed EPA 2021 targets in Mexico with respect to 2016 targets—low costs (2016 USD).



	Car	Truck	Fleet
BMW	$276	$717	$323
CHRYSLER	$211	$513	$400
DAIMLER	$402	$263	$361
FORD	$529	$312	$430
GENERAL MOTORS	$629	$190	$582
HONDA	$376	$347	$358
NISSAN	$666	$327	$558
PEUGEOT	$456	$295	$383
RENAULT	$530	$476	$511
SUZUKI	$419	$521	$443
TOYOTA	$321	$385	$357
VOLKSWAGEN	$465	$548	$471
Total	$534	$377	$484

Average incremental cost

$190 – $717

	Car	Truck	Fleet
BMW	17%	23%	18%
CHRYSLER	8%	14%	13%
DAIMLER	18%	11%	15%
FORD	15%	11%	13%
GENERAL MOTORS	20%	6%	18%
HONDA	15%	15%	15%
NISSAN	21%	12%	17%
PEUGEOT	18%	13%	15%
RENAULT	17%	17%	17%
SUZUKI	16%	22%	17%
TOYOTA	13%	12%	13%
VOLKSWAGEN	18%	18%	18%
Total	18%	13%	16%

Average Reduction in Test Cycle CO_2/km

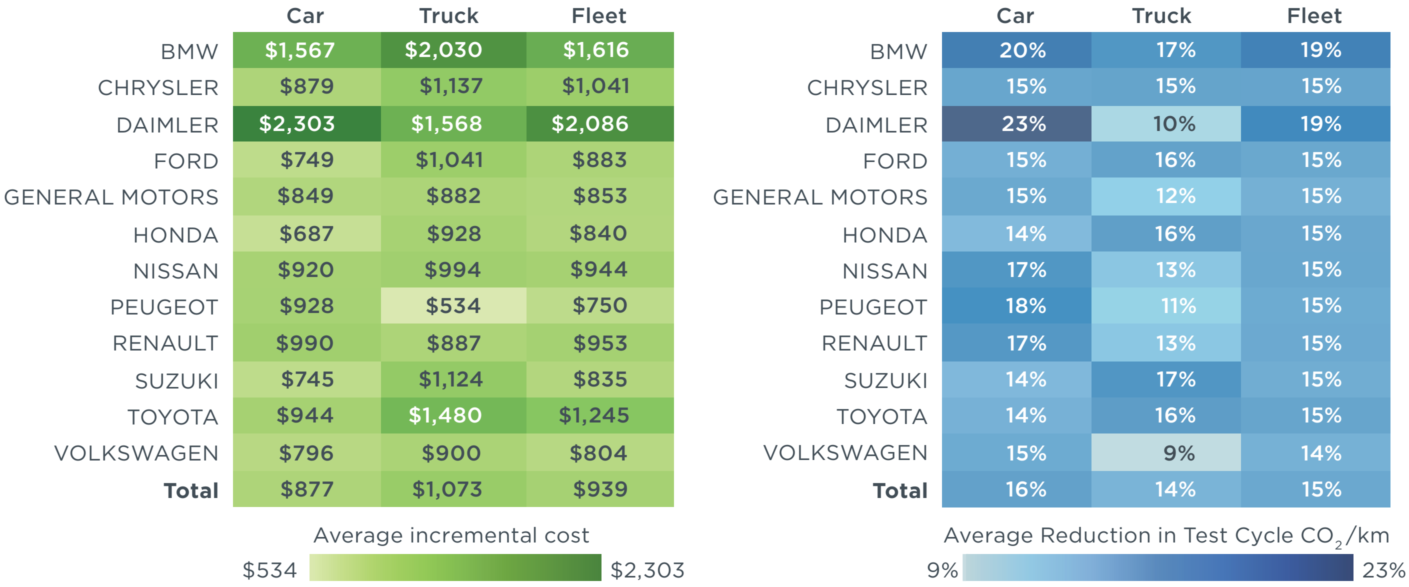
6% – 23%

EPA 2025 costs with respect to EPA 2021 targets

Tables 14 and 15 present the incremental costs and benefits for reaching compliance with EPA 2025 targets with respect to the EPA 2021 targets. As the lowest-cost technology options become fully deployed, the incremental costs of further emissions reductions rise. As a result, both the high-cost and low-cost cases have higher fleet-average costs than the EPA 2021 targets, although EPA 2025 L has a lower average cost than EPA 2021 H; this suggests that further technology research and development will continue to reduce the costs of meeting increasingly stringent emissions standards.

Under the high-cost case, the model projects that the average cost of compliance for the Mexican fleet to meet EPA 2025 targets is $939 per vehicle; costs for cars are lower, averaging $877, versus an average of $1,073 for light trucks. Using updated technology cost data, the average cost of compliance drops to $668 per vehicle overall, $625 for cars, and $763 for trucks (low-cost case). The required CO_2 performance improvement for most manufactures converges to 15%. Only Daimler and BMW show higher numerical requirements under the high-cost case, as their relatively higher EV adoption and use of super credits for EVs is no longer available for 2025 compliance; in the low-cost case, even though EV costs are assumed to be much lower, the EV adoption for these two manufacturers is very small, relying on other types of advanced technologies, which makes the progression look much smoother.

Table 14. Costs to meet proposed EPA 2025 targets in Mexico compared to 2021 targets—high costs (2016 USD).



	Car	Truck	Fleet
BMW	$1,567	$2,030	$1,616
CHRYSLER	$879	$1,137	$1,041
DAIMLER	$2,303	$1,568	$2,086
FORD	$749	$1,041	$883
GENERAL MOTORS	$849	$882	$853
HONDA	$687	$928	$840
NISSAN	$920	$994	$944
PEUGEOT	$928	$534	$750
RENAULT	$990	$887	$953
SUZUKI	$745	$1,124	$835
TOYOTA	$944	$1,480	$1,245
VOLKSWAGEN	$796	$900	$804
Total	$877	$1,073	$939

Average incremental cost

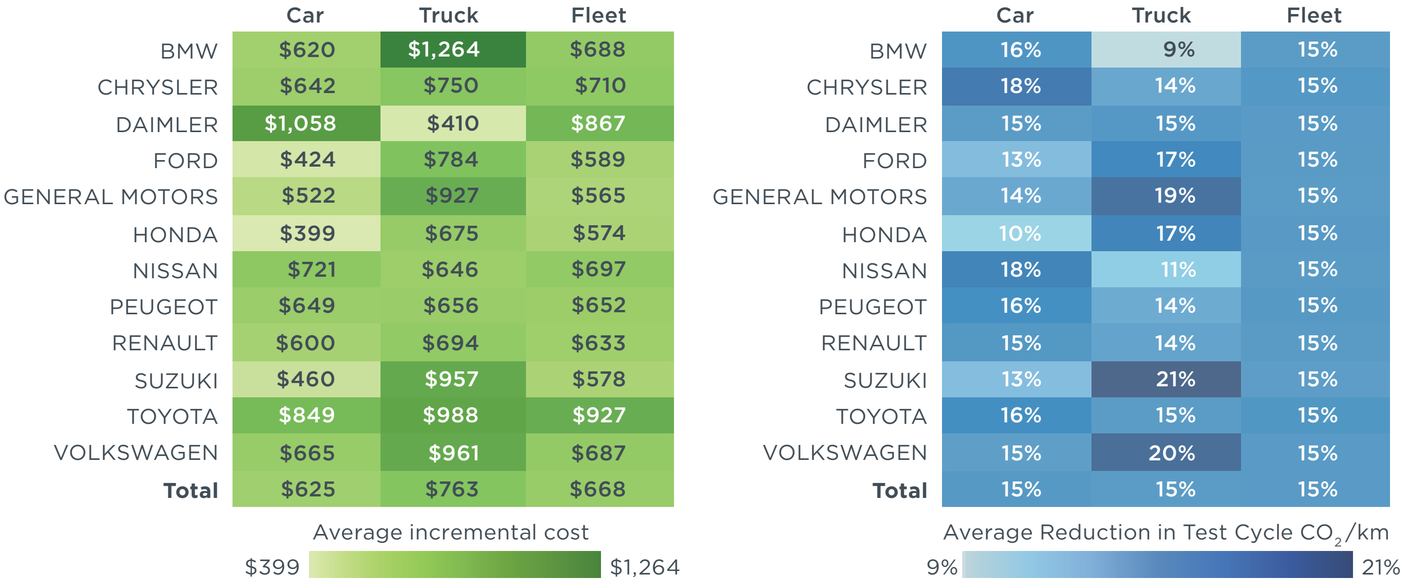
$534 $2,303

	Car	Truck	Fleet
BMW	20%	17%	19%
CHRYSLER	15%	15%	15%
DAIMLER	23%	10%	19%
FORD	15%	16%	15%
GENERAL MOTORS	15%	12%	15%
HONDA	14%	16%	15%
NISSAN	17%	13%	15%
PEUGEOT	18%	11%	15%
RENAULT	17%	13%	15%
SUZUKI	14%	17%	15%
TOYOTA	14%	16%	15%
VOLKSWAGEN	15%	9%	14%
Total	16%	14%	15%

Average Reduction in Test Cycle CO_2/km

9% 23%

Table 15. Costs to meet proposed EPA 2025 targets in Mexico compared to 2021 targets—low costs (2016 USD).



	Car	Truck	Fleet
BMW	$620	$1,264	$688
CHRYSLER	$642	$750	$710
DAIMLER	$1,058	$410	$867
FORD	$424	$784	$589
GENERAL MOTORS	$522	$927	$565
HONDA	$399	$675	$574
NISSAN	$721	$646	$697
PEUGEOT	$649	$656	$652
RENAULT	$600	$694	$633
SUZUKI	$460	$957	$578
TOYOTA	$849	$988	$927
VOLKSWAGEN	$665	$961	$687
Total	$625	$763	$668

Average incremental cost

$399 $1,264

	Car	Truck	Fleet
BMW	16%	9%	15%
CHRYSLER	18%	14%	15%
DAIMLER	15%	15%	15%
FORD	13%	17%	15%
GENERAL MOTORS	14%	19%	15%
HONDA	10%	17%	15%
NISSAN	18%	11%	15%
PEUGEOT	16%	14%	15%
RENAULT	15%	14%	15%
SUZUKI	13%	21%	15%
TOYOTA	16%	15%	15%
VOLKSWAGEN	15%	20%	15%
Total	15%	15%	15%

Average Reduction in Test Cycle CO_2/km

9% 21%

FLEET-AVERAGE COSTS AND BENEFITS OF ALL SCENARIOS

Tables 16 and 17 show the average cost to comply with each of the studied standards for the overall Mexican fleet. It is evident that more stringent targets demand higher adoption of efficient technologies, which increases the costs of compliance but also the benefits and payback to consumers. From an economic standpoint, the most attractive policy option is the one that yields the greatest net benefits (benefits minus costs) to society. As demonstrated in the next section, the net benefits continue to increase through 2025 under both technology pathways considered.

These tables summarize the technology penetration, emissions performance, and associated costs needed to comply with AMIA 2021, EPA 2021 (high and low), and EPA 2025 (high and low) standards. The AMIA 2021 target provides a very small net benefit, which suggests that the AMIA proposal would provide little incentive for manufacturers to modernize their fleets sold in the Mexican market or provide consumers with access to the money-saving technologies that are available in North American markets.

Compliance with the EPA 2021 target results in a Mexican light-duty vehicle fleet that would be 16% more efficient than the one complying with NOM-163 2016, with 25% lower net CO_2 emissions. Depending on the technology assessment input for OMEGA, the technology adoption and cost incurred varies. OMEGA outputs based on the original EPA technology files predict wider adoption of mild hybrids and battery EVs and a reduced benefit from conventional technologies, resulting in higher costs, around $881 per vehicle. OMEGA results based on the updated technology files show a reduction in costs, $484 per vehicle. The update indicates that advances in combustion technologies are enabling substantially lower compliance costs to achieve model year 2021 standards. As shown in Table 16, the primary technology differences in the modeling are related to the lower penetration of hybrid technology. This is largely due to the greater CO_2 reduction benefits at lower costs from advanced combustion technologies such as high-compression Atkinson-cycle engines and cylinder deactivation, as previously shown (Lutsey et al., 2017).

EPA 2025 standards result in a reduction of fleetwide net CO_2 emissions of 38% relative to 2016 emissions. The costs associated with reaching the standard are more similar under the high-cost and low-cost cases but are still lower for the updated technology pathway. Advanced combustion is expected to continue increasing market share beyond the expectations in the EPA 2021 L scenario, reaching 83% to 95% of the market. As under the EPA 2021 L scenario, OMEGA optimization prioritizes advanced combustion technologies because of their greater cost effectiveness. However, by 2025, the rapidly falling costs of EV technologies also make electrification a cost-effective option under the low-cost technology pathway.

Table 16. Technology penetration and costs to meet potential 2021 standards.

Area	Technology	NOM-163	AMIA 2021	EPA 2021 high cost	EPA 2021 low cost
Advanced combustion (non-hybrid)		100%	100%	96%	100%
Hybrid	Mild hybrid	0%	0%	3%	0%
	Full hybrid	0%	0%	0%	0%
Electric	Plug-in hybrid electric	0%	0%	0%	0%
	Battery electric	0%	0%	1%	0%
Incremental technology cost from 2016 standards		$0	$165	$881	$484
Fuel economy, test cycle (km/liter)		16	16	18	18
Fuel economy, real world (km/liter)		12	13	15	15
CO_2 emissions test cycle (g/km)		151	149	127	127
Net CO_2 emissions with productive credits (g/km)		151	144	113	113
Reduction in test cycle CO_2 from 2016 standards		0%	1-2%	16%	16%
Reduction in net CO_2 from 2016 standards		0%	5%	25%	25%

Table 17. Technology penetration and costs to meet potential 2025 standards.

Area	Technology	EPA 2025 high cost	EPA 2025 low cost
Advanced combustion (non-hybrid)		83%	95%
Hybrid	Mild hybrid	16%	2%
	Full hybrid	0%	0%
Electric	Plug-in hybrid electric	0%	0%
	Battery electric	1%	3%
Incremental technology cost from 2021 standards		$939	$668
Incremental technology cost from 2016 standards		$1,821	$1,153
Fuel economy, test cycle (km/liter)		22	22
Fuel economy, real world (km/liter)		18	18
CO_2 emissions test cycle (g/km)		108	108
Net CO_2 emissions with productive credits (g/km)		94	94
Reduction in test cycle CO_2 from 2016 standards		28%	28%
Reduction in net CO_2 from 2016 standards		38%	38%

The discussion of compliance flexibilities in section 2 highlighted the impact that credits can have on standard stringency. Tables 16 and 17 compare the net CO_2 emissions of the scenarios taking into account the productive credits that are assumed to be used, including off-cycle and AC refrigerant credits. As discussed in section 2, AMIA proposes a number of unproductive credits that will not result in actual GHG benefits, substantially reducing the overall impact of the scenario. In all cases, the application of credits increases the benefits of the standards. However, the benefits are much more pronounced under the EPA scenarios because a much greater portion of the credits results in real GHG benefits.

RESULTS OF PAYBACK ANALYSIS

From the consumer perspective, the scenarios analyzed achieve benefits in terms of operational savings due to lower fuel consumption over the lifetime of the vehicle. Under all scenarios, the upfront costs of cleaner technologies can be recouped within a few years of typical use, with further benefits accruing in the following years. Unless otherwise noted, all costs and benefits below are given in 2016 USD.[10]

Both 2021 and 2025 standards would have substantial benefits for buyers of new light-duty vehicles in Mexico. At a fuel price of 0.83 USD/liter (15 MXN/liter) and a 7% discount rate, the average buyer of a model year 2025 vehicle would save approximately $4,000 in fuel costs, compared to initial technology costs of $1,153 to $1,821 (Figure 16). Over 20 years, this represents a net gain of $2,176 to $2,844. More than $1,000 in savings occur in the first 7 to 10 years even under the highest-cost scenarios, meaning that even first owners are likely to see substantial benefits. However, even if the vehicle is sold earlier, the benefits should be reflected in the resale value of the vehicle, because more fuel-efficient vehicles will reduce fuel expenditures for buyers of second-hand vehicles.

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[10] Values in 2010 USD can be converted to 2016 USD by multiplying by a factor of 1.1 (U.S. BLS, 2016).

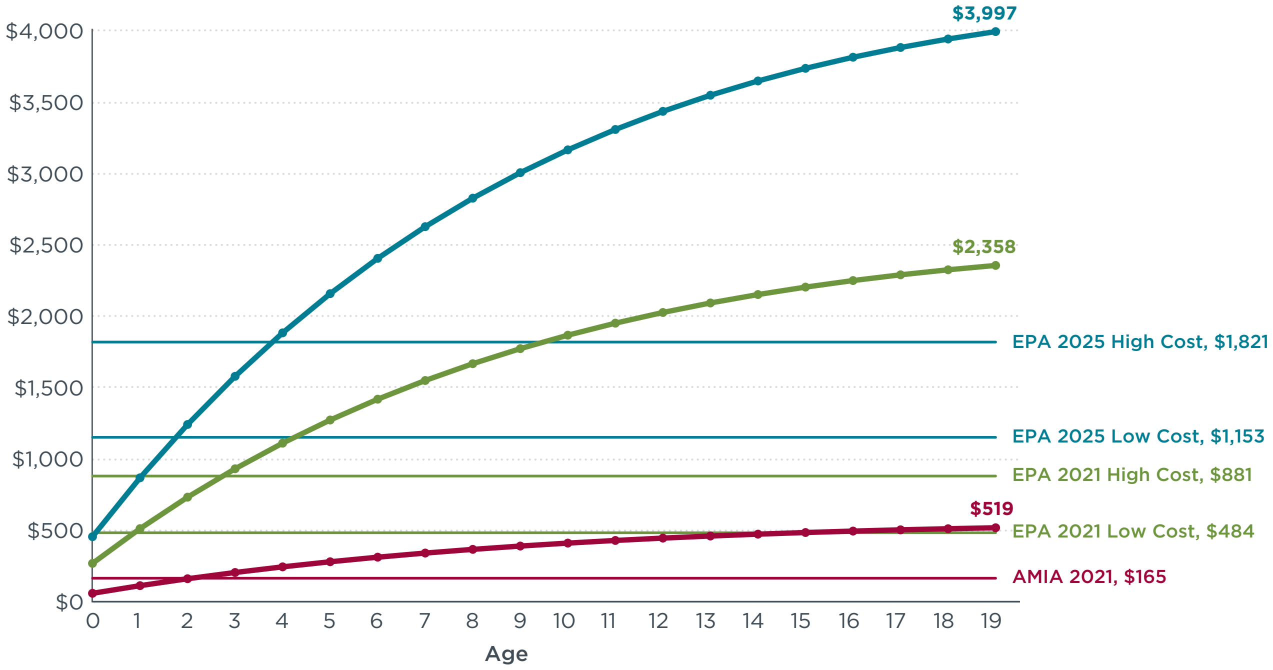

Figure 16. Consumer payback of potential 2021 and 2025 standards. The range of costs reported for EPA 2021 and EPA 2025 corresponds to the “low” and “high” costs reported elsewhere. Fuel savings are not differentiated by cost scenario. The left and right data labels show incremental technology costs and cumulative discounted fuel savings, respectively, relative to 2016 standards.

Another metric of interest for consumers is the length of time it takes to pay back the incremental cost of vehicle technology.[11] Payback periods provide a helpful metric for how long it could take for vehicle efficiency technologies to effectively pay for themselves. The average consumer payback period can be found by looking at the intersection of cumulative discounted fuel savings and the incremental cost of vehicle technology. Assuming a 7% discount rate applied to fuel savings, EPA 2021 standards would fully pay back the incremental cost within 1 to 3 years of operation, and EPA 2025 standards would pay back this cost within 2 to 4 years of operation.

Although the consumer perspective is important to consider, regulations should also account for the net social benefits of policy outcomes. Figure 17 shows the net benefits of each scenario for a single model year (either 2021 or 2025), equal to the cumulative value of fuel savings and climate benefits minus the initial cost of vehicle technology. The climate portion of these benefits is shown under four scenarios for the social cost of carbon (see the discussion of Table 9 for a description of these scenarios). For example, under a scenario in which future fuel savings and climate damages are discounted at a rate of 5% per year, the EPA 2025 targets for model year 2025 vehicles would generate net benefits valued at $5.5 billion to $6.8 billion over 20 years. These net benefits could be up to $11 billion under a scenario with higher-than-expected climate damages (3% 95th percentile).

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[11] Note that many considerations factor into manufacturer suggested retail prices and end user prices; therefore, the incremental cost of technology may not translate into a one-for-one increase in vehicle purchase price.

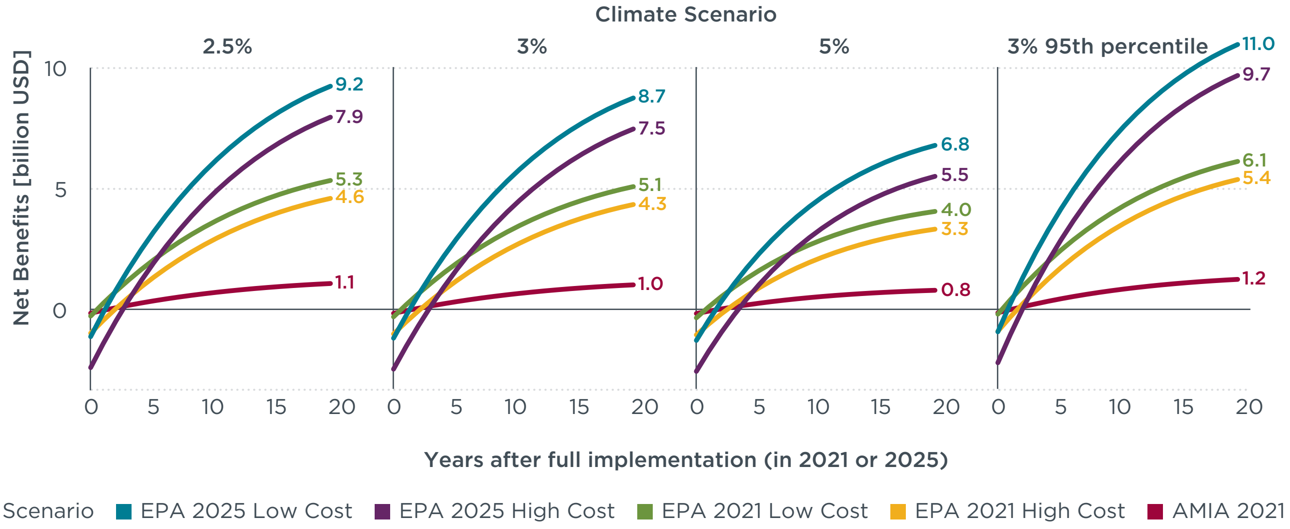

Figure 17. Net benefits to society of regulatory targets for model year 2021 and 2025 vehicles (2016 USD).

Table 18 compares the fleetwide costs and benefits of the evaluated targets for model year 2021 or 2025 vehicles over a range of social costs of carbon and consumer discount rate assumptions. If all model years 2018 through 2025 were accounted for as well, using a linear extrapolation, the cumulative net benefits of adoption of standards would be on the order of 25 billion to 50 billion USD. The EPA 2025 targets yield the highest net benefits of the evaluated targets—a conclusion that holds across the various assumptions for social cost of carbon and discount rate. The benefits of the EPA 2025 targets for model year 2025 vehicles are 3 to 6 times the costs under all scenarios.

Table 18. Sensitivity of net benefits to climate and discounting assumptions for a single model year's fleet.

Scenario	Discount rate	Climate scenario	Fleet technology cost	Fleet fuel savings	Fleet climate benefits	Fleet net benefits
			(billion 2016 USD)			
AMIA 2021	**3%**	2.5%	0.29	1.2	0.17	1.1
		3%			0.11	1.0
		3% 95th percentile			0.34	1.2
	5%	5%		1	0.04	0.78
EPA 2021 low cost	**3%**	2.5%	0.86	5.4	0.78	5.3
		3%			0.52	5.1
		3% 95th percentile			1.6	6.1
	5%	5%		4.7	0.16	4.0
EPA 2021 high cost	**3%**	2.5%	1.6	5.4	0.77	4.6
		3%			0.52	4.3
		3% 95th percentile			1.6	5.4
	5%	5%		4.7	0.16	3.3
EPA 2025 low cost	**3%**	2.5%	2.2	9.9	1.6	9.2
		3%			1.1	8.7
		3% 95th percentile			3.3	11
	5%	5%		8.6	0.35	6.8
EPA 2025 high cost	**3%**	2.5%	3.5	9.9	1.6	7.9
		3%			1.1	7.5
		3% 95th percentile			3.3	9.7
	5%	5%		8.6	0.35	5.5

As discussed above, the more stringent vehicle efficiency targets are associated with both higher benefits and higher costs. From an economic standpoint, the best option is the one with the greatest net benefits to society (i.e., the highest value added). As shown in Table 19, while the AMIA 2021 scenario would have the lowest costs (0.3 billion USD), it would also have the lowest fuel savings and net benefits. In contrast, the EPA 2025 scenario has the highest costs (2.2 billion to 3.5 billion USD) but also the greatest fuel savings and net benefits. Both the EPA 2021 and EPA 2025 targets are justified even when considering only consumer fuel savings; however, consideration of climate benefits adds approximately 5% to 30% to the total benefits.

Table 19. Range of net benefits for a single model year (2021 and 2025) considering different regulatory targets. Range of technology costs includes low and high costs for EPA 2021 and EPA 2025. Ranges of fuel savings and climate benefits account for variation in discount rates and climate scenarios.

Scenario	Technology cost	Fuel savings	Climate benefits	Net benefits
	(billion 2016 USD)			
AMIA 2021	0.29	1 to 1.2	0.04 to 0.34	0.78 to 1.2
EPA 2021	0.86 to 1.6	4.7 to 5.4	0.16 to 1.6	3.3 to 6.1
EPA 2025	2.2 to 3.5	8.6 to 9.9	0.35 to 3.3	5.6 to 11

5. CONCLUSIONS

In support of Mexico's commitment to reduce GHG emissions from the rapidly growing passenger vehicle fleet, we evaluated the costs and benefits of extending Mexico's light-duty vehicle efficiency program to 2025 according to the U.S. standards. Costs were evaluated by adapting EPA's OMEGA model for Mexico. The version of the model used incorporated the technology pathways that had been updated in support of the technical assessment report finalized in 2016. To capture the latest research and findings on the benefits and costs of emerging and improving technologies, this analysis also considered the technology package and cost dataset developed by the ICCT and finalized in 2017. The increasingly rapid pace of technology improvement has resulted in much faster deployment of technologies, and at lower costs, than had been predicted when the standards were first adopted in the United States, and there is every indication that the costs will continue to fall and that the benefits will continue to grow. Benefits were calculated following classic payback analysis methods based on fuel savings achieved by implementing the standards and projected costs of fuel.

The technology projections show that improvements to the internal combustion engine, along with more efficient transmissions, are the core of the technology changes to reach even the most ambitious targets. Although updated cost estimates show falling costs, electrification of the powertrain is still expected to be kept at a minimum. EVs are expected to be required by <1% to 3% (depending on the technology cost package chosen) of the Mexican fleet by 2025 and only in a handful of vehicle segments. Some of the technologies that may be superseded by improvements to internal combustion engines, such as start-stop systems, mild hybrids, and even turbocharging, may actually find wider deployment in Mexico because of their performance advantages in highly congested and high-altitude conditions.

The comparison clearly demonstrates the importance of regulatory design, especially concerning manufacturer flexibilities in the form of credits. Well-designed credits offer the automaker flexibility to choose the lowest-cost option to comply with the standards while still producing real GHG reductions. Poorly designed credits quickly erode the stringency and the consumer and social benefits of the program. Most of the credits included in the EPA program allow automakers credit for adoption of technologies that will result in real GHG savings and in many cases also fuel economy savings; these savings are not apparent on the official test cycle.

We find that the EPA 2025 program would achieve a fleet-average test cycle fuel economy for model year 2025 vehicles of 22 km/liter or 108 gCO_2/km. This is a reduction of fuel consumption for new vehicles of 28% (including efficient air conditioning and off-cycle benefits) and a reduction of net CO_2/km (accounting for GHG benefits of off-cycle improvements and low-carbon refrigerants) of 38% from a 2016 baseline. Relative to a 2016 baseline, the fleet-average per-vehicle costs would be between $1,153 and $1,821, similar to the anticipated costs in the rest of the North American market.

The average new vehicle sold in 2025 would save consumers $4,000 (72,000 MXN) over 20 years, equivalent to 2.2 to 3.5 times the cost of additional vehicle technology, with net savings of $2,000 to $3,000. Accounting for both the fuel savings and the climate benefits, the savings to society for a single model year (2025) would be 6 billion to 11 billion USD, with cumulative benefits of 25 billion to 50 billion USD for a standard regulating model years 2018 through 2025.

As the rapid pace of technology improvement demonstrates, Mexico cannot afford to fall behind on technology. Stringent, technology-forcing standards can only help improve the competitiveness of the automotive manufacturing and supplier industry in Mexico. These standards are a critical piece of Mexico's climate commitment and will also help increase energy security, a new and growing concern for Mexico. Most important, the adoption of well-designed, stringent GHG emissions standards for passenger vehicles will have tremendous benefits for consumers and society alike.

ACRONYMS AND ABBREVIATIONS

0sp	electric vehicle in which an electric motor is directly connected to the drive wheels, obviating the need for a transmission
4VDI3	four-valve DOHC I3 engine
4VDI4	four-valve DOHC I4 engine
4sp	four-speed transmission
Aero1	aerodynamic drag reduction, level 1
Aero2	aerodynamic drag reduction, level 2
AT	automatic transmission
ATK1	Atkinson-cycle engine, level 1
ATK2	Atkinson-cycle engine, level 2
CAFE	Corporate Average Fuel Economy, the U.S. fuel economy regulatory program; as used in this report, CAFE includes all associated definitions, testing, and reporting requirements
CO_2	carbon dioxide
CVT	continuously variable transmission, able to change gear ratio continuously between a maximum and minimum value
DCP	dual cam phasers
DOHC	4v dual overhead cam engine with four valves per cylinder
DVVL	discrete variable valve lift
EFR1	engine friction reduction, level 1
EFR2	engine friction reduction, level 2
EGR	exhaust gas recirculation
EPS	electric power steering
EV	vehicle with electric motor exclusively powered by energy stored in a battery; examples include Tesla and Nissan Leaf
EV75 mile	electric vehicle with a 75-mile range
EV100 mile	electric vehicle with a 100-mile range
FE	fuel efficiency
GDI	gasoline direct injection
GHG	greenhouse gas(es)
HEG	high-efficiency gearbox
HEV	hybrid electric vehicle
IACC1	improved accessories, level 1
IACC2	improved accessories, level 2
I4	inline engine constructed as a single row of four cylinders
kW	kilowatt, an SI unit for power
LDB	low-drag brakes

LRRT1	low-rolling-resistance tires level 1
LRRT2	low-rolling-resistance tires, level 2
LT	light truck
LUB	low-friction lubricant
MHEV	mild hybrid electric vehicle
MPFI	multi-port fuel injection
MPG	miles per gallon
MT	manual transmission
OHV 2v	overhead valve engine with two valves per cylinder
PV	passenger vehicle
REEV20	range-extended electric vehicle (plug-in hybrid electric vehicle) with a 20-mile all-electric range
REEV40	range-extended electric vehicle (plug-in hybrid electric vehicle) with a 40-mile all-electric range
SAX	secondary axle disconnect
SOHC 2v	single overhead cam engine with two valves per cylinder
SOHC 3v	single overhead cam engine with three valves per cylinder
SS	start-stop (idle off) technology
TDS18	18-bar turbocharged downsized engine
TDS24	24-bar turbocharged downsized engine
TDS27	27-bar turbocharged downsized engine
V6	six-cylinder engine constructed as two banks of three cylinders offset at an angle (typically 60 to 90 degrees) from the crankshaft
V8	eight-cylinder engine constructed as two banks of four cylinders offset at an angle (typically 60 to 90 degrees) from the crankshaft
VKT	vehicle kilometers traveled

REFERENCES

AMIA (2016). *Proyecto de Modificación de la Norma Oficial Mexicana NOM-163-SEMARNAT-ENER-SCFI-20XX, Emisiones de bióxido de carbono (CO_2) provenientes del escape y su equivalencia en términos de rendimiento de combustible, aplicable a vehículos ligeros nuevos de peso bruto vehicular de hasta 3 857 kilogramos.* Undated draft with revisions from 2016.

Declaración de Líderes de América del Norte sobre la Alianza del Clima, Energía Limpia y Medio Ambiente (2016); www.gob.mx/cms/uploads/attachment/file/110477/Declaraci_n_Clima__Energ_a_Limpia_y_Medio_Ambiente.pdf.

Diario Oficial de la Federación (DOF) (2013). *NORMA Oficial Mexicana NOM-163-SEMARNAT-ENER-SCFI-2013, Emisiones de bióxido de carbono (CO_2) provenientes del escape y su equivalencia en términos de rendimiento de combustible, aplicable a vehículos automotores nuevos de peso bruto vehicular de hasta 3 857 kilogramos*; http://dof.gob.mx/nota_detalle.php?codigo=5303391&fecha=21/06/2013.

Diario Oficial de la Federación (DOF) (2016). *AVISO mediante el cual se dan a conocer los parámetros para el cálculo de las emisiones de bióxido de carbono (CO)* [sic] *en los vehículos automotores ligeros nuevos con peso bruto vehicular que no exceda los 3 857 kilogramos, que utilizan gasolina o diésel como combustible cuyo año-modelo sea 2017*; http://dof.gob.mx/nota_detalle.php?codigo=5442432&fecha=24/06/2016.

German, J. (2014). *More efficient new Ford F150: A shift from the old horsepower wars?* International Council on Clean Transportation, Washington, DC; www.theicct.org/blogs/staff/more-efficient-new-ford-f150-shift-old-horsepower-wars

Hansen, J., et al. (2016). Ice melt, sea level rise and superstorms: Evidence from paleoclimate data, climate modeling, and modern observations that 2°C global warming could be dangerous. *Atmospheric Chemistry and Physics, 16,* 3761–3812; doi:10.5194/acp-16-3761-2016.

Iliff, L. (2017). Mexico sells record 1.6 million vehicles in 2016. *Automotive News*, January 5; www.autonews.com/article/20170105/RETAIL01/170109917/mexico-sells-record-1.6-million-vehicles-in-2016.

INECC (2014). Elaboración del Inventario Nacional de Emisiones de Fuentes Móviles para México 2013 y proyección 2030 mediante el uso del modelo Motor Vehicle Emission Simulator (MOVES). www.inecc.gob.mx/descargas/calaire/2014_inf_fin_moves.pdf

Instituto Nacional de Ecologia y Cambio Climático (INECC) (2015). Database of Vehicle Sales.

Isenstadt, A., et. Al. (2016). *Lightweighting technology development and trends in U.S. passenger vehicles*. International Council on Clean Transportation, Washington, DC; http://www.theicct.org/lightweighting-technology-development-and-trends-us-passenger-vehicles

Lutsey, N., Meszler, D., Isenstadt, A., German, J., & Miller, J. (2017). *Efficiency Technology and Cost Assessment for U.S. 2025–2030 Light-Duty Vehicles*. International Council on Clean Transportation, Washington, DC; www.theicct.org/US-2030-technology-cost-assessment.

México (2015). Intended Nationally Determined Contribution; www.gob.mx/cms/uploads/attachment/file/162973/2015_indc_ing.pdf.

National Research Council (NRC) (2011). *Assessment of Fuel Economy Technologies for Light-Duty Vehicles*. National Academies Press, Washington, DC; doi:10.17226/12924.

Nelson, M. (2016). "Mexico fuel prices list." Data retrieved March 13, 2016; www.mexicomike.com/database/runner/public/mx_fuel_prices_list.php.

TomTom (2016). TomTom Traffic Index; www.tomtom.com/es_mx/trafficindex/list.

U.S. Bureau of Labor Statistics (BLS) (2016). *CPI Inflation Calculator*; http://data.bls.gov/cgi-bin/cpicalc.pl?

U.S. Energy Information Administration (EIA) (2015). Annual Energy Outlook 2015. www.eia.gov/outlooks/aeo/pdf/0383(2015).pdf

U.S. Environmental Protection Agency (EPA) (2010). Chapter 6: Discounting future benefits and costs. In *Guidelines for Preparing Economic Analyses*; https://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0568-50.pdf/$file/EE-0568-50.pdf.

U.S. Environmental Protection agency (EPA) (2012). *Regulatory Impact Analysis: Final Rulemaking for 2017–2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards* (EPA-420-R-12-016); https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100EZI1.txt.

U.S. Environmental Protection Agency (EPA) (2015a). *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2015* (EPA-420-R-15-016); www.epa.gov/fueleconomy/download-co2-and-fuel-economy-trends-report-1975-2015.

U.S. Environmental Protection Agency (EPA) (2015b). "Social Cost of Carbon." Fact Sheet; www3.epa.gov/climatechange/Downloads/EPAactivities/social-cost-carbon.pdf.

U.S. Environmental Protection Agency (2016). *Optimization Model for Reducing Emissions of Greenhouse Gases from Automobiles (OMEGA)*, version v1.4.56; www.epa.gov/regulations-emissions-vehicles-and-engines/optimization-model-reducing-emissions-greenhouse-gases.

U.S. Environmental Protection Agency, National Highway Traffic Safety Administration, and California Air Resources Board (EPA/NHTSA/CARB) (2016a). *Draft Technical Assessment Report: Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022–2025*; https://nepis.epa.gov/Exe/ZyPDF.cgi/P100OXEO.PDF?Dockey=P100OXEO.PDF.

U.S. Environmental Protection Agency, National Highway Traffic Safety Administration, and California Air Resources Board (EPA/NHTSA/CARB) (2016b). *Draft Technical Assessment Report: Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022–2025, Appendix* (EPA-420-D-16-900app); https://nepis.epa.gov/Exe/ZyPDF.cgi/P100OYCH.PDF?Dockey=P100OYCH.PDF.

ANNEX A: TECHNOLOGIES PROJECTED BY OMEGA

Source: EPA's joint technical support document (EPA, 2016).[12],[13]

Technology	Code	Description
Turbocharging and downsizing	TDS 18, TDS 24, TDS 27	Turbocharging increases the specific power level, allowing a reduced engine size while maintaining performance. OMEGA considers three levels of boost—18-bar, 24-bar, and 27-bar BMEP (brake mean effective pressure)—as well as three levels of downsizing: 18-bar BMEP is applied with 33% downsizing, 24-bar BMEP is applied with 50% downsizing, and 27-bar BMEP is applied with 56% downsizing. EGR is also used for the 24- and 27-bar systems, and the 27-bar system uses a two-stage turbocharger. Downsizing represents a change in engine configuration from four cylinders (I4) to smaller I4 or I3, from V6 to I4, and from V8 to V6 or I4. In addition to the efficiency benefits, turbocharging improves performance, especially in steep and high-altitude conditions.[12]
Gasoline direct injection	DI	GDI injects fuel at high pressure directly into the combustion chamber. This provides evaporative cooling of the air/fuel charge within the cylinder, which allows for higher compression ratios and increased thermodynamic efficiency. GDI is generally paired with TDS to further support engine downsizing for improved efficiency.
Automatic transmissions	AT6, AT8	Conventional ATs are optimized by adding additional forward gears, which reduces gear ratio spacing and increases the overall gear ratio spread. This enables the engine to operate more efficiently over a broader range of vehicle operating conditions, with options for six and eight gears. In addition to the efficiency benefits, the higher number of gears improves performance, especially in steep and high-altitude conditions.[13]
Manual Transmission	MT	Improvements to MTs include 6-speed manual transmissions, which offer an additional gear ratio, often with a higher (numerically lower) overdrive gear ratio than that of the fifth gear in a baseline 5-speed manual transmission.
Advanced transmissions –Dual clutch transmission	DCT6, DCT8	DCTs resemble manual transmissions, but instead of the driver operating a foot-pedal clutch, the vehicle's computer controls shifting and launch functions. Because DCTs use separate clutches for even-numbered and odd-numbered gears, the next expected gear is preselected, which allows for faster, smoother shifting.
Advanced diesel	DSL	Diesel engines have good fuel efficiency due to reduced pumping losses and a combustion cycle that operates at a high compression ratio, with a very lean air/fuel mixture. This technology requires the addition of relatively costly emissions control equipment, including NO_x after-treatment and diesel particulate filters.
Start-stop system	SS	Also known as idle-stop or 12V micro hybrid and commonly implemented as a 12-volt belt-driven integrated starter-generator, this is the most basic hybrid system that facilitates idle-stop capability. This system replaces a conventional alternator with an enhanced-power starter/alternator, both belt-driven, and a revised accessory drive system.
Mild-hybrid electric vehicle	MHEV	MHEVs provide regenerative braking and acceleration assist capacity in addition to idle-stop capability. A higher-voltage battery is used, with greater energy capacity than baseline automotive batteries. The higher voltage allows the use of a smaller, more powerful electric motor and reduces the weight of the motor, inverter, and battery wiring harnesses. This system replaces a standard alternator with an enhanced-power, higher-voltage, higher-efficiency belt-driven starter. The battery capacity is smaller than that of HEV batteries.

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[12] Turbocharging boost increases the air pressure in the inlet manifold, eliminating altitude performance degradation. At the same time, turbocharging provides more torque at a lower engine rpm, increasing performance during hill climbing.

[13] The wider gear ratio range allows for a steeper numeric first gear, which provides more torque multiplication for vehicle start from rest. The smaller steps between gears enable the engine to stay at higher rpm after a shift, increasing power.

Technology	Code	Description
Hybrid electric vehicle	HEV	A full hybrid vehicle has larger-capacity electric motors and batteries, enabling higher rates of regenerative braking energy and acceleration assist, as well as limited operation on the electric motor alone. An example of a hybrid vehicle is the Toyota Prius.
Plug-in hybrid electric vehicle	PHEV	PHEVs are hybrid electric vehicles with the means to charge their battery packs from an outside source of electricity (usually the electric grid). These vehicles have larger battery packs than HEVs with more energy storage and a greater capability to be discharged.
Electric vehicle	EV	EVs are vehicles with all drive and other systems powered by energy-optimized batteries charged primarily from grid electricity. OMEGA includes EVs with ranges of 75, 100, and 150 miles as potential technologies.
Low-rolling-resistance tires, level 2	LRRT2	Relative to the now-common LRRTs available on baseline vehicles, second-generation LRRTs offer further reduction of frictional losses associated with the energy dissipated in the deformation of the tires under load. LRRTs tend to be stiffer than conventional tires, giving them more resistance to rough roads.
High-efficiency gearbox	HEG	Improvement in seals, bearings, and clutches, surface super finishing of gearbox parts, and advances in lubrication are intended to reduce frictional and other parasitic load in the system for an automatic, DCT, or manual transmission
Improved accessories, level 2	IACC2	Second-generation improved accessories include high-efficiency alternators, electrically driven (i.e., on-demand) water pumps and cooling systems, and alternator regenerative braking. This excludes other electrical accessories such as electric oil pumps and electrically driven air conditioner compressors.
Engine friction reduction, level 2	EFR2	The second generation of components to reduce engine friction includes low-tension piston rings, roller cam followers, improved material coatings, more optimal thermal management, piston surface treatments, and other improvements in the design of engine components and subsystems that improve engine operation.
Cooled exhaust gas recirculation	EGR	Adopted with boost, EGR increases the exhaust gas recirculation rate used in the combustion process to increase thermal efficiency and reduce pumping losses. Levels of exhaust gas recirculation approach 25% by volume in the highly boosted engines modeled.
Active aerodynamics	AERO	Reducing the aerodynamic drag of a vehicle reduces fuel consumption. OMEGA considers two levels of aerodynamic improvements: changes to vehicle shape (which are constrained primarily by design considerations and should have zero implementation cost), and active aerodynamics technologies such as active grill shutters. Active grill shutters close off the area behind the front grill under highway driving conditions, reducing vehicle aerodynamic drag and thus fuel consumption.
High-compression Atkinson cycle	ATK	An Atkinson-cycle engine trades decreased power for increased efficiency. Essentially, the intake valve remains open for a longer duration on the intake stroke and closes during the normal compression stroke. This results in an effective compression ratio that is less than the expansion ratio during the power stroke, and allows the geometric compression ratio to be increased. This allows more work to be extracted per volume of fuel, relative to a typical Otto-cycle engine. However, because of a smaller trapped air mass (a consequence of air being forced out of the cylinder through the intake valve early in the compression stroke), the power density in the Atkinson cycle is lower than in the Otto cycle. Increasing the compression ratio can partially compensate for this drawback.
Weight reduction	WR	Vehicle weight reduction (also referred to as downweighting or lightweighting) reduces the energy needed to overcome inertial forces, thus yielding lower fuel consumption and GHG emissions. Lightweighting was modeled in OMEGA assuming per-vehicle changes of 0%, 5%, 10%, 15%, and 20%; the maximum, 20%, was applied only to 2025 vehicles.

ANNEX B: EXAMPLE TECHNOLOGY PACKAGES

Tech package number	OMEGA technology package components for vehicle type 2	Transmission	Cost in 2021 (2010 USD)	CO_2 reduction
0	Passenger Car (Auto) 4VDI4 with MPFI+4sp (Baseline Package)	4sp AT	$0	0.0%
1	Auto 4VDI4+X1+DCP+WR5	Auto, DCT, CVT; 6 speed	$395	21.78%
2	Auto 4VDI4+X1+DCP+WR5	Auto, DCT, CVT; 7, 8, 9 speed	$151	7.58%
3	Auto 4VDI4+X2+DCP+WR5	Auto, DCT, CVT; 7, 8, 9 speed	$53	2.26%
4	Auto 4VDI4+X1+DCP+WR5	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$392	12.72%
5	Auto 4VDI4+X2+DCP+WR10	Auto, DCT, CVT; 7, 8, 9 speed	$119	3.28%
6	Auto 4VDI4+X2+DCP+Deac+WR10	Auto, DCT, CVT; 7, 8, 9 speed	$109	2.76%
7	Auto 4VDI4+X3+DCP+WR10	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$341	8.00%
8	Auto 4VDI4+X4+DCP+Deac+WR10	Auto, DCT, CVT; 7, 8, 9 speed	$222	4.55%
9	Auto 4VDI4+X2+DCP+Deac+GDI+ATK2+EGR+WR10	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$981	16.01%
10	Auto 4VDI4+X3+DCP+Deac+GDI+ATK2+EGR+WR10	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$849	13.53%
11	Auto 4VDI4+X4+DCP+Deac+WR15	Auto, DCT, CVT; 7, 8, 9 speed	$249	3.58%
12	Auto 4VDI4+X5+DCP+Deac+SS+WR15	Auto, DCT, CVT; 7, 8, 9 speed	$385	3.19%
13	Auto 4VDI4+X5+DCP+Deac+GDI+SS+ATK2+OC1+WR15	Auto, DCT, CVT; 7, 8, 9 speed	$493	4.62%
14	Auto 4VDI4+X1+DCP+WR10	Auto, DCT, CVT; 7, 8, 9 speed	$119	3.32%
15	Auto 4VDI4+X1+DCP+Deac+WR10	Auto, DCT, CVT; 7, 8, 9 speed	$109	2.76%
16	Auto 4VDI4+X1+DCP+Deac+WR15	Auto, DCT, CVT; 7, 8, 9 speed	$249	3.48%
17	Auto 4VDI4+X2+DCP+Deac+WR15	Auto, DCT, CVT; 7, 8, 9 speed	$249	3.43%
18	Auto 4VDI4+X1+DCP+Deac+SS+WR15	Auto, DCT, CVT; 7, 8, 9 speed	$315	2.33%
19	Auto 4VDI4+X2+DCP+Deac+SS+WR15	Auto, DCT, CVT; 7, 8, 9 speed	$315	2.33%
20	Auto 4VDI4+X3+DCP+Deac+GDI+ATK2+EGR+WR15	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$249	3.62%
21	Auto 4VDI4+X2+DCP+Deac+GDI+ATK2+EGR+WR15	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$249	3.43%
22	Auto 4VDI4+X2+DCP+Deac+GDI+SS+ATK2+EGR+WR15	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$315	2.29%
23	Auto 4VDI4+X3+DCP+Deac+GDI+SS+ATK2+EGR+WR15	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$315	2.17%
24	Auto 4VDI4+X5+DCP+Deac+SS+SAX+OC1+WR15	Auto, DCT, CVT; 7, 8, 9 speed	$176	0.80%
25	+X6+EV75 mile+WR20%+0sp		$8,407	100.00%
26	Auto 4VDI4+X7+DCP+Deac+SAX+WR15	Auto, DCT, CVT; 7, 8, 9 speed	$(96)	1.70%
27	Auto 4VDI4+X7+DCP+Deac+SS+WR15	Auto, DCT, CVT; 7, 8, 9 speed	$220	1.45%
28	+X6+EV100 mile+WR20%+0sp		$9,260	100.00%
29	Auto 4VDI4+X4+DCP+Deac+GDI+SS+ATK2+EGR+WR15	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$53	2.28%
30	Auto 4VDI4+X7+DCP+Deac+SS+SAX+WR15	Auto, DCT, CVT; 7, 8, 9 speed	$166	1.78%

Tech package number	OMEGA technology package components for vehicle type 2	Transmission	Cost in 2021 (2010 USD)	CO$_2$ reduction
31	+X6+EV100 mile+WR20%+0sp		$8,943	100.00%
32	Auto 4VDI4+X5+DCP+Deac+GDI+SS+SAX+ATK2+OC2+WR15	Auto, DCT, CVT; 7, 8, 9 speed	$212	0.75%
33	Auto 4VDI3+X7+DCP+DVVL+GDI+SS+SAX+TDS18+WR15	Auto, DCT, CVT; 7, 8, 9 speed	$779	5.68%
34	Auto 4VDI3+X7+DCP+DVVL+GDI+SS+SAX+TDS18+WR15	Auto, DCT, CVT; 7, 8, 9 speed	$684	4.92%
35	Auto 4VDI4+X5+DCP+Deac+GDI+MHEV48V+ATK2+TURBM+EGR+OC2	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$1,835	12.45%
36	EV200 mile+WR20%+0sp		$12,149	100.00%
37	Auto 4VDI4+X4+DCP+Deac+GDI+SS+ATK2+EGR+WR15	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$53	2.28%
38	Auto 4VDI4+X5+DCP+Deac+GDI+MHEV48V+ATK2+EGR+OC2+WR15	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$880	4.61%
39	Auto 4VDI4+X5+DCP+Deac+GDI+SS+ATK2+TURBM+EGR+OC2	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$290	2.33%
40	Auto 4VDI4+X4+DCP+Deac+GDI+SS+ATK2+TURBM+EGR+OC2	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$1,099	5.91%
41	Auto 4VDI4+X2+DCP+Deac+GDI+SS+ATK2+TURBM+EGR+WR15	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$902	6.04%
42	Auto 4VDI4+X7+DCP+DVVL+GDI+HEV+SAX+ATK1+WR15	Auto, DCT, CVT; 7, 8, 9 speed	$2,778	16.58%
43	Auto 4VDI4+X8+DCP+DVVL+GDI+ATK1+REEV40+WR20	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$11,308	70.77%
44	Auto 4VDI4+X8+DCP+DVVL+GDI+ATK1+REEV40+WR20	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$11,161	69.47%
45	Auto 4VDI4+X3+DCP+Deac+GDI+MHEV48V+SAX+ATK2+TURBM+EGR	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$1,609	9.52%
46	Auto 4VDI4+X9+DCP+DVVL+GDI+HEV+SAX+ATK1+WR15	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$2,084	9.08%
47	Auto 4VDI4+X8+DCP+DVVL+GDI+ATK1+REEV20+WR20	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$6,020	44.28%
48	Auto 4VDI4+X9+DCP+DVVL+GDI+HEV+SAX+ATK1+WR15	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$1,664	4.46%
49	Auto 4VDI4+X8+DCP+DVVL+GDI+ATK1+REEV20+WR20	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$7,275	41.64%
50	Auto 4VDI4+X5+DCP+Deac+GDI+MHEV48V+SAX+ATK2+TURBM+EGR	Auto, DCT, CVT; 7, 8, 9 speed; high eff.	$95	0.39%

Note: X1=LUB+EFR1+LRRT1+IACC1+EPS+Aero1+LDB

X2=LUB+EFR1+LRRT2+IACC1+EPS+Aero1+LDB

X3=LUB+EFR1+LRRT1+IACC2+EPS+Aero2+LDB

X4=LUB+EFR1+LRRT2+IACC2+EPS+Aero2+LDB

X5=+EFR2+LRRT2+IACC2+EPS+Aero2+LDB

X7=+EFR2+LRRT2+IACC1+EPS+Aero1+LDB

X8=+EFR2+LRRT2+IACC1+EPS+Aero2+LDB
X9=LUB+EFR1+LRRT2+IACC1+EPS+Aero2+LDB