WHITE PAPER

OCTOBER 2017

CO_2 REDUCTION TECHNOLOGIES FOR THE EUROPEAN CAR AND VAN FLEET, A 2025–2030 ASSESSMENT

IMPACT OF MASS REDUCTION DISCOUNTING ON COMPLIANCE COSTS FOR FUTURE EU CO_2 STANDARDS

Dan Meszler, John German, Peter Mock, and Anup Bandivadekar

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

www.theicct.org

communications@theicct.org

BEIJING | BERLIN | BRUSSELS | SAN FRANCISCO | WASHINGTON

ACKNOWLEDGEMENTS

The authors thank the reviewers of this report for their guidance and constructive comments.

For additional information:
International Council on Clean Transportation Europe
Neue Promenade 6, 10178 Berlin
+49 (30) 847129-102

communications@theicct.org | www.theicct.org | @TheICCT

Funding for this work was generously provided by the ClimateWorks Foundation and the Stiftung Mercator.

TABLE OF CONTENTS

ABBREVIATIONS

AER	All-electric range
BEV	Battery electric vehicle (with the battery being the sole energy source)
BEV-xxx	BEV with an AER of xxx miles as measured over the NEDC
CO2	Carbon dioxide
DMC	Direct manufacturing cost
EPA	U.S. Environmental Protection Agency
EU	European Union
EV	A vehicle which relies on an electric machine as its primary propulsion technology and which is capable of off-board recharging, meaning for purposes of this study PHEVs, BEVs, and FCVs
EV Strategy	Compliance strategy wherein EVs are introduced as soon as they are more cost effective from a CO_2 reduction standpoint than alternative ICE technology
ExhICE Strategy	Compliance strategy wherein ICE technology is exhausted before EVs are introduced
FCV	Hydrogen fuel cell vehicle, with the fuel cell being the sole energy
source	
FEV	FEV Consulting GmbH
g	Gram(s)
HEV	Hybrid electric vehicle, without off-board charging capability
ICCT	International Council on Clean Transportation
ICE	Internal combustion engine
ICM	Indirect cost multiplier
kg	Kilogram(s)
km	Kilometer(s)
LB	lower bound scenario
LCV	light commercial vehicle
M0	The parameter used in the EU regulatory structure for motor vehicle CO_2 as the basis for establishing manufacturer-specific CO_2 standards on the basis of vehicle mass. The parameter specifically reflects the fleet average value of vehicle mass in running order.
NEDC	New European Driving Cycle
NRC	U.S. National Research Council
OEM	Original equipment manufacturer (a vehicle manufacturer)
PHEV	Plug-in hybrid electric vehicle, with off-board charging capability
PHEV-xxx	PHEV with an AER of xxx miles as measured over the NEDC
SUV	Sport utility vehicle
UB	Upper bound scenario
U.S.	United States
VCR	Variable compression ratio
WLTP	Worldwide Harmonized Light Vehicles Test Procedure
Δ costs	Change in costs

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

This paper serves as a supplement to a set of technology-neutral cost curves published by the International Council Clean Transportation (ICCT) in November 2016 that describe the cost of carbon dioxide (CO_2) reduction technology as applied to the European Union (EU) passenger car and light commercial vehicle (LCV) fleet in the 2025–2030 time frame (Meszler, German, Mock, & Bandivadekar, 2016).[1] These curves allow for the determination of the average per-vehicle cost to achieve compliance with various CO_2 emission standard levels. However, the regulatory structure currently employed in the EU is not technology neutral, but rather relies on vehicle mass as the basis for standard determination. This paper presents the results of an analysis that quantifies the extent to which mass reduction technology is discounted under the current EU regulatory structure and the impact of this discount on average per-vehicle compliance costs.

The data and methodologies employed in this analysis are identical to those of the previous work. The primary CO_2 and associated technology cost data are from simulation modeling and bottom-up cost estimation work performed for the ICCT by FEV, Inc. (2015). These data are combined with supplemental data, as appropriate, to generate CO_2 cost curves for 10 EU vehicle classes. Individual class cost curves are sales weighted to estimate fleet average compliance costs for a range of potential CO_2 standards.

Because FEV did not estimate the cost of changes in vehicle road load parameters (i.e., mass, rolling resistance, and aerodynamic drag), supplemental data sources were used. The costs of mass reduction technology are taken from work previously performed by FEV for the ICCT (FEV, 2013). The cost of rolling resistance and aerodynamic drag reduction technology are based on relationships developed by the U.S. Environmental Protection Agency (EPA), as documented in that agency's technical support document for its 2017–2025 U.S. light-duty vehicle greenhouse gas (GHG) standards rulemaking (U.S. Environmental Protection Agency [EPA] and National Highway Traffic Safety Administration [NHTSA], 2012).

FEV technology costs and the supplemental road load costs are estimated as high volume production direct manufacturing costs (DMCs) in 2014. To properly estimate retail level costs in future years, both learning effects and indirect cost multipliers (ICMs) are applied to base year DMC estimates. The applied learning and indirect cost factors are derived from the U.S. EPA's technical support document for its 2017–2025 U.S. light-duty vehicle greenhouse gas standards rulemaking (EPA & NHTSA, 2012).

Generally, the primary FEV data focus on internal combustion engine (ICE) and powertrain technology as extended through onboard-only charged hybrid electric vehicle systems. To incorporate the CO_2 benefits of electric vehicle (EV) technology, cost estimates for such vehicles are taken from a recently released ICCT study on the cost of such technology in Europe in the 2020–2030 time frame (Wolfram & Lutsey, 2016) and from an analysis conducted by the U.S. National Research Council (NRC, 2013).

Construction of the EU cost curves is conceptually straightforward. Incremental CO_2 emissions and costs for a series of technology packages are estimated relative to the current baseline fleet. The resulting CO_2 cost data points are subjected to regression analysis to estimate a generalized CO_2 cost curve. For CO_2 standards that are achieved through the introduction of EV technology, ICE cost curves are integrated with a market share function to estimate the penetration of electric vehicles required for compliance with the given standard. The analysis assumes that any EV technology is distributed

1 Technology neutral in this context means that all technologies are treated as though their CO_2 impacts are fully creditable. No CO_2 reduction technology is discounted and no technology is rewarded with credits that exceed CO_2 impacts.

across vehicle classes in accordance with current class sales shares. In other words, EVs are allocated across all classes so that costs are not artificially minimized by assuming that EVs will be preferentially sold in the least expensive classes.

There is a degree of freedom associated with introducing EVs into the fleet that creates uncertainty with regard to the precise integration of ICE and EV cost data. There is no requirement that a vehicle manufacturer exhaust all ICE technology before introducing EVs into the fleet. This means that there are an infinite number of ways in which the ICE and EV cost data can be integrated. This analysis resolves this uncertainty by evaluating the integration of EVs under two scenarios. Under one scenario, the transition to EV technology is assumed to take place only after all ICE technology has been exhausted. This scenario is generally referred to as the ICE exhaustion, or ExhICE, strategy. Under the second scenario, the transition to EV technology is assumed to take place at the point of cost optimization, which is to say, when the marginal cost of EVs is less than the marginal cost of additional ICE technology. This scenario is generally referred to as the EV optimization strategy. The fact that the marginal cost of EVs can be lower than the marginal cost of additional ICE technology does not imply that EVs are less expensive than the alternative ICE technology, but rather that the cost per unit CO_2 reduction is lower.

Compliance costs for a range of CO_2 targets were evaluated for calendar years 2020, 2025, and 2030. In each case, costs were evaluated under two sets of assumptions, one reflective of lower bound compliance costs and one reflective of corresponding upper bound costs. Both are based on the same fundamental data, but differ with regard to assumptions related to mass reduction costs, exploitation of test flexibilities, performance-based CO_2 adjustments, allocation of costs to technology co-benefits, the use of off-cycle technology credits, and EV battery costs.

The current EU regulatory structure for motor vehicle CO_2 discounts mass reduction technology through the establishment of standards that vary with vehicle mass. Based on a detailed analysis of the EU structure, this paper assumes average mass reduction discount rates of 76% and 100% for passenger cars and light commercial vehicles respectively. For light commercial vehicles, there are a wide range of conditions for which the actual discount rate often exceeds 100%; but this analysis caps the discount at 100% as that level of discount is sufficient to fully discourage manufacturers from implementing mass reduction technology.

The paper includes an extensive discussion of the derivation of assumed discount rates and the various aspects of the current EU regulatory structure that negatively influence a vehicle manufacturer's decision-making with regard to an investment in mass reduction technology. As shown in that discussion and a variety of example calculations, individual manufacturers have no ability to ensure that an investment in mass reduction technology will be fully credited under the EU system and therefore will make the conservative assumption that such investment will be substantially discounted.

In reviewing the derived cost curves, it is important to understand that EVs are substantially unaffected by inclusion or exclusion of mass reduction technology. As a result, differentials between "with mass reduction technology" and "without mass reduction technology" cost curves decline as compliance demands move away from ICE technology and toward greater shares of EV technology. This results primarily from the fact that the analysis assumes zero CO_2 for battery electric vehicles and zero CO_2 for plug-in hybrid electric vehicles operating in all-electric mode. At a zero CO_2 level, there is little regulatory incentive for EV manufacturers to reduce mass under a standard that would respond by reducing CO_2 compliance credits, so the analysis assumes no change in battery electric vehicle cost under either a with-mass-reduction technology or without-mass-reduction technology scenario. Because they rely on ICE technology in their design basis, plug-in hybrid electric vehicle emissions are somewhat sensitive to changes in ICE vehicle CO_2 because of the exclusion of mass reduction technology. However, the fact that a considerable portion of plug-in hybrid electric vehicle operations occur in all-electric mode, as documented in Meszler et al. (2016), this results in only a moderate net change in CO_2. Thus with-mass-reduction technology and without-mass-reduction technology cost curve differentials decline as EV market penetration increases.

Figures ES-1a and ES-1b present passenger car fleet average compliance cost curves for CO_2 targets measured over the New European Driving Cycle (NEDC) in 2025. The figures depict both the cost curves developed in the Meszler et al. (2016) report under an assumption that mass reduction technology is fully creditable and corresponding cost curves developed in this analysis under an assumption of discounted mass reduction technology. Both figures also include corresponding EV market penetrations. Figure ES-1a presents curves developed for the ICE exhaustion strategy, and Figure ES-1b presents curves developed for the EV optimization strategy. Figures ES-2a and ES-2b present corresponding compliance cost curves for CO_2 targets measured over the NEDC in 2030.

The discounting of mass reduction technology will add between 230 and 350 euros (2014 euros) to the cost of compliance with a 95 g/km passenger car standard in 2020, and between 175 and 600 euros (2014 euros) to the cost of compliance with a 147 g/km light commercial vehicle standard in that same year.[2] It is difficult to generalize impacts in the absence of a specific post-2020 CO_2 reduction target, but the following conclusions can be drawn for the average EU market in the 2025–2030 time frame.

- » Passenger car NEDC standards as low as 60–70 g/km can be achieved with either no or only modest levels of EV penetration under a fully creditable mass reduction regulatory structure, but will require a 5 to 13 percentage point increase in EV market penetration under the current regulatory structure that discounts mass reduction technology.
- » Given the current state of ICE technology, a passenger car NEDC standard of 70 g/km can be attained by 2025 for between 1,500 and 2,400 euros per vehicle (2014 euros) with 10% to 23% EV market penetration using an ICE technology exhaustion strategy under the current regulatory structure that discounts mass reduction. Costs would be 300 to 500 euros per vehicle (2014 euros) lower under a least cost EV transition strategy, but EV market shares would increase to 27% to 32%. These costs are between 250 and 500 euros higher and these EV market shares are between 6 and 12 percentage points higher than would be the case under a regulatory structure in which mass reduction is fully creditable.

2 Data for 2020 are not presented in this executive summary, but are included in the body of the report. See specifically Table 3 in the body of the report for a summary of differential compliance costs.

Figure ES-1a. 2025 NEDC CO_2 costs for passenger cars (ExhICE Strategy).

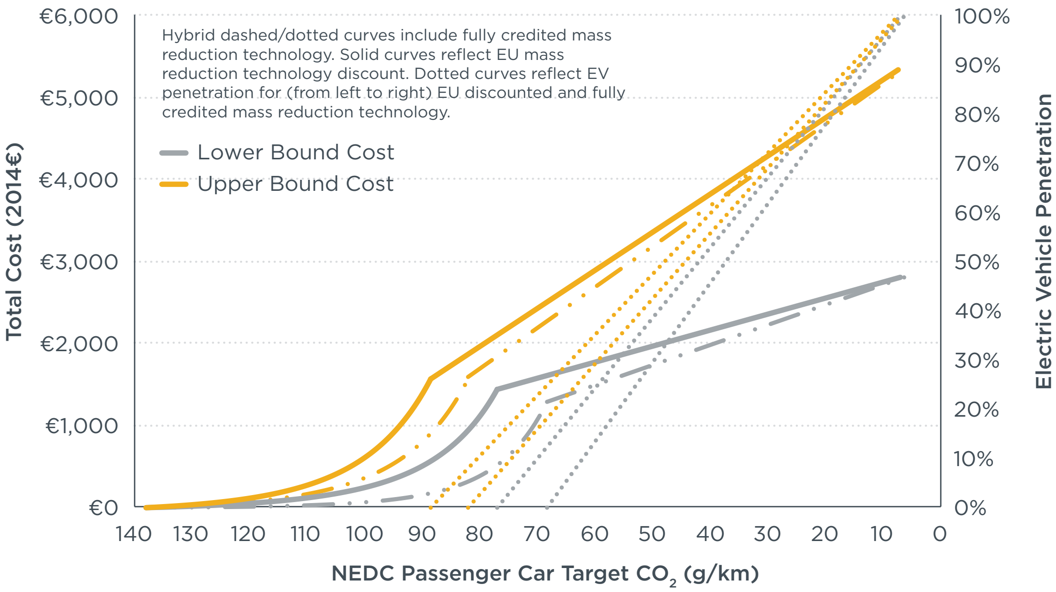


Figure ES-1b. 2025 NEDC CO_2 costs for passenger cars (EV Strategy).

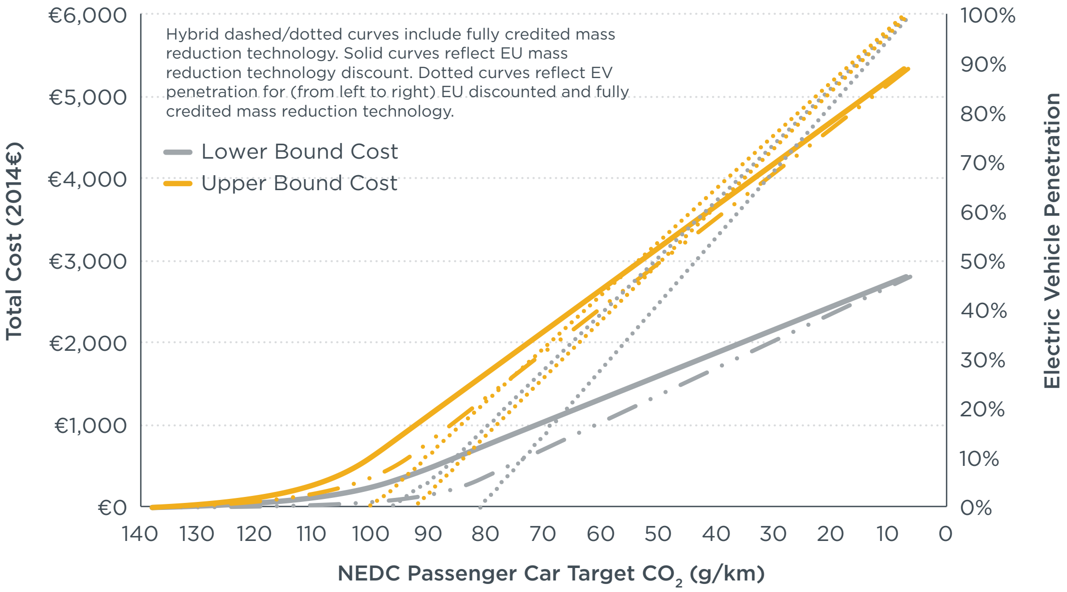


Figure ES-2a. 2030 NEDC CO_2 costs for passenger cars (ExhICE Strategy).

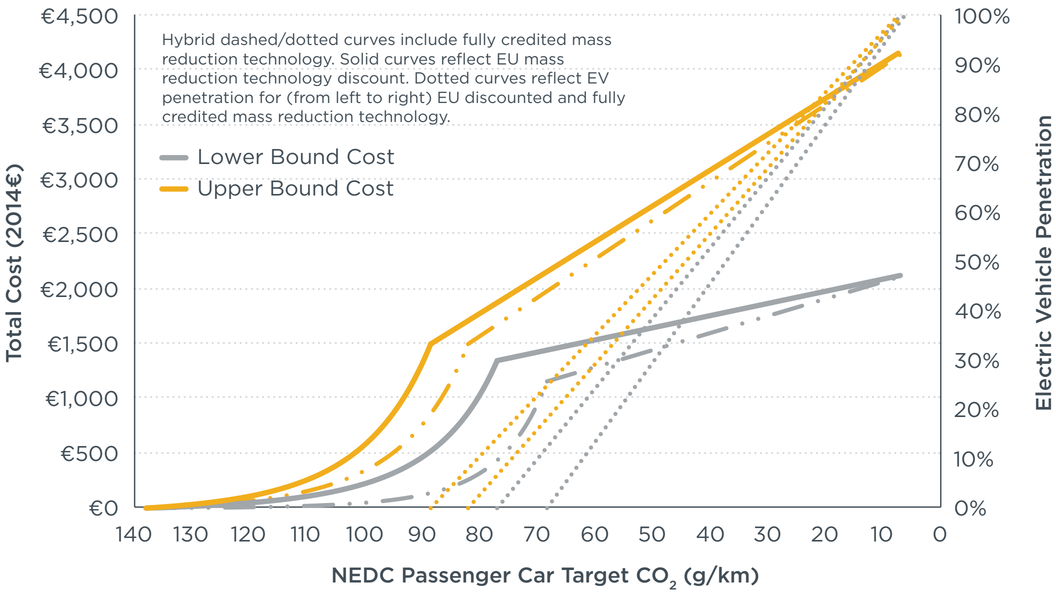
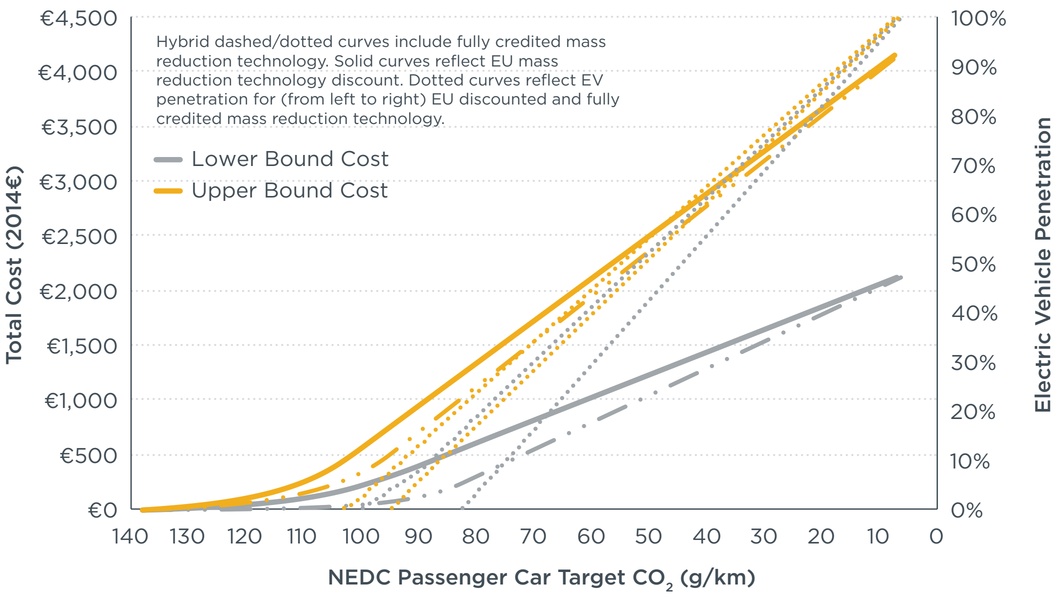


Figure ES-2b. 2030 NEDC CO_2 costs for passenger cars (EV Strategy)



» Passenger car standards as low as 40 g/km can be achieved by 2030 for costs of between 1,400 and 3,300 euros per vehicle (2014 euros) under either the NEDC or Worldwide Harmonized Light Vehicles Test Procedures (WLTP) cycles (WLTP curves are shown in the body of the report), as compliance with such standards is dominated by large EV market shares. Because of the large EV market shares (50%–70%), the cost differential due to mass discounting is relatively more modest at 100 to 200 euros per vehicle (2014 euros).

The presented cost curves are based on extensive vehicle simulation modeling and detailed bottom-up cost assessments, mirroring the industry approach of assessing the emission reduction potential and cost of future technologies. However, it is important to understand that the compliance costs presented in this paper only apply to the average vehicle market. Costs for individual manufacturers will be different, as will the technology mix applied by individual manufacturers. Unlike the compliance cost estimates previously published in Meszler et al. (2016), the compliance costs presented in this paper are not technology neutral. In accordance with the current regulatory structure in the EU, the value of mass reduction technology as a CO_2 reduction strategy is discounted and both costs and required EV market penetrations increase relative to technology neutral compliance requirements.

Limitations to the presented approach and cost curves include:

» An inability to equate the linear formulation of the EU regulatory structure for CO_2 to a mass reduction discount rate that applies to every vehicle. The inherent nonlinearity of the CO_2 response to changing mass precludes a precise translation.

» An assumption that manufacturers will not take advantage of the incentives to increase vehicle mass that are inherent in the EU regulatory structure, especially with regard to light commercial vehicles. We assume that safeguards such as the M_0 adjustment process as well as practical considerations, such as maximizing the cargo carrying capacity of commercial vehicles, will inhibit much of this incentive. However, should vehicle manufacturers elect to use mass increases as a mechanism to reduce investments in CO_2 reduction technology, compliance costs could be reduced from those estimated herein.

» An underlying assumption of the cost assessment is that high-volume mass production costs are assumed, but no consideration is made for future improvements in the design of a technology as compared with today's state of the science. This means that any potential redesign of a technology to optimize efficiency and reduce associated costs is not considered in the analysis.

» Specific limitations with respect to FEV's simulation development, including non-consideration of engine downsizing potential in hybrid technology simulations, non-consideration of the impacts of road load reduction on required constant performance hybrid system size and cost, non-consideration of improvements in hybrid battery power density, and non-consideration of increases in gasoline engine compression ratio except for simulations explicitly including VCR and Miller cycle technology.

» No attempt to incorporate assumptions about genuine new technology developments. Given the massive technology developments that have occurred in the past 10 years, it is certain that there will be significant new technology developments by 2025, and even more so by 2030, that have not been incorporated into the cost curves.

» For the development of the cost curves in this paper it is assumed that market shares of fuels and vehicle segments will not change in the future. In particular, it is assumed that the market shares of gasoline and diesel vehicles will remain constant over time. However, there is a strong likelihood that the market share of diesel vehicles will decrease in the EU in the future. Such a shift could have an impact on fleet average compliance costs. A detailed assessment of this effect has been released in a separate report (Diaz, Miller, Mock, Minjares, Anenberg, & Meszler, 2017).

» All CO_2 emission reduction technology is evaluated on a constant performance basis. It is assumed that the power and top speed of reduced CO_2 vehicles are unchanged from those of associated baseline vehicles. CO_2 emission reduction costs for reduced performance vehicles would be lower than depicted in the presented cost curves.

Given these limitations, the cost curves presented in this paper are expected to be more reflective of the upper range of actual future costs, and that the real costs for meeting potential CO_2 emission targets are likely to be lower than indicated above. Finally, we reiterate the weakness inherent in a regulatory structure that relies on vehicle mass as a utility parameter and the potential incentives for gaming that result from associated mass reduction discounting and mass increase incentivizing. We strongly encourage the EU to consider adopting a revised regulatory structure that does not rely on vehicle mass or any other parameter upon which CO_2 is directly dependent as a utility parameter.

1. INTRODUCTION

In November 2016, the International Council on Clean Transportation (ICCT) published a series of cost curves describing the cost of CO_2 reduction technology as applied to the EU passenger car and light commercial vehicle (LCV) fleet (sometimes referred to as vans in the EU) in the 2025–2030 time frame (Meszler, German, Mock, & Bandivadekar, 2016). These curves allow for the determination of the average per-vehicle cost to achieve compliance with various CO_2 emission standard levels.[3] However, as detailed in Meszler et al. (2016), the developed curves are strictly technology neutral and do not consider the impacts associated with any potential regulatory structure that might discount the value of any particular CO_2 reduction technology, including vehicle mass reduction, either in whole or in part. In effect, the cost curves assume an underlying regulatory structure that is itself technology neutral, such as a fleet average flat standard or a vehicle size-based standard.

The regulatory structure currently employed in the EU is not technology neutral, but rather relies on vehicle mass as the basis for standard determination. Two vehicles of identical size, identical aerodynamic characteristics, identical non-mass rolling resistance characteristics, and identical powertrain characteristics, but differing masses, are subject to differing CO_2 standards. The manufacturer that has invested in mass reduction technology will not garner the full value of that investment. Instead, some fraction of that investment will be consumed in complying with a more stringent CO_2 standard. This paper presents the results of an analysis intended to quantify the extent to which mass reduction technology is discounted under the current EU regulatory structure for CO_2 and the impact of this discount on average per-vehicle compliance costs.

Section 2 presents background information on the underlying technology-neutral cost curve study. Section 3 summarizes the extent to which the current EU structure discounts mass reduction technology. Section 4 discusses the methodology employed to adjust the technology-neutral ICCT analysis for the quantified discount, and Section 5 presents associated cost curve impacts. Section 6 presents a concluding discussion of how the estimated compliance costs might be interpreted, including a discussion of associated limitations.

3 CO_2 emissions in this study are type-approval emissions as would be measured over the official EU test procedure. These emissions will differ from in-use emission levels due to differences between official testing requirements and real-world vehicle operation. By design, the study does not address life-cycle emissions or operational benefits associated with potential energy savings. The study is designed to evaluate the cost of manufacturer compliance with potential EU standards and is thus intentionally limited to that question.

2. BACKGROUND

This paper builds upon work previously undertaken by the ICCT to develop technology-neutral CO_2 cost curves for the European passenger car and LCV fleet in the 2025–2030 time frame (Meszler et al., 2016). To provide appropriate context, this section presents a brief methodological summary of that previous work, as published in November 2016. This summary is necessarily abbreviated, so the referenced report should be consulted directly by readers desiring more detailed information. Unless otherwise stated, the data and methodologies used in the analysis presented in this paper are identical to those of the previous work.

The primary CO_2 and associated technology cost data used in the development of the cost curves are from simulation modeling and bottom-up cost estimation work performed for the ICCT by FEV, Inc. (2015). These data are combined with supplemental data, as needed, to generate CO_2 cost curves for 10 EU vehicle classes, namely, diesel B, C, D, E, SUV, and LCV classes and gasoline B, C, D, and E classes. Individual class curves are sales weighted to estimate fleet average compliance costs for a range of potential CO_2 standards. As described in the following text, several limitations associated with the FEV cost data necessitate the use of supplemental data sources for some technologies.

FEV modeled, but did not cost, the CO_2 impact of changes in vehicle road load parameters (i.e., mass, rolling resistance, and aerodynamic drag). Therefore, supplemental data sources were referenced for such associated cost estimates. The costs of mass reduction technology were taken from work previously performed by FEV for the ICCT (FEV, 2013). Using the previous FEV work, the ICCT has developed relations describing cost as a function of the magnitude of mass reduction. The methodology and associated relations are documented as part of a series of papers previously produced by the ICCT for an earlier analysis on the cost of potential 2020–2025 EU CO_2 standards (Meszler, German, Mock, & Bandivadekar, 2012a, 2012b, 2013; Meszler, German, Mock, Bandivadekar, & Tu, 2014). The cost of rolling resistance and aerodynamic drag reduction technology are based on relationships developed by the U.S. EPA, as documented in that agency's technical support document for its 2017–2025 U.S. light-duty vehicle greenhouse gas standards rulemaking (U.S. Environmental Protection Agency [EPA] and U.S. National Highway Traffic Safety Administration [NHTSA], 2012).

FEV technology costs are estimated as high volume production direct manufacturing costs in 2014. In other words, the costs reflect those that would be expected to be incurred at the manufacturer level in 2014 if the technology were in high volume production. Such costs are not directly appropriate for cost curve development because they do not directly reflect retail level costs, also referred to as total costs in this paper, nor do they consider the effects of learning between 2014 and future evaluation years. To properly estimate retail level costs in future years, both learning effects and indirect cost multipliers are applied to base year direct manufacturing cost estimates. The applied learning and indirect cost factors are derived from the U.S. EPA's technical support document for its 2017–2025 U.S. light-duty vehicle greenhouse gas standards rulemaking (EPA & NHTSA, 2012).

The employed simulation modeling data regarding CO_2 are limited in the scope of technology considered. Generally, these data focus on internal combustion engine and powertrain technology as extended through onboard-only charged hybrid electric vehicle (HEV) systems. Vehicle technology capable of reducing CO_2 below levels observed in the simulation modeling data is required to attain some of the evaluated CO_2 targets. Such technology could include pure (i.e., no internal combustion engine [ICE]) battery electric vehicles (BEVs), off-board charging-capable or plug-in hybrid electric vehicles (PHEVs), or hydrogen fuel cell vehicles (FCVs). Cost estimates for such electric vehicle[4] technology are taken from a recently released ICCT study on the cost of such technology in Europe in the 2020–2030 time frame (Wolfram & Lutsey, 2016).[5]

Conceptually, construction of the EU cost curves is straightforward. First, CO_2 emissions and technology penetration are estimated for the baseline fleet. These data serve as the zero-cost baseline for cost curve development. The baseline data are combined with CO_2 and associated incremental cost estimates for a series of future technology packages to generate a series of CO_2/cost data points that are then subjected to regression analysis to estimate a generalized CO_2 cost curve. There are nuances, however, related to the integration of ICE and EV data, as required to meet some of the evaluated target CO_2 levels. Technology cost curves per se are only developed for ICE data, as these data reflect the cost of reducing CO_2 through the continuous application of technology. However, attainment of some CO_2 targets requires the introduction of EVs into the fleet and this introduction is controlled not by the continuous introduction of new technology, but rather by continuously increasing EV technology penetration. The continuous addition of technology cost is replaced by the continuous addition of ever greater EV market shares. Thus, evaluation of the cost of attaining very low CO_2 levels is a two-step process consisting of determining the cost associated with ICE technology and then determining the fraction of EVs, and their associated cost, required to further reduce CO_2 emissions to the desired level.[6]

For CO_2 levels requiring the introduction of EVs, the analysis assumes that such vehicles are distributed across vehicle classes in accordance with current class sales shares. In other words, EVs are allocated across all classes so that costs are not artificially minimized by assuming that EVs will be preferentially sold in the least expensive classes. The analysis does assume, however, that manufacturers will employ a least cost solution within each class to the extent practical. For B and C class vehicles, the analysis assumes that BEV-100 vehicles will be used to satisfy any EV demand. For all larger vehicle classes, the analysis assumes that BEVs will not be practical in the time frame considered and that PHEV-40s will be employed to satisfy any EV demand.[7]

4 Readers referencing the Meszler et al. 2016 cost curve report that serves as the basis for this report should note that “electric vehicles” were defined as “non-ICE” vehicles in that report. There is a continuum of technology between internal combustion and electric vehicles, generally progressing from ICE-only through onboard-only rechargeable HEVs and off-board rechargeable PHEVs to battery-only EVs. There is no fine line between these categories where one switches from ICE to EV technology because both HEVs and PHEVs incorporate both ICE and electric vehicle technology. Under the assumption that readers might mistakenly associate the term EV as synonymous with BEV, the 2016 Meszler et al. report used the less common terminology non-ICE to force a thoughtful distinction. Although non-ICE is similarly flawed because of the same lack of a fine line technology distinction, it nonetheless avoids any EV/BEV preconception weakness. For this report, the more common EV terminology is used and includes both PHEV and BEV technology.

5 Although the ICCT EV cost estimates are the primary data source for such vehicles, the analysis contrasts these estimates with corresponding battery cost estimates from the U.S. National Research Council (NRC, 2013) as discussed in the text that follows.

6 The two-step nature of cost curve generation should not be confused with the multitude of data development steps that underlie curve construction. Detailed cost and CO_2 emissions have been estimated for both ICE vehicles and EVs. However, unlike ICE vehicles, where a variety of technology packages are available offering a variety of CO_2 emission levels with varying associated costs, the costs and CO_2 emissions of EVs are held constant for a given evaluation year. After all the component costs and CO_2 emission levels are determined for both ICE vehicles and EVs, CO_2 compliance cost estimation involves first determining the cost and CO_2 emissions available through the various ICE technology packages and then determining what level of EV penetration, if any, is required to further reduce fleetwide emissions to the desired CO_2 target. After the cost of an EV is estimated, the EV technology cost associated with attainment of various CO_2 levels becomes solely a function of market penetration.

7 Note that this assumption is primarily meant to be conservative with regard to cost estimation and not to be a definitive statement with regard to BEV viability in larger vehicle classes. Tesla in particular has shown that BEVs can be viable in larger vehicle classes, but most manufacturers continue to focus BEV development efforts across smaller class vehicles. Given the substantial EV market shares required to achieve some of the more stringent CO_2 emission levels evaluated in this analysis, we elected to limit BEV penetration to B and C class vehicles. In this analysis, PHEV-40s carry a cost premium over BEV-100s due to the requirement to maintain both electric and ICE technology under all scenarios after 2024 and all low-cost battery scenarios after 2017. We assume BEV-100 compliance across all vehicle classes would result in lower estimated compliance costs than reported herein.

Compliance costs for a range of CO_2 targets were evaluated for calendar years 2020, 2025, and 2030. In each case, costs were evaluated under two sets of assumptions, one reflective of lower bound compliance costs and one reflective of corresponding upper bound costs. Both are based on the same fundamental data, but differ in the following assumptions:

- Mass reduction costs are included in both lower and upper bound compliance cost estimates, but upper bound estimates assume that no level of mass reduction can be achieved at less than zero cost, although lower bound costs directly reflect lightweighting teardown cost assessments that found modest amounts of weight reduction can be achieved while also reducing cost.[8]
- The lower bound estimates include both test flexibility exploitation and performance-based CO_2 adjustments; upper bound estimates include neither. Test flexibility adjustments capture the CO_2 benefit available to vehicle manufacturers through nuances in vehicle testing procedures. Performance-based CO_2 adjustments are designed to capture engine downsizing benefits not explicitly reflected in the simulation modeling data.
- The lower bound estimates include cost adjustments based on technology co-benefits; upper bound estimates do not. Fundamental technology cost estimates assign 100% of the cost of technology to CO_2 reduction. However, there are both co-benefits and other market drivers for many CO_2 reduction technologies. Such co-benefits include improved performance, reduced noise, improved handling, improved braking, enhanced safety, and increased durability. Lower bound cost estimates adjust the technology cost of CO_2 reduction by assigning a portion of total technology cost to applicable technology co-benefits.
- Lower bound estimates include off-cycle technology credits; upper bound estimates do not. Off-cycle credits are available to vehicle manufacturers for technologies with CO_2 reduction impacts that are not captured through standardized regulatory testing procedures.
- Lower bound cost estimates for EVs are based exclusively on ICCT estimates; upper bound estimates substitute the generally higher U.S. National Research Council battery cost assumptions (NRC, 2013).

As mentioned, CO_2 compliance cost estimation consists of the integration of two independent components, one reflecting the level of CO_2 reduction that can be achieved through the introduction of progressively more effective ICE technology and one reflecting the CO_2 reduction that can be achieved by increasing the market penetration of EVs. The cost of ICE technology is generally reflected as an upwardly sloping exponential curve. The cost of increasing EV market penetration is a linear function that serves to extend the ICE technology cost curve to lower levels of CO_2.

Although this generalization always holds true, there is a degree of freedom associated with introducing EVs into the fleet that creates uncertainty with regard to the precise integration of ICE and EV cost data. There is no requirement that a vehicle manufacturer exhaust all ICE technology before introducing EVs into the fleet. This means there are an infinite number of ways in which the ICE and EV cost data can be integrated. The analysis resolves this uncertainty by evaluating the integration of EVs under two scenarios. Under one scenario, the transition to EV technology is assumed to take place

8 This assumption applies only to the original Meszler et al. 2016 analysis, against which the analysis results presented in this paper are compared. The specific mass reduction assumptions employed for the comparative analysis summarized herein are presented in Section 4.

only after all ICE technology has been exhausted.[9] Under the second scenario, the transition to EV technology is assumed to take place at the point of cost optimization, which is to say when the marginal cost of EVs is less than the marginal cost of additional ICE technology.[10]

The fact that the marginal cost of EVs can be lower than the marginal cost of additional ICE technology does not imply that EVs are less expensive than the alternative ICE technology, but rather that the cost per unit CO_2 reduction is lower. BEVs are treated as zero CO_2 vehicles in the analysis, so they provide substantial CO_2 reductions over which to spread costs. Although PHEV CO_2 emissions are non-zero, they still provide reductions of more than 50%. EV reductions are such that they can carry a cost-effective CO_2 reduction signal even though per-vehicle absolute costs are high. Because EVs enter the market starting from a near-zero market share, fleetwide incremental cost impacts are initially modest, as only a small fraction of vehicles is affected. It is this relatively small fractional cost that can be more cost effective than transitioning an entire fleet to more expensive ICE technology.

It is important to recognize that for both ICE vehicles and EVs the focus on vehicle technology costs, as employed in the analysis, does not equate to a full assessment of consumer impacts. The analysis focuses on vehicle purchase price impacts only. Impacts on the total cost of ownership for both ICE vehicles and EVs would include offsetting savings due to reduced fuel use for ICE vehicles and alternative energy economies for EVs. Such life-cycle assessments can be developed from the vehicle technology cost estimates described herein, but are not considered in this or the underlying paper by Meszler et al. (2016).

---

9 Technology exhaustion as defined herein refers only to technology as reflected in the simulation modeling data employed in this analysis. Continuing advancements, in addition to more expensive technologies not included in the simulation modeling work, will push the level of CO_2 reduction available through ICE technology to progressively lower levels than are modeled in this report. Because this analysis does not attempt to quantify these advancements, the maximum technology packages included in the simulation modeling data represent an ICE technology constraint only in the context of this analysis.

10 We necessarily assume that consumers will view ICE and EV technology as viable alternatives in the time frame considered and market shares required. Adoption of the two-scenario analysis approach buffers this assumption to some extent because one scenario requires the preferential exhaustion of ICE technology prior to EV introduction, but there may still be market barriers to widespread EV introduction that could affect a manufacturer's ability to sell EVs in the quantities required to comply with very low CO_2 targets. The effect of any such barriers that may persist through the evaluation period of this analysis should be considered in determining the ultimate viability of any particular CO_2 standard.

3. EU REGULATORY STRUCTURE FOR CO_2 STANDARDS

The EU standards for passenger cars and LCV CO_2 emissions are not technology neutral. Instead, a regulatory structure is in place under which the applicable CO_2 standards vary with vehicle mass (European Union [EU], 2009, 2011). The specific form of both standards is:

$$CO_2 = (CO_2 \text{ at } M_0) + [a \times (M - M_0)]$$

where:

CO_2 is the CO_2 standard for a given vehicle,
CO_2 at M_0 is the nominal CO_2 standard for a vehicle with a fleet average mass,
a is the slope of the EU standard function,
M is the vehicle mass in running order (kg), and
M_0 is the fleet average value of M.

For 2020 and later passenger cars, the slope parameter *a* is set at 0.0333, M_0 is currently set at 1,392.4 kg, and CO_2 at M_0 is set at 95 g/km (EU, 2014b, 2015). For 2020 and later LCVs, the slope parameter *a* is set at 0.096, M_0 is currently set at 1,706 kg, and CO_2 at M_0 is set at 147 g/km (EU, 2011, 2014a). All three values are subject to regulatory revision for model years after 2020. Parameter M_0 is explicitly subject to review and revision every three years, and is scheduled to be reviewed prior to 2020, so the values presented for 2020 herein reflect a current situation subject to change.

The critical element of the EU regulatory structure is the fact that the CO_2 standard for a given vehicle is a function of its mass. If a manufacturer alters the mass of a given vehicle with all other technology unchanged, both the CO_2 performance of the vehicle and the CO_2 standard to which it is held change. In effect, part of the CO_2 reduction generated by an investment in mass reduction technology goes toward compliance with a more stringent CO_2 standard so that the value of that investment to the manufacturer is diminished.[11] For the referenced EU regulatory structures, the passenger car and light commercial vehicle standards are made more stringent by 0.0333 g/km and 0.096 g/km respectively for each kg of mass reduced. A technology-neutral standard would hold CO_2 standards constant for any change in vehicle mass.

On a pound-for-pound basis, the light commercial vehicle standard, with a slope parameter of 0.096, is nearly three times as sensitive as the passenger car standard that has a slope parameter of 0.0333. Some deviation is expected given that the average masses and CO_2 standards of the two vehicle classes are substantially different, but the expected deviation is much smaller than that reflected in the slope ratio. For example, a 10% mass reduction from the average light commercial vehicle mass would result in a standard adjustment of 16.4 g/km {0.096 × [(0.9 × 1706) - 1706]} from a base standard of 147 g/km. This represents an 11.2% change in standard for a 10% change in mass. A comparative 10% mass reduction from the average passenger car mass would generate a standard change of 4.6 g/km {0.0333 × [(0.9 × 1392.4) - 1392.4]} from a base standard of 95 g/km; a 4.9% change in standard for a 10% change in mass. Thus, the effective sensitivity of the light commercial vehicle standard is 2.3 times as large as expected for a given change in passenger car mass. The slope of the light commercial vehicle standard

11 Of course, the CO_2 reduction associated with a given mass reduction is independent of the associated standard, so the net environmental effect of a given mass reduction is similarly independent of the form of the standard. The critical influence is not on the CO_2 emission level achieved, but on the incentive to implement a given mass reduction. If a manufacturer is not allowed to use the full CO_2 reduction value of mass reduction technology in the CO_2 compliance calculation, the incentive to consider mass reduction as a CO_2 compliance technology is discounted because the manufacturer can fully utilize an investment in alternative CO_2 reduction technology.

relation would have to be set at 0.0421 to deliver a mass reduction sensitivity equivalent to that of the passenger car standard relation.

The physical properties of motion do not support a disparity in mass sensitivity. Mass reduction as a technology does not generally affect the efficiency of a vehicle powertrain, providing the powertrain is properly optimized for any given change in vehicle mass. Instead, mass reduction affects the amount of energy required to propel a given vehicle over a drive cycle. In technical terms, mass reduction changes the road load, which is to say the resistance to movement, that the vehicle must overcome to execute a specified maneuver or set of maneuvers. Reducing the road load reduces the energy required. Reducing the energy requirement reduces fuel consumption. Consuming less fuel reduces the associated CO_2 emissions. In effect, physics does not care whether a vehicle is a light commercial vehicle, a passenger car, or a brick with wheels; reducing mass by a specific percentage should result in a specific reduction in CO_2. Of course, this is a bit of an oversimplification because aerodynamic drag and rolling resistance also contribute to the determination of road load. That means individual vehicles can be somewhat more or less sensitive to mass changes than an average vehicle, but such sensitivity is generally minor for the types of vehicles in operation.

Using the physical properties of motion, it is relatively straightforward to estimate the change in CO_2 emissions associated with a given change in mass. Strictly speaking, road load consists of the forces required to overcome vehicle rolling resistance and aerodynamic drag and to induce motion. Although the rolling resistance and motive forces are directly dependent on vehicle mass, the aerodynamic drag force is not. Thus, even if mass could somehow be reduced to zero, resistance would still be encountered for a vehicle with a non-zero volume. Moreover, the relationship between rolling resistance, aerodynamic drag, and motive force is not constant across vehicles. Streamlined vehicles as well as those with operations restricted to relatively low speeds will be more sensitive to mass reduction than vehicles with poor aerodynamic characteristics or vehicles operated at relatively high speeds. Although vehicle speed and acceleration are controlled during CO_2 testing through the use of defined driving cycles, different road load characteristics, and thus different mass reduction sensitivities, are still observable. It is, therefore, impossible to define a precise relationship between CO_2 emissions and mass reduction that applies to all vehicles. Nevertheless, it is possible to generate an accurate estimate of this relationship as it applies to the EU testing procedure by calculating the forces required to execute the NEDC for a series of vehicles of differing masses and differing rolling resistance and aerodynamic drag characteristics.

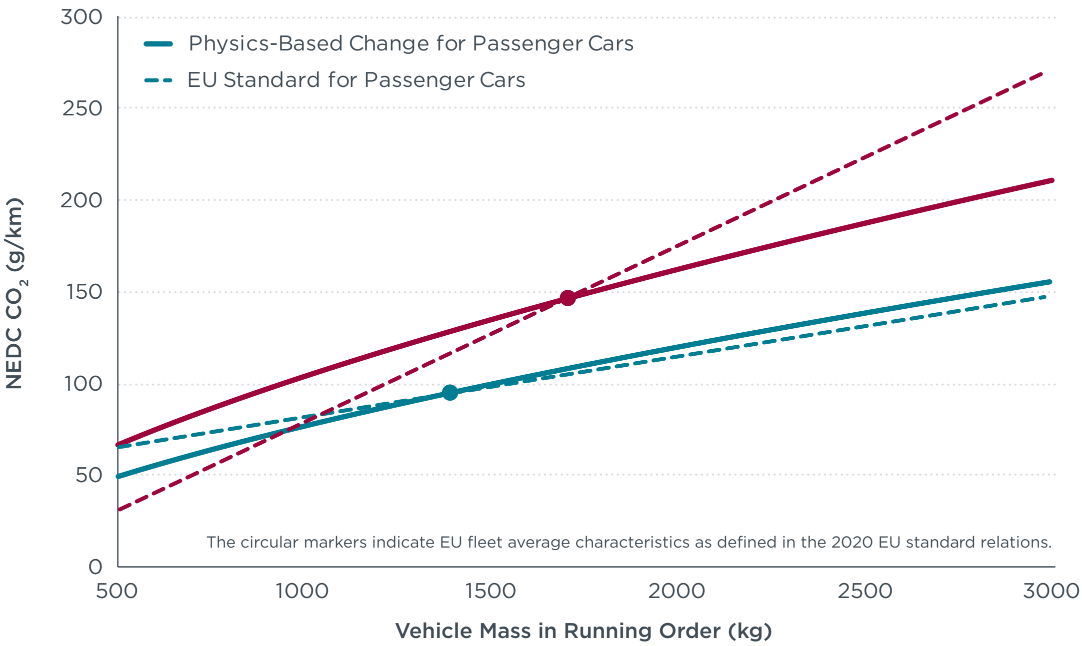
For this analysis, such calculations were performed for six vehicles with masses ranging from 1,000 to 2,700 kg, rolling resistance coefficients ranging from 0.007 to 0.011, and aerodynamic drag characteristics—defined as the coefficient of drag times vehicle frontal area—ranging from 0.69 to 1.34 m^2. For such vehicles, fuel consumption and thus CO_2 emissions were calculated to decline over the NEDC by 0.590% to 0.693% per percent decrease in vehicle mass, with an arithmetic average effect of 0.645% per percent.[12] For convenience, all physics-based calculations presented in this paper are based on this average effect, but precise equivalencies can be developed for any given vehicle. Based on this effect, the degree to which the EU regulatory structures discount mass reduction technology can be estimated.

12 The estimated effects assume that the vehicle powertrain is appropriately adjusted so that energy delivery efficiency is unchanged by the mass reduction. Because reducing the road load can affect the operational speed and load characteristics of a powertrain calibrated for a different (prereduction) road load, adjustments must be implemented to maintain energy delivery efficiency. This can be accomplished either by downsizing the vehicle engine or adjusting the vehicle transmission shift strategy to reflect the characteristics of the reduced road load.

Figure 1 depicts the generalized physics-based relationship between NEDC CO_2 and vehicle mass as developed from the fleet average mass and CO_2 characteristics expressed in the EU standard relations for 2020, which are 1,392.4 kg and 95 g/km for passenger cars and 1706 kg and 147 g/km for light commercial vehicles. In other words, the figure shows what happens to the CO_2 level of a vehicle with an initial fleet average mass and emissions initially at the fleet average standard as the mass of that vehicle is changed. These relationships are plotted alongside the CO_2 versus mass relationships codified in the EU standards.

A relatively simplistic illustration of the basic issues associated with the EU standard function can be gleaned from Figure 1. Although the physical form of the mass versus CO_2 relation is multiplicative (i.e., nonlinear), a linear approximation of the multiplicative function is possible over a reasonably wide range of vehicle masses. In other words, a linear function with an appropriately set slope parameter can mimic the multiplicative function for vehicles with baseline CO_2 emissions near the EU standard and baseline masses near the EU fleet average mass. Such a function would alter the EU standard exactly in accordance with mass-induced CO_2 changes, fully consuming any CO_2 reduction by increasing the stringency of the applicable CO_2 standard and thereby discounting (to zero) the value of mass reduction technology to vehicle manufacturers. The fact that the slopes of the EU relationships deviate from those of the generalized mass functions indicate that the degree of mass reduction discounting actually associated with the EU standards is something other than 100%.

Figure 1. CO_2 impacts for mass changes from EU fleet average emissions



For passenger cars, the slope of the EU standard is less than that of the physical relation, implying that the standard changes less rapidly than a mass-induced change in CO_2. Therefore, the CO_2 benefits of mass reduction are not fully offset through a more stringent standard and increases in CO_2 due to mass increases are not fully accommodated. However, the slope of the EU standard for light commercial vehicles is greater than that of the physical relation, implying that vehicles subject to mass reductions will be assigned a standard that is more stringent than the mass-induced CO_2 reduction can attain and that vehicles subject to mass increases will be rewarded with a standard that more than accommodates the mass-induced change in CO_2. In short, the slope of the light commercial vehicle standard encourages increasing mass.

Before investigating these effects further, it is important to recognize the potential influence of the EU's 3-year adjustment cycle for the CO_2 standard parameter M_0 as defined at the beginning of this section. This adjustment effectively serves as a safeguard against runaway mass increases because every three years it shifts the fleet average CO_2 target to the new fleet average weight, thereby limiting the effective lifetime of any CO_2 benefits associated with mass increases to less than 3 years. In effect, manufacturer's might buy themselves a few extra years of lead time by increasing their effective standard using the mass allowance embedded in the EU regulatory structure, but they will ultimately have to comply with the original numeric standard and do so at whatever level of mass increase they used to buy time.[13] This exercise could, of course, continue as a pas de deux[14] through any number of M_0 review cycles, but it is hard to envision an open-ended upside to such a dance.

Perhaps less obvious is the fact that M_0 adjustment also can serve as a mechanism to overcome the mass reduction discounting aspects of the EU mass-based structure. The 3-year adjustment mandate does not include a directional aspect, so that if the industry moved to implement an across-the-board mass reduction, that reduction would indeed be discounted for up to 3 years on the basis of the prereduction value of M_0. However, the mass reduction should ultimately become fully creditable, albeit after a lag of up to 3 years, as the induced M_0 adjustment effectively moves the preadjustment CO_2 target to the new reduced mass level. As with mass increases, this pas de deux could continue through any number of M_0 review cycles.

The complication that constrains the value of the M_0 adjustment is the fact that it penalizes or rewards manufacturers equitably only under conditions where the industry acts in lockstep. Either all manufacturers must reduce mass and do so by the same fraction, or all manufacturers increase mass by the same fraction. Under such conditions, the M_0 adjustment effectively makes the EU structure technology neutral, although there is an inherent lag time due to the periodicity of the M_0 adjustment. However, this functionality is limited to these very restricted conditions. When only a subset of manufacturers choose to act, they affect the fleet average mass (i.e., the future value of M_0) only in accordance with their sales share, while garnering the full effect of their mass change for their individual compliance purposes. For mass increases, such manufacturers

13 Note that a manufacturer would also have to implement complementary technology changes such as powertrain modifications to maintain constant performance for an upweighted vehicle, and such changes would offset some of the savings associated with the use of less expensive heavier mass materials. This also serves as a factor to be considered in a manufacturer's decision-making. Nevertheless, there is substantial evidence that vehicles have been getting heavier on average for a considerable period of time. For example, the EU revised the value of M_0 for passenger cars upward by 20.4 kg on October 31, 2014 (EU, 2015). Although the value of M_0 for light commercial vehicles has yet to be revised from its original value established in 2011 (EU, 2011), there is considerable evidence that fleet average mass has increased substantially since that time. Data compiled by the ICCT (2016) show the mass in running order for light commercial vehicles to have increased by nearly 10% from 2009 to 2015.

14 A pas de deux (French for "step of two") is an intricate relationship between independent parties. It derives from classical ballet in which two partners perform independent yet interrelated dance steps. It is a term particularly appropriate for the independent yet interrelated actions of manufacturers under the M_0 adjustment process.

will gain a permanent windfall that will be collected in the form of tighter CO_2 standards for those manufacturers that do not increase mass. The most perverse results will accrue when one manufacturer acts in opposition to the remainder. A manufacturer choosing to decrease mass in an era of general mass increases, will not only face a discounted value of mass reduction for a given M_0, but also will be subject to further discounting when the value of M_0 is increased in response to the general trend and the CO_2 standard for the decreasing mass manufacturer is lowered due to an increased deviation from the fleet average mass. These situations are magnified even further for model-level decision-making of an individual manufacturer. The appendix provides a quantitative analysis of these interactions.

Notwithstanding potential interactive effects, individual manufacturers will always know that their ability to influence fleetwide mass is proportional to their market share. No matter what other manufacturers do, the individual manufacturer alone can effectively control only a small segment of the market. That manufacturer will, therefore, base its internal decision-making on an assumption that the change in M_0 caused by its own mass reduction is not influenced by the actions of other manufacturers, and will assume that any of its mass reduction efforts will be discounted in accordance with a constant, or near constant, M_0 regulatory structure because individual manufacturer market shares are generally modest. As shown in Table A2 in the appendix and in the detailed discussion that follows, such a manufacturer would assume that only a modest fraction of its CO_2 reduction due to reduced mass—about 32%, given a near zero market share, to 45% for a 20% market share for the hypothetical set of conditions associated with the table data—will be credited toward its individual compliance status, even after adjustment of M_0.

Moreover, as shown in the appendix, under the current regulatory structure an individual manufacturer's "best move" in an environment in which fleetwide mass is decreasing might be to *not* reduce mass, because it then reaps the benefits of a higher CO_2 standard once M_0 is adjusted. This serves as an inertial influence for each manufacturer to let others act first. Both this and the internal information effect serve as major disincentives for an individual manufacturer to reduce mass.

Given the uncertainty a manufacturer faces with regard to the actions of other manufacturers, we assume that internal decision-making will largely be constrained by that information that is known with certainty, namely the level of mass reduction technology discounting imposed by the EU regulatory structure for a given value of M_0. This is the basis upon which the discounted mass reduction technology cost curves are constructed. We recognize the value of M_0 adjustments in constraining large scale mass increases, but also recognize the potential for smaller scale gaming by an individual manufacturer or with an individual model. The net result is that although we believe the discounted mass reduction cost curves presented later in this report provide the most reasonable assessment of the impacts of discounting mass reduction technology, it is possible under the M_0 adjustment process for manufacturers to act in a coordinated fashion to reduce the level of discounting from that depicted.

As previously mentioned, the simplified nature of Figure 1 only examines changes undertaken on vehicles with baseline CO_2 emissions near the EU standard and baseline masses near the EU fleet average mass. The actual universe of vehicles subject to these standards will possess mass and CO_2 characteristics that deviate from both the fleet average mass and the CO_2 target, which will induce mass-based CO_2 responses that differ from the responses associated with the standard relations. For example, a vehicle with a fleet average mass but higher than average CO_2 emissions will achieve greater absolute CO_2 reductions for a given change in mass than a vehicle of fleet average mass and lower than average CO_2 emissions undergoing the same mass change. Thus, it is important to investigate, in a more generalized manner, the degree to which mass induced changes in CO_2 are discounted by the form of the EU standard. However, a more detailed examination of the underlying principles, based on the quantification of effects about the restricted case of vehicles of fleet average mass and target-level CO_2 emissions, is helpful in illustrating the mechanisms associated with mass reduction discounting. A generalized discussion follows this restricted case examination.

Figures 2 and 3 provide a quantitative illustration of the degree of mass reduction discounting associated with vehicles of masses and CO_2 emissions at the 2020 EU standards. Figure 2 illustrates mass reduction and increase allowances inherent in the standard for passenger cars, whereas Figure 3 illustrates corresponding allowances for light commercial vehicles. Both depict a standard that provides little (passenger cars) to no (light commercial vehicles) incentive to incorporate vehicle mass reduction technology into a vehicle manufacturer's CO_2 compliance strategy. At the same time, these standards provide substantial incentive to actually increase vehicle mass to the detriment of fleet average CO_2.

The dotted line in Figure 2 running from the lower left to upper right through points 1a, 0, and 2a depicts a portion of the passenger car standard function for 2020. Point 0 represents the 2020 passenger car standard of 95 g/km as measured over the NEDC, which is applicable at the EU-defined fleet average passenger car mass of 1,392.4 kg. Point 1b reflects the change in CO_2 that would result from a 10% reduction in vehicle mass for a vehicle with a prereduction fleet average mass. Point 1a reflects the change in the vehicle-specific CO_2 standard that results under the EU mass-based regulatory structure for a vehicle with a prereduction fleet average mass that undergoes a 10% mass reduction. As indicated, the subject standard would decline to 90.4 g/km from 95 g/km. Thus, 4.6 g/km of the 6.1 g/km mass-driven reduction in CO_2 (76 percent) is "consumed" by the more stringent CO_2 standard, leaving only 1.5 g/km (24 percent of the mass-driven reduction) as creditable as reflected by the CO_2 reduction between points 1a and 1b. Of course, the resulting CO_2 is not affected by the "bookkeeping" associated with mass reduction accounting. What is affected is a vehicle manufacturer's incentive to invest in mass reduction technology, an incentive that can affect both the magnitude and cost of vehicle-specific and fleet average CO_2.

Figure 2. Mass impacts of the EU regulatory structure for passenger cars.

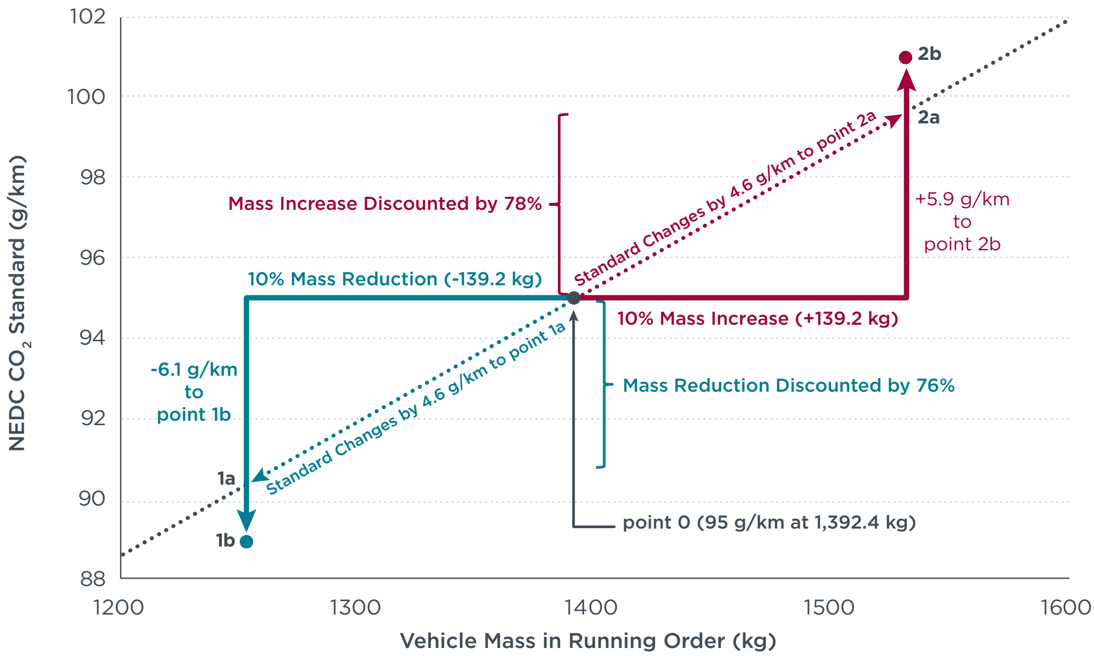


Figure 3. Mass impacts of the EU regulatory structure for light commercial vehicles.

Take, for example, a vehicle with a fleet average mass and CO_2 emissions of 101.6 g/km. Such a vehicle would come into compliance with a 95 g/km standard if the manufacturer reduced the vehicle mass by 10% and the associated standard did not change due to that mass reduction. However, the standard does change to 90.4 g/km. The vehicle, out of compliance by 6.6 g/km at a 95 g/km standard, is still out of compliance by 4.6 g/km at a 90.4 g/km standard. Only 1.9 g/km, which is 29%, of the mass-driven CO_2 reduction is allocated to standard compliance.[15] The manufacturer's investment in mass reduction technology has been discounted by 71%. Note that the magnitude of the discount varies from that of the example vehicle in Figure 2 that has prereduction CO_2 emissions of 95 g/km. This results from the fact that mass-driven reductions are generally multiplicative in nature. Reductions are a fraction of prereduction CO_2. A vehicle with higher prereduction emissions will garner a greater absolute CO_2 reduction for a given mass reduction than a lower emitting counterpart of the same mass, although the associated change in applicable CO_2 standards for the vehicles is constant. Thus, the fraction of CO_2 reduction allocated to the changing standard varies with prereduction CO_2 emissions.

As shown in Figure 2, discounting of mass impacts under the EU regulatory structure also accrues for mass increases. Point 0 represents the 2020 EU CO_2 standard of 95 g/km as measured over the NEDC, which is applicable at the EU-defined fleet average passenger car mass of 1,392.4 kg. Point 2b reflects the change in CO_2 that would result from a 10% increase in vehicle mass for a vehicle with a preincrease fleet average mass. Point 2a reflects the change in the vehicle-specific CO_2 standard that results under the EU mass-based regulatory structure for a vehicle with a prereduction fleet average mass that undergoes a 10% mass increase. As indicated, the subject standard would increase to 99.6 g/km from 95 g/km. Thus, 4.6 g/km of the 5.9 g/km mass-driven increase in CO_2, in this case 78%, is "accommodated" by the less stringent CO_2 standard, leaving only 1.3 g/km, or 22%, of the mass-driven increase to be offset. This is reflected by the CO_2 increase between points 2a and 2b. Thus, a vehicle manufacturer has the option of increasing vehicle mass with only marginal penalty, potentially allowing for investment decisions that consider cost savings associated with less expensive heavier vehicle components as a potential offset against the cost of investment in mass-neutral CO_2 reduction technology.

Figure 3 presents similar mass reduction and increase allowances for EU light commercial vehicles. As with Figure 2, the dotted line in Figure 3 running from the lower left to upper right through points 1a, 0, and 2a depicts a portion of the light commercial vehicle standard function for 2020. Point 0 represents the 2020 light commercial vehicle standard of 147 g/km as measured over the NEDC, which is applicable at the EU-defined fleet average light commercial vehicle mass of 1706 kg. Point 1b reflects the change in CO_2 that would result from a 10% reduction in vehicle mass for a vehicle with a prereduction fleet average mass. Point 1a reflects the change in the vehicle-specific CO_2 standard that results under the EU mass-based regulatory structure for a vehicle with a prereduction fleet average mass that undergoes a 10% mass reduction. As indicated, the subject standard would decline to 130.6 g/km from 147 g/km. Thus, 16.4 g/km of the 9.5 g/km mass-driven reduction in CO_2—173%—is "consumed" by the more stringent CO_2 standard, requiring an additional 6.9 g/km of CO_2 reduction to maintain standard compliance, as reflected by additional CO_2 reduction required to equilibrate point 1b with point 1a. In effect, the value of mass reduction technology is discounted to less than zero under the light commercial vehicle standard. In other words, any manufacturer implementing mass reduction technology will be required to implement additional non-mass reduction technology simply to maintain its prereduction compliance status.

Conversely, the light commercial vehicle standard offers essentially unlimited incentive to increase vehicle mass.[16] Point 0 of Figure 3 represents the 2020 EU CO_2 standard of 147 g/km as measured over the NEDC, which is applicable at the EU-defined fleet average light commercial vehicle mass of 1706 kg. Point 2b reflects the change in CO_2 that would result from a 10% increase in vehicle mass for a vehicle with a preincrease fleet average

15 Note that indicated values do not resolve precisely when expressed to the nearest tenth (i.e., $4.6 + 1.9 \neq 6.6$), but are accurate representations of more resolved values.

16 Ignoring for illustrative purposes the constraining effects of periodic M_0 adjustment.

mass. Point 2a reflects the change in the vehicle-specific CO_2 standard that results under the EU mass-based regulatory structure for a vehicle with a prereduction fleet average mass that undergoes a 10% mass increase. As indicated, the subject standard would increase from 147 g/km to 163.4 g/km. Thus, 16.4 g/km of the 9.2 g/km mass-driven increase in CO_2 (179%) is "accommodated" by the less stringent CO_2 standard, leaving a windfall compliance cushion of 7.2 g/km, as reflected by the CO_2 reduction between points 2a and 2b. Thus, a vehicle manufacturer has the option of increasing vehicle mass without penalty, allowing for investment decisions that consider cost savings associated with less expensive heavier vehicle components as a hedge against the cost of investment in mass-neutral CO_2 reduction technology.

The degree of discounting actually associated with the EU standards is substantially more complex than indicated in Figures 1 through 3 as absolute (i.e., g/km) CO_2 changes depend not only on vehicle mass, but on baseline CO_2 as well. Vehicles with CO_2 emissions greater than the EU standard will achieve greater absolute CO_2 changes for a given mass change than vehicles with CO_2 emissions less than the EU standard, so that deviations based on a constant absolute CO_2 change function like the EU function are informative only under very limited conditions. The EU standard functions define a constant change in the value of the CO_2 standard for a unit change in mass, which is 0.0333 g/km per kg for passenger cars and 0.096 g/km per kg for light commercial vehicles. Absolute CO_2 changes depend on both the fractional mass change and the prechange level of CO_2.[17] As a result, the actual degree of discounting associated with mass changes under the EU standards is vehicle specific.

Figures 4 and 5 illustrate the initial condition dependency of mass reduction discounting for passenger cars and light commercial vehicles respectively. Both figures show the degree of mass reduction discounting associated with a constant fractional change in mass not only for vehicles emitting CO_2 at levels at or near the 2020 EU standards, but for a wide range of baseline CO_2 emission levels and a wide range of baseline masses. As the figures show, the rate of discounting declines with baseline mass as the absolute mass change for a constant percentage change similarly declines, which results in smaller changes in the unit mass-based EU CO_2 standards. Discounting also declines with increasing baseline CO_2 as the fractional mass change generates larger CO_2 changes with increasing baseline CO_2 although associated EU CO_2 standard changes are independent of baseline CO_2. Note that the EU passenger car standard does credit vehicle manufacturers for some level of mass reduction for a wide range of baseline mass and CO_2 levels, as indicated by the range of conditions in Figure 4 where the discount rate is less than 100%. However, there are comparatively few conditions in which mass reduction for light commercial vehicles is not more than fully discounted. In fact, mass reductions for light commercial vehicles would actually require additional non-mass technology investments simply to maintain a constant compliance status

17 CO_2 is dependent on fractional changes in mass as such changes are more directly related to fractional changes in road load and thus fractional changes in vehicle tractive energy requirements. For example, it is not reasonable to expect that a 50 kg (2%) mass reduction on a 2,500 kg base mass vehicle would generate the same impact as a 50 kg (5%) mass reduction on a 1,000 kg base mass vehicle. Yet that is exactly what the EU standard formulation assumes. Similarly, vehicles with higher baseline CO_2 will derive greater absolute emissions reductions for a given percentage change than vehicles with lower baseline CO_2. Note that this relationship, and the entirety of the discussion in this report, is investigated from the standpoint of a particular vehicle and not the overall fleet. At least for passenger cars, the EU has purposefully adjusted the slope of the standard in an effort to require greater reductions on average for manufacturers producing heavier vehicles. This evaluation makes no statement with regard to the efficacy of that effort, but rather focuses on the ability of any manufacturer to use weight reduction as a viable compliance strategy for any vehicle of above or below average mass, given a specific CO_2 target, regardless of magnitude. In other words, after a standard is established on the basis of the mass of a given vehicle, or fleet of manufacturer vehicles, *regardless of how that standard was determined,* can mass reduction serve as a viable compliance mechanism? Barring a technology-neutral basis for establishing a CO_2 standard, such as a fleet average flat standard or vehicle size-based standard, there must necessarily be some degree of discounting associated with whatever non-neutral basis—in this case mass—is used to establish the standard. The goal here is to quantify that degree and its effect on overall CO_2 compliance costs.

between pre- and post-mass reduction conditions as reflected by discount rates greater than 100% in Figure 5.

The fact that the physical relation between mass and CO_2 is multiplicative (i.e., nonlinear) means that absolute CO_2 reductions vary with base mass CO_2. At the same time, the EU standards define linear CO_2 adjustments that are independent of base mass CO_2. As a result, the degree of mass reduction discounting, as shown in Figures 4 and 5, is dependent on base mass CO_2. This necessitates the need for three dimensions to fully depict the mass discounting relations associated with the EU standards. Figures 4 and 5 accomplish such depiction in two-dimensional space by showing the mass discounts for a series of discrete two-dimensional curves representing 10 g/km increments in base mass CO_2 ranging from 40 to 170 g/km for passenger cars and 90 to 220 g/km for light commercial vehicles. The discount for intermediate levels of CO_2 can be interpolated from the depicted increments. For example, as shown in Figure 4, an investment in mass reduction technology for a 1,500 kg passenger car with baseline CO_2 emissions of 120 g/km would be discounted by 64.5%. (Follow the 1,500 kg base mass line vertically to its point of intersection with the 120 g/km prereduction CO_2 line; from that point, move left horizontally to read the discount value on the vertical axis.)

The darker black curves in Figures 4 and 5 reflect the restricted case of vehicles with base mass and CO_2 emissions that fall exactly along the line of the EU standard. The nonlinearity of these curves results from the fact that the EU standard functions attempt to linearly approximate a multiplicative (i.e., nonlinear) physical relation. Note the black curves cross the 95 and 147 g/km base CO_2 lines at the EU-defined fleet average masses. They then cross each incremental base CO_2 curve at the standard that would be associated with each prereduction mass level. For example, the passenger car standard at 500 kg would be 65 g/km and 115 g/km at 2,000 kg. Figure 4 shows the black curve falling between the 10 g/km incremental base CO_2 lines for these points and all points in between.

Figure 4. Mass reduction discount under 2020 EU passenger car standards.

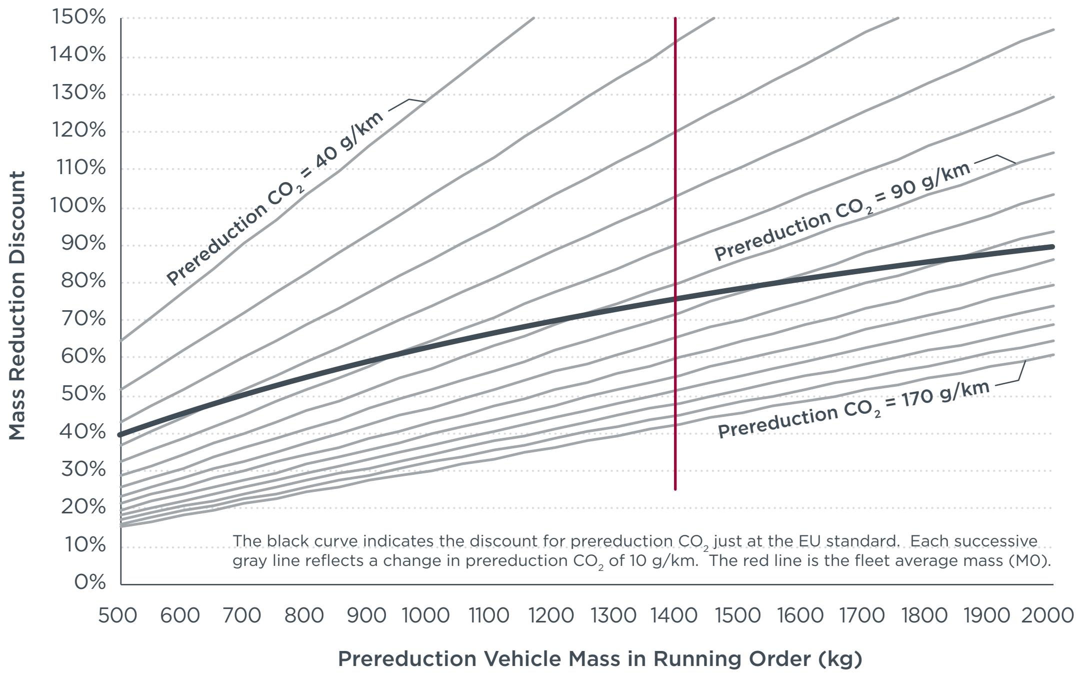
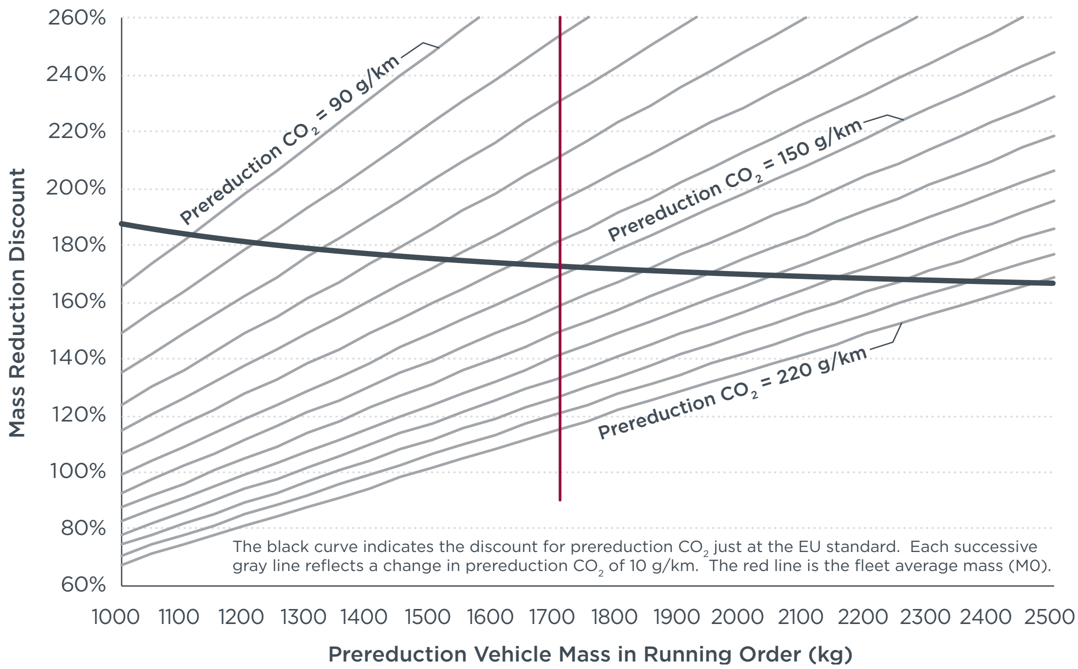


Figure 5. Mass reduction discount under 2020 EU light commercial vehicle standards.



For this paper, average mass reduction discount rates of 76% and100% are assumed for passenger cars and light commercial vehicles respectively. Both are based on the discount rate for a prereduction vehicle with a fleet average mass and CO_2 emission rate at the fleet average standard.[18] Although differential vehicle-specific discount rates can and will apply under the current form of the EU standard, compliance with standards in the 2025–2030 time frame presumes underlying compliance with existing 2020 standards. For light commercial vehicles, the actual discount rate for these conditions is 173%, but capping the discount at 100% is appropriate if manufacturers are discouraged from implementing mass reduction technology due to an inability to garner compliance benefits. Any manufacturers that nevertheless do implement mass reduction technology will be required to supplement such introduction with even greater investment in non-mass technology and such investments are not reflected in the cost estimates presented in this paper. This is appropriate for a no-mass-reduction cost curve, but will underestimate compliance costs if some level of cost inefficient mass reduction does occur. Conversely, light commercial vehicle compliance costs may be overestimated if M_0 adjustment and cargo carrying restrictions fail to keep manufacturers from taking advantage of the incentive inherent in the current slope of the EU standard to increase vehicle mass and thereby reduce their compliance burden.

18 The actual discount rate for light commercial vehicles is 173%, but we cap this in practice at 100% because any incentive to pursue mass reduction technology is fully offset at the 100% level. As indicated in the discussion preceding this footnote, a greater than 100% discount rate could induce manufacturers to explore the effectiveness of mass increases, but we assume that safeguards such as the M_0 adjustment process inherent in the EU standards and practical considerations such as maximizing the cargo carrying capacity of commercial vehicles will inhibit much of this incentive.

4. ANALYSIS METHODOLOGY

With one exception, the methodology employed to generate the fundamental cost curves that underlie this analysis is identical to the methodology employed for the technology neutral analysis by Meszler et al. (2016). The difference is that the cost curves for this analysis exclude mass reduction technology. As documented in Meszler et al. (2016):

> "Mass reduction costs are included in both lower and upper bound compliance cost estimates, but upper bound estimates assume that no level of mass reduction can be achieved at less than zero cost (while lower bound costs assume mass reduction cost savings when such savings are appropriate). (p. vii)"

For this analysis, mass reduction technology is excluded in its entirety from both the lower and upper bound compliance cost scenarios. This means that both the costs or savings and CO_2 impacts of mass reduction technology have been excluded from the cost curve development process. As a result, a series of four fundamental cost curves are produced: lower and upper bound curves from the analysis by Meszler et al. (2016) that include mass reduction technology, and lower and upper bound curves from this analysis that exclude mass reduction technology. These curves are then weighted on the basis of EU mass reduction discount rates defined in Section 3 to generate a set of EU-specific discounted mass reduction cost curves.

Eliminating the cost impacts of mass reduction technology is straightforward, as these can simply be removed from any technology package that included any level of mass reduction during the simulation modeling process. Backing out the CO_2 impacts is more complicated because the simulation modeling was based on the net effect of a package of included technologies. Moreover, because the simulation modeling data included technology packages with various levels of mass reduction, the approach to CO_2 adjustment must be continuous in nature to accommodate the specific mass reduction assumptions associated with each package. To generalize the CO_2 effects of mass reduction as reflected in the simulation modeling data, a detailed analysis was performed using 26 technology packages spanning all modeled vehicle classes where mass reduction was the only technology variant. The results of this evaluation revealed average CO_2 emission changes of 0.456%, 0.467%, and 0.447% per percent change in vehicle mass for vehicles executing the NEDC, WLTP low road load, and WLTP high road load cycles, respectively.[19]

Using these data, the average CO_2 effect of mass reduction technology can be factored out of any of the simulation modeling packages in which it is included. The required adjustment is mathematically expressed as:

$$\text{AdjFac} = \frac{1}{1 - (\text{PerPct}_{\text{Modeled}} \times \text{PctMassRed})}$$

Where:

AdjFac = CO_2 multiplier,
PerPct = Fractional change in CO_2 per percent change in mass,
Modeled = Effect observed in the simulation modeling data, and
PctMassRed = Fractional change in mass

19 The derived changes differ from the average physics-based change discussed in Section 3 due to the fact that the simulation modeling did not properly account for powertrain optimization. These optimization effects were included in the Meszler et al. (2016) analysis through appropriate CO_2 adjustments. Because the desire here is to remove the mass reduction effects as actually simulated, it is the simulation CO_2 impacts that are the critical factor, as opposed to the more robust physics-based relationship cited earlier in this report. In effect, the analysis for this report "removes" the mass reduction CO_2 impacts from the simulation modeling estimates using the average impacts inherent in that modeling to derive equivalent no-mass-reduction CO_2 values. For the with-mass-reduction analysis supporting the Meszler et al. (2016) cost curve report, the simulation modeling CO_2 impacts were enhanced by a modest amount, as documented in the that same report, to reflect appropriate powertrain optimized CO_2 impacts. Both adjustments move from the simulated CO_2 value, one toward lower CO_2 (with mass reduction technology) and one toward higher CO_2 (without mass reduction technology).

As indicated, the function is continuous and is evaluated in accordance with the specific mass reduction (if any) associated with a given technology package. For illustrative purposes, the derived CO_2 multipliers to factor out a 10% mass reduction are 1.048, 1.049, and 1.047 for the NEDC, WLTP low road load, and WLTP high road load cycles, respectively. The respective derived multipliers for a 20% mass reduction are 1.100, 1.103, and 1.098. Nominally, these reflect the mass reduction ranges included in the simulation modeling data, so that total CO_2 adjustments generally are about 5% for the nominal 10% reductions and 10% for the nominal 20% reductions.[20]

It is important to note that the CO_2 adjustments are average in nature. The majority of the technology packages included in the simulation modeling database consist of multiple varying technologies, so that the precise effects of any one specific technology cannot be isolated. Thus, although this analysis applies average factors to eliminate the effects of mass reduction technology, the actual effects may be moderately different so that the adjustments, although reasonably accurate, are not precise.

Following the adjustments to remove mass reduction technology costs and CO_2 impacts, cost curves were generated exactly as was done for the Meszler et al. 2016 technology-neutral analysis.

Although not a deviation from the approach employed Meszler et al. in their 2016 technology-neutral analysis, it is important to understand that EVs are substantially unaffected by the mass reduction technology exclusion. Thus, differentials between with-mass-reduction-technology and without-mass-reduction-technology cost curves decline as compliance demands move away from ICE technology and toward greater shares of EV technology. This results primarily from the fact that the analysis assumes zero CO_2 for battery electric vehicles and zero CO_2 for plug-in hybrid electric vehicles operating in all-electric mode. At a zero CO_2 level, there is little regulatory incentive for BEV manufacturers to reduce mass under a standard that would respond by reducing CO_2 compliance credits, so the analysis assumes no change in BEV cost under either a with-mass-reduction-technology or without-mass-reduction-technology scenario. Because they rely on ICE technology in their design basis, PHEV emissions are somewhat sensitive to changes in ICE vehicle CO_2 due to the exclusion of mass reduction technology, but the fact that a considerable portion of PHEV operations occur in all-electric mode, as documented in the Meszler et al. 2016 cost curve report, results in only a moderate net change in CO_2. Thus with-mass-reduction-technology and without-mass-reduction-technology cost curve differentials decline as EV market penetration increases.

20 Actual mass reductions deviate from nominally specified 10% and 20% reductions because of modest mass impacts of other included technologies. Deviations from nominal are no more than one or two percentage points.

5. DERIVED CO_2 COMPLIANCE COSTS

As discussed in Section 2, CO_2 compliance cost estimation consists of the integration of two independent components: one reflecting the level of CO_2 reduction that can be achieved through the introduction of progressively more effective ICE technology and one reflecting the CO_2 reduction that can be achieved by increasing the market penetration of EVs. The cost of ICE technology is generally reflected as an upwardly sloping exponential curve. (See for example Figure 6a.) Because the underlying EV cost is constant for a given vehicle class and driving cycle in a given evaluation year, the cost of increasing EV market penetration is a linear function that serves to extend the ICE technology cost curve to lower levels of CO_2 than would otherwise be possible to attain. The rightmost end of the integrated cost curve represents the CO_2 reductions and cost associated with 100% EV market penetration.[21]

There is no physical or regulatory constraint prohibiting a manufacturer from introducing EVs at any time. There is no requirement that all ICE technology be exhausted before introducing EVs into the fleet. This means that there are an infinite number of ways in which the ICE and EV cost curve data can be integrated. However, one, and only one, of the possible transitional alternatives has special significance, in that it transitions from ICE technology to EV market penetration at exactly the point where the latter becomes more cost effective from a CO_2 standpoint than the former. In other words, adding EVs to the fleet is cheaper than adding more expensive ICE technologies. In mathematical terms, this transition point is defined as the point where the marginal cost of ICE technology exceeds the marginal cost of EV technology.

Despite the ability to identify the least cost transition point, this analysis (like the underlying Meszler et al. 2016 analysis) includes two transition points for every evaluated ICE cost curve. One transition point is based on ICE technology exhaustion and effectively represents the point at which further CO_2 reduction *requires* EV market penetration, given the constraints associated with the simulation modeling data. For convenience, this curve type is hereafter characterized as the ICE technology exhaustion strategy and abbreviated as the ExhICE Strategy. The second transition point is based on the least cost transition from ICE technology to EV market introduction. With this strategy, hereafter referred to as the EV optimization strategy and abbreviated as the EV Strategy, transition occurs when the marginal cost of EVs is less than the marginal cost of additional ICE technology. Between these two approaches, there can be substantial differences in the estimated CO_2 compliance costs for small EV market penetrations, especially when the marginal cost of additional ICE technology is comparatively large. However, compliance cost differences will always converge to zero as the penetration of EVs approaches 100% because cost at this limit is independent of the point of ICE technology transition.

The analysis retains the two-strategy compliance cost approaches for two primary reasons. First, the EV cost data include vehicle technology costs only. Costs associated with overcoming market barriers to widespread EV introduction, for example, availability of a supporting infrastructure, are not considered. Assuming cost effectiveness on the basis of vehicle technology cost alone may overstate the ability of manufacturers to deliver market shares as efficiently as such cost effectiveness estimates may imply. Second, this analysis evaluates costs for a given year, and it is highly unlikely that large EV market penetration shifts can occur over a similarly limited time frame. Because the

21 As discussed in Section 2, the analysis assumes that BEV-100 vehicles will be used to satisfy any EV demand for B and C class vehicles. For all larger vehicle classes, the analysis assumes that BEVs will not be practical in the time frame considered and that PHEVs will be employed to satisfy any EV demand. In a compromise between consumer utility, required market penetration (CO_2 declines with increasing all electric range [AER]), and cost, the analysis assumes that PHEVs with an NEDC AER of 40 miles will be the preferred PHEV solution.

EV data imply substantial cost reductions between 2015 and 2030, it is likely that the costs associated with facilitating large EV market penetrations in one year, say 2030, will require significantly more expensive EV investments in earlier years. For these reasons, this analysis presents compliance cost data for both ICE technology exhaustion and least cost EV transition CO_2 reduction strategies.[22]

Figures 6a and 6b present passenger car fleet average compliance cost curves for CO_2 targets measured over the NEDC in 2020. The figures depict both the cost curves developed in the Meszler et al. 2016 analysis under an assumption that mass reduction technology is fully creditable and corresponding cost curves developed in this analysis under an assumption of discounted mass reduction technology. Both figures also include corresponding EV market penetrations. Figures 7a and 7b present corresponding light commercial vehicle compliance cost curves for CO_2 targets measured over the NEDC in 2020. Figures 8a and 8b present passenger car fleet average compliance cost curves for CO_2 targets measured over the WLTP in 2020, whereas Figures 9a and 9b present light commercial vehicle compliance cost curves for that same driving cycle and evaluation year. Figures 10 through 13 present corresponding data for a 2025 evaluation year; Figures 14 through 17 do the same for a 2030 evaluation year.[23]

As previously discussed, each curve actually consists of two components. The leftmost component reflects the level of CO_2 reduction that can be achieved through the introduction of progressively more effective ICE technology. Generally, this is reflected as an upwardly sloping exponential curve. The rightmost component is a linear extension that reflects the level of CO_2 reduction that can be achieved by introducing EVs into an ICE fleet in ever increasing market shares. The rightmost end of each curve represents the CO_2 reduction and cost associated with 100% EV market penetration.

Of particular interest in this analysis is the differential compliance cost between fully creditable and discounted mass reduction technology. To more directly illustrate such differential costs, Figures 18 through 29 depict the differential cost and differential EV market penetration data inherent in Figures 6 through 17 respectively. Generally, the differential cost curves follow a three-step function for the ICE technology exhaustion strategy. Differential costs initially rise sharply as the ICE technology portion of the cost curve generates significantly less CO_2 reduction when mass reduction technology is discounted. The cost differential then undergoes a period of sharp decline as the discounted curve is forced to transition to fixed-cost EV technology while the fully creditable mass reduction technology curve continues to rise through exponentially increasing ICE technology costs. The cost differential ultimately transitions to a less rapidly declining linear status when both the discounted and fully creditable cost curves have transitioned to EV technology to achieve lower CO_2 levels. A more stable two-step cost differential function is observed under the EV optimization strategy. Here, costs again rise rapidly as the discounted mass reduction curve is forced to transition to EV technology much sooner than the fully creditable mass reduction technology curve. However, because both curves avoid the cost-ineffective portions of the ICE technology cost curves by optimizing transition to EV technology, the initial rise in the compliance

22 As indicated in the Section 2 background discussion, this report focuses solely on vehicle technology costs. Offsetting savings due to reduced energy use are not considered.

23 It should be recognized that the depicted "fully creditable" mass reduction curves do not assume that a homogenous level of mass reduction is implemented across the fleet. These curves are based on the technology packages simulated by FEV. Some of these packages include mass reduction technology, with nominal reductions of either 10% or 20% as defined in the Meszler et al. 2016 cost curve report. For this analysis, corresponding cost curves were developed for an identical set of technology packages, except for the complete removal of all mass reduction technology impacts on both cost and CO_2. The resulting with-mass and without-mass cost curves are weighted in accordance with the degree to which the EU regulatory structure for CO_2 discounts mass reduction technology to derive composite discounted cost curves. In a probabilistic sense, the passenger car discounted curve consists of 76% of the without-mass curve and 24% of the with-mass curve. The 100% discount for the LCV regulatory structure means that the discounted curve is identical to the no-mass curve.

cost differential undergoes a subsequently ordered linear decline with CO_2 target levels demanding large EV market shares.

It is important to point out that the small cost savings that accrue when mass reduction technology is discounted for light commercial vehicles over the WLTP cycle under the ICE technology exhaustion strategy (as depicted in Figures 21a, 25a, and 29a) come from the very limited CO_2 benefits exhibited in the simulation modeling data for this set of conditions. The ICE technology portion of the cost curve is quite abbreviated and the forced early transition to EVs is slightly more cost effective than the extended ICE technology portion of the curve when mass reduction technology is fully creditable. The light commercial vehicle fleet, assumed to be 100% diesel powered in the FEV simulation modeling, can achieve ICE-based reductions of about 38% over the NEDC with mass reduction technology. However, this potential drops to 26% over the WLTP, primarily because the FEV simulation modeling shows very small benefits for hybrid technology over the cycle, less than a 1.5% CO_2 reduction relative to advanced nonhybrid technology. Without mass reduction technology, the CO_2 reduction potential drops to 28% over the NEDC and 17% over the WLTP. Therefore, the discounted cost curves for light commercial vehicles switch very quickly from ICE to EV technology for emissions measured over the WLTP.

Finally, it should be recognized that in all cases, the discounting of mass reduction technology has two effects. The first is the obvious cost effect. The second is an earlier transition to EV technology because of the constriction of the ICE portion of the cost curve. For moderate CO_2 reductions, EV market share requirements can be as much as 20 percentage points higher under conditions in which mass reduction technology is discounted. Thus, although the early transition to EV technology serves as a cap to the compliance cost differential, that cap comes at the expense of greater EV market share demands.

Figure 6a. 2020 NEDC CO_2 costs for passenger cars (ExhICE Strategy).

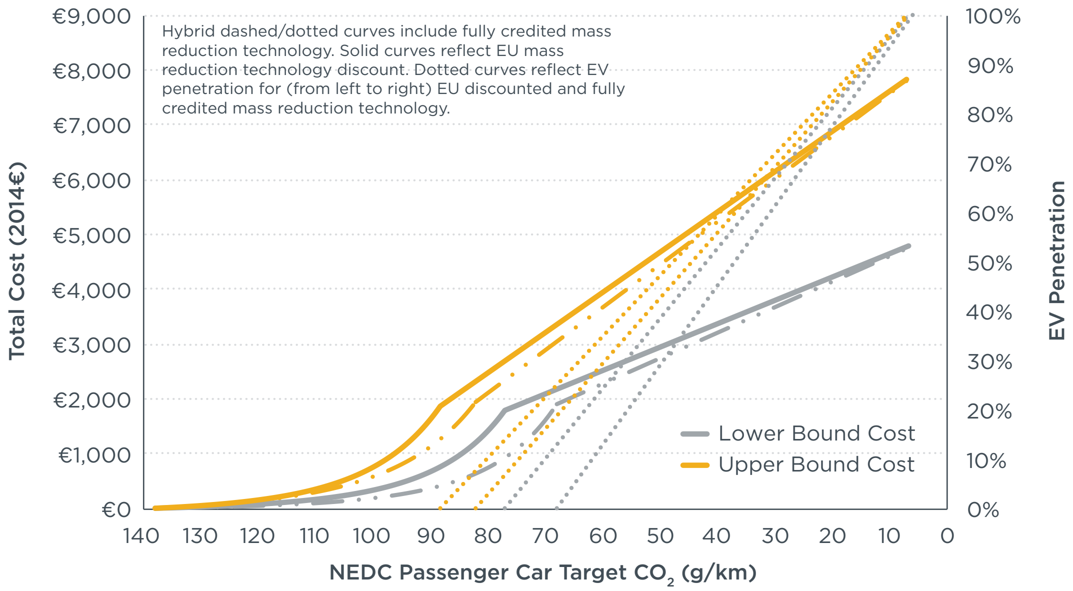


Figure 6b. 2020 NEDC CO_2 costs for passenger cars (EV Strategy).

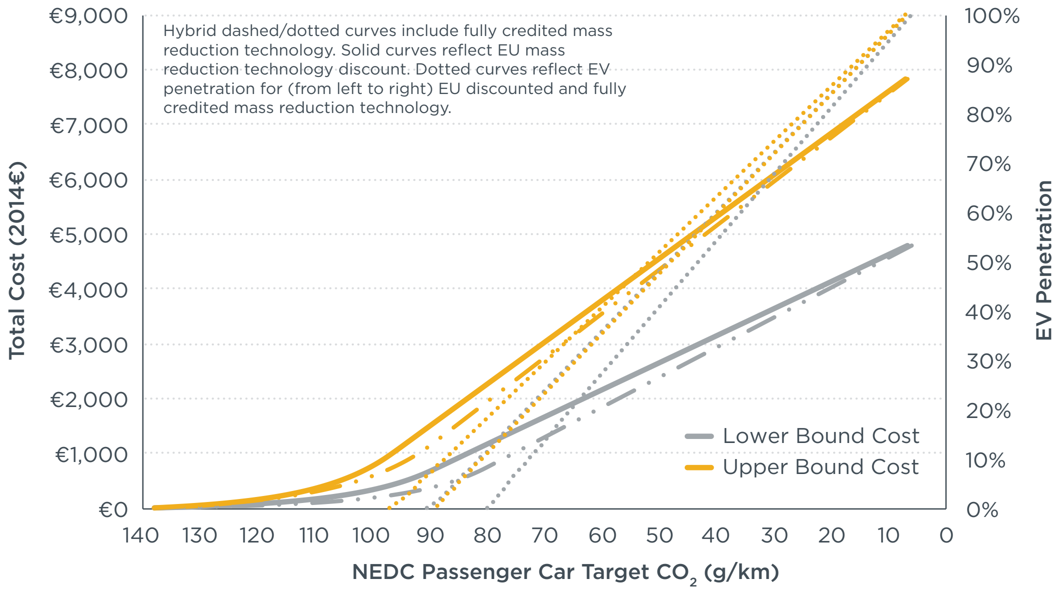


Figure 7a. 2020 NEDC CO_2 costs for light commercial vehicles (ExhICE Strategy).

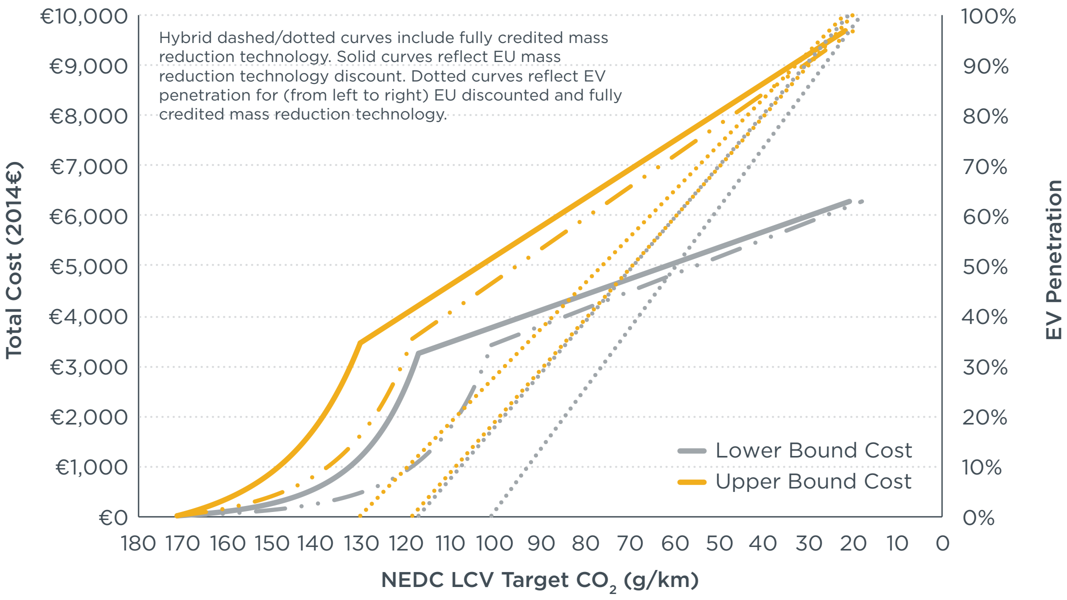


Figure 7b. 2020 NEDC CO_2 costs for light commercial vehicles (EV Strategy).

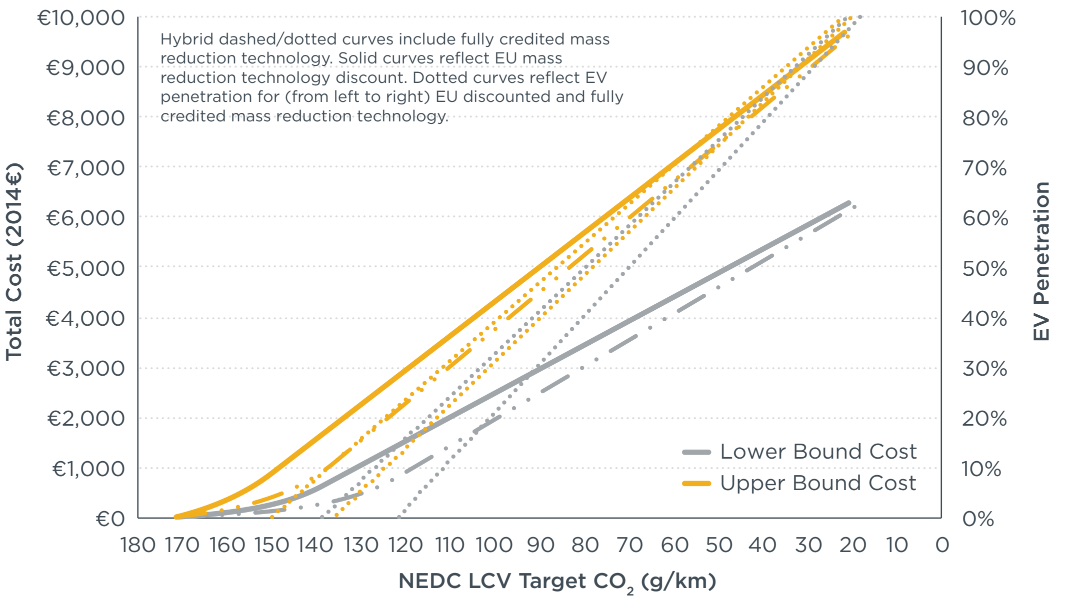


Figure 8a. 2020 WLTP CO_2 costs for passenger cars (ExhICE Strategy).

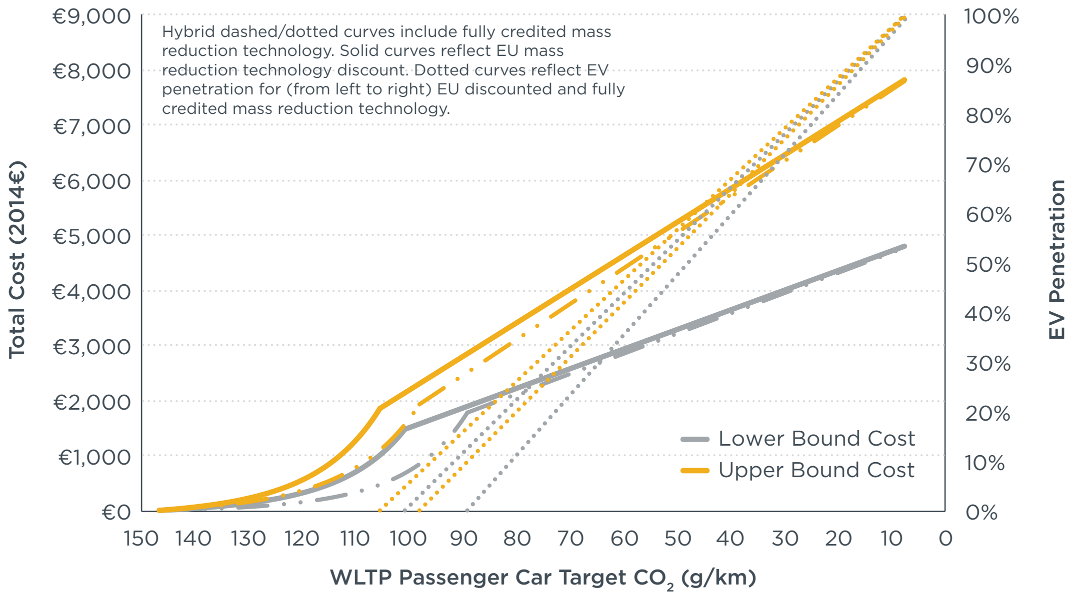


Figure 8b. 2020 WLTP CO_2 costs for passenger cars (EV Strategy).

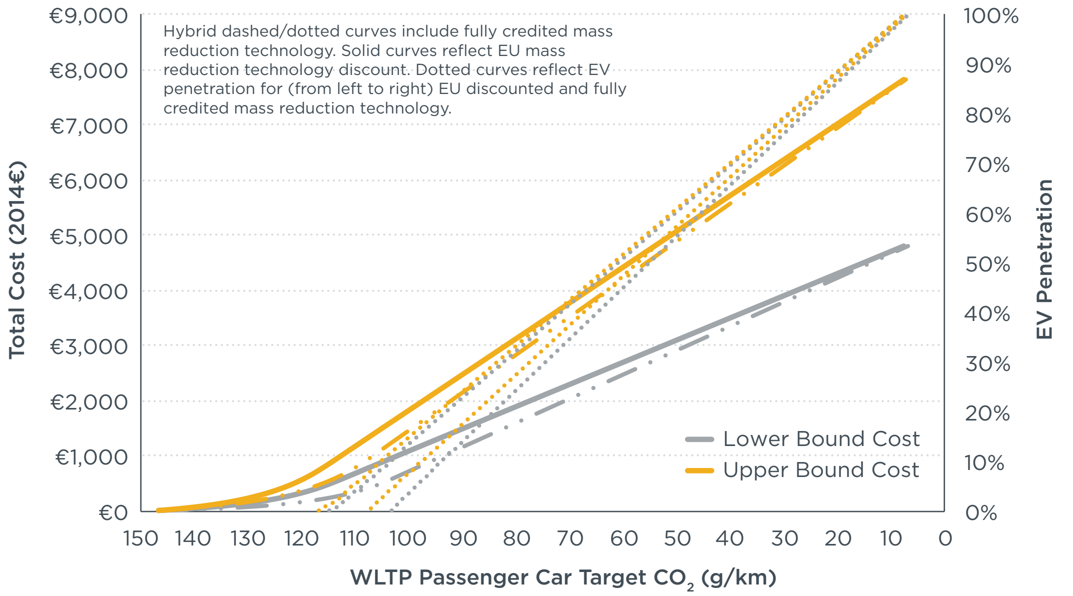


Figure 9a. 2020 WLTP CO_2 costs for light commercial vehicles (ExhICE Strategy).

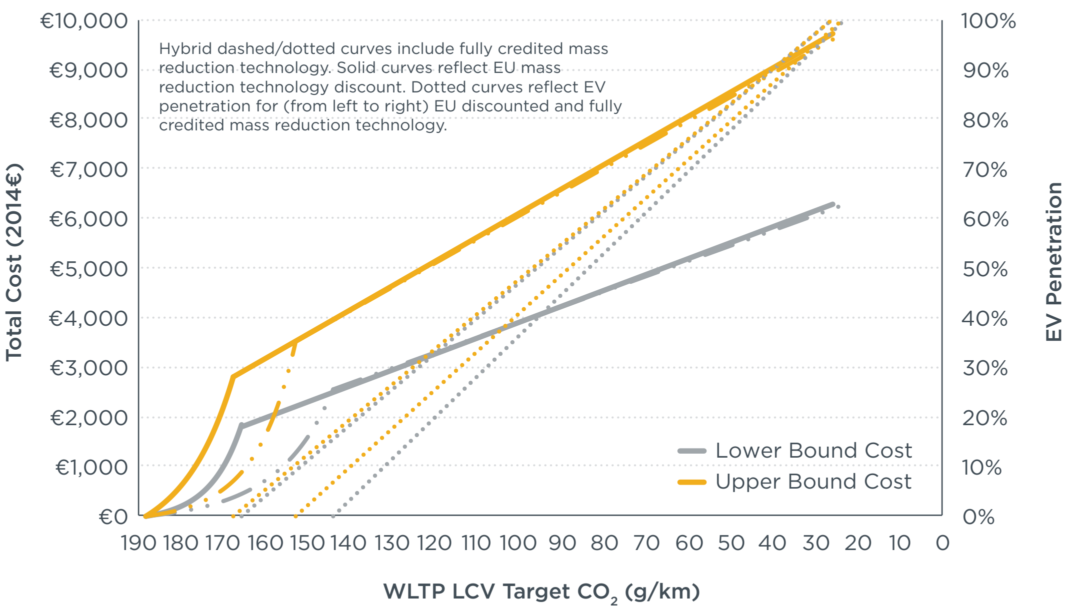


Figure 9b. 2020 WLTP CO_2 costs for light commercial vehicles (EV Strategy).

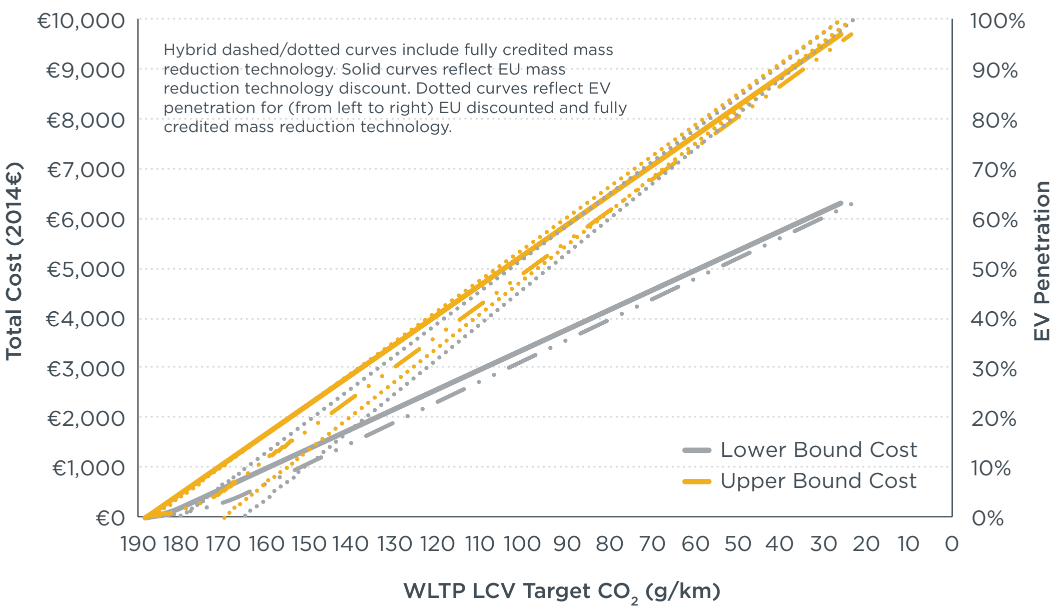


Figure 10a. 2025 NEDC CO_2 costs for passenger cars (ExhICE Strategy).

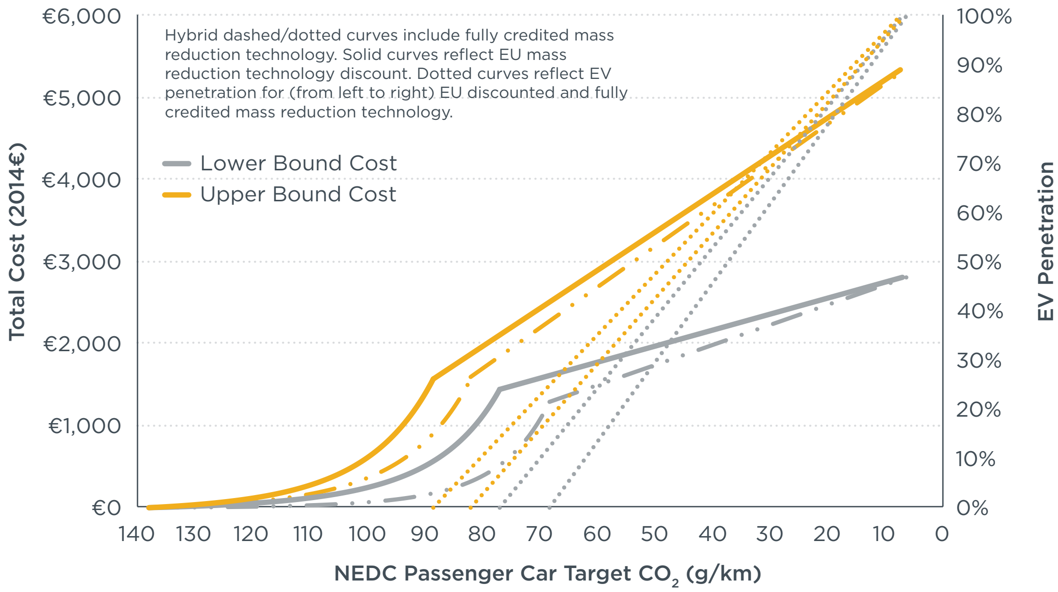


Figure 10b. 2025 NEDC CO_2 costs for passenger cars (EV Strategy).

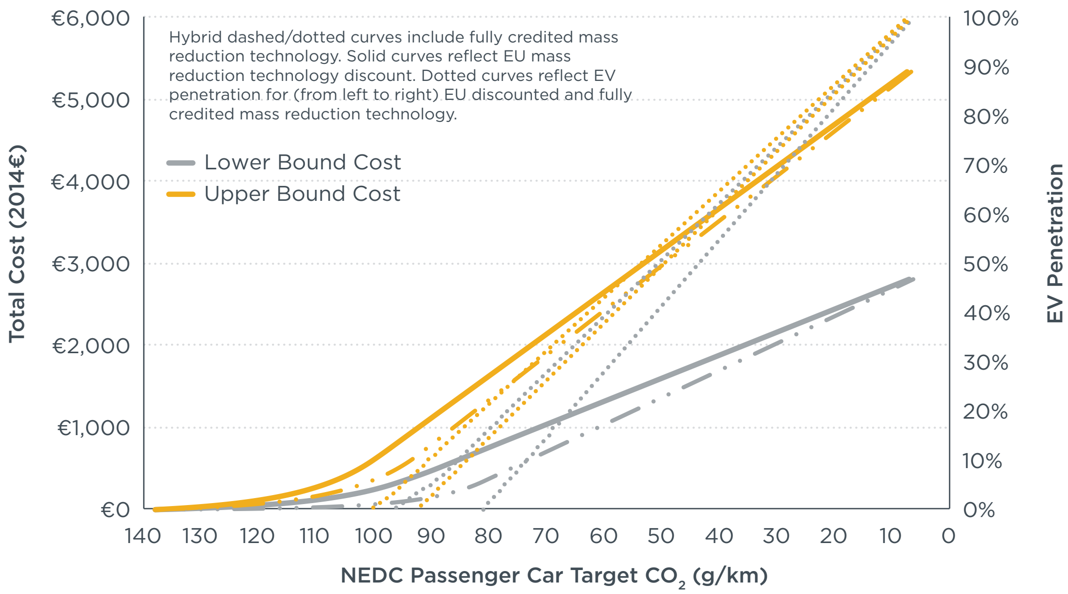


Figure 11a. 2025 NEDC CO_2 costs for light commercial vehicles (ExhICE Strategy).

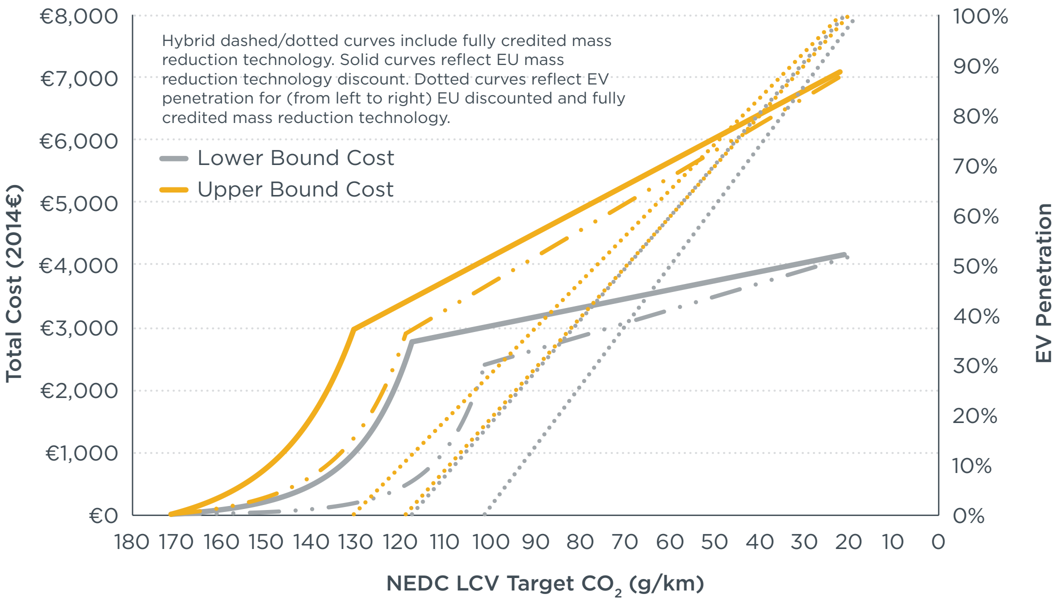


Figure 11b. 2025 NEDC CO_2 costs for light commercial vehicles (EV Strategy).

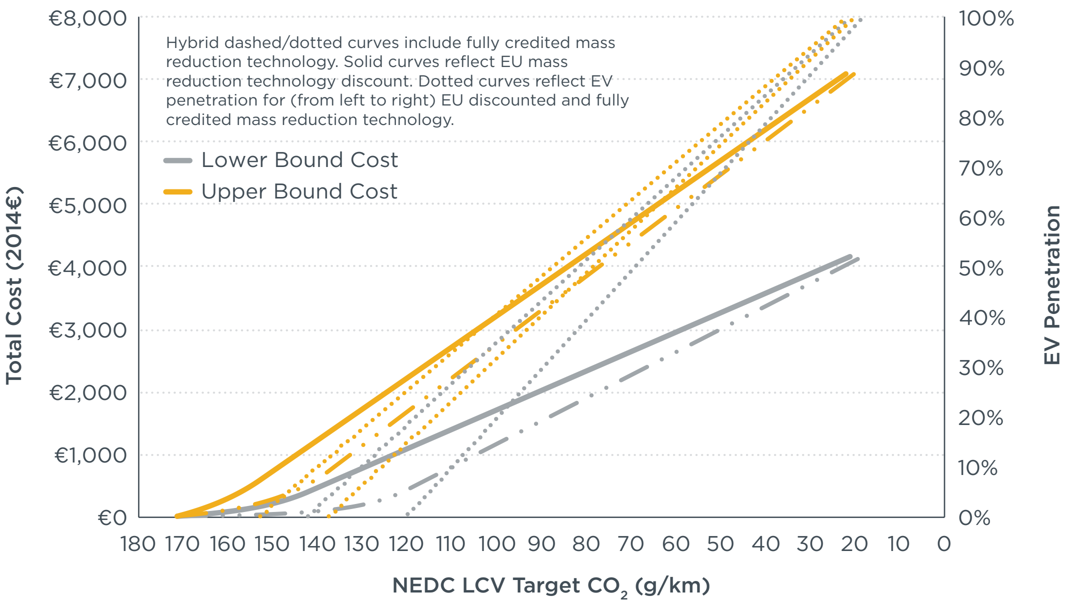


Figure 12a. 2025 WLTP CO_2 costs for passenger cars (ExhICE Strategy).

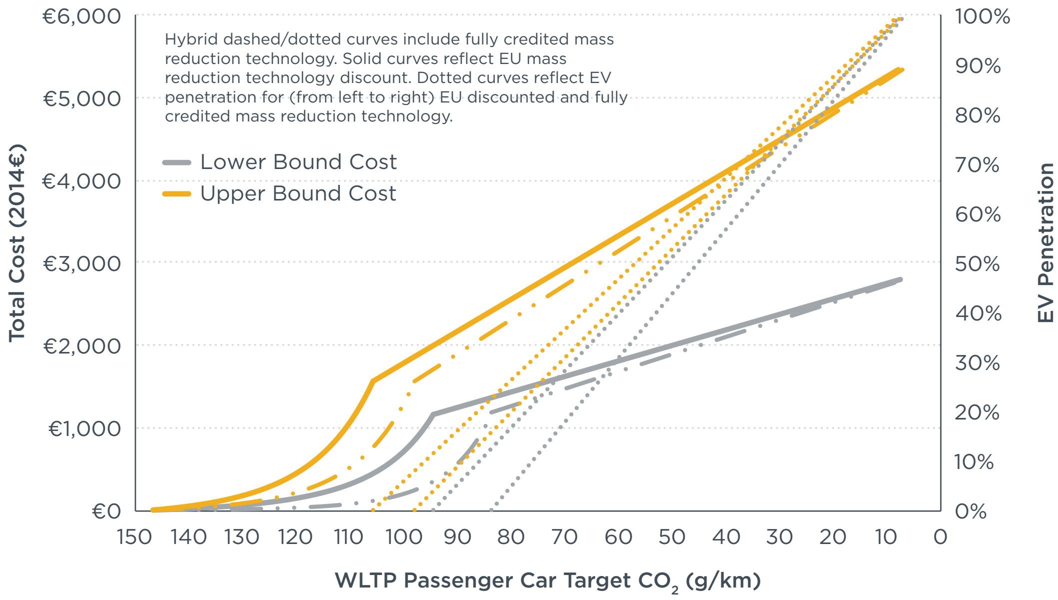


Figure 12b. 2025 WLTP CO_2 costs for passenger cars (EV Strategy).

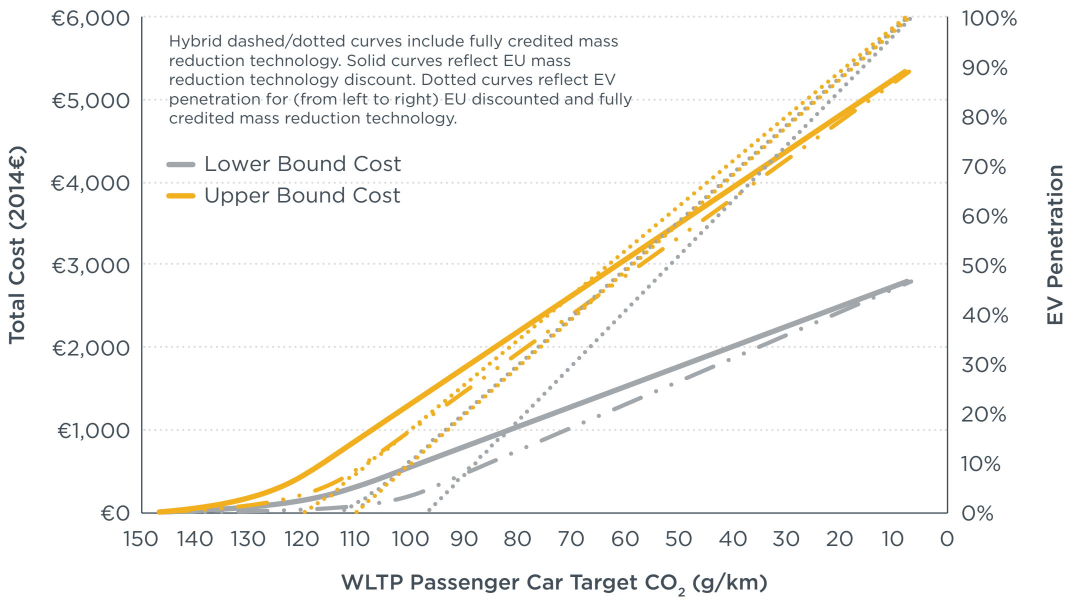


Figure 13a. 2025 WLTP CO_2 costs for light commercial vehicles (ExhICE Strategy).

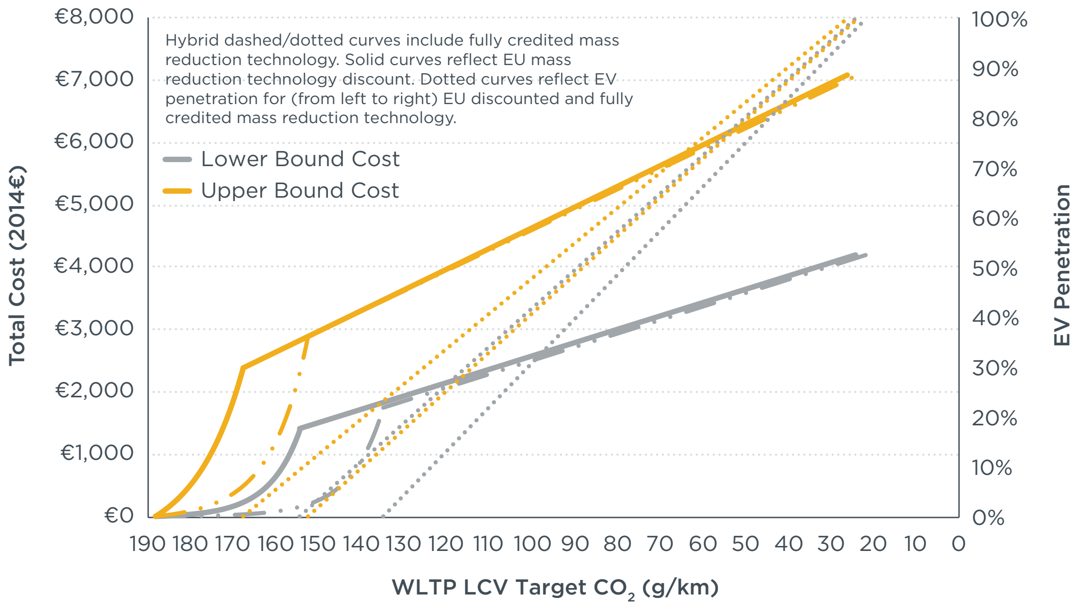


Figure 13b. 2025 WLTP CO_2 costs for light commercial vehicles (EV Strategy).

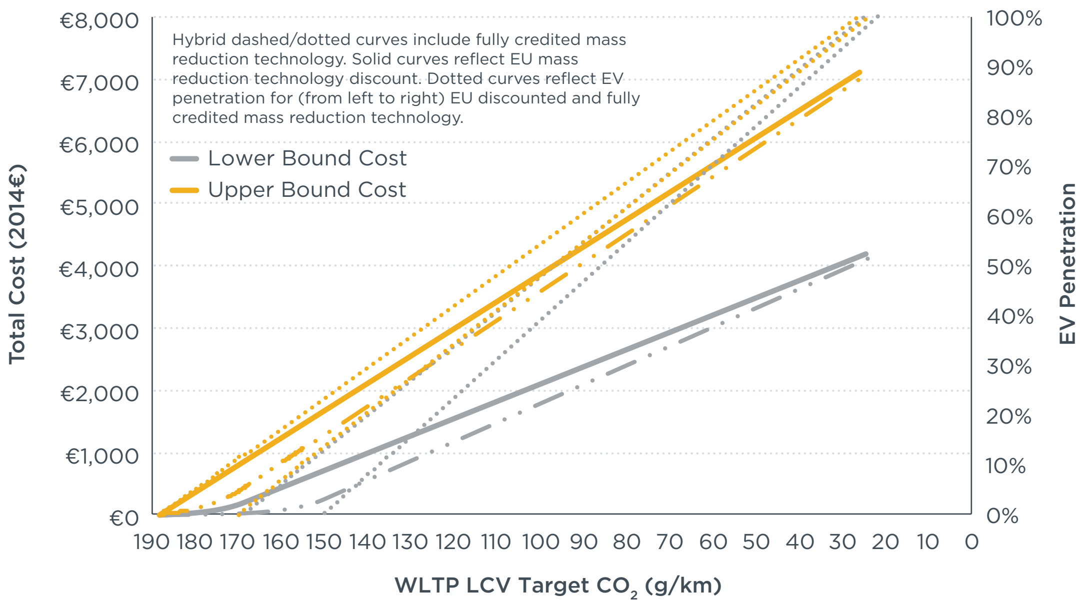


Figure 14a. 2030 NEDC CO_2 costs for passenger cars (ExhICE Strategy).

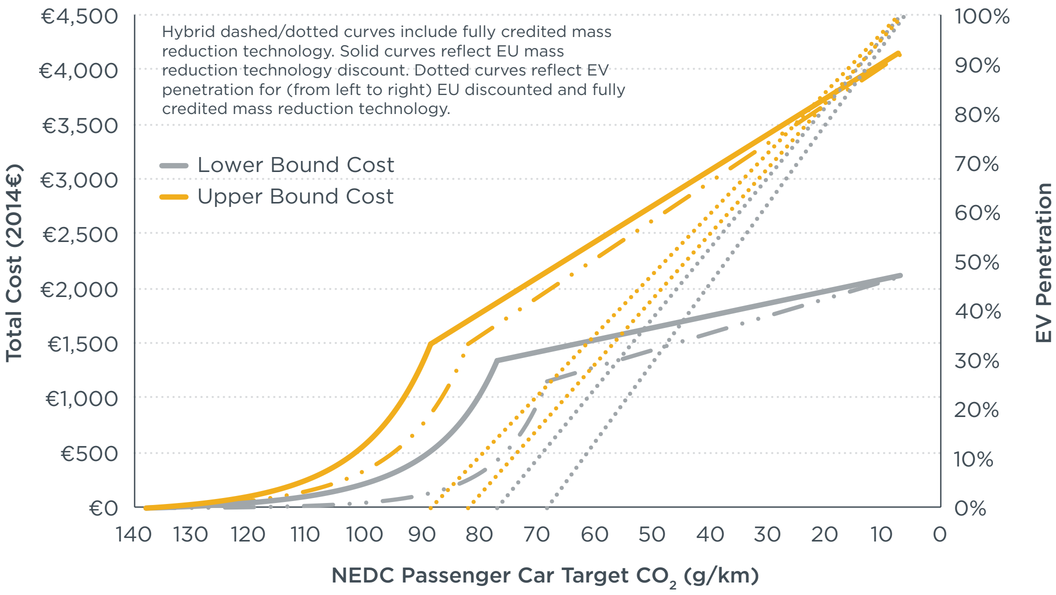


Figure 14b. 2030 NEDC CO_2 costs for passenger cars (EV Strategy).

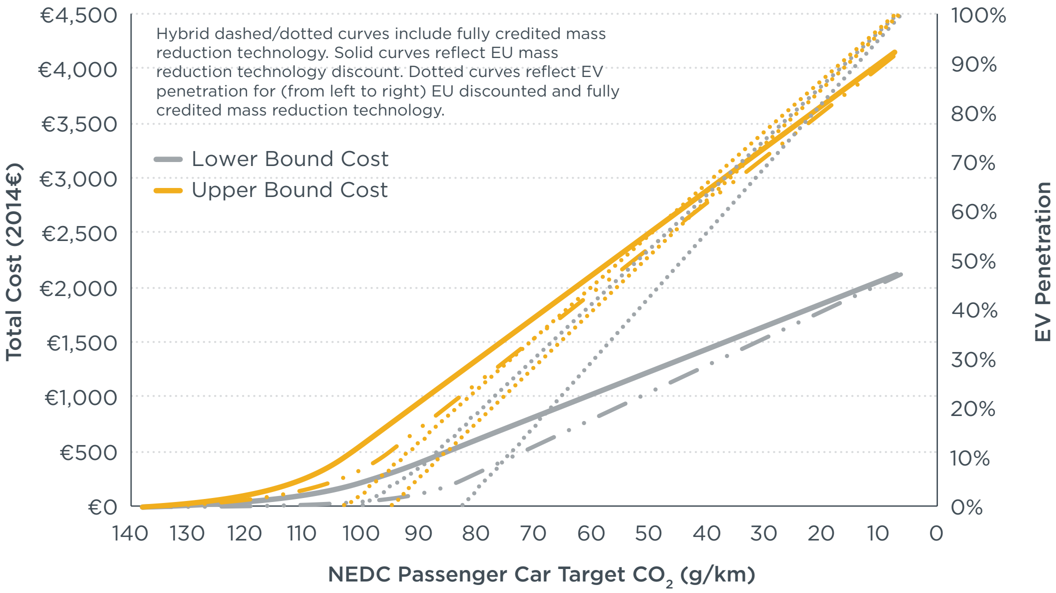


Figure 15a. 2030 NEDC CO_2 costs for light commercial vehicles (ExhICE Strategy).

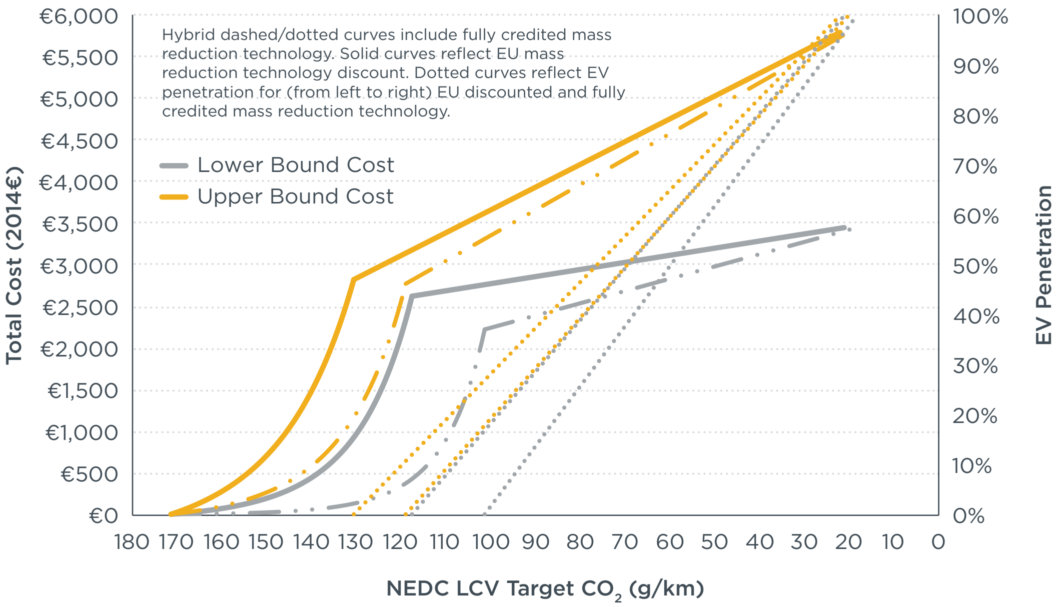


Figure 15b. 2030 NEDC CO_2 costs for light commercial vehicles (EV Strategy).

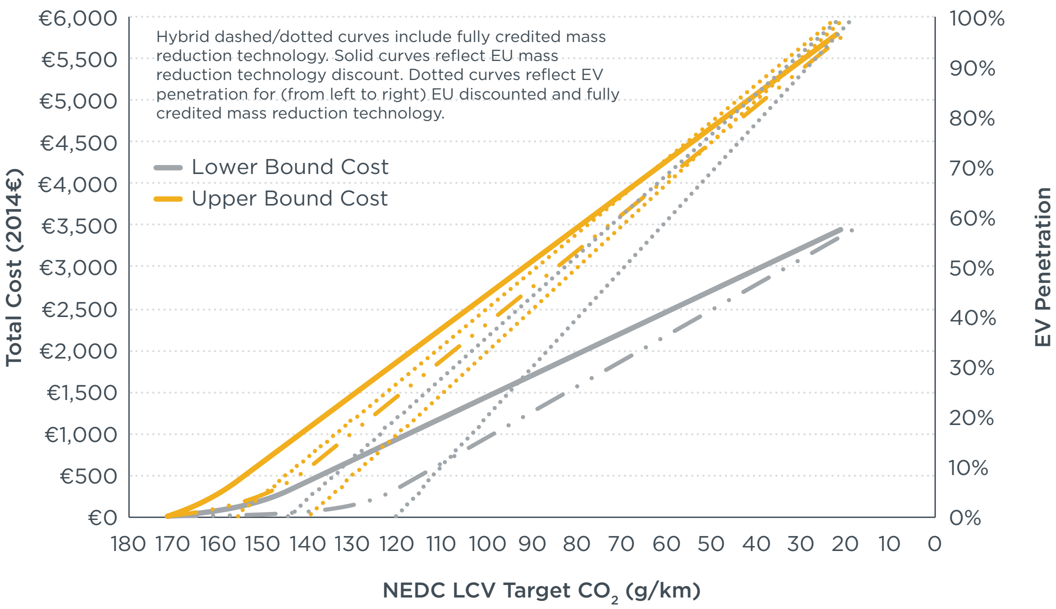


Figure 16a. 2030 WLTP CO_2 costs for passenger cars (ExhICE Strategy).

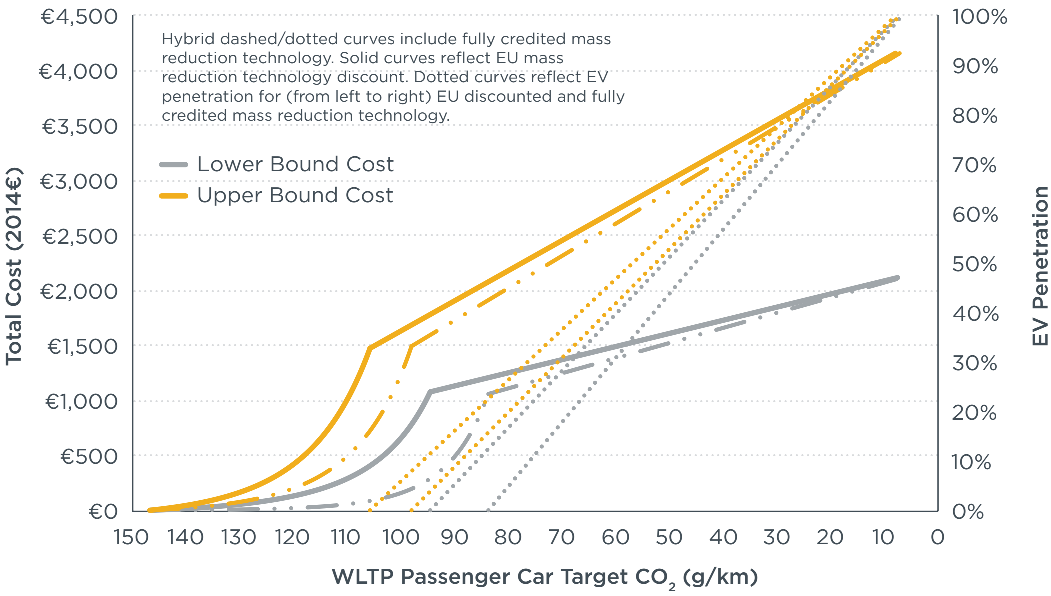


Figure 16b. 2030 WLTP CO_2 costs for passenger cars (EV Strategy).

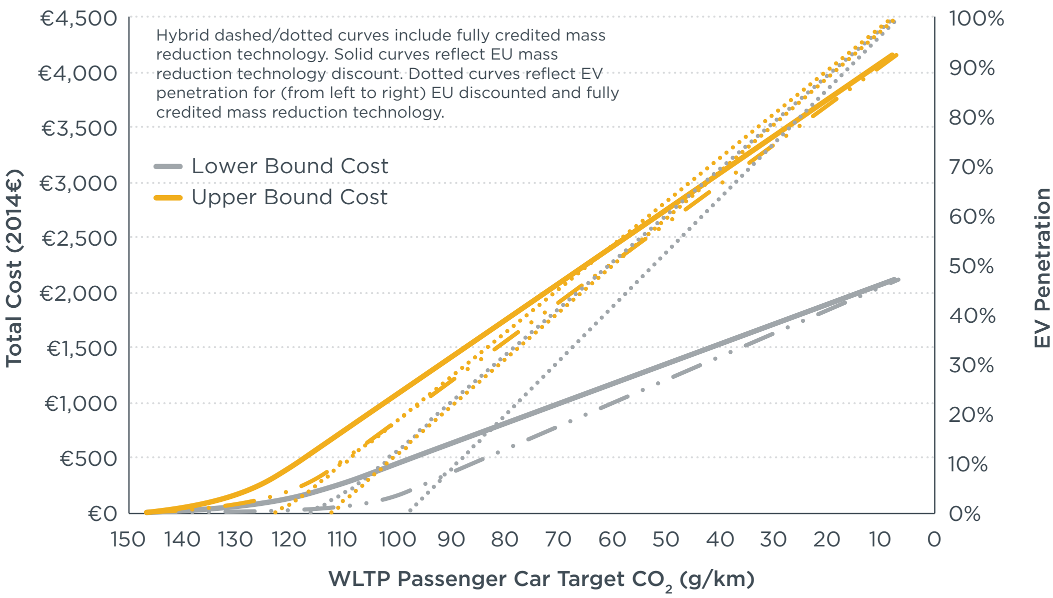


Figure 17a. 2030 WLTP CO_2 costs for light commercial vehicles (ExhICE Strategy).

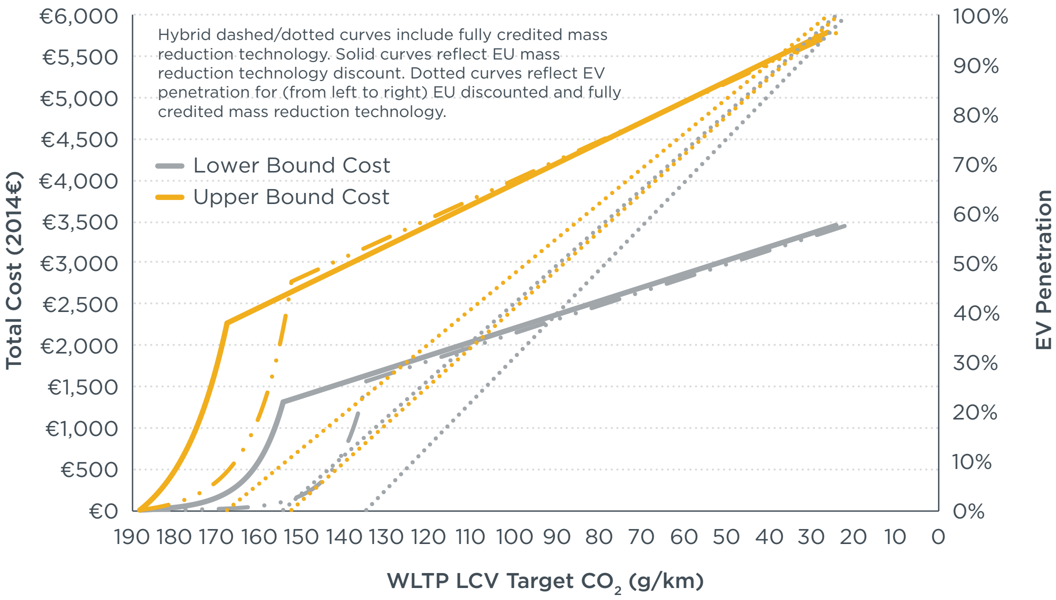


Figure 17b. 2030 WLTP CO_2 costs for light commercial vehicles (EV Strategy).

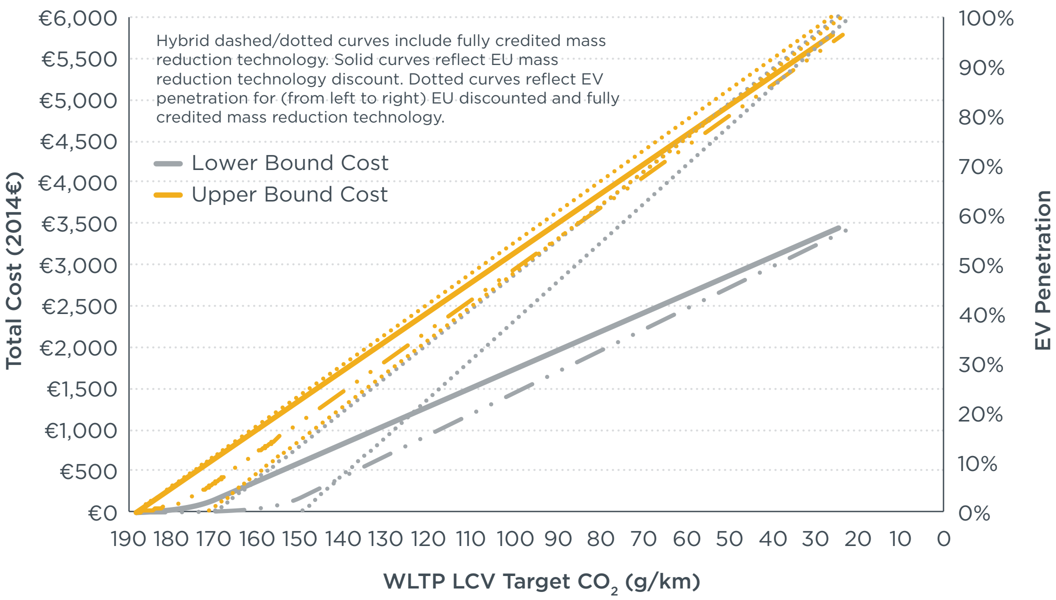


Figure 18a. 2020 NEDC Δ costs for passenger cars (ExhICE Strategy).

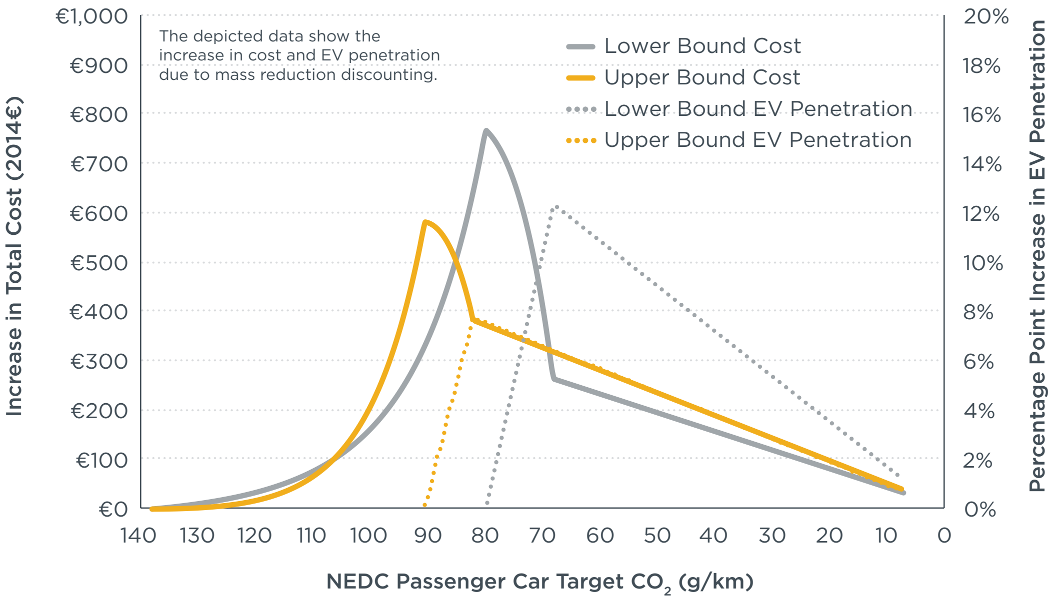


Figure 18b. 2020 NEDC Δ costs for passenger cars (EV Strategy).

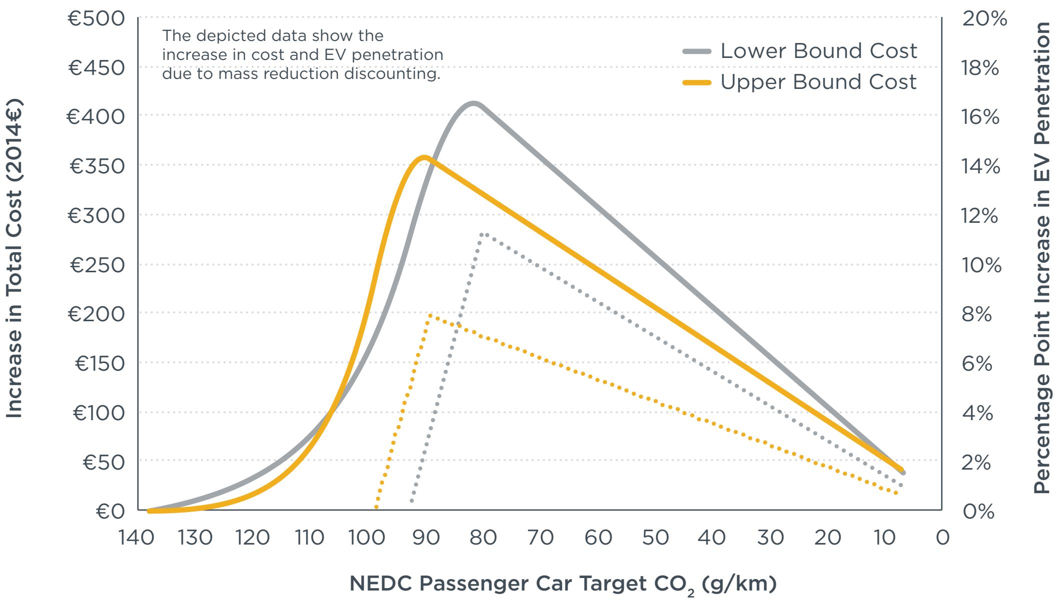


Figure 19a. 2020 NEDC Δ costs for light commercial vehicles (ExhICE Strategy).

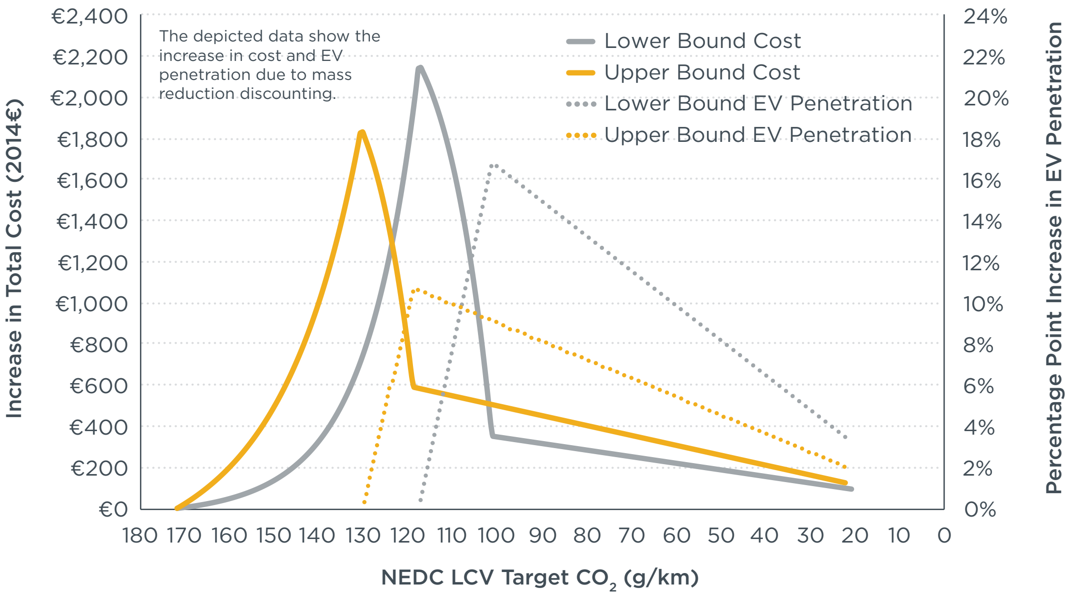


Figure 19b. 2020 NEDC Δ costs for light commercial vehicles (EV Strategy).

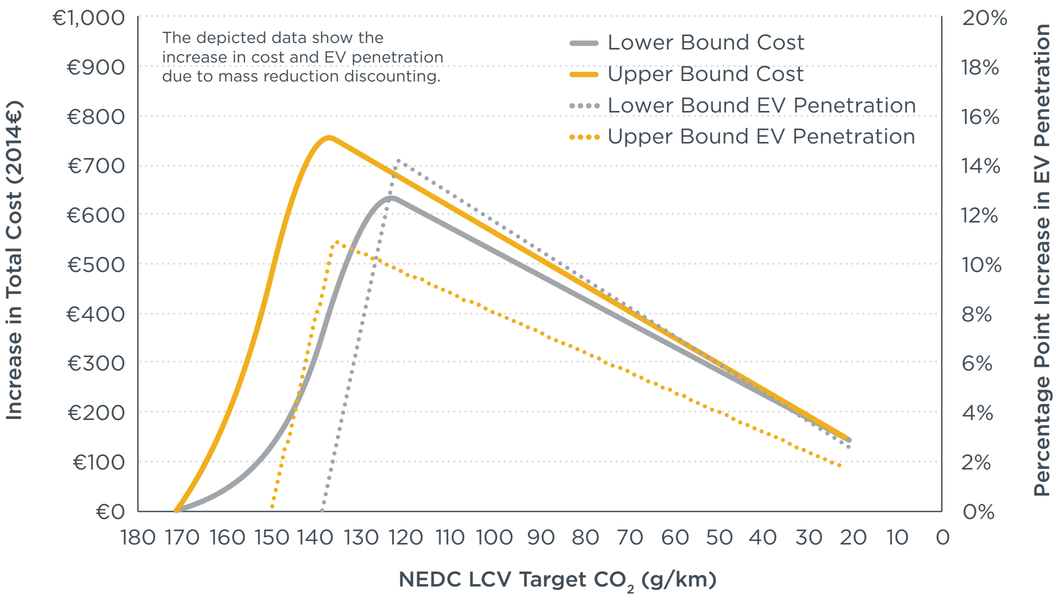


Figure 20a. 2020 WLTP Δ costs for passenger cars (ExhICE Strategy).

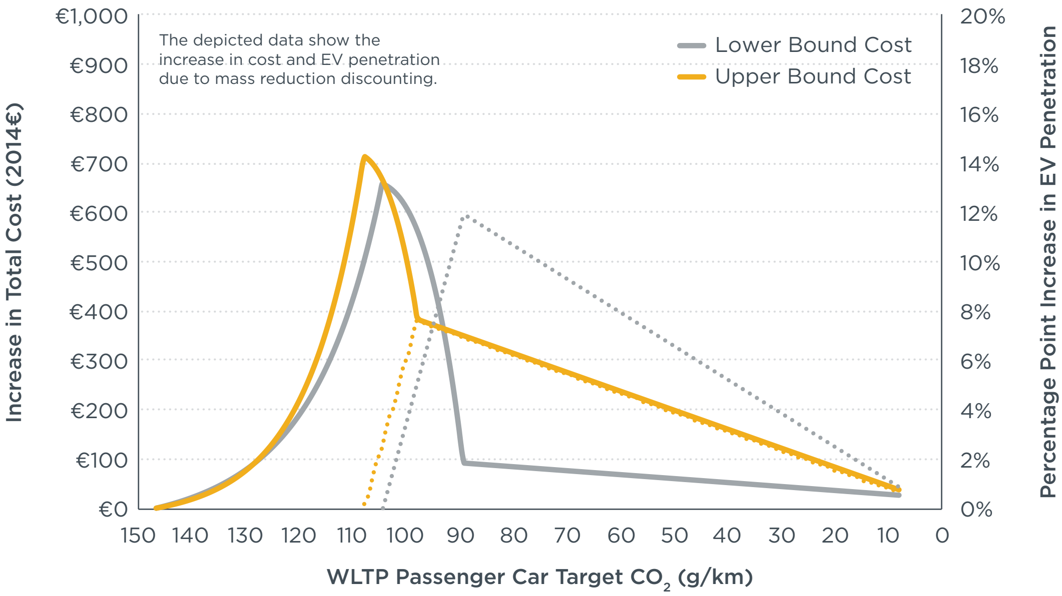


Figure 20b. 2020 WLTP Δ costs for passenger cars (EV Strategy).

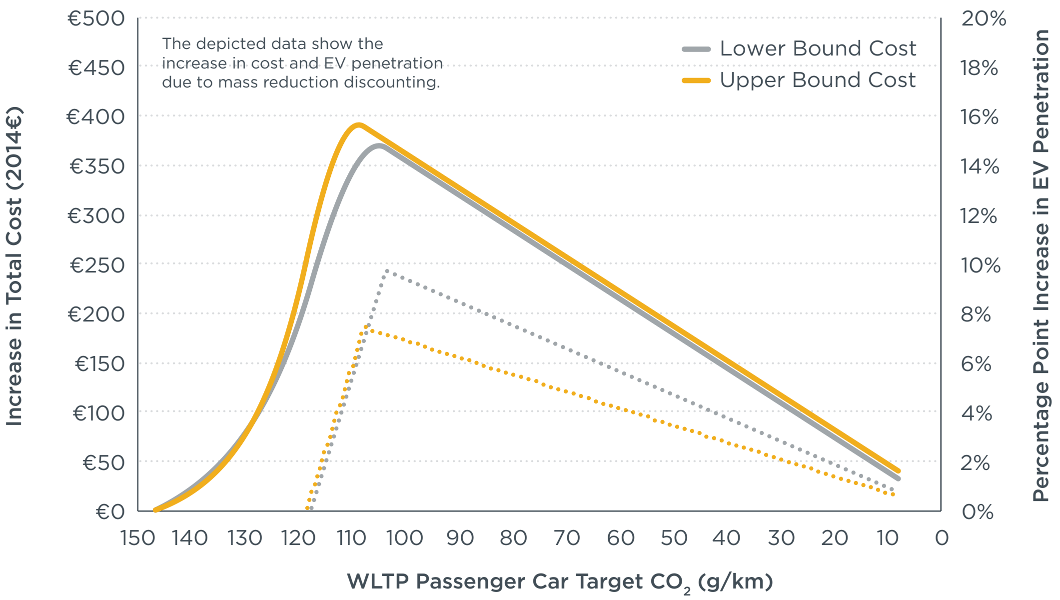


Figure 21a. 2020 WLTP Δ costs for light commercial vehicles (ExhICE Strategy).

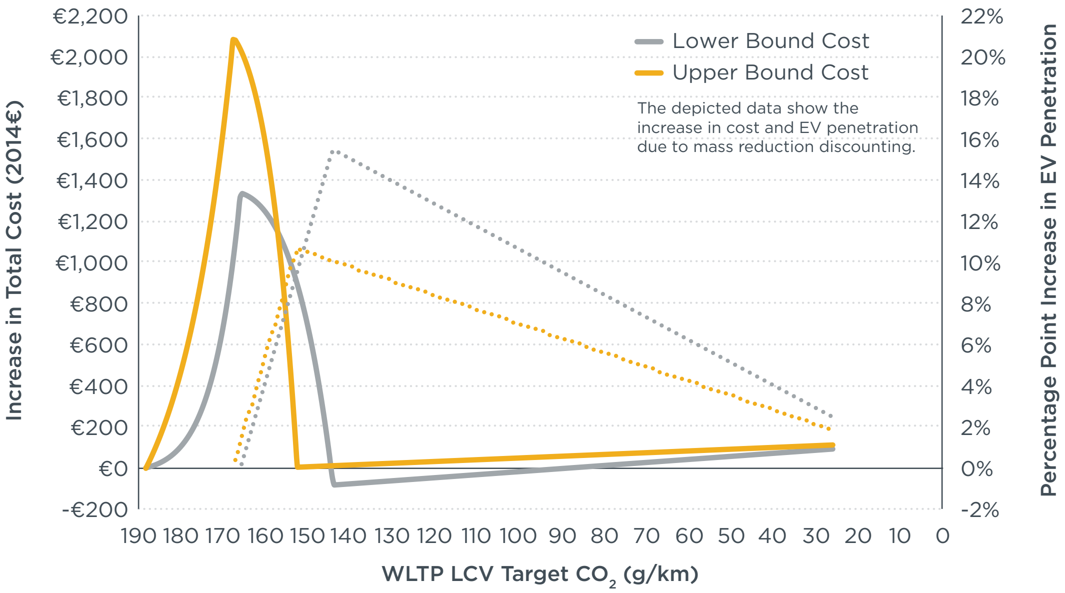


Figure 21b. 2020 WLTP Δ costs for light commercial vehicles (EV Strategy).

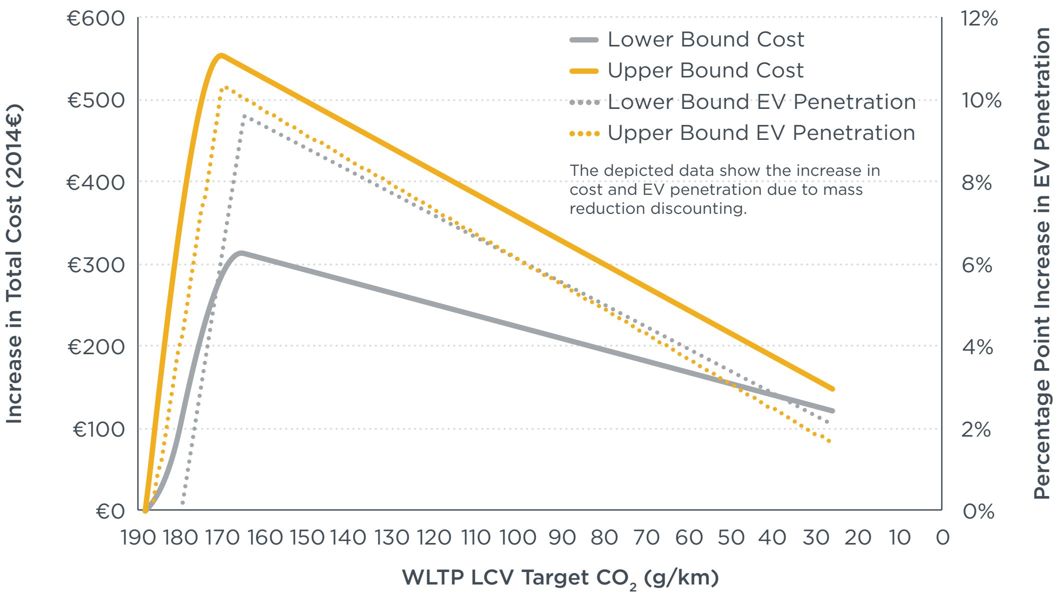


Figure 22a. 2025 NEDC Δ costs for passenger cars (ExhICE Strategy).

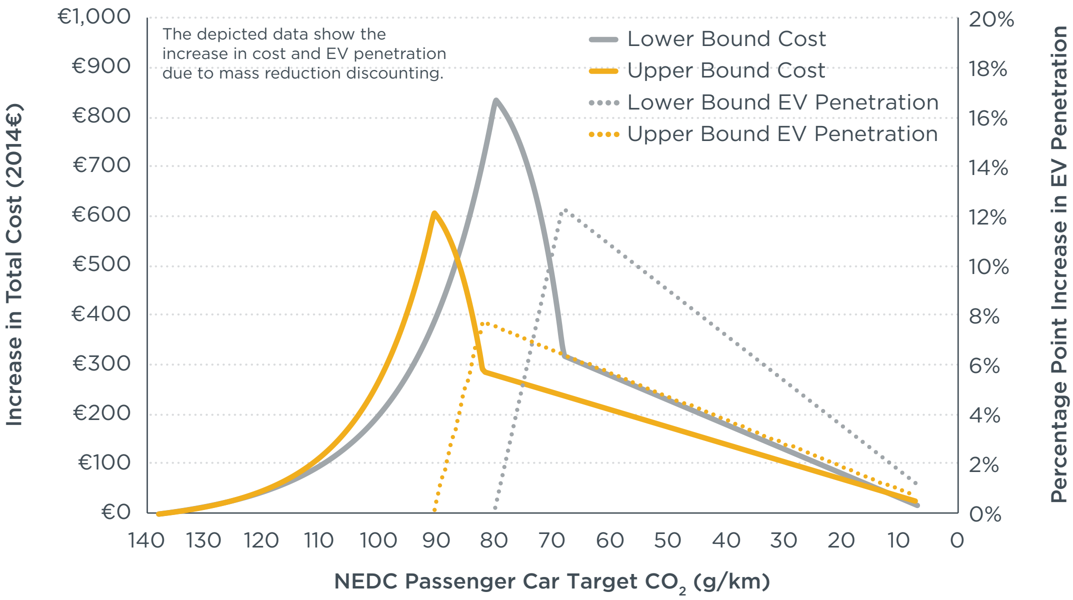


Figure 22b. 2025 NEDC Δ costs for passenger cars (EV Strategy).

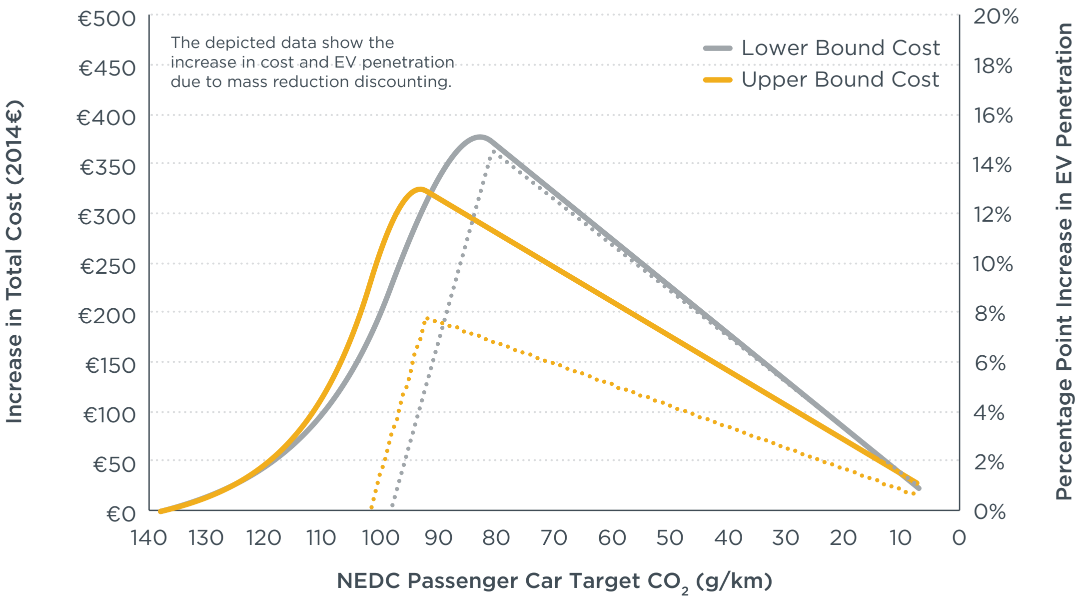


Figure 23a. 2025 NEDC Δ costs for light commercial vehicles (ExhICE Strategy).

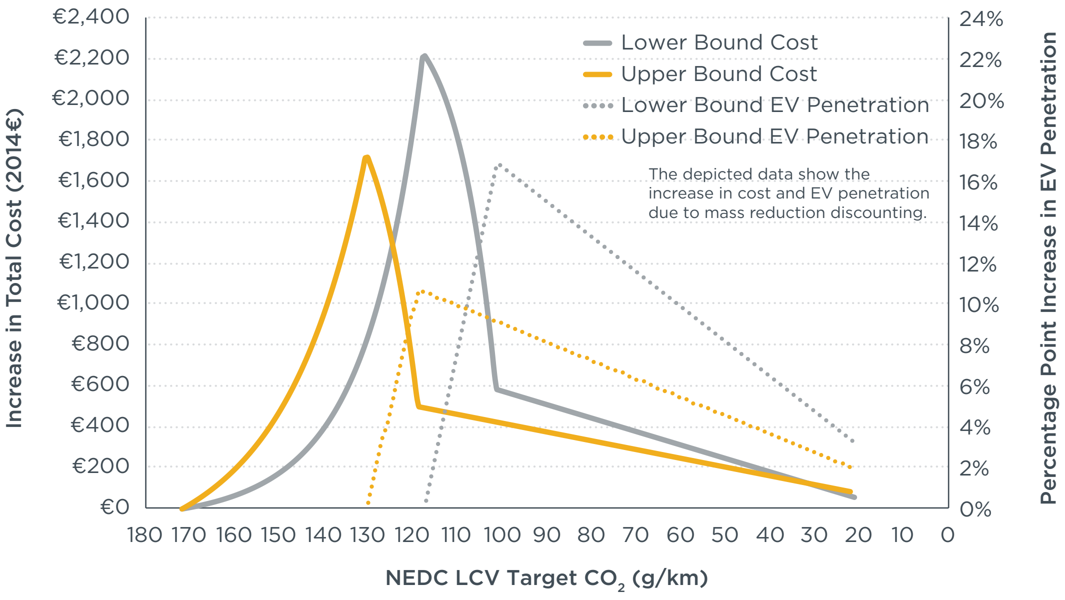


Figure 23b. 2025 NEDC Δ costs for light commercial vehicles (EV Strategy).

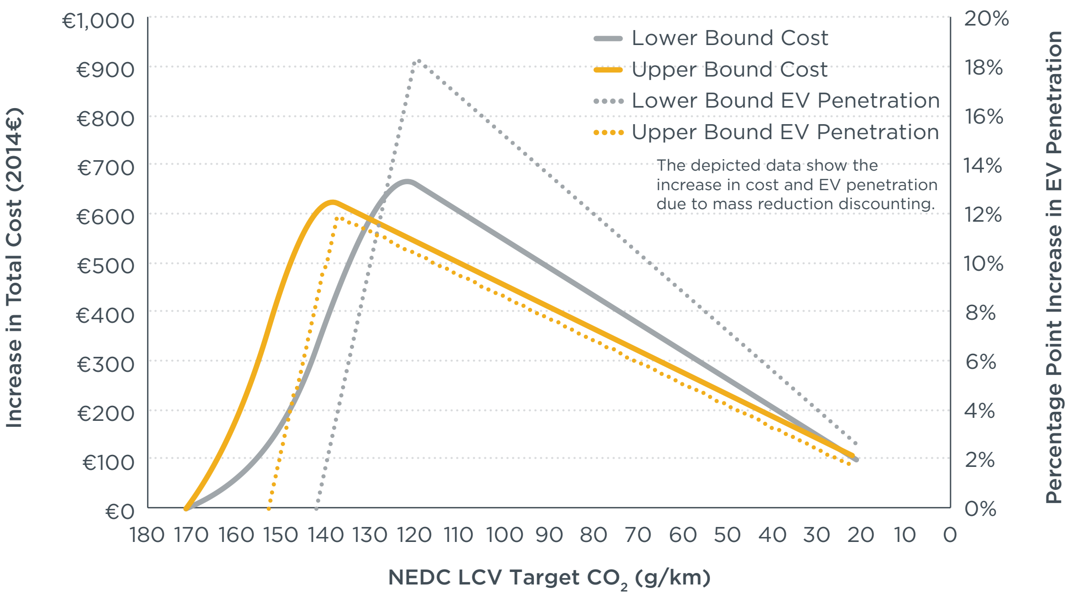


Figure 24a. 2025 WLTP Δ costs for passenger cars (ExhICE Strategy).

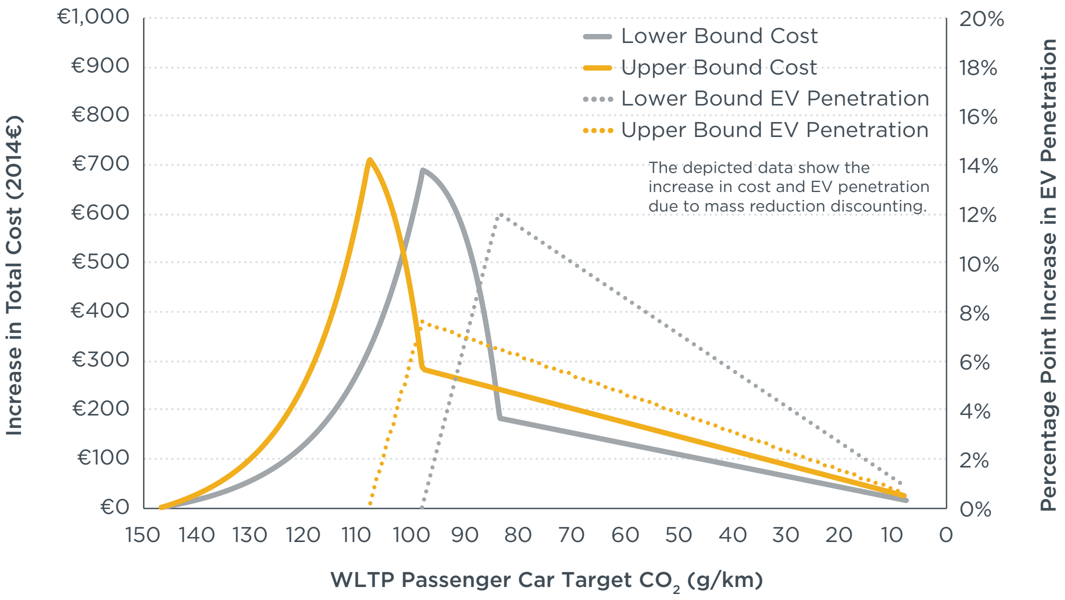


Figure 24b. 2025 WLTP Δ costs for passenger cars (EV Strategy).

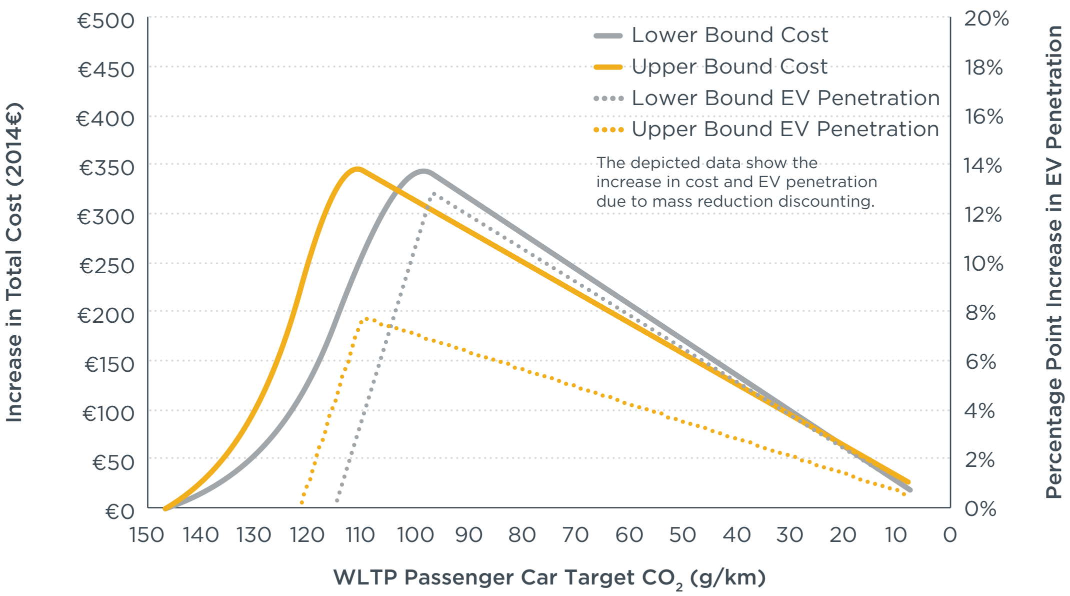


Figure 25a. 2025 WLTP Δ costs for light commercial vehicles (ExhICE Strategy).

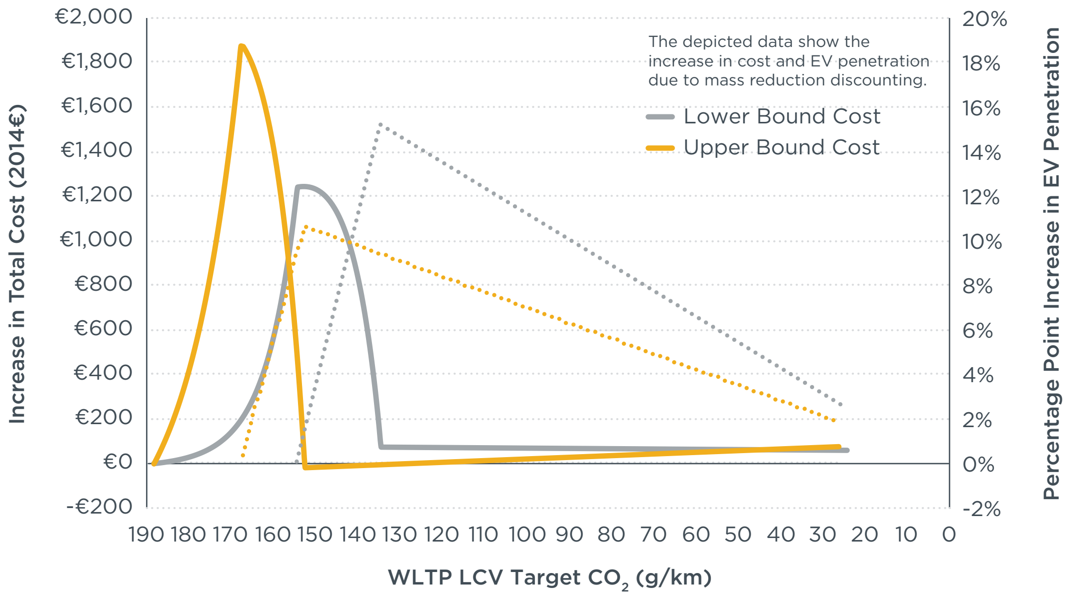


Figure 25b. 2025 WLTP Δ costs for light commercial vehicles (EV Strategy).

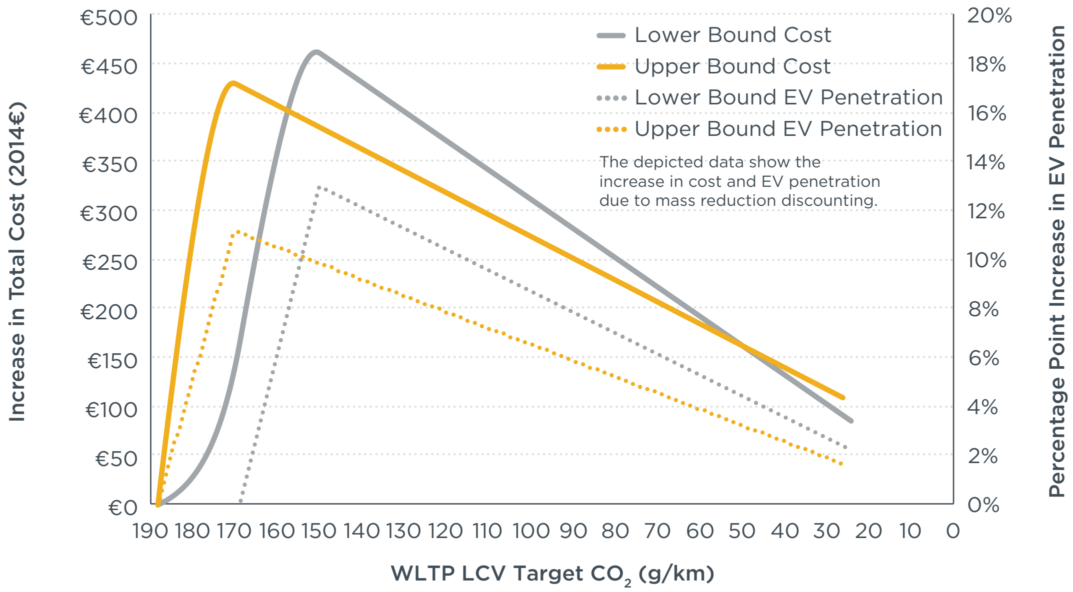


Figure 26a. 2030 NEDC Δ costs for passenger cars (ExhICE Strategy).

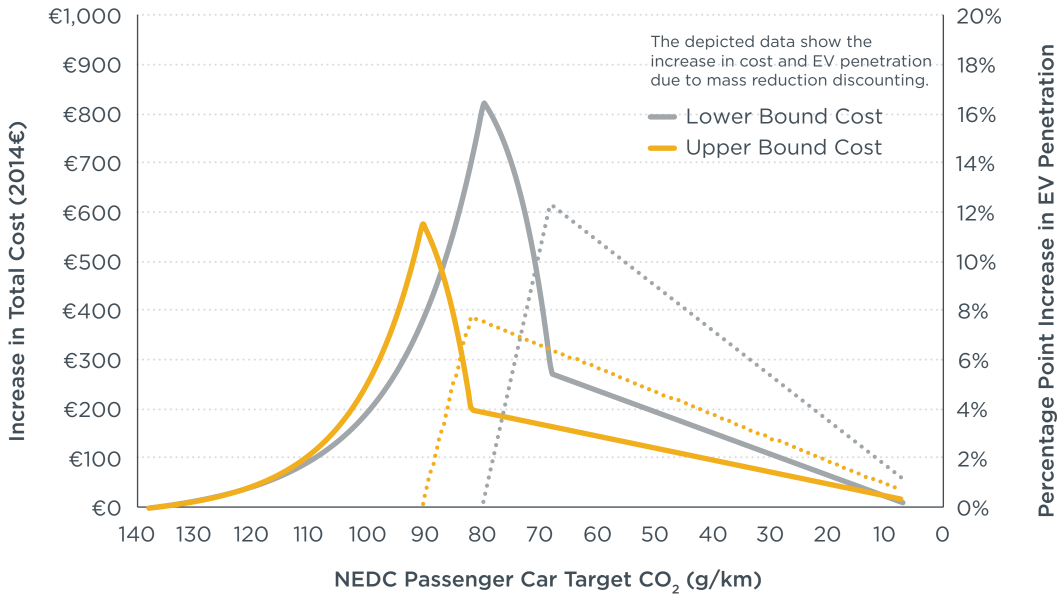


Figure 26b. 2030 NEDC Δ costs for passenger cars (EV Strategy).

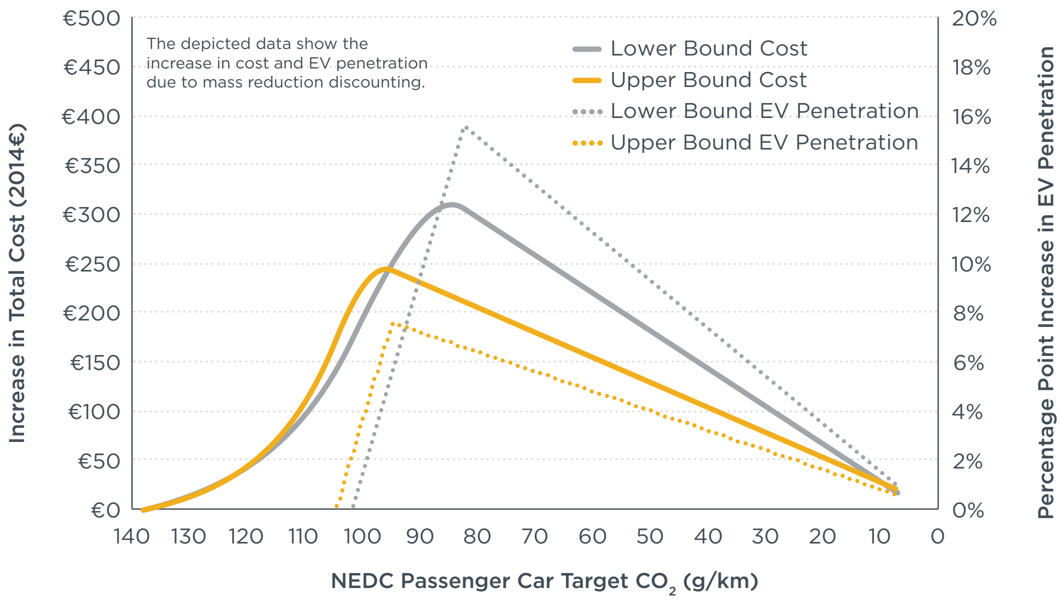


Figure 27a. 2030 NEDC Δ costs for light commercial vehicles (ExhICE Strategy).

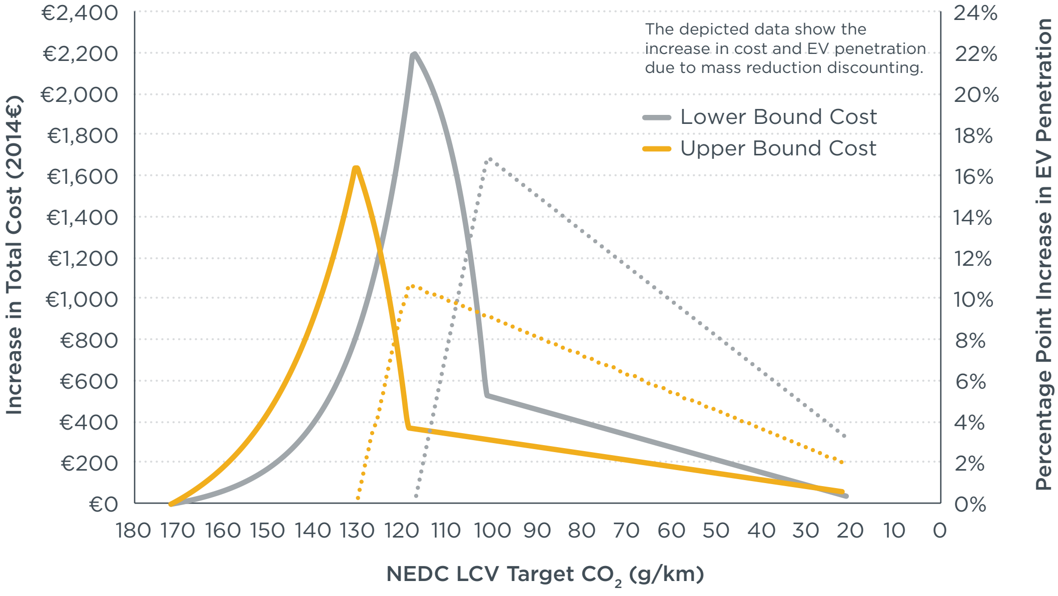


Figure 27b. 2030 NEDC Δ costs for light commercial vehicles (EV Strategy).

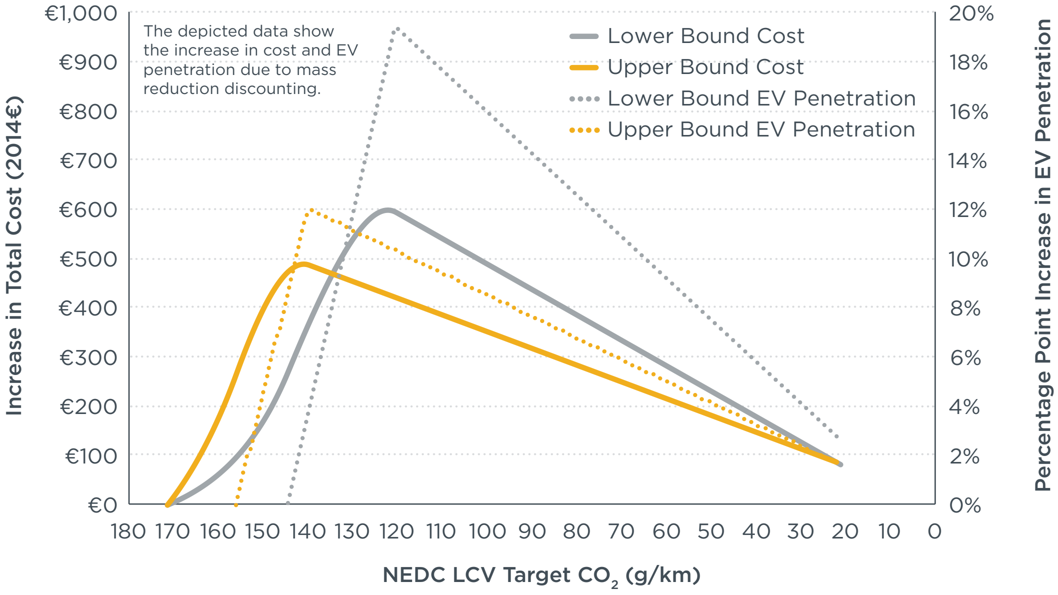


Figure 28a. 2030 WLTP Δ costs for passenger cars (ExhICE Strategy).

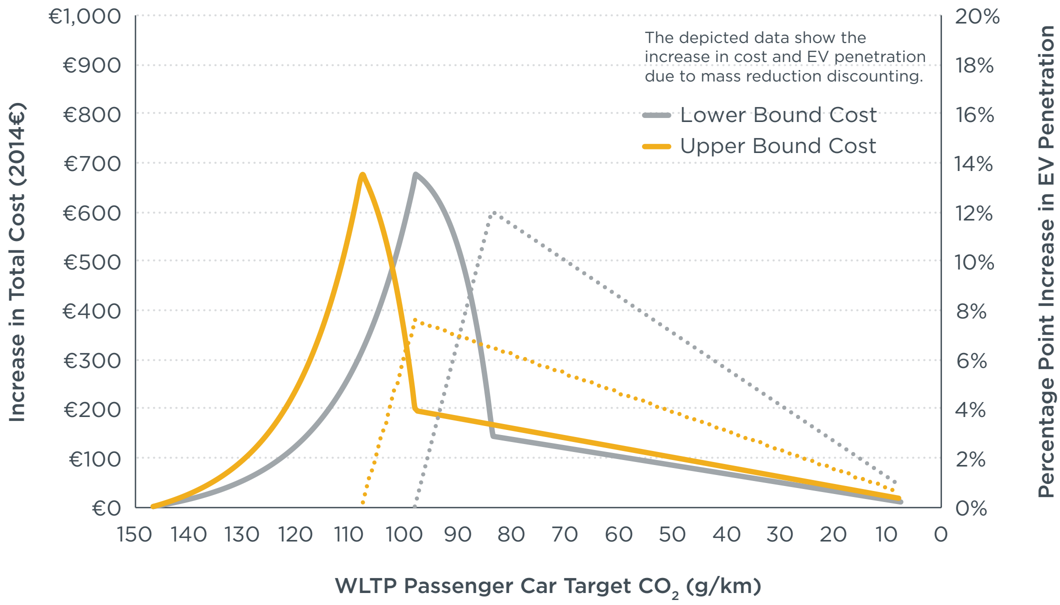


Figure 28b. 2030 WLTP Δ costs for passenger cars (EV Strategy).

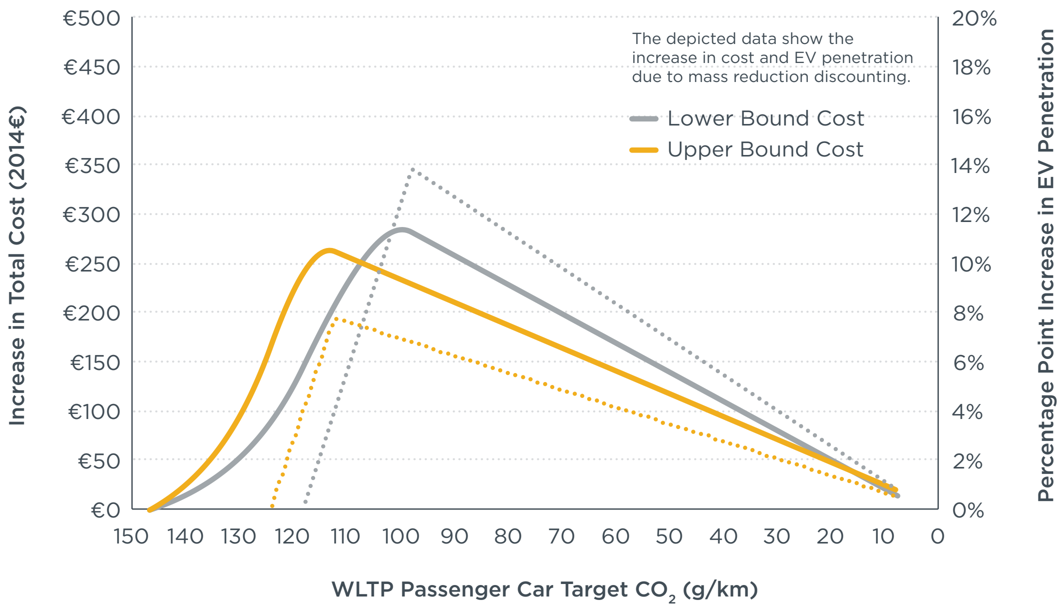


Figure 29a. 2030 WLTP Δ costs for light commercial vehicles (ExhICE Strategy).

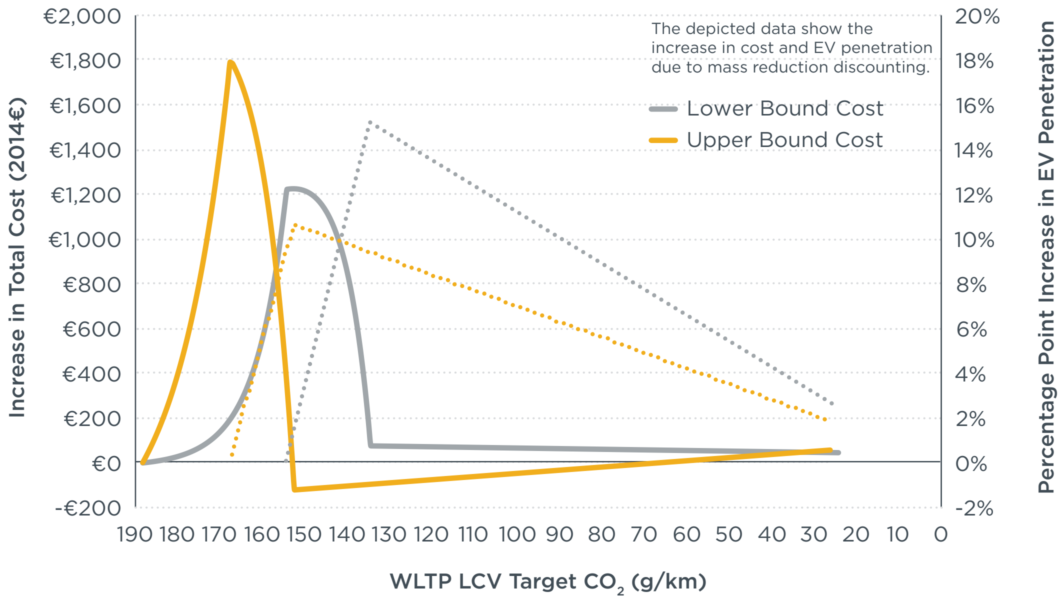
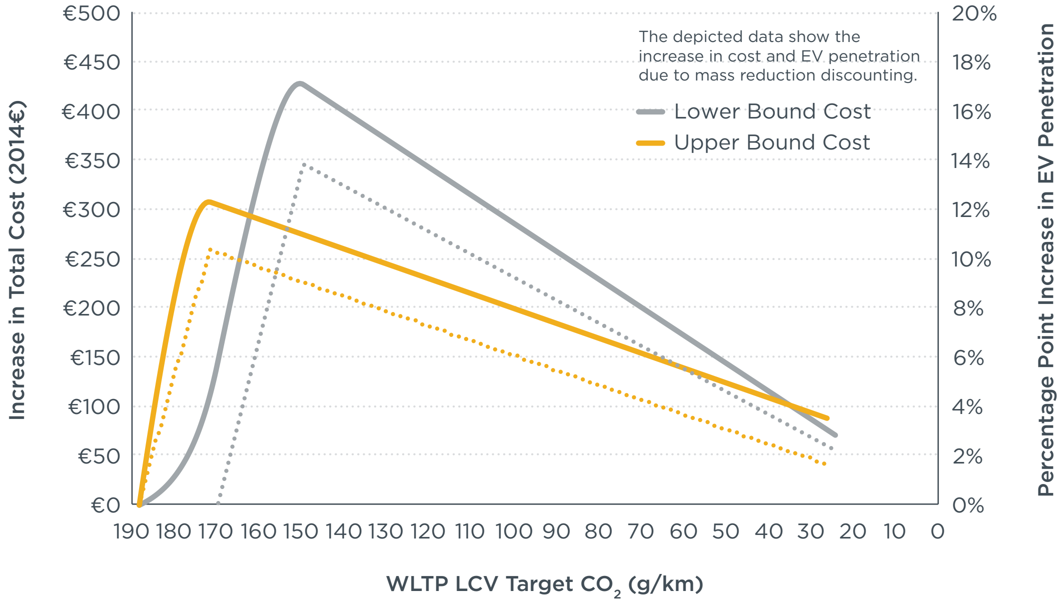


Figure 29b. 2030 WLTP Δ costs for light commercial vehicles (EV Strategy).



6. FINAL REMARKS AND OUTLOOK

This paper presents a set of retail level CO_2 cost curves for the EU light-duty vehicle fleet and describes the methodology employed in their development. Unlike a companion paper by Meszler et al. (2016), the cost curves presented in this paper reflect the fact that the current EU regulatory structure discounts the value of mass reduction technology as a CO_2 compliance strategy. Based on the derived curves, compliance costs at the retail level can be estimated for a wide range of potential CO_2 standards. Moreover, the differential compliance costs between the curves presented in this paper and those presented in the 2016 Meszler et al. paper reflect the magnitude of the compliance cost premium imposed by the mass-based regulatory structure in the EU. This premium exists not just in terms of absolute cost, but also in terms of the increased share of EVs required to achieve specified CO_2 standards.

Table 1 summarizes lower and upper bound[24] total cost estimates for both passenger cars and LCVs under the current EU regulatory structure that discounts mass reduction technology. Table 1a presents costs for a compliance strategy that relies on the exhaustion of ICE technology prior to the widespread introduction of EVs, whereas Table 1b assumes the introduction of EVs as soon as their onboard technology is more cost effective, from a g CO_2/km reduction standpoint, than alternative ICE technology. Tables 2a and 2b present corresponding EV market share estimates. Tables 3 and 4 express the costs and EV market share premiums that result from the current EU regulatory structure compared to a regulatory structure that fully credits mass reduction technology as a CO_2 control strategy. For convenience, Tables 5 and 6 summarize the cost and EV market share data previously developed, and documented in the Meszler et al. 2016 cost curve report, for a regulatory structure that fully credits mass reduction technology. These latter tables serve as the basis for the mass reduction discounting premiums reported in Tables 3 and 4.

The discounting of mass reduction technology will add between 230 and 350 euros (2014 euros) to the cost of compliance with a 95 g/km passenger car standard in 2020, and between 175 and 600 euros (2014 euros) to the cost of compliance with a 147 g/km light commercial vehicle standard in that same year (see Table 3). It is difficult to generalize impacts in the absence of a specific post-2020 CO_2 reduction target, but the following conclusions can be drawn for the average EU market in the 2025–2030 time frame.

- As documented in the Meszler et al. 2016 cost curve report, passenger car NEDC standards as low as 60–70 g/km can be achieved with either no or only modest levels of EV penetration under a fully creditable mass reduction regulatory structure (see Table 6a), but will require a 5 to 13 percentage point increase in EV market penetration under the current regulatory structure that discounts mass reduction technology (see Table 4).

24 As discussed in Section 2, this study includes two sets of cost estimates, one reflective of lower bound compliance costs and one reflective of corresponding upper bound costs. Both are based on the same fundamental data, but differ with regard to assumptions about mass reduction costs, test flexibility exploitation potential, performance-based CO_2 benefits, apportionment of costs to technology co-benefits, the use of off-cycle credits, and EV battery costs. Additional detail is provided in Section 2.

Table 1a. Summary of retail compliance costs for various CO_2 targets (ExhICE Strategy, Discounted Mass Reduction Technology)

CO_2 Target (g/km)	Total cost (2014€) to achieve in:					
	2020		2025		2030	
	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario
Passenger Cars over the NEDC						
95	€ 492	€ 1,160	€ 360	€ 940	€ 328	€ 890
80	€ 1,498	€ 2,492	€ 1,184	€ 1,954	€ 1,107	€ 1,764
70	€ 2,039	€ 3,224	€ 1,504	€ 2,418	€ 1,356	€ 2,091
60	€ 2,515	€ 3,957	€ 1,752	€ 2,882	€ 1,523	€ 2,418
50	€ 2,943	€ 4,690	€ 1,949	€ 3,346	€ 1,635	€ 2,745
40	€ 3,371	€ 5,423	€ 2,147	€ 3,811	€ 1,748	€ 3,072
Passenger Cars over the WLTP Cycle						
95	€ 1,574	€ 2,506	€ 980	€ 1,961	€ 899	€ 1,766
80	€ 2,223	€ 3,422	€ 1,423	€ 2,541	€ 1,249	€ 2,176
70	€ 2,580	€ 4,033	€ 1,613	€ 2,929	€ 1,369	€ 2,449
60	€ 2,936	€ 4,644	€ 1,803	€ 3,316	€ 1,489	€ 2,722
50	€ 3,292	€ 5,254	€ 1,993	€ 3,703	€ 1,610	€ 2,995
40	€ 3,649	€ 5,865	€ 2,183	€ 4,090	€ 1,730	€ 3,268
LCVs over the NEDC						
147	€ 325	€ 1,112	€ 267	€ 933	€ 251	€ 888
120	€ 2,656	€ 4,054	€ 2,254	€ 3,357	€ 2,142	€ 3,110
110	€ 3,480	€ 4,629	€ 2,873	€ 3,738	€ 2,692	€ 3,383
100	€ 3,796	€ 5,205	€ 3,020	€ 4,119	€ 2,776	€ 3,656
90	€ 4,113	€ 5,780	€ 3,167	€ 4,500	€ 2,860	€ 3,930
80	€ 4,429	€ 6,355	€ 3,314	€ 4,881	€ 2,945	€ 4,203
70	€ 4,746	€ 6,931	€ 3,461	€ 5,262	€ 3,029	€ 4,476
60	€ 5,062	€ 7,506	€ 3,607	€ 5,644	€ 3,113	€ 4,749
50	€ 5,378	€ 8,081	€ 3,754	€ 6,025	€ 3,198	€ 5,023
40	€ 5,695	€ 8,657	€ 3,901	€ 6,406	€ 3,282	€ 5,296
LCVs over the WLTP Cycle						
147	€ 2,391	€ 3,803	€ 1,556	€ 3,070	€ 1,445	€ 2,784
120	€ 3,262	€ 5,117	€ 2,134	€ 3,967	€ 1,885	€ 3,455
110	€ 3,585	€ 5,604	€ 2,348	€ 4,300	€ 2,048	€ 3,703
100	€ 3,908	€ 6,091	€ 2,562	€ 4,632	€ 2,211	€ 3,951
90	€ 4,231	€ 6,578	€ 2,776	€ 4,965	€ 2,374	€ 4,200
80	€ 4,554	€ 7,065	€ 2,991	€ 5,297	€ 2,536	€ 4,448
70	€ 4,877	€ 7,552	€ 3,205	€ 5,630	€ 2,699	€ 4,696
60	€ 5,199	€ 8,039	€ 3,419	€ 5,962	€ 2,862	€ 4,945
50	€ 5,522	€ 8,525	€ 3,633	€ 6,295	€ 3,025	€ 5,193
40	€ 5,845	€ 9,012	€ 3,847	€ 6,627	€ 3,188	€ 5,441

Costs in this table (and in all report figures unless otherwise specified) are total (retail-level, exclusive of taxes) costs. Basic technology costs are estimated in terms of direct manufacturing costs, which are essentially the capital cost of the technology to the vehicle manufacturer. Such costs do not include various expenses such as warranty, research and development, depreciation, maintenance, corporate overhead, and sales and distribution costs. These so-called indirect costs are added (using the methodology described in Section 4 of Meszler et al., 2106) to direct manufacturing costs to derive total retail-level cost estimates.

Table 1b. Summary of retail compliance costs for various CO_2 targets (EV Strategy, Discounted Mass Reduction Technology)

CO_2 Target (g/km)	Total cost (2014€) to achieve in:					
	2020		2025		2030	
	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario
Passenger Cars over the NEDC						
95	€ 492	€ 1,122	€ 352	€ 853	€ 300	€ 747
80	€ 1,150	€ 2,250	€ 725	€ 1,615	€ 582	€ 1,328
70	€ 1,648	€ 3,016	€ 1,009	€ 2,126	€ 792	€ 1,714
60	€ 2,145	€ 3,782	€ 1,293	€ 2,636	€ 1,002	€ 2,101
50	€ 2,643	€ 4,548	€ 1,576	€ 3,147	€ 1,213	€ 2,488
40	€ 3,141	€ 5,314	€ 1,860	€ 3,658	€ 1,423	€ 2,875
Passenger Cars over the WLTP Cycle						
95	€ 1,270	€ 2,140	€ 641	€ 1,517	€ 509	€ 1,234
80	€ 1,876	€ 3,119	€ 1,011	€ 2,174	€ 785	€ 1,735
70	€ 2,280	€ 3,772	€ 1,257	€ 2,612	€ 969	€ 2,069
60	€ 2,685	€ 4,425	€ 1,504	€ 3,050	€ 1,153	€ 2,403
50	€ 3,089	€ 5,078	€ 1,750	€ 3,488	€ 1,337	€ 2,737
40	€ 3,493	€ 5,730	€ 1,997	€ 3,926	€ 1,521	€ 3,071
LCVs over the NEDC						
147	€ 325	€ 1,092	€ 267	€ 877	€ 251	€ 780
120	€ 1,528	€ 2,949	€ 1,087	€ 2,219	€ 929	€ 1,862
110	€ 2,010	€ 3,637	€ 1,400	€ 2,716	€ 1,183	€ 2,262
100	€ 2,491	€ 4,325	€ 1,712	€ 3,213	€ 1,437	€ 2,663
90	€ 2,973	€ 5,013	€ 2,024	€ 3,710	€ 1,690	€ 3,063
80	€ 3,454	€ 5,701	€ 2,336	€ 4,208	€ 1,944	€ 3,464
70	€ 3,935	€ 6,389	€ 2,649	€ 4,705	€ 2,198	€ 3,864
60	€ 4,417	€ 7,077	€ 2,961	€ 5,202	€ 2,451	€ 4,265
50	€ 4,898	€ 7,765	€ 3,273	€ 5,699	€ 2,705	€ 4,666
40	€ 5,380	€ 8,453	€ 3,586	€ 6,196	€ 2,959	€ 5,066
LCVs over the WLTP Cycle						
147	€ 1,509	€ 2,466	€ 800	€ 1,808	€ 675	€ 1,476
120	€ 2,577	€ 4,078	€ 1,545	€ 2,987	€ 1,285	€ 2,438
110	€ 2,973	€ 4,676	€ 1,820	€ 3,424	€ 1,510	€ 2,794
100	€ 3,369	€ 5,273	€ 2,096	€ 3,860	€ 1,736	€ 3,151
90	€ 3,764	€ 5,870	€ 2,372	€ 4,297	€ 1,962	€ 3,507
80	€ 4,160	€ 6,468	€ 2,648	€ 4,734	€ 2,187	€ 3,864
70	€ 4,556	€ 7,065	€ 2,924	€ 5,171	€ 2,413	€ 4,220
60	€ 4,952	€ 7,662	€ 3,199	€ 5,607	€ 2,639	€ 4,576
50	€ 5,347	€ 8,260	€ 3,475	€ 6,044	€ 2,864	€ 4,933
40	€ 5,743	€ 8,857	€ 3,751	€ 6,481	€ 3,090	€ 5,289

Costs in this table (and in all report figures unless otherwise specified) are total (retail-level, exclusive of taxes) costs. Basic technology costs are estimated in terms of direct manufacturing costs, which are essentially the capital cost of the technology to the vehicle manufacturer. Such costs do not include various expenses such as warranty, research and development, depreciation, maintenance, corporate overhead, and sales and distribution costs. These so-called indirect costs are added (using the methodology described in Section 4 of Meszler et al., 2016) to direct manufacturing costs to derive total retail-level cost estimates.

Table 2a. Summary of EV market penetration for various CO_2 targets (ExhICE Strategy, Discounted Mass Reduction Technology)

CO_2 Target (g/km)	EV market share to achieve in:					
	2020		2025		2030	
	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario
Passenger Cars over the NEDC						
95	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
80	0.0%	10.2%	0.0%	10.2%	0.0%	10.2%
70	10.3%	22.5%	10.3%	22.5%	10.3%	22.5%
60	23.8%	34.8%	23.8%	34.8%	23.8%	34.8%
50	38.1%	47.2%	38.1%	47.2%	38.1%	47.2%
40	52.4%	59.5%	52.4%	59.5%	52.4%	59.5%
Passenger Cars over the WLTP Cycle						
95	7.5%	10.6%	2.4%	10.6%	2.4%	10.6%
80	22.0%	26.0%	16.1%	26.0%	16.1%	26.0%
70	32.8%	36.3%	27.7%	36.3%	27.7%	36.3%
60	43.6%	46.5%	39.2%	46.5%	39.2%	46.5%
50	54.4%	56.8%	50.7%	56.8%	50.7%	56.8%
40	65.2%	67.0%	62.3%	67.0%	62.3%	67.0%
LCVs over the NEDC						
147	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
120	0.0%	9.5%	0.0%	9.5%	0.0%	9.5%
110	7.8%	18.7%	7.8%	18.7%	7.8%	18.7%
100	18.1%	28.0%	18.1%	28.0%	18.1%	28.0%
90	28.5%	37.2%	28.5%	37.2%	28.5%	37.2%
80	38.8%	46.4%	38.8%	46.4%	38.8%	46.4%
70	49.2%	55.6%	49.2%	55.6%	49.2%	55.6%
60	59.5%	64.9%	59.5%	64.9%	59.5%	64.9%
50	69.9%	74.1%	69.9%	74.1%	69.9%	74.1%
40	80.2%	83.3%	80.2%	83.3%	80.2%	83.3%
LCVs over the WLTP Cycle						
147	13.4%	14.6%	5.8%	14.6%	5.8%	14.6%
120	32.8%	33.7%	26.5%	33.7%	26.5%	33.7%
110	39.9%	40.7%	34.2%	40.7%	34.2%	40.7%
100	47.1%	47.8%	41.9%	47.8%	41.9%	47.8%
90	54.2%	54.8%	49.6%	54.8%	49.6%	54.8%
80	61.4%	61.9%	57.3%	61.9%	57.3%	61.9%
70	68.5%	68.9%	64.9%	68.9%	64.9%	68.9%
60	75.7%	76.0%	72.6%	76.0%	72.6%	76.0%
50	82.8%	83.0%	80.3%	83.0%	80.3%	83.0%
40	90.0%	90.1%	88.0%	90.1%	88.0%	90.1%

Costs in this table (and in all report figures unless otherwise specified) are total (retail-level, exclusive of taxes) costs. Basic technology costs are estimated in terms of direct manufacturing costs, which are essentially the capital cost of the technology to the vehicle manufacturer. Such costs do not include various expenses such as warranty, research and development, depreciation, maintenance, corporate overhead, and sales and distribution costs. These so-called indirect costs are added (using the methodology described in Section 4 of Meszler et al., 2016) to direct manufacturing costs to derive total retail-level cost estimates.

Table 2b. Summary of EV market penetration for various CO_2 targets (EV Strategy, Discounted Mass Reduction Technology)

CO_2 Target (g/km)	EV market share to achieve in:					
	2020		2025		2030	
	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario
Passenger Cars over the NEDC						
95	0.0%	3.2%	2.7%	5.5%	5.4%	7.4%
80	11.4%	18.3%	15.6%	20.9%	18.3%	23.2%
70	23.5%	29.5%	27.1%	31.8%	29.4%	33.7%
60	35.6%	40.7%	38.6%	42.6%	40.6%	44.3%
50	47.7%	51.9%	50.1%	53.5%	51.7%	54.8%
40	59.7%	63.2%	61.7%	64.3%	62.9%	65.4%
Passenger Cars over the WLTP Cycle						
95	17.8%	19.3%	14.7%	21.2%	16.8%	23.1%
80	31.9%	33.2%	29.3%	34.8%	31.0%	36.3%
70	41.4%	42.4%	39.0%	43.8%	40.5%	45.1%
60	50.8%	51.7%	48.8%	52.9%	50.0%	53.9%
50	60.2%	60.9%	58.5%	61.9%	59.5%	62.8%
40	69.6%	70.2%	68.2%	70.9%	69.0%	71.6%
LCVs over the NEDC						
147	0.0%	2.5%	0.0%	4.6%	0.0%	6.7%
120	15.9%	23.5%	18.4%	25.2%	19.8%	26.9%
110	24.4%	31.3%	26.6%	32.8%	27.9%	34.3%
100	32.9%	39.1%	34.9%	40.4%	36.0%	41.8%
90	41.4%	46.9%	43.1%	48.1%	44.1%	49.2%
80	49.9%	54.7%	51.3%	55.7%	52.2%	56.7%
70	58.4%	62.5%	59.6%	63.3%	60.3%	64.2%
60	66.9%	70.3%	67.8%	71.0%	68.4%	71.6%
50	75.3%	78.1%	76.0%	78.6%	76.5%	79.1%
40	83.8%	85.9%	84.3%	86.2%	84.6%	86.5%
LCVs over the WLTP Cycle						
147	21.4%	24.7%	15.1%	25.4%	15.7%	25.5%
120	39.0%	41.5%	33.8%	42.0%	34.2%	42.1%
110	45.4%	47.7%	40.7%	48.2%	41.1%	48.3%
100	51.9%	53.9%	47.6%	54.4%	48.0%	54.4%
90	58.4%	60.1%	54.6%	60.5%	54.9%	60.6%
80	64.9%	66.4%	61.5%	66.7%	61.8%	66.7%
70	71.4%	72.6%	68.4%	72.9%	68.6%	72.9%
60	77.9%	78.8%	75.3%	79.0%	75.5%	79.0%
50	84.4%	85.0%	82.3%	85.2%	82.4%	85.2%
40	90.9%	91.3%	89.2%	91.3%	89.3%	91.4%

Costs in this table (and in all report figures unless otherwise specified) are total (retail-level, exclusive of taxes) costs. Basic technology costs are estimated in terms of direct manufacturing costs, which are essentially the capital cost of the technology to the vehicle manufacturer. Such costs do not include various expenses such as warranty, research and development, depreciation, maintenance, corporate overhead, and sales and distribution costs. These so-called indirect costs are added (using the methodology described in Section 4 of Meszler et al., 2016) to direct manufacturing costs to derive total retail-level cost estimates.

Table 3a. Summary of retail cost changes for various CO_2 targets (ExhICE Strategy, Discounted versus Non-Discounted Mass Reduction)

CO_2 Target (g/km)	Increase in total cost (2014€) to achieve in:					
	2020		2025		2030	
	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario
Passenger Cars over the NEDC						
95	€ 233	€ 354	€ 334	€ 405	€ 338	€ 387
80	€ 756	€ 374	€ 867	€ 279	€ 862	€ 195
70	€ 421	€ 328	€ 492	€ 245	€ 453	€ 170
60	€ 234	€ 282	€ 280	€ 210	€ 238	€ 146
50	€ 196	€ 236	€ 230	€ 175	€ 196	€ 122
40	€ 158	€ 190	€ 181	€ 140	€ 153	€ 98
Passenger Cars over the WLTP Cycle						
95	€ 461	€ 373	€ 710	€ 274	€ 699	€ 189
80	€ 84	€ 315	€ 175	€ 231	€ 137	€ 160
70	€ 76	€ 277	€ 153	€ 202	€ 120	€ 140
60	€ 68	€ 238	€ 131	€ 173	€ 102	€ 120
50	€ 60	€ 199	€ 109	€ 144	€ 84	€ 100
40	€ 52	€ 161	€ 86	€ 116	€ 67	€ 80
LCVs over the NEDC						
147	€ 176	€ 608	€ 221	€ 579	€ 221	€ 552
120	€ 1,740	€ 817	€ 1,825	€ 721	€ 1,805	€ 596
110	€ 1,674	€ 548	€ 1,831	€ 462	€ 1,803	€ 344
100	€ 347	€ 500	€ 578	€ 419	€ 522	€ 312
90	€ 315	€ 452	€ 512	€ 376	€ 461	€ 279
80	€ 283	€ 404	€ 446	€ 333	€ 400	€ 247
70	€ 251	€ 356	€ 380	€ 290	€ 339	€ 215
60	€ 219	€ 307	€ 314	€ 248	€ 278	€ 183
50	€ 187	€ 259	€ 249	€ 205	€ 217	€ 151
40	€ 155	€ 211	€ 183	€ 162	€ 155	€ 119
LCVs over the WLTP Cycle						
147	€ 346	€ 10	€ 1,186	-€ 13	€ 1,174	-€ 115
120	-€ 48	€ 33	€ 72	€ 7	€ 72	-€ 77
110	-€ 33	€ 42	€ 71	€ 15	€ 69	-€ 62
100	-€ 18	€ 50	€ 70	€ 22	€ 67	-€ 48
90	-€ 3	€ 59	€ 68	€ 29	€ 64	-€ 34
80	€ 11	€ 67	€ 67	€ 37	€ 61	-€ 20
70	€ 26	€ 76	€ 66	€ 44	€ 58	-€ 6
60	€ 41	€ 84	€ 64	€ 52	€ 56	€ 8
50	€ 56	€ 93	€ 63	€ 59	€ 53	€ 22
40	€ 71	€ 102	€ 62	€ 67	€ 50	€ 36

Costs in this table (and in all report figures unless otherwise specified) are total (retail-level, exclusive of taxes) costs. Basic technology costs are estimated in terms of direct manufacturing costs, which are essentially the capital cost of the technology to the vehicle manufacturer. Such costs do not include various expenses such as warranty, research and development, depreciation, maintenance, corporate overhead, and sales and distribution costs. These so-called indirect costs are added (using the methodology described in Section 4 of Meszler et al., 2016) to direct manufacturing costs to derive total retail-level cost estimates.

Table 3b. Summary of retail cost changes for various CO_2 targets (EV Strategy, Discounted versus Non-Discounted Mass Reduction)

CO_2 Target (g/km)	Increase in total cost (2014€) to achieve in:					
	2020		2025		2030	
	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario
Passenger Cars over the NEDC						
95	€ 233	€ 315	€ 326	€ 318	€ 309	€ 244
80	€ 408	€ 321	€ 410	€ 281	€ 348	€ 206
70	€ 358	€ 283	€ 357	€ 246	€ 303	€ 181
60	€ 307	€ 244	€ 305	€ 211	€ 257	€ 155
50	€ 256	€ 206	€ 252	€ 177	€ 212	€ 130
40	€ 206	€ 167	€ 199	€ 142	€ 167	€ 104
Passenger Cars over the WLTP Cycle						
95	€ 337	€ 344	€ 379	€ 297	€ 325	€ 222
80	€ 284	€ 292	€ 317	€ 251	€ 272	€ 187
70	€ 249	€ 257	€ 276	€ 220	€ 237	€ 164
60	€ 214	€ 222	€ 235	€ 189	€ 201	€ 141
50	€ 179	€ 187	€ 194	€ 157	€ 166	€ 118
40	€ 144	€ 152	€ 153	€ 126	€ 130	€ 95
LCVs over the NEDC						
147	€ 176	€ 587	€ 221	€ 523	€ 221	€ 444
120	€ 620	€ 665	€ 658	€ 543	€ 592	€ 418
110	€ 572	€ 612	€ 602	€ 499	€ 541	€ 384
100	€ 523	€ 560	€ 545	€ 454	€ 489	€ 350
90	€ 475	€ 507	€ 489	€ 410	€ 438	€ 316
80	€ 427	€ 454	€ 432	€ 366	€ 386	€ 283
70	€ 379	€ 401	€ 376	€ 321	€ 335	€ 249
60	€ 331	€ 349	€ 320	€ 277	€ 283	€ 215
50	€ 283	€ 296	€ 263	€ 232	€ 232	€ 181
40	€ 234	€ 243	€ 207	€ 188	€ 180	€ 148
LCVs over the WLTP Cycle						
147	€ 288	€ 489	€ 450	€ 377	€ 418	€ 270
120	€ 251	€ 413	€ 370	€ 317	€ 342	€ 230
110	€ 237	€ 385	€ 340	€ 295	€ 313	€ 215
100	€ 224	€ 357	€ 310	€ 273	€ 285	€ 200
90	€ 210	€ 329	€ 281	€ 251	€ 257	€ 185
80	€ 196	€ 301	€ 251	€ 229	€ 228	€ 169
70	€ 182	€ 272	€ 221	€ 206	€ 200	€ 154
60	€ 168	€ 244	€ 191	€ 184	€ 172	€ 139
50	€ 155	€ 216	€ 161	€ 162	€ 143	€ 124
40	€ 141	€ 188	€ 132	€ 140	€ 115	€ 109

Costs in this table (and in all report figures unless otherwise specified) are total (retail-level, exclusive of taxes) costs. Basic technology costs are estimated in terms of direct manufacturing costs, which are essentially the capital cost of the technology to the vehicle manufacturer. Such costs do not include various expenses such as warranty, research and development, depreciation, maintenance, corporate overhead, and sales and distribution costs. These so-called indirect costs are added (using the methodology described in Section 4 of Meszler et al., 2016) to direct manufacturing costs to derive total retail-level cost estimates.

Table 4a. Summary of EV sales changes for various CO_2 targets (ExhICE Strategy, Discounted versus Non-Discounted Mass Reduction)

CO_2 Target (g/km)	Percentage point increase in EV market share to achieve in:					
	2020		2025		2030	
	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario
Passenger Cars over the NEDC						
95	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
80	0.0%	7.5%	0.0%	7.5%	0.0%	7.5%
70	10.3%	6.6%	10.3%	6.6%	10.3%	6.6%
60	10.8%	5.7%	10.8%	5.7%	10.8%	5.7%
50	9.0%	4.7%	9.0%	4.7%	9.0%	4.7%
40	7.2%	3.8%	7.2%	3.8%	7.2%	3.8%
Passenger Cars over the WLTP Cycle						
95	7.5%	7.4%	2.4%	7.4%	2.4%	7.4%
80	10.6%	6.2%	11.5%	6.2%	11.5%	6.2%
70	9.3%	5.4%	10.1%	5.4%	10.1%	5.4%
60	7.9%	4.7%	8.6%	4.7%	8.6%	4.7%
50	6.6%	3.9%	7.1%	3.9%	7.1%	3.9%
40	5.2%	3.1%	5.7%	3.1%	5.7%	3.1%
LCVs over the NEDC						
147	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
120	0.0%	9.5%	0.0%	9.5%	0.0%	9.5%
110	7.8%	9.9%	7.8%	9.9%	7.8%	9.9%
100	16.7%	9.0%	16.7%	9.0%	16.7%	9.0%
90	15.0%	8.1%	15.0%	8.1%	15.0%	8.1%
80	13.3%	7.2%	13.3%	7.2%	13.3%	7.2%
70	11.6%	6.3%	11.6%	6.3%	11.6%	6.3%
60	9.9%	5.4%	9.9%	5.4%	9.9%	5.4%
50	8.2%	4.5%	8.2%	4.5%	8.2%	4.5%
40	6.5%	3.6%	6.5%	3.6%	6.5%	3.6%
LCVs over the WLTP Cycle						
147	13.4%	10.3%	5.8%	10.3%	5.8%	10.3%
120	12.9%	8.4%	13.5%	8.4%	13.5%	8.4%
110	11.7%	7.7%	12.4%	7.7%	12.4%	7.7%
100	10.6%	7.0%	11.2%	7.0%	11.2%	7.0%
90	9.5%	6.3%	10.1%	6.3%	10.1%	6.3%
80	8.4%	5.6%	8.9%	5.6%	8.9%	5.6%
70	7.3%	4.9%	7.7%	4.9%	7.7%	4.9%
60	6.2%	4.2%	6.6%	4.2%	6.6%	4.2%
50	5.1%	3.5%	5.4%	3.5%	5.4%	3.5%
40	4.0%	2.8%	4.3%	2.8%	4.3%	2.8%

Costs in this table (and in all report figures unless otherwise specified) are total (retail-level, exclusive of taxes) costs. Basic technology costs are estimated in terms of direct manufacturing costs, which are essentially the capital cost of the technology to the vehicle manufacturer. Such costs do not include various expenses such as warranty, research and development, depreciation, maintenance, corporate overhead, and sales and distribution costs. These so-called indirect costs are added (using the methodology described in Section 4 of Meszler et al., 2016) to direct manufacturing costs to derive total retail-level cost estimates.

Table 4b. Summary of EV sales changes for various CO_2 targets (EV Strategy, Discounted versus Non-Discounted Mass Reduction)

CO_2 Target (g/km)	Percentage point increase in EV market share to achieve in:					
	2020		2025		2030	
	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario
Passenger Cars over the NEDC						
95	0.0%	3.2%	2.7%	5.5%	5.4%	7.4%
80	11.2%	7.1%	14.1%	6.8%	14.7%	6.4%
70	9.8%	6.2%	12.3%	5.9%	12.8%	5.6%
60	8.4%	5.3%	10.5%	5.1%	10.9%	4.8%
50	7.0%	4.4%	8.7%	4.2%	9.1%	4.0%
40	5.6%	3.5%	6.9%	3.4%	7.2%	3.2%
Passenger Cars over the WLTP Cycle						
95	8.9%	6.5%	12.3%	6.7%	13.1%	6.6%
80	7.5%	5.5%	10.3%	5.7%	11.0%	5.5%
70	6.6%	4.8%	9.0%	4.9%	9.6%	4.8%
60	5.6%	4.1%	7.7%	4.2%	8.2%	4.2%
50	4.7%	3.5%	6.4%	3.5%	6.7%	3.5%
40	3.7%	2.8%	5.0%	2.8%	5.3%	2.8%
LCVs over the NEDC						
147	0.0%	2.5%	0.0%	4.6%	0.0%	6.7%
120	14.0%	9.6%	18.4%	10.4%	19.4%	10.3%
110	12.9%	8.8%	16.8%	9.5%	17.7%	9.4%
100	11.7%	8.0%	15.2%	8.6%	16.0%	8.5%
90	10.6%	7.2%	13.6%	7.7%	14.3%	7.6%
80	9.4%	6.4%	12.0%	6.8%	12.6%	6.8%
70	8.3%	5.6%	10.4%	5.9%	10.9%	5.9%
60	7.1%	4.8%	8.8%	5.1%	9.2%	5.0%
50	5.9%	4.0%	7.3%	4.2%	7.5%	4.1%
40	4.8%	3.2%	5.7%	3.3%	5.9%	3.2%
LCVs over the WLTP Cycle						
147	8.6%	8.9%	12.7%	9.6%	13.6%	8.9%
120	7.2%	7.3%	10.4%	7.8%	11.1%	7.2%
110	6.6%	6.7%	9.5%	7.2%	10.1%	6.6%
100	6.1%	6.1%	8.7%	6.5%	9.2%	6.0%
90	5.5%	5.5%	7.8%	5.9%	8.3%	5.4%
80	5.0%	4.9%	6.9%	5.2%	7.3%	4.8%
70	4.5%	4.3%	6.1%	4.5%	6.4%	4.2%
60	3.9%	3.7%	5.2%	3.9%	5.5%	3.6%
50	3.4%	3.1%	4.4%	3.2%	4.6%	3.0%
40	2.8%	2.5%	3.5%	2.5%	3.6%	2.4%

Costs in this table (and in all report figures unless otherwise specified) are total (retail-level, exclusive of taxes) costs. Basic technology costs are estimated in terms of direct manufacturing costs, which are essentially the capital cost of the technology to the vehicle manufacturer. Such costs do not include various expenses such as warranty, research and development, depreciation, maintenance, corporate overhead, and sales and distribution costs. These so-called indirect costs are added (using the methodology described in Section 4 of Meszler et al., 2016) to direct manufacturing costs to derive total retail-level cost estimates.

Table 5a. Summary of retail compliance costs for various CO_2 targets (ExhICE Strategy, Fully Creditable Mass Reduction Technology)

CO_2 Target (g/km)	Total cost (2014€) to achieve in:					
	2020		2025		2030	
	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario
Passenger Cars over the NEDC						
95	€ 259	€ 807	€ 26	€ 535	-€ 10	€ 504
80	€ 742	€ 2,118	€ 317	€ 1,674	€ 245	€ 1,569
70	€ 1,618	€ 2,897	€ 1,012	€ 2,173	€ 903	€ 1,920
60	€ 2,281	€ 3,675	€ 1,472	€ 2,672	€ 1,284	€ 2,272
50	€ 2,747	€ 4,454	€ 1,719	€ 3,171	€ 1,440	€ 2,623
40	€ 3,214	€ 5,232	€ 1,966	€ 3,671	€ 1,595	€ 2,974
Passenger Cars over the WLTP Cycle						
95	€ 1,113	€ 2,133	€ 270	€ 1,687	€ 201	€ 1,577
80	€ 2,139	€ 3,107	€ 1,248	€ 2,311	€ 1,112	€ 2,016
70	€ 2,504	€ 3,756	€ 1,460	€ 2,727	€ 1,250	€ 2,309
60	€ 2,868	€ 4,406	€ 1,672	€ 3,143	€ 1,387	€ 2,602
50	€ 3,232	€ 5,055	€ 1,884	€ 3,559	€ 1,525	€ 2,895
40	€ 3,597	€ 5,704	€ 2,096	€ 3,975	€ 1,663	€ 3,188
LCVs over the NEDC						
147	€ 150	€ 504	€ 46	€ 354	€ 30	€ 336
120	€ 916	€ 3,237	€ 429	€ 2,636	€ 337	€ 2,514
110	€ 1,806	€ 4,081	€ 1,042	€ 3,276	€ 889	€ 3,039
100	€ 3,449	€ 4,705	€ 2,442	€ 3,700	€ 2,254	€ 3,345
90	€ 3,798	€ 5,328	€ 2,655	€ 4,124	€ 2,400	€ 3,650
80	€ 4,146	€ 5,952	€ 2,867	€ 4,548	€ 2,545	€ 3,956
70	€ 4,495	€ 6,575	€ 3,080	€ 4,972	€ 2,690	€ 4,261
60	€ 4,843	€ 7,199	€ 3,293	€ 5,396	€ 2,836	€ 4,566
50	€ 5,192	€ 7,822	€ 3,506	€ 5,820	€ 2,981	€ 4,872
40	€ 5,540	€ 8,445	€ 3,719	€ 6,244	€ 3,126	€ 5,177
LCVs over the WLTP Cycle						
147	€ 2,045	€ 3,793	€ 370	€ 3,083	€ 272	€ 2,899
120	€ 3,310	€ 5,084	€ 2,062	€ 3,960	€ 1,813	€ 3,531
110	€ 3,618	€ 5,563	€ 2,277	€ 4,285	€ 1,978	€ 3,765
100	€ 3,926	€ 6,041	€ 2,493	€ 4,610	€ 2,144	€ 4,000
90	€ 4,234	€ 6,519	€ 2,708	€ 4,935	€ 2,310	€ 4,234
80	€ 4,542	€ 6,997	€ 2,924	€ 5,260	€ 2,475	€ 4,468
70	€ 4,850	€ 7,476	€ 3,139	€ 5,586	€ 2,641	€ 4,703
60	€ 5,158	€ 7,954	€ 3,355	€ 5,911	€ 2,807	€ 4,937
50	€ 5,466	€ 8,432	€ 3,570	€ 6,236	€ 2,972	€ 5,171
40	€ 5,775	€ 8,911	€ 3,785	€ 6,561	€ 3,138	€ 5,405

Costs in this table (and in all report figures unless otherwise specified) are total (retail-level, exclusive of taxes) costs. Basic technology costs are estimated in terms of direct manufacturing costs, which are essentially the capital cost of the technology to the vehicle manufacturer. Such costs do not include various expenses such as warranty, research and development, depreciation, maintenance, corporate overhead, and sales and distribution costs. These so-called indirect costs are added (using the methodology described in Section 4 of Meszler et al., 2016) to direct manufacturing costs to derive total retail-level cost estimates.

Table 5b. Summary of retail compliance costs for various CO_2 targets (EV Strategy, Fully Creditable Mass Reduction Technology)

CO_2 Target (g/km)	Total cost (2014€) to achieve in:					
	2020		2025		2030	
	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario
Passenger Cars over the NEDC						
95	€ 259	€ 807	€ 26	€ 535	-€ 10	€ 504
80	€ 742	€ 1,929	€ 315	€ 1,334	€ 234	€ 1,122
70	€ 1,290	€ 2,734	€ 652	€ 1,880	€ 490	€ 1,534
60	€ 1,838	€ 3,538	€ 988	€ 2,425	€ 745	€ 1,946
50	€ 2,387	€ 4,342	€ 1,324	€ 2,971	€ 1,000	€ 2,358
40	€ 2,935	€ 5,146	€ 1,661	€ 3,516	€ 1,256	€ 2,770
Passenger Cars over the WLTP Cycle						
95	€ 933	€ 1,796	€ 263	€ 1,219	€ 184	€ 1,012
80	€ 1,592	€ 2,828	€ 694	€ 1,923	€ 513	€ 1,548
70	€ 2,031	€ 3,515	€ 981	€ 2,392	€ 733	€ 1,905
60	€ 2,471	€ 4,203	€ 1,269	€ 2,862	€ 952	€ 2,263
50	€ 2,910	€ 4,891	€ 1,557	€ 3,331	€ 1,172	€ 2,620
40	€ 3,349	€ 5,579	€ 1,844	€ 3,800	€ 1,391	€ 2,977
LCVs over the NEDC						
147	€ 150	€ 504	€ 46	€ 354	€ 30	€ 336
120	€ 908	€ 2,284	€ 429	€ 1,676	€ 337	€ 1,444
110	€ 1,438	€ 3,025	€ 798	€ 2,218	€ 642	€ 1,878
100	€ 1,968	€ 3,766	€ 1,167	€ 2,759	€ 947	€ 2,313
90	€ 2,497	€ 4,506	€ 1,535	€ 3,301	€ 1,252	€ 2,747
80	€ 3,027	€ 5,247	€ 1,904	€ 3,842	€ 1,558	€ 3,181
70	€ 3,557	€ 5,988	€ 2,273	€ 4,384	€ 1,863	€ 3,616
60	€ 4,086	€ 6,729	€ 2,641	€ 4,925	€ 2,168	€ 4,050
50	€ 4,616	€ 7,469	€ 3,010	€ 5,467	€ 2,473	€ 4,484
40	€ 5,146	€ 8,210	€ 3,379	€ 6,008	€ 2,778	€ 4,919
LCVs over the WLTP Cycle						
147	€ 1,221	€ 1,976	€ 350	€ 1,431	€ 257	€ 1,205
120	€ 2,326	€ 3,665	€ 1,175	€ 2,670	€ 943	€ 2,208
110	€ 2,736	€ 4,291	€ 1,480	€ 3,129	€ 1,197	€ 2,580
100	€ 3,145	€ 4,916	€ 1,786	€ 3,588	€ 1,451	€ 2,951
90	€ 3,555	€ 5,542	€ 2,091	€ 4,046	€ 1,705	€ 3,323
80	€ 3,964	€ 6,167	€ 2,397	€ 4,505	€ 1,959	€ 3,694
70	€ 4,374	€ 6,793	€ 2,703	€ 4,964	€ 2,213	€ 4,066
60	€ 4,783	€ 7,418	€ 3,008	€ 5,423	€ 2,467	€ 4,437
50	€ 5,192	€ 8,044	€ 3,314	€ 5,882	€ 2,721	€ 4,809
40	€ 5,602	€ 8,669	€ 3,619	€ 6,341	€ 2,975	€ 5,180

Costs in this table (and in all report figures unless otherwise specified) are total (retail-level, exclusive of taxes) costs. Basic technology costs are estimated in terms of direct manufacturing costs, which are essentially the capital cost of the technology to the vehicle manufacturer. Such costs do not include various expenses such as warranty, research and development, depreciation, maintenance, corporate overhead, and sales and distribution costs. These so-called indirect costs are added (using the methodology described in Section 4 of Meszler et al., 2016) to direct manufacturing costs to derive total retail-level cost estimates.

Table 6a. Summary of EV market penetration for various CO_2 targets (ExhICE Strategy, Fully Creditable Mass Reduction Technology)

CO_2 Target (g/km)	EV market share to achieve in:					
	2020		2025		2030	
	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario
Passenger Cars over the NEDC						
95	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
80	0.0%	2.6%	0.0%	2.6%	0.0%	2.6%
70	0.0%	15.9%	0.0%	15.9%	0.0%	15.9%
60	13.0%	29.2%	13.0%	29.2%	13.0%	29.2%
50	29.1%	42.4%	29.1%	42.4%	29.1%	42.4%
40	45.3%	55.7%	45.3%	55.7%	45.3%	55.7%
Passenger Cars over the WLTP Cycle						
95	0.0%	3.3%	0.0%	3.3%	0.0%	3.3%
80	11.4%	19.8%	4.6%	19.8%	4.6%	19.8%
70	23.5%	30.8%	17.6%	30.8%	17.6%	30.8%
60	35.7%	41.9%	30.6%	41.9%	30.6%	41.9%
50	47.8%	52.9%	43.6%	52.9%	43.6%	52.9%
40	60.0%	63.9%	56.6%	63.9%	56.6%	63.9%
LCVs over the NEDC						
147	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
120	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
110	0.0%	8.8%	0.0%	8.8%	0.0%	8.8%
100	1.4%	18.9%	1.4%	18.9%	1.4%	18.9%
90	13.5%	29.1%	13.5%	29.1%	13.5%	29.1%
80	25.6%	39.2%	25.6%	39.2%	25.6%	39.2%
70	37.6%	49.3%	37.6%	49.3%	37.6%	49.3%
60	49.7%	59.4%	49.7%	59.4%	49.7%	59.4%
50	61.7%	69.6%	61.7%	69.6%	61.7%	69.6%
40	73.8%	79.7%	73.8%	79.7%	73.8%	79.7%
LCVs over the WLTP Cycle						
147	0.0%	4.3%	0.0%	4.3%	0.0%	4.3%
120	19.9%	25.3%	13.0%	25.3%	13.0%	25.3%
110	28.2%	33.0%	21.8%	33.0%	21.8%	33.0%
100	36.4%	40.8%	30.7%	40.8%	30.7%	40.8%
90	44.7%	48.5%	39.5%	48.5%	39.5%	48.5%
80	52.9%	56.3%	48.4%	56.3%	48.4%	56.3%
70	61.2%	64.0%	57.2%	64.0%	57.2%	64.0%
60	69.4%	71.8%	66.0%	71.8%	66.0%	71.8%
50	77.7%	79.5%	74.9%	79.5%	74.9%	79.5%
40	86.0%	87.3%	83.7%	87.3%	83.7%	87.3%

Costs in this table (and in all report figures unless otherwise specified) are total (retail-level, exclusive of taxes) costs. Basic technology costs are estimated in terms of direct manufacturing costs, which are essentially the capital cost of the technology to the vehicle manufacturer. Such costs do not include various expenses such as warranty, research and development, depreciation, maintenance, corporate overhead, and sales and distribution costs. These so-called indirect costs are added (using the methodology described in Section 4 of Meszler et al., 2016) to direct manufacturing costs to derive total retail-level cost estimates.

Table 6b. Summary of EV market penetration for various CO_2 targets (EV Strategy, Fully Creditable Mass Reduction Technology)

CO_2 Target (g/km)	EV market share to achieve in:					
	2020		2025		2030	
	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario	Lower Bound Scenario	Upper Bound Scenario
Passenger Cars over the NEDC						
95	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
80	0.1%	11.2%	1.5%	14.2%	3.5%	16.8%
70	13.6%	23.3%	14.8%	25.9%	16.6%	28.1%
60	27.1%	35.4%	28.1%	37.6%	29.6%	39.5%
50	40.6%	47.5%	41.4%	49.3%	42.7%	50.8%
40	54.1%	59.6%	54.8%	60.9%	55.7%	62.1%
Passenger Cars over the WLTP Cycle						
95	8.9%	12.7%	2.4%	14.5%	3.7%	16.5%
80	24.4%	27.6%	19.0%	29.1%	20.1%	30.7%
70	34.8%	37.6%	30.0%	38.9%	30.9%	40.3%
60	45.2%	47.5%	41.1%	48.6%	41.8%	49.8%
50	55.5%	57.5%	52.1%	58.4%	52.7%	59.3%
40	65.9%	67.4%	63.2%	68.1%	63.6%	68.8%
LCVs over the NEDC						
147	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
120	1.9%	13.9%	0.0%	14.8%	0.4%	16.6%
110	11.6%	22.5%	9.8%	23.3%	10.2%	24.9%
100	21.2%	31.1%	19.7%	31.8%	20.0%	33.3%
90	30.8%	39.7%	29.5%	40.4%	29.8%	41.6%
80	40.5%	48.3%	39.3%	48.9%	39.5%	49.9%
70	50.1%	56.9%	49.1%	57.4%	49.3%	58.3%
60	59.8%	65.5%	59.0%	65.9%	59.1%	66.6%
50	69.4%	74.1%	68.8%	74.4%	68.9%	74.9%
40	79.0%	82.8%	78.6%	82.9%	78.7%	83.3%
LCVs over the WLTP Cycle						
147	12.8%	15.7%	2.4%	15.8%	2.1%	16.6%
120	31.8%	34.2%	23.4%	34.2%	23.2%	34.9%
110	38.8%	41.0%	31.2%	41.0%	31.0%	41.6%
100	45.8%	47.8%	39.0%	47.8%	38.8%	48.4%
90	52.9%	54.6%	46.8%	54.7%	46.6%	55.1%
80	59.9%	61.5%	54.6%	61.5%	54.4%	61.9%
70	66.9%	68.3%	62.3%	68.3%	62.2%	68.6%
60	74.0%	75.1%	70.1%	75.1%	70.0%	75.4%
50	81.0%	82.0%	77.9%	82.0%	77.8%	82.2%
40	88.0%	88.8%	85.7%	88.8%	85.6%	88.9%

Costs in this table (and in all report figures unless otherwise specified) are total (retail-level, exclusive of taxes) costs. Basic technology costs are estimated in terms of direct manufacturing costs, which are essentially the capital cost of the technology to the vehicle manufacturer. Such costs do not include various expenses such as warranty, research and development, depreciation, maintenance, corporate overhead, and sales and distribution costs. These so-called indirect costs are added (using the methodology described in Section 4 of Meszler et al., 2016) to direct manufacturing costs to derive total retail-level cost estimates.

- Given the current state of ICE technology, a passenger car NEDC standard of 70 g/km can be attained by 2025 for between 1,500 and 2,400 euros per vehicle (2014 euros) with 10% to 23% EV market penetration using an ICE technology exhaustion strategy *under the current regulatory structure that discounts mass reduction*. Costs would be 300 to 500 euros per vehicle (2014 euros) lower under a least cost EV transition strategy, but EV market shares would increase to 27% to 32% (Tables 1 and 2). These costs are between 250 and 500 euros higher and these EV market shares are between 6 and 12 percentage points higher than would be the case *under a regulatory structure in which mass reduction is fully creditable* (see Tables 3 and 4).
- For passenger car standards numerically identical to those of the NEDC, the WLTP will require a substantial cost premium for standards attainable without significant EV penetrations. For example, premiums for a 95 g/km standard range from 600 to 1,200 euros per vehicle (2014 euros). The premium will decline as EV market shares increase because EVs are credited with very low CO_2 under either driving cycle (see Tables 1 and 2). The cost premium ultimately declines to zero at 100% EV market penetration, although the standards attainable through PHEV technology are cycle dependent because of cycle-specific all-electric range influences. For standards in the 60–80 g/km range, EV market shares under the WLTP are generally 10 to 17 percentage points greater than under the NEDC.
- Passenger car standards as low as 40 g/km can be achieved by 2030 for costs of between 1,400 and 3,300 euros per vehicle (2014 euros) under either the NEDC or WLTP cycles, as compliance with such standards is dominated by large EV market shares (see Tables 1 and 2). Because of the large EV market shares (50% to 70%), the cost differential due to mass discounting is relatively more modest at 100 to 200 euros per vehicle (2014 euros).
- As documented in the Meszler et al. 2016 cost curve report, LCV NEDC standards as low as 90–100 g/km can be achieved with either no or only modest levels of EV penetration under a fully creditable mass reduction regulatory structure (see Table 6a), but will require a 14 to 17 percentage point increase in EV market penetration under the current regulatory structure that discounts mass reduction technology (see Table 4).
- Given the current state of ICE technology, an LCV NEDC standard of 110 g/km in 2025 will cost between 2,900 and 3,750 euros per vehicle (2014 euros) with an 8% to 19% EV market penetration under the current regulatory structure with an ICE technology exhaustion strategy. A 90 g/km standard will cost between 3,150 and 4,500 euros per vehicle (2014 euros), but will require a 29% to 37% EV market penetration. Costs would be 800 to 1,500 euros per vehicle (2014 euros) lower under a least cost EV transition strategy, but EV market shares would increase to 27% to 48% (Tables 1 and 2). These costs are between 400 and 1,850 euros higher and these EV market shares are between 8 and 17 percentage points higher than would be the case under a regulatory structure in which mass reduction is fully creditable (see Tables 3 and 4).
- For LCV standards numerically identical to those of the NEDC, the WLTP will require a substantial cost premium for standards attainable without significant EV penetrations. For example, premiums for a 120 g/km standard range from 550 to 2,150 euros per vehicle (2014 euros). The premium will decline as EV market shares increase because EVs are credited with very low CO_2 under either driving cycle (see Tables 1 and 2). As with passenger cars, the cost premium ultimately declines to zero at 100% EV market penetration, although the standards attainable through PHEV technology are cycle dependent due to cycle-specific all-electric range influences.
- In some cases, the simulation modeling data show either lower costs or very minor cost increases for LCVs on the WLTP relative to costs for the same numeric

standard under the NEDC. This is an artifact of a much more rapid switch to LCV EV technology necessitated by very limited ICE technology potential for LCVs over the WLTP in the absence of mass reduction technology, according to the FEV simulation modeling data. EV market shares are up to 25 percentage points higher for the WLTP under the ICE technology exhaustion strategy. The EV optimization strategy shows lesser market share increases of up to 10 percentage points, but this strategy always exhibits a cost premium (see Tables 1 and 2).

» LCV standards as low as 40 g/km can be achieved by 2030 for costs of between 3,000 and 5,500 euros per vehicle (2014 euros) under either the NEDC or WLTP cycles, as compliance with such standards is dominated by large EV market shares (see Tables 1 and 2). Because of the large EV market shares (80% to 90%), the cost differential due to mass discounting is relatively more modest at 50 to 200 euros per vehicle (2014 euros).

The presented cost curves are based on extensive vehicle simulation modeling and detailed bottom-up cost assessments, mirroring the industry approach of assessing the emission reduction potential and cost of future technologies. However, it is important to understand that the compliance costs presented in this paper apply only to the average vehicle market. Costs for individual manufacturers will be different, as will the technology mix applied by individual manufacturers. Unlike the compliance cost estimates previously published in 2016 by Meszler et al., the compliance costs presented in this paper are not technology neutral. In accordance with the current regulatory structure in the EU, the value of mass reduction technology as a CO_2 reduction strategy is discounted and both costs and required EV market penetrations increase relative to technology neutral compliance requirements.

Limitations to the approach and the presented cost curves include:

» An inability to equate the linear formulation of the EU regulatory structure for CO_2 to a mass reduction discount rate that applies to every vehicle. The inherent nonlinearity of the CO_2 response to changing mass precludes a precise translation.

» An assumption that manufacturers will not take advantage of the incentives to increase vehicle mass that are inherent in the EU regulatory structure, especially with regard to light commercial vehicles. We assume that safeguards such as the M_0 adjustment process as well as practical considerations such as maximizing the cargo carrying capacity of commercial vehicles will inhibit much of this incentive. However, should vehicle manufacturers elect to use mass increases as a mechanism to reduce investments in CO_2 reduction technology, compliance costs could be reduced from those estimated herein.

» An underlying assumption of the cost assessment is that high volume mass production costs are assumed, but no consideration is made for future changes in the design of a technology compared with today's state of the science. This means that any potential redesign of a technology to optimize efficiency and reduce associated costs is not considered in the analysis.

» Specific limitations with respect to FEV's simulation development, including non-consideration of engine downsizing potential in hybrid technology simulations, non-consideration of the impacts of road load reduction on required constant performance hybrid system size and cost, non-consideration of improvements in hybrid battery power density, and non-consideration of increases in gasoline engine compression ratio, except for simulations explicitly including VCR and Miller cycle technology.

» No attempt to incorporate assumptions about genuine new technology developments. Given the massive technology developments that have occurred in the past 10 years,[25] it is certain that there will be significant new technology developments by 2025, and even more so by 2030, that have not been incorporated into the cost curves.

» For the development of the cost curves in this paper it is assumed that market shares of fuels and vehicle segments will not change in the future. In particular, it is assumed that the market shares of gasoline and diesel vehicles will remain constant over time. However, there is some likelihood that the market share of diesel vehicles will decrease in the EU in the future. Such a shift could have an impact on fleet average compliance costs. A detailed assessment of this effect has been released in a separate report (Diaz, Miller, Mock, Minjares, Anenberg, & Meszler, 2017).
» All CO_2 emission reduction technology is evaluated on a constant performance basis. It is assumed that the power and top speed of reduced CO_2 vehicles are unchanged from those of associated baseline vehicles. CO_2 emission reduction costs for reduced performance vehicles would be lower than depicted in the presented cost curves.

Given these limitations, the cost curves presented in this paper are expected to be more reflective of the upper range of actual future costs, and that the real costs for meeting potential CO_2 emission targets are likely to be lower than indicated above. Finally, we reiterate the weakness inherent in a regulatory structure that relies on vehicle mass as a utility parameter and the potential incentives for gaming that result from associated mass reduction discounting and mass increase incentivizing. Given the slope of the CO_2 standard adjustment algorithm for light commercial vehicles, we especially encourage the EU to closely monitor vehicle mass in this sector to ensure that the M_0 adjustment provisions of the current regulatory structure are performing their desired function and to specifically ensure that such adjustments are not further penalizing those manufacturers that do elect to adopt mass reduction technology despite the disincentive inherent in the current EU system. We strongly encourage the EU to consider adopting a revised regulatory structure that does not rely on vehicle mass, or any other parameter upon which CO_2 is directly dependent, as a utility parameter.

25 Examples of such advancements include dual clutch automated manual transmissions, electric turbocharging (e-boost), Miller cycle engine operation, cooled EGR (for gasoline engines), dynamic cylinder deactivation, Atkinson cycle operation for nonhybrid vehicles, VCR operation, and 48-volt hybrid systems. Even the first lithium ion battery application was less than 10 years ago.

REFERENCES

Diaz, S., Miller, J., Mock, P., Minjares, R., Anenberg, S., & Meszler, D. (2017). *Shifting gears: The effects of a future decline in diesel market share on tailpipe CO_2 and NO_x emissions in Europe*. Retrieved from the International Council on Clean Transportation, http://www.theicct.org/sites/default/files/publications/Shifting-gears-EU-diesel-futures_ICCT-white-paper_06072017_vF.pdf

European Union. (2009). Regulation (EC) No 443/2009 of the European Parliament and of the Council of 23 April 2009 setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO2 emissions from light-duty vehicles. *Official Journal of the European Union*, l140/1, June 5, 2009. Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32009R0443

European Union. (2011). Regulation (EU) No 510/2011 of the European Parliament and of the Council of 11 May 2011 setting emission performance standards for new light commercial vehicles as part of the Union's integrated approach to reduce CO2 emissions from light-duty vehicles. *Official Journal of the European Union*, l145/1, May 31, 2011. Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32011R0510

European Union. (2014a). Regulation (EU) No 253/2014 of the European Parliament and of the Council of 26 February 2014 amending Regulation (EU) No 510/2011 to define the modalities for reaching the 2020 target to reduce CO2 emissions from new light commercial vehicles. *Official Journal of the European Union*, l84/38, March 20, 2014. Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32014R0253

European Union. (2014b). Regulation (EU) No 333/2014 of the European Parliament and of the Council of 11 March 2014 amending Regulation (EC) No 443/2009 to define the modalities for reaching the 2020 target to reduce CO2 emissions from new passenger cars. *Official Journal of the European Union*, l103/15, April 5, 2014. Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2014.103.01.0015.01.ENG

European Union. (2015). Commission Delegated Regulation (EU) 2015/6 of 31 October 2014 amending Annex I to Regulation (EC) No 443/2009 of the European Parliament and of the Council in order to take into account the evolution of the mass of new passenger cars registered in 2011, 2012 and 2013. *Official Journal of the European Union*, l3/1, January 7, 2015. Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2015.003.01.0001.01.ENG

FEV, Inc. (2013). *Light-duty vehicle mass reduction and cost analysis – European market* (FEV 11-683-001).

FEV, Inc. (2015). *2025 passenger car and light commercial vehicle powertrain technology analysis, final report* (Project Number P33597). Retrieved from http://www.theicct.org/sites/default/files/publications/PV-LCV-Powertrain-Tech-Analysis_FEV-ICCT_2015.pdf

International Council on Clean Transportation. (2016). *European vehicle market statistics, pocketbook 2016/17*, retrieved from http://www.theicct.org/sites/default/files/publications/ICCT_Pocketbook_2016.pdf

Meszler, D., German, J., Mock, P., & Bandivadekar, A. (2012a). *Initial processing of Ricardo vehicle simulation modeling CO_2 data* (Working paper 2012–4). Retrieved from the International Council on Clean Transportation, http://www.theicct.org/sites/default/files/publications/ICCT_wkpaper_RicardoData_july2012.pdf

Meszler, D., German, J., Mock, P., & Bandivadekar, A. (2012b). *Summary of the EU cost curve development methodology* (Working paper 2012–5). Retrieved from the International Council on Clean Transportation, http://www.theicct.org/sites/default/files/publications/ICCT_CostCurveSummary_wkp20121102.pdf

Meszler, D., German, J., Mock, P., & Bandivadekar, A. (2013). *Summary of mass reduction impacts on EU cost curves* (Working paper 2013–1). Retrieved from the International Council on Clean Transportation, http://www.theicct.org/sites/default/files/publications/ICCT_MassReductionImpacts_feb2013.pdf

Meszler, D., German, J., Mock, P., & Bandivadekar, A. (2016). *CO_2 reduction technologies for the European car and van fleet, a 2025–2030 assessment*. Retrieved from the International Council on Clean Transportation, http://www.theicct.org/sites/default/files/publications/EU-Cost-Curves_ICCT_nov2016.pdf

Meszler, D., German, J., Mock, P., Bandivadekar, A., & Tu, J. (2014). *Summary of Eastern EU labor rate impacts on EU cost curves* (Working paper 2014–3). Retrieved from the International Council on Clean Transportation, http://www.theicct.org/sites/default/files/publications/ICCT_EasternEU_costcurves_20140227.pdf

U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration. (2012). *Joint technical support document: Final rulemaking for 2017-2025 light-duty vehicle greenhouse gas emission standards and corporate average fuel economy standards* (EPA-420-R-12-901). Retrieved from https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/joint_final_tsd.pdf

U.S. National Research Council, National Academy of Sciences. (2013). *Transitions to alternative vehicles and fuels*. The National Academies Press, Washington, D.C. https://doi.org/10.17226/18264

Wolfram, P., & Lutsey, N. (2016). *Electric vehicles: literature review of technology costs and carbon emissions* (Working paper 2016-14). Retrieved from the International Council on Clean Transportation, http://www.theicct.org/sites/default/files/publications/ICCT_litRvw_EV-tech-costs_201607.pdf

APPENDIX: EXPANDED DISCUSSION OF M_0 IMPACTS

Section 3 of this report provides an overview of the potential effects of the M_0 adjustment process associated with the EU's CO_2 regulatory structure.[26] Because such effects can be nuanced in a multimanufacturer marketplace, such as that associated with motor vehicle production, it is helpful to understand how the effects are influenced by differences in manufacturer decision-making. This appendix provides such insight.

In reviewing this material, the reader should recognize that the scenarios presented here are but a subset of an infinite number of possible interactions. Individual vehicle manufacturers begin with a slate of vehicles, each with varying CO_2 performance, and a slate of possible vehicle mass decisions for each (e.g., decrease mass and by how much, maintain mass, or increase mass and by how much). These decisions then interact with the corresponding decisions of all other manufacturers to determine the net effect on the M_0 regulatory structure parameter and the resulting feedback effect on the efficacy of each manufacturer's decision-making. Nevertheless, it is possible to garner insight into potential M_0 adjustment effects by investigating scenarios that span a range of possible decisions, keeping in mind that these scenarios are both hypothetical and arbitrary and are not intended to signify the characteristics or decision-making of any actual vehicle manufacturer.

For simplification purposes, this appendix treats the vehicle fleet in terms of one manufacturer (denoted as OEM-A, where OEM signifies original equipment manufacturer and A is an arbitrary designator) and all other manufacturers as a group (denoted as "all others"). This latter grouping can be thought of as homogeneous or as representing the net effects of the decisions of all manufacturers other than OEM-A. There is no effective distinction between the two interpretations for purposes of this investigation. Of course, the all others group in practice is influenced by the decisions of all its component manufacturers, rendering a robust treatment subject to multivariate influences. Although these influences can be treated in the aggregate for scenario analysis such as this, it is important to recognize that real-world decision-making is taking place at the individual manufacturer level and is thus considerably more complex than the "two player" decision-making presented herein.

A total of 18 scenarios are investigated in this analysis, nine each for the passenger car and LCV standards. Each of the nine can be broken down into three subsets of three scenarios. In the first subset, OEM-A reduces mass by 10% while all other manufacturers maintain mass without change (scenario 1), reduce mass by 10% (scenario 2), and increase mass by 10% (scenario 3). The second subset (scenarios 4, 5, and 6) are analogous to scenarios 1, 2, and 3 respectively, except that OEM-A now maintains mass without change. The third subset (scenarios 7, 8, and 9) is also analogous, except that OEM-A increases mass by 10%. Table A1 summarizes these scenarios as well as provides the values assumed for additional analysis parameters. As indicated above, the values for the additional parameters are arbitrarily selected from an infinite palette and are not meant to signify any specific set of conditions other than to fulfill the need for valuation. They are 100% hypothetical and do not represent any one or group of manufacturers. They serve solely as a basis for evaluation.

26 As discussed in Section 3, the M_0 parameter serves as a basis for determining how EU regulatory CO_2 standards vary with vehicle mass. To ensure that changes in fleetwide mass do not result in changes in the fleetwide stringency of the EU standards, the M_0 parameter is reviewed and adjusted as necessary on a 3-year cycle. Under certain limited conditions, this adjustment can have the effect of making the EU standard technology neutral with regard to mass. But, as illustrated in this appendix, the effect is considerably more diverse for a much wider set of conditions.

Table A1. M_0 analysis scenario definitions

Scenario	Mass Change		Market Share		Base CO_2 (g/km)		Base Mass (kg)	
	OEM-A	All Others	OEM-A	All Others	OEM-A	All Others	OEM-A	All Others
Passenger Cars								
1	-10%	0%	20%	80%	105	110	1392.4	1392.4
2		-10%						
3		+10%						
4	0%	0%						
5		-10%						
6		+10%						
7	+10%	0%						
8		-10%						
9		+10%						
Light Commercial Vehicles								
1	-10%	0%	20%	80%	165	130	1706	1706
2		-10%						
3		+10%						
4	0%	0%						
5		-10%						
6		+10%						
7	+10%	0%						
8		-10%						
9		+10%						

Even with simplifying assumptions, it can be challenging to understand the cross-manufacturer implications of the EU regulatory structure. Figures A1 through A4 provide an illustrative framework designed to show the major parameters that affect cross-manufacturer issues. To maximize presentation and isolate concepts, these figures illustrate the implications as they would affect a single manufacturer, in this case designated as OEM-A. The implications on other manufacturers or the fleet as a whole are not fully depicted, but the concepts for evaluating such implications are identical to those depicted for the single illustrative manufacturer. Tables A2 through A7 present a robust set of parameters for all three entities, which is to say manufacturer OEM-A, all other manufacturers, and the fleet as a whole.

Figure A1. Analysis concepts based on passenger car scenario 1

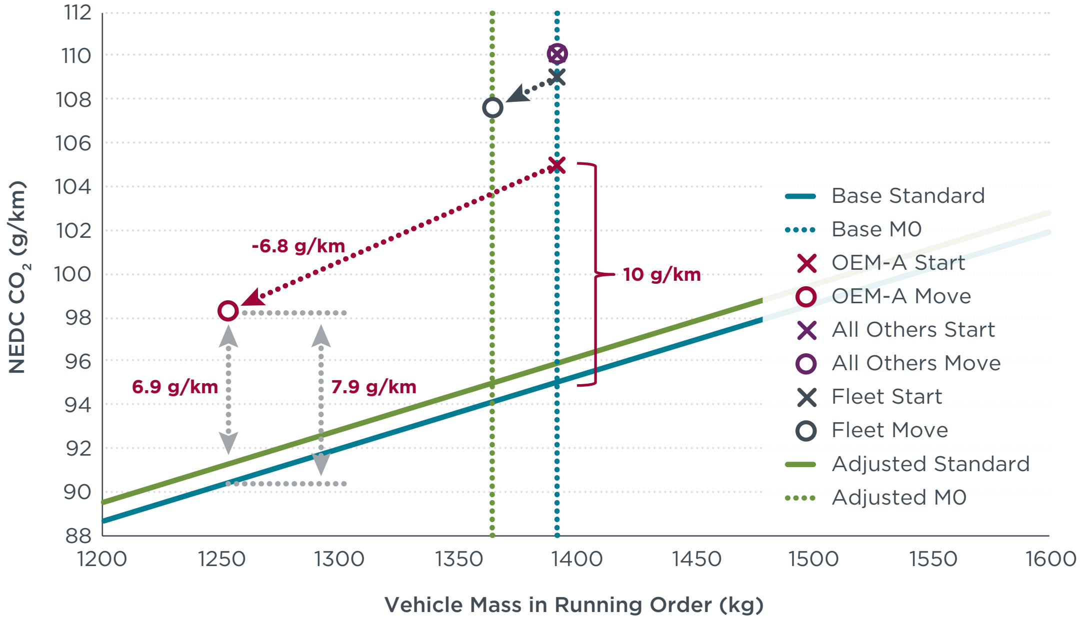


Figure A2. Analysis concepts based on passenger car scenario 2

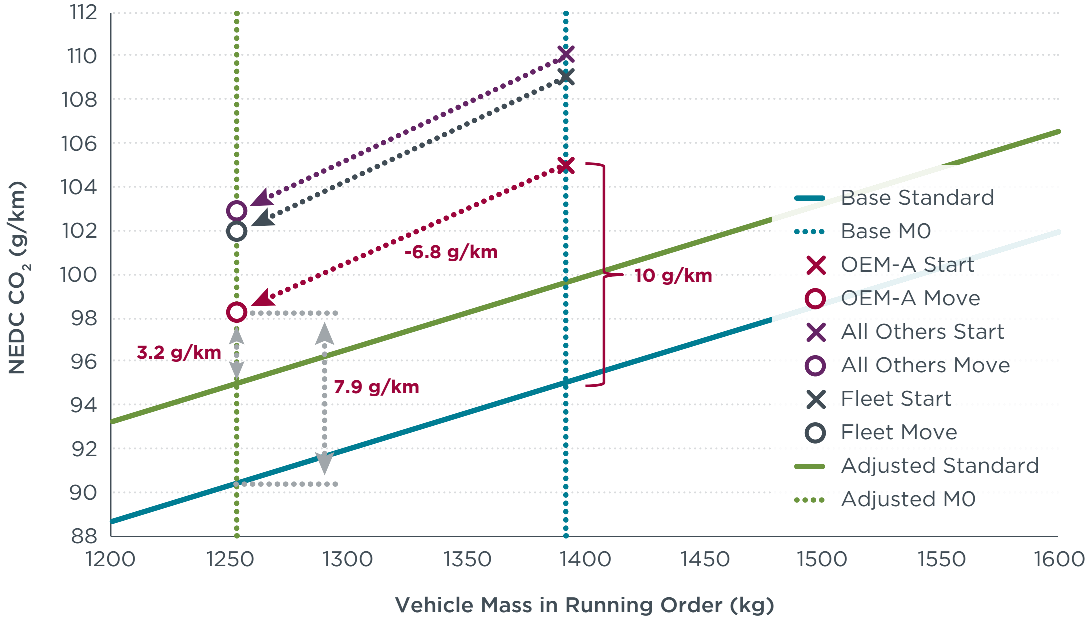


Figure A3. Analysis concepts based on light commercial vehicle scenario 1

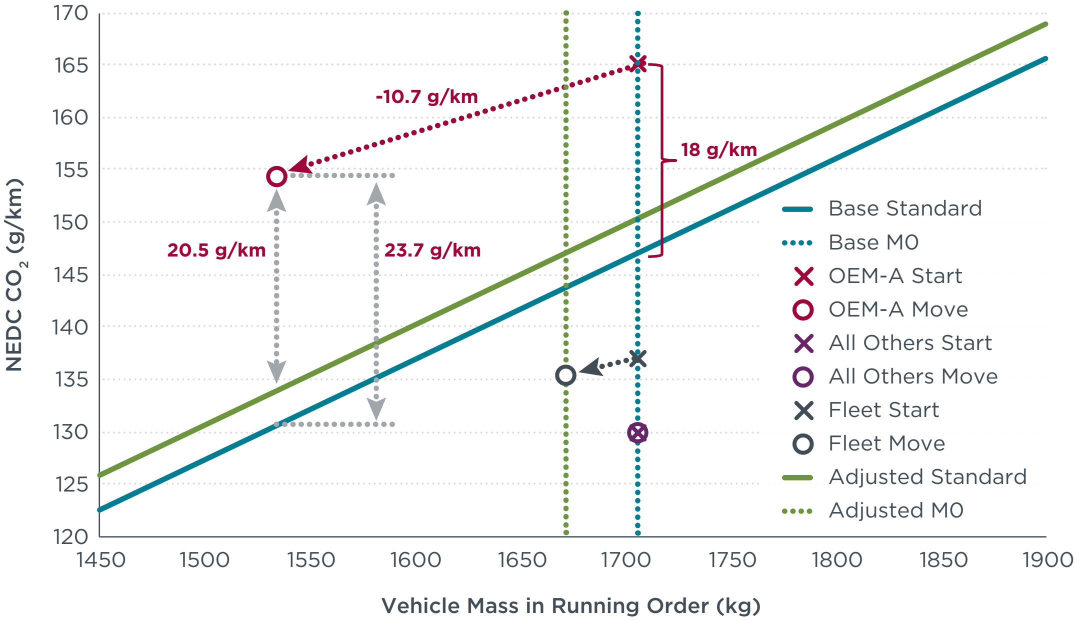


Figure A4. Analysis concepts based on light commercial vehicle scenario 2

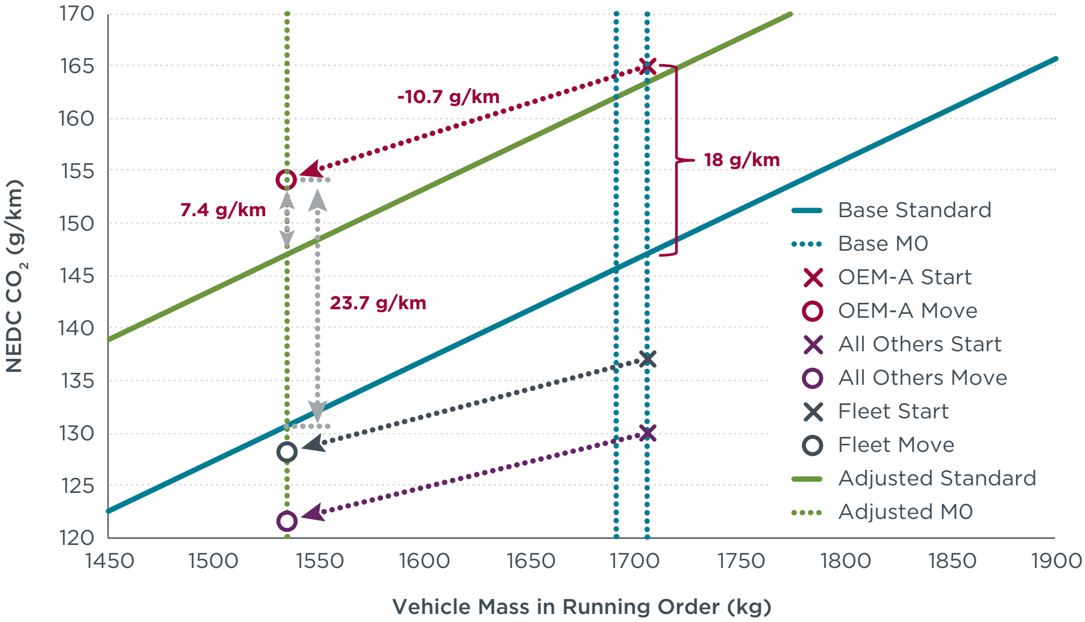


Figure A1 depicts the effects observed by manufacturer OEM-A of a scenario where passenger car manufacturer OEM-A implements a 10% mass reduction while all other manufacturers maintain mass without change. All analysis parameters are as defined under passenger car scenario 1 in Table A1. The solid blue line depicts the EU standard for passenger cars, whereas the intersecting dotted blue line indicates the position of the fleetwide mass parameter M_0. As indicated by the red x-shaped marker, OEM-A begins the scenario 10 g/km out of compliance. The beginning positions of all other manufacturers and the fleet as a whole are depicted by the violet and black x-shaped markers respectively. In implementing a 10% mass reduction with complementary powertrain changes to maintain operating efficiency, OEM-A reduces its CO_2 by 6.8 g/km, as indicated by the red circular-shaped marker. All other manufacturers maintain their CO_2 levels, as indicated by the violet circular-shaped marker, while fleetwide CO_2, indicated by the black circular-shaped marker, drops in accordance with the market share of OEM-A.

Because of its mass reduction, OEM-A faces a different standard than it did under its original mass conditions. As indicated, OEM-A is 7.9 g/km out of compliance with the original (blue line) CO_2 standard. In reducing CO_2 by 6.8 g/km through mass reduction, OEM-A moved only 2.1 g/km closer to compliance (a 10 g/km prereduction compliance gap minus a 7.9 g/km post-reduction compliance gap). The net effect, then, is that OEM-A is credited with only 2.1/6.8 —32%, when rounding is eliminated—of its mass-driven CO_2 reduction. However, because the OEM-A mass reduction affects the fleetwide mass, the EU regulatory review process should result in an adjustment to the fleetwide mass parameter M_0. This has the effect of shifting the EU standard from the blue line of Figure A1 to the green line of the figure, with the dotted green line indicating the new position of parameter M_0. This effectively alters the standard to which OEM-A and all other manufacturers are held so that the post-reduction compliance gap for OEM-A is reduced from 7.9 g/km to 6.9 g/km. This increases the credited portion of its CO_2 reduction from 2.1 g/km to 3.1 g/km, and its credited fraction from 32% to 45%. These are the influences that come into play as mass changes interact with the M_0 adjustment process.

As indicated above, the full suite of influences is reported not only for OEM-A, but for all other manufacturers and the fleet as a whole in Tables A2 through A7. The intent of the figure is to introduce the basic concepts visually and provide a reference to assist in processing the more detailed tabulated data. Three additional figures provide additional supporting evidence of how the parameters of influence can vary. Figure A2 depicts the effects observed by manufacturer OEM-A of a scenario where all passenger car manufacturers implement a 10% mass reduction. All analysis parameters are as defined under passenger car scenario 2 in Table A1. The concepts are identical to those depicted in Figure A1, but now the standard shift illustrated by the green line is larger due to the 10% fleetwide mass reduction. So, instead of being 10 g/km out of compliance prior to the 10% mass reduction and 7.9 g/km out of compliance after the mass reduction but prior to the M_0 shift, OEM-A is only 3.2 g/km out of compliance after the M_0 shift. Under such a scenario, OEM-A is actually credited for 6.8 g/km, or 100%, of a 6.8 g/km CO_2 reduction.

Figures A3 and A4 present data for light commercial vehicles that respectively correspond to the data depicted in Figures A1 and A2 for passenger cars. All associated analysis parameters are as defined under light commercial vehicle scenarios 1 and 2 in Table A1. Although the CO_2 influences are entirely analogous to those shown for passenger cars, the larger slope of the EU LCV standard creates substantially greater risk to manufacturers. Figure A3 shows that if OEM-A implements a 10% mass reduction in isolation, the associated CO_2 compliance gap increases from 18 g/km prior to the mass reduction to 23.7 g/km after the mass reduction but prior to the M_0 shift, dropping back to 20.5 g/km after the M_0 shift. Thus, even with the M_0 shift, OEM-A is farther out of compliance with the mass reduction than without, essentially getting negative credit for implementing CO_2 reduction technology.

Figure A4 shows that the perverse disincentive disappears under a scenario in which all manufacturers implement a 10% mass reduction. Here OEM-A sees a CO_2 compliance gap that increases from 18 g/km prior to the mass reduction to 23.7 g/km after the mass reduction but prior to the M_0 shift, and then drops back to 7.4 g/km after the M_0 shift. Under such a scenario, OEM-A receives credit when rounding effects are eliminated for 10.7 g/km, or 100%, of a 10.7 g/km CO_2 reduction. However, as was the case for passenger cars, this situation only occurs when all manufacturers act in lockstep.

Tables A2 through A4 present detailed analysis parameter data analogous to that depicted in Figures A1 through A4 for each of the nine passenger car scenarios defined in Table A1. Tables A5 through A7 present corresponding data for each of the nine light commercial vehicle scenarios. Figures A5 through A10 graphically depict the CO_2 reductions implemented and credited under the nine passenger car scenarios, whereas Figures A11 through A16 depict the corresponding data for the nine light commercial vehicle scenarios. Note that the values shown in red in Tables A2 through A7 correspond to the three CO_2 compliance gaps depicted in Figures A1 through A4, whereas the values shown in green reflect the CO_2 reduction achieved and the CO_2 reduction credited. These latter two parameters are summarized graphically in Figures A5 through A16. A brief description of the associated implications follows.

In passenger car scenario 1 (Table A2, Figures A5 and A6), OEM-A implements a 10% mass reduction, reducing CO_2 by 6.8 g/km, while all others hold mass constant. Without any adjustment in M_0, OEM-A marginally benefits from its 6.8 g/km CO_2 reduction by moving only 2.1 g/km closer to its standard. Because the actions of OEM-A affect the overall fleet in accordance with its market share, fleetwide CO_2 is reduced by 1.4 g/km and the fleet moves 0.5 g/km closer to its standard, for a constant M_0. However, because the OEM-A mass reduction also reduces overall fleetwide mass, a corresponding adjustment in M_0 should follow. After adjustment, the fleetwide CO_2 reduction credit properly increases to 1.4 g/km, commensurate with the fleetwide CO_2 reduction, but the CO_2 reduction credit for OEM-A increases only from 2.1 g/km to 3.1 g/km. Although the books are properly balanced, from a fleetwide perspective, OEM-A continues to see a discount applied to its CO_2 reduction efforts. The reason is that adjusting M_0 on a fleetwide basis effectively credits a portion of the efforts of OEM-A to all manufacturers, treating the actions of OEM-A as a coordinated series of smaller actions by all manufacturers, which is to say, averaging the actions of OEM-A over the entire fleet. Thus, OEM-A receives an additional CO_2 reduction credit exactly equal to that allocated to all manufacturers; 0.9 g/km. This reduction credit is a windfall for all other manufacturers as they have undertaken no CO_2 reduction action, yet receive a 0.9 g/km credit.

Table A2. Parameters for passenger car scenarios 1, 2, and 3 (OEM-A = -10%)

Analysis Parameter	Scenario 1			Scenario 2			Scenario 3		
	OEM-A	All Others	Fleet	OEM-A	All Others	Fleet	OEM-A	All Others	Fleet
Base Mass / Base M_0									
Beginning Mass (kg)	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4
Beginning M_0 (kg)	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4
Beginning CO_2 (g/km)	105	110	109	105	110	109	105	110	109
Beginning Standard (g/km)	95	95	95	95	95	95	95	95	95
Undercompliance (g/km)	10	15	14	10	15	14	10	15	14
Changed Mass / Base M_0									
New Mass (kg)	1253.2	1392.4	1364.6	1253.2	1253.2	1253.2	1253.2	1531.6	1475.9
Mass Change	-10.0%	0.0%	-2.0%	-10.0%	-10.0%	-10.0%	-10.0%	+10.0%	+6.0%
CO_2 Reduction (g/km)	6.78	0.00	1.41	6.78	7.10	7.03	6.78	-6.85	-4.13
Standard Change (g/km)	-4.64	0.00	-0.93	-4.64	-4.64	-4.64	-4.64	4.64	2.78
New CO_2 (g/km)	98.22	110.00	107.59	98.22	102.90	101.97	98.22	116.85	113.13
New Standard (g/km)	90.36	95.00	94.07	90.36	90.36	90.36	90.36	99.64	97.78
Undercompliance (g/km)	7.86	15.00	13.52	7.86	12.54	11.60	7.86	17.22	15.35
Credited CO_2 Reduction (g/km)	2.14	0.00	0.48	2.14	2.46	2.40	2.14	-2.22	-1.35
Fraction of CO_2 Reduction Credited	32%	n/a	34%	32%	35%	34%	32%	32%	33%
Changed Mass / M_0 Adjusted to New Fleet Average Mass									
Adjusted M_0 (kg)	1364.6	1364.6	1364.6	1253.2	1253.2	1253.2	1475.9	1475.9	1475.9
New Standard (g/km)	91.29	95.93	95.00	95.00	95.00	95.00	87.58	96.85	95.00
Undercompliance (g/km)	6.93	14.07	12.59	3.22	7.90	6.97	10.64	20.00	18.13
Credited CO_2 Reduction (g/km)	3.07	0.93	1.41	6.78	7.10	7.03	-0.64	-5.00	-4.13
Benefit of M_0 Revision (g/km)	0.93	0.93	0.93	4.64	4.64	4.64	-2.78	-2.78	-2.78
Fraction of CO_2 Reduction Credited	45%	Free	100%	100%	100%	100%	-9%	73%	100%
CO_2 Reduction Windfall	n/a	100%	n/a	n/a	n/a	n/a	n/a	n/a	n/a

In passenger car scenario 2 (Table A2, Figures A5 and A6), all manufacturers act in lockstep and implement a 10% mass reduction. Without any adjustment in M_0, all manufacturers receive a similarly discounted CO_2 reduction credit.[27] Because all manufacturers implement a 10% mass reduction, the fleet as a whole will also exhibit the same reduction and a corresponding adjustment in M_0 should follow. After that adjustment is made, the CO_2 reduction credits for all manufacturers increase to exactly match their individual CO_2 reductions, and the EU regulatory structure effectively becomes technology neutral. This occurs only when all manufacturers undertake the same actions, because under such conditions the apportioning of credits that is inherent in the M_0 adjustment process will be equitable to the actions actually undertaken by each manufacturer. This will not happen under any circumstances in which the actions of any single manufacturer differ from those of another, as they almost always will.

27 Because of the interaction between what is a multiplicative relationship between mass and CO_2 and the linear approximation of that relationship that is embedded in the EU standard structure, the degree of discounting is not identical across manufacturers, but instead varies with their prereduction CO_2 emissions level (i.e., all mass changes of a given magnitude trigger identical standard adjustments, whereas the actual change in CO_2 depends on both the mass change and the level of prereduction CO_2).

Table A3. Parameters for passenger car scenarios 4, 5, and 6 (OEM-A = 0%)

Analysis Parameter	Scenario 1			Scenario 2			Scenario 3		
	OEM-A	All Others	Fleet	OEM-A	All Others	Fleet	OEM-A	All Others	Fleet
Base Mass / Base M_0									
Beginning Mass (kg)	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4
Beginning M_0 (kg)	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4
Beginning CO_2 (g/km)	105	110	109	105	110	109	105	110	109
Beginning Standard (g/km)	95	95	95	95	95	95	95	95	95
Undercompliance (g/km)	10	15	14	10	15	14	10	15	14
Changed Mass / Base M_0									
New Mass (kg)	1392.4	1392.4	1392.4	1392.4	1253.2	1281.0	1392.4	1531.6	1503.8
Mass Change	0.0%	0.0%	0.0%	0.0%	-10.0%	-8.0%	0.0%	+10.0%	+8.0%
CO_2 Reduction (g/km)	0.00	0.00	0.00	0.00	7.10	5.63	0.00	-6.85	-5.47
Standard Change (g/km)	0.00	0.00	0.00	0.00	-4.64	-3.71	0.00	4.64	3.71
New CO_2 (g/km)	105.00	110.00	109.00	105.00	102.90	103.37	105.00	116.85	114.47
New Standard (g/km)	95.00	95.00	95.00	95.00	90.36	91.29	95.00	99.64	98.71
Undercompliance (g/km)	10.00	15.00	14.00	10.00	12.54	12.08	10.00	17.22	15.76
Credited CO_2 Reduction (g/km)	0.00	0.00	0.00	0.00	2.46	1.92	0.00	-2.22	-1.76
Fraction of CO_2 Reduction Credited	n/a	n/a	n/a	n/a	35%	34%	n/a	32%	32%
Changed Mass / M_0 Adjusted to New Fleet Average Mass									
Adjusted M_0 (kg)	1392.4	1392.4	1392.4	1281.0	1281.0	1281.0	1503.8	1503.8	1503.8
New Standard (g/km)	95.00	95.00	95.00	98.71	94.07	95.00	91.29	95.93	95.00
Undercompliance (g/km)	10.00	15.00	14.00	6.29	8.83	8.37	13.71	20.93	19.47
Credited CO_2 Reduction (g/km)	0.00	0.00	0.00	3.71	6.17	5.63	-3.71	-5.93	-5.47
Benefit of M_0 Revision (g/km)	0.00	0.00	0.00	3.71	3.71	3.71	-3.71	-3.71	-3.71
Fraction of CO_2 Reduction Credited	n/a	n/a	n/a	Free	87%	100%	Free	86%	100%
CO_2 Reduction Windfall	n/a	n/a	n/a	100%	n/a	n/a	100%	n/a	n/a

In passenger car scenario 3 (Table A2, Figures A5 and A6), OEM-A implements a 10% mass reduction, reducing CO_2 by 6.8 g/km, while all others increase mass by 10%. Without any adjustment in M_0, OEM-A marginally benefits from its 6.8 g/km CO_2 reduction by moving 2.1 g/km closer to its standard. Conversely, although the 10% mass increase implemented by all other manufacturers results in a 6.9 g/km increase in CO_2, the manufacturers only move 2.2 g/km farther from their standard. On a fleetwide basis, the aggregate mass change generates a 4.1 g/km increase in CO_2, but only a 1.4 g/km increase in the fleetwide compliance gap between emitted CO_2 and the associated CO_2 standard. Given the overall change in mass, a corresponding adjustment in M_0 should follow. After such adjustment, the fleetwide CO_2 compliance gap properly increases to 4.1 g/km, commensurate with the fleetwide CO_2 change. However, the compliance gap for manufacturers increasing mass increases only to 5.0 g/km, relative to an actual CO_2 increase of 6.9 g/km. This is because a portion of the net fleetwide mass increase is assigned to OEM-A despite the fact that OEM-A implemented a mass reduction. Instead of being 2.1 g/km closer to its standard, OEM-A finds itself 0.6 g/km farther from its standard. The mass increase undertaken by all other manufacturers has entirely offset the already discounted CO_2 reduction credits to which OEM-A would have been entitled prior to the shift in M_0.

Table A4. Parameters for passenger car scenarios 7, 8, and 9 (OEM-A = +10%)

Analysis Parameter	Scenario 1			Scenario 2			Scenario 3		
	OEM-A	All Others	Fleet	OEM-A	All Others	Fleet	OEM-A	All Others	Fleet
Base Mass / Base M_0									
Beginning Mass (kg)	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4
Beginning M_0 (kg)	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4	1392.4
Beginning CO_2 (g/km)	105	110	109	105	110	109	105	110	109
Beginning Standard (g/km)	95	95	95	95	95	95	95	95	95
Undercompliance (g/km)	10	15	14	10	15	14	10	15	14
Changed Mass / Base M_0									
New Mass (kg)	1531.6	1392.4	1420.2	1531.6	1253.2	1308.9	1531.6	1531.6	1531.6
Mass Change	+10.0%	0.0%	+2.0%	+10.0%	-10.0%	-6.0%	+10.0%	+10.0%	+10.0%
CO_2 Reduction (g/km)	-6.54	0.00	-1.40	-6.54	7.10	4.22	-6.54	-6.85	-6.79
Standard Change (g/km)	4.64	0.00	0.93	4.64	-4.64	-2.78	4.64	4.64	4.64
New CO_2 (g/km)	111.54	110.00	110.40	111.54	102.90	104.78	111.54	116.85	115.79
New Standard (g/km)	99.64	95.00	95.93	99.64	90.36	92.22	99.64	99.64	99.64
Undercompliance (g/km)	11.91	15.00	14.47	11.91	12.54	12.56	11.91	17.22	16.16
Credited CO_2 Reduction (g/km)	-1.91	0.00	-0.47	-1.91	2.46	1.44	-1.91	-2.22	-2.16
Fraction of CO_2 Reduction Credited	29%	n/a	34%	29%	35%	34%	29%	32%	32%
Changed Mass / M_0 Adjusted to New Fleet Average Mass									
Adjusted M_0 (kg)	1420.2	1420.2	1420.2	1308.9	1308.9	1308.9	1531.6	1531.6	1531.6
New Standard (g/km)	98.71	94.07	95.00	102.42	93.15	95.00	95.00	95.00	95.00
Undercompliance (g/km)	12.83	15.93	15.40	9.12	9.76	9.78	16.54	21.85	20.79
Credited CO_2 Reduction (g/km)	-2.83	-0.93	-1.40	0.88	5.24	4.22	-6.54	-6.85	-6.79
Benefit of M_0 Revision (g/km)	-0.93	-0.93	-0.93	2.78	2.78	2.78	-4.64	-4.64	-4.64
Fraction of CO_2 Reduction Credited	43%	Free	100%	-13%	74%	100%	100%	100%	100%
CO_2 Reduction Windfall	n/a	100%	n/a	n/a	n/a	n/a	n/a	n/a	n/a

In summary, when OEM-A implements a 10% mass reduction, the resulting compliance status impacts are directly dependent on the actions of other manufacturers. If those manufacturers do nothing (scenario 1), OEM-A gets a discounted compliance credit while all other manufacturers receive a CO_2 reduction windfall. If all other manufacturers increase mass (scenario 3), they are penalized for only a portion of their associated CO_2 increase and OEM-A absorbs the remainder. Only when all other manufacturers also reduce mass by 10% (scenario 2) are the books balanced and all manufacturers treated equitably and granted full credit for their CO_2 impacts. Under this limited latter scenario, the EU regulatory structure becomes technology neutral.

In passenger car scenario 4 (Table A3, Figures A7 and A8), all manufacturers hold mass constant. This is, of course, a bounding status quo case in which there are no CO_2 impacts or credits.

In passenger car scenario 5 (Table A3, Figures A7 and A8), OEM-A holds mass constant, while all other manufacturers implement a 10% mass reduction. This is the converse of scenario 1 and the impacts are entirely equivalent. Without any adjustment in M_0, all other

Table A5. Parameters for LCV scenarios 1, 2, and 3 (OEM-A = -10%)

Analysis Parameter	Scenario 1			Scenario 2			Scenario 3		
	OEM-A	All Others	Fleet	OEM-A	All Others	Fleet	OEM-A	All Others	Fleet
Base Mass / Base M_0									
Beginning Mass (kg)	1706	1706	1706	1706	1706	1706	1706	1706	1706
Beginning M_0 (kg)	1706	1706	1706	1706	1706	1706	1706	1706	1706
Beginning CO_2 (g/km)	165	130	137	165	130	137	165	130	137
Beginning Standard (g/km)	147	147	147	147	147	147	147	147	147
Undercompliance (g/km)	18	-17	-10	18	-17	-10	18	-17	-10
Changed Mass / Base M_0									
New Mass (kg)	1535.4	1706.0	1671.9	1535.4	1706.0	1671.9	1535.4	1876.6	1808.4
Mass Change	-10.0%	0.0%	-2.0%	-10.0%	0.0%	-2.0%	-10.0%	+10.0%	+6.0%
CO_2 Reduction (g/km)	10.65	0.00	1.77	10.65	0.00	1.77	10.65	-8.10	-5.19
Standard Change (g/km)	-16.38	0.00	-3.28	-16.38	0.00	-3.28	-16.38	16.38	9.83
New CO_2 (g/km)	154.35	130.00	135.23	154.35	130.00	135.23	154.35	138.10	142.19
New Standard (g/km)	130.62	147.00	143.72	130.62	147.00	143.72	130.62	163.38	156.83
Undercompliance (g/km)	23.73	-17.00	-8.49	23.73	-17.00	-8.49	23.73	-25.28	-14.63
Credited CO_2 Reduction (g/km)	-5.73	0.00	-1.51	-5.73	0.00	-1.51	-5.73	8.28	4.63
Fraction of CO_2 Reduction Credited	-54%	n/a	-85%	-54%	n/a	-85%	-54%	-102%	-89%
Changed Mass / M_0 Adjusted to New Fleet Average Mass									
Adjusted M_0 (kg)	1671.9	1671.9	1671.9	1535.4	1535.4	1535.4	1808.4	1808.4	1808.4
New Standard (g/km)	133.90	150.28	147.00	147.00	147.00	147.00	120.80	153.55	147.00
Undercompliance (g/km)	20.45	-20.28	-11.77	7.35	-25.39	-18.84	33.56	-15.45	-4.81
Credited CO_2 Reduction (g/km)	-2.45	3.28	1.77	10.65	8.39	8.84	-15.56	-1.55	-5.19
Benefit of M_0 Revision (g/km)	3.28	3.28	3.28	16.38	16.38	16.38	-9.83	-9.83	-9.83
Fraction of CO_2 Reduction Credited	-23%	Free	100%	100%	100%	100%	-146%	19%	100%
CO_2 Reduction Windfall	n/a	100%	n/a	n/a	n/a	n/a	n/a	n/a	0%

manufacturers reduce CO_2 by 7.1 g/km but move only 2.5 g/km closer to their standard. Fleetwide CO_2 is reduced by 5.6 g/km and the fleet moves 1.9 g/km closer to its standard for a constant M_0. Because the all other manufacturer mass reduction reduces overall fleetwide mass, a corresponding adjustment in M_0 should follow. After adjustment, the fleetwide CO_2 reduction credit properly increases to 5.6 g/km, commensurate with the fleetwide CO_2 reduction. However, the CO_2 reduction credit for all other manufacturers, which increases from 2.5 g/km to 6.2 g/km, is still shy of the actual 7.1 g/km reductions generated. While the books are properly balanced from a fleetwide perspective, all other manufacturers continue to see a discount applied to their CO_2 reduction efforts. The reason is that adjusting M_0 on a fleetwide basis effectively credits a portion of the all other manufacturer efforts to OEM-A. OEM-A receives a substantial windfall CO_2 reduction credit of 3.7 g/km, exactly equal in magnitude to that allocated to all other manufacturers in the M_0 adjustment process. Note that the windfall for OEM-A under this scenario is substantially larger than the windfall allocated to all other manufacturers under scenario 1. This is due to the larger market share assumed for all other manufacturers—80% versus 20% for OEM-A—which has the effect of creating a larger change in fleetwide mass and thus a larger associated M_0 adjustment.

Table A6. Parameters for LCV scenarios 4, 5, and 6 (OEM-A = 0%)

Analysis Parameter	Scenario 1			Scenario 2			Scenario 3		
	OEM-A	All Others	Fleet	OEM-A	All Others	Fleet	OEM-A	All Others	Fleet
Base Mass / Base M_0									
Beginning Mass (kg)	1706	1706	1706	1706	1706	1706	1706	1706	1706
Beginning M_0 (kg)	1706	1706	1706	1706	1706	1706	1706	1706	1706
Beginning CO_2 (g/km)	165	130	137	165	130	137	165	130	137
Beginning Standard (g/km)	147	147	147	147	147	147	147	147	147
Undercompliance (g/km)	18	-17	-10	18	-17	-10	18	-17	-10
Changed Mass / Base M_0									
New Mass (kg)	1706.0	1706.0	1706.0	1706.0	1535.4	1569.5	1706.0	1876.6	1842.5
Mass Change	0.0%	0.0%	0.0%	0.0%	-10.0%	-8.0%	0.0%	+10.0%	+8.0%
CO_2 Reduction (g/km)	0.00	0.00	0.00	0.00	8.39	7.07	0.00	-8.10	-6.88
Standard Change (g/km)	0.00	0.00	0.00	0.00	-16.38	-13.10	0.00	16.38	13.10
New CO_2 (g/km)	165.00	130.00	137.00	165.00	121.61	129.93	165.00	138.10	143.88
New Standard (g/km)	147.00	147.00	147.00	147.00	130.62	133.90	147.00	163.38	160.10
Undercompliance (g/km)	18.00	-17.00	-10.00	18.00	-9.01	-3.97	18.00	-25.28	-16.22
Credited CO_2 Reduction (g/km)	0.00	0.00	0.00	0.00	-7.99	-6.03	0.00	8.28	6.22
Fraction of CO_2 Reduction Credited	n/a	n/a	n/a	n/a	-95%	-85%	n/a	-102%	-91%
Changed Mass / M_0 Adjusted to New Fleet Average Mass									
Adjusted M_0 (kg)	1706.0	1706.0	1706.0	1569.5	1569.5	1569.5	1842.5	1842.5	1842.5
New Standard (g/km)	147.00	147.00	147.00	160.10	143.72	147.00	133.90	150.28	147.00
Undercompliance (g/km)	18.00	-17.00	-10.00	4.90	-22.11	-17.07	31.10	-12.17	-3.12
Credited CO_2 Reduction (g/km)	0.00	0.00	0.00	13.10	5.11	7.07	-13.10	-4.83	-6.88
Benefit of M_0 Revision (g/km)	0.00	0.00	0.00	13.10	13.10	13.10	-13.10	-13.10	-13.10
Fraction of CO_2 Reduction Credited	Free	Free	Free	Free	61%	100%	Free	60%	100%
CO_2 Reduction Windfall	100%	100%	100%	100%	n/a	n/a	100%	n/a	n/a

In passenger car scenario 6 (Table A3, Figures A7 and A8), OEM-A holds mass constant, while all other manufacturers implement a 10% mass increase. Without any adjustment in M_0, the 6.9 g/km increase in CO_2 that results from the action of all other manufacturers moves those manufacturers only 2.2 g/km farther from their standard. On a fleetwide basis, the overall mass change generates a 5.5 g/km increase in CO_2, but only a 1.8 g/km increase in the fleetwide CO_2 compliance gap. Given the overall change in mass, a corresponding adjustment in M_0 should follow. After such adjustment, the fleetwide CO_2 compliance gap properly increases to 5.5 g/km, commensurate with the fleetwide CO_2 change. However, the compliance gap for manufacturers increasing mass increases only to 5.9 g/km for an actual CO_2 increase of 6.9 g/km. This is because a portion of the net fleetwide mass increase is assigned to OEM-A despite the fact that OEM-A held mass constant. Despite undertaking no mass-related changes, OEM-A finds itself 3.7 g/km farther from its standard.

In summary, when OEM-A holds mass constant, the resulting compliance status impacts continue to be directly dependent on the actions of other manufacturers. If all manufacturers hold mass constant (scenario 4), then OEM-A is unaffected. If all other manufacturers decrease mass (scenario 5), OEM-A receives a CO_2 reduction windfall while all other manufacturers get a

Table A7. Parameters for LCV scenarios 7, 8, and 9 (OEM-A = +10%)

Analysis Parameter	Scenario 1			Scenario 2			Scenario 3		
	OEM-A	All Others	Fleet	OEM-A	All Others	Fleet	OEM-A	All Others	Fleet
Base Mass / Base M_0									
Beginning Mass (kg)	1706	1706	1706	1706	1706	1706	1706	1706	1706
Beginning M_0 (kg)	1706	1706	1706	1706	1706	1706	1706	1706	1706
Beginning CO_2 (g/km)	165	130	137	165	130	137	165	130	137
Beginning Standard (g/km)	147	147	147	147	147	147	147	147	147
Undercompliance (g/km)	18	-17	-10	18	-17	-10	18	-17	-10
Changed Mass / Base M_0									
New Mass (kg)	1876.6	1706.0	1740.1	1876.6	1535.4	1603.6	1876.6	1876.6	1876.6
Mass Change	+10.0%	0.0%	+2.0%	+10.0%	-10.0%	-6.0%	+10.0%	+10.0%	+10.0%
CO_2 Reduction (g/km)	-10.28	0.00	-1.76	-10.28	8.39	5.30	-10.28	-8.10	-8.54
Standard Change (g/km)	16.38	0.00	3.28	16.38	-16.38	-9.83	16.38	16.38	16.38
New CO_2 (g/km)	175.28	130.00	138.76	175.28	121.61	131.70	175.28	138.10	145.54
New Standard (g/km)	163.38	147.00	150.28	163.38	130.62	137.17	163.38	163.38	163.38
Undercompliance (g/km)	11.90	-17.00	-11.52	11.90	-9.01	-5.48	11.90	-25.28	-17.84
Credited CO_2 Reduction (g/km)	6.10	0.00	1.52	6.10	-7.99	-4.52	6.10	8.28	7.84
Fraction of CO_2 Reduction Credited	-59%	n/a	-87%	-59%	-95%	-85%	-59%	-102%	-92%
Changed Mass / M_0 Adjusted to New Fleet Average Mass									
Adjusted M_0 (kg)	1740.1	1740.1	1740.1	1603.6	1603.6	1603.6	1876.6	1876.6	1876.6
New Standard (g/km)	160.10	143.72	147.00	173.20	140.45	147.00	147.00	147.00	147.00
Undercompliance (g/km)	15.18	-13.72	-8.24	2.08	-18.84	-15.30	28.28	-8.90	-1.46
Credited CO_2 Reduction (g/km)	2.82	-3.28	-1.76	15.92	1.84	5.30	-10.28	-8.10	-8.54
Benefit of M_0 Revision (g/km)	-3.28	-3.28	-3.28	9.83	9.83	9.83	-16.38	-16.38	-16.38
Fraction of CO_2 Reduction Credited	-27%	Free	100%	-155%	22%	100%	100%	100%	100%
CO_2 Reduction Windfall	n/a	100%	0%	n/a	n/a	n/a	n/a	n/a	n/a

discounted compliance credit. If all other manufacturers increase mass (scenario 6), they are penalized for only a portion of their associated CO_2 increase and OEM-A absorbs the remainder.

In passenger car scenario 7 (Table A4, Figures A9 and A10), OEM-A implements a 10% mass increase, increasing CO_2 by 6.5 g/km, while all others hold mass constant. Without any adjustment in M_0, OEM-A benefits from its 6.5 g/km CO_2 increase by moving only 1.9 g/km farther from its standard. Because the actions of OEM-A affect the overall fleet in accordance with its market share, fleetwide CO_2 increases by 1.4 g/km and the fleet moves 0.5 g/km farther from its standard, for a constant M_0. However, because the OEM-A mass increase also increases overall fleetwide mass, a corresponding adjustment in M_0 should follow. After adjustment, the fleetwide CO_2 increase is properly credited at 1.4 g/km, but the CO_2 increase for OEM-A is credited only at 2.8 g/km as opposed to the induced 6.5 g/km increase in CO_2. Although the books are properly balanced from a fleetwide perspective, OEM-A continues to receive a discount for its CO_2 increasing actions. The reason is that adjusting M_0 on a fleetwide basis effectively credits a portion of the efforts of OEM-A to all manufacturers, treating the individual actions of OEM-A as a coordinated series of smaller actions undertaken by all manufacturers, which is to say, averaging the actions of OEM-A over the entire fleet. Thus, all other

Figure A5. CO_2 crediting for passenger car scenarios 1, 2, and 3 (M_0 not adjusted)

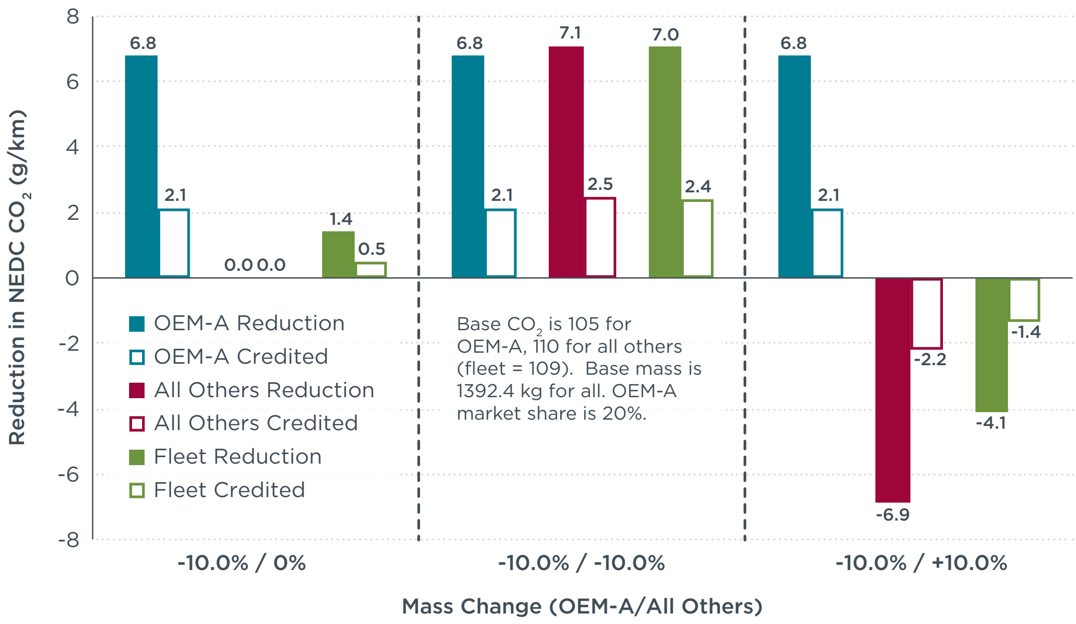


Figure A6. CO_2 crediting for passenger car scenarios 1, 2, and 3 (M_0 adjusted)

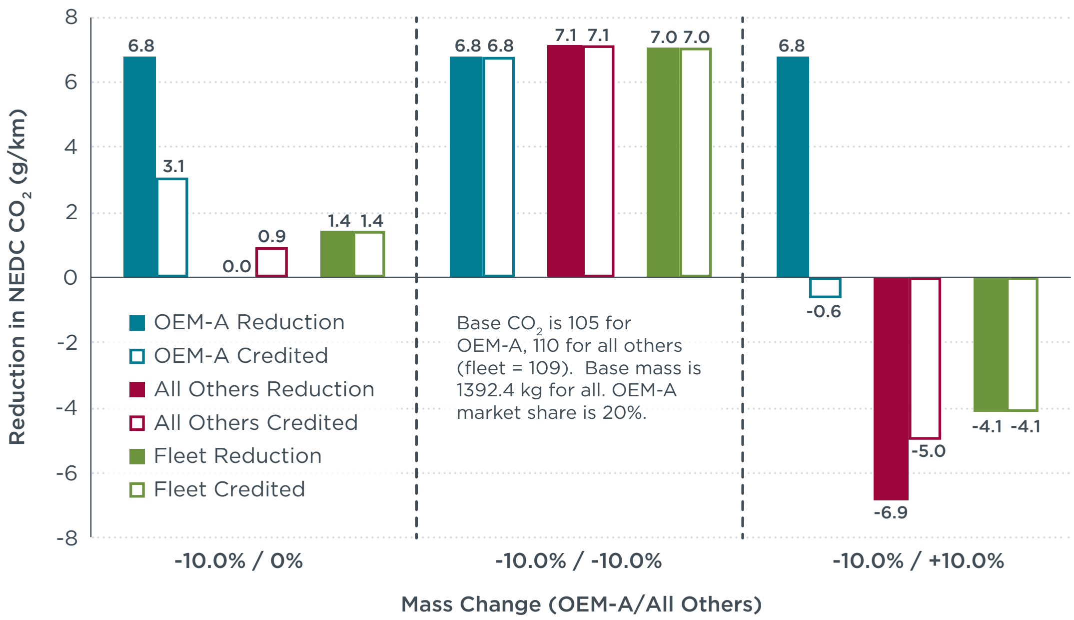


Figure A7. CO_2 crediting for passenger car scenarios 4, 5, and 6 (M_0 not adjusted)

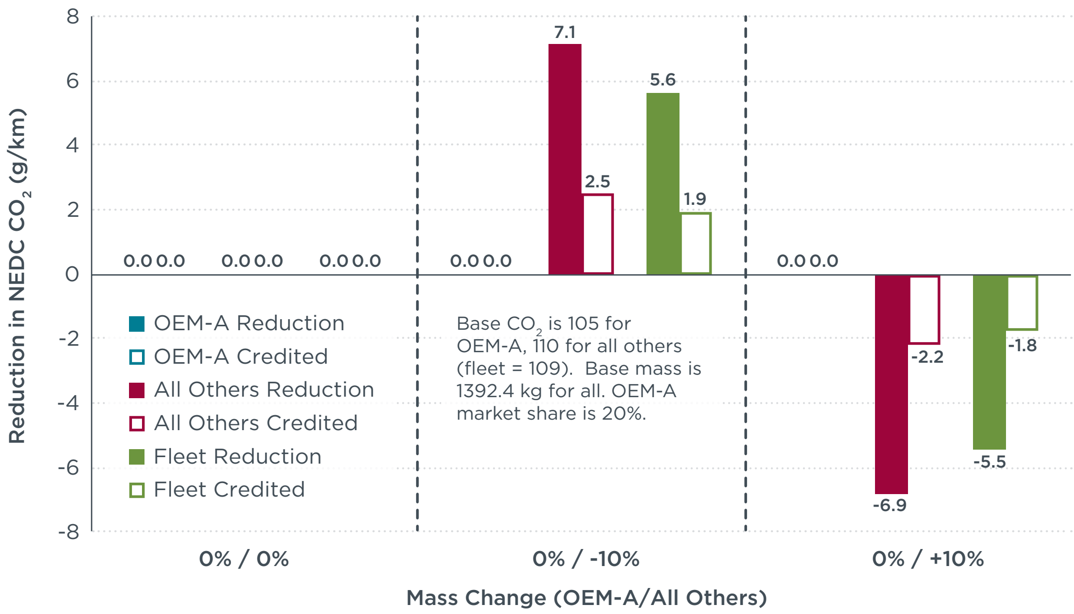


Figure A8. CO_2 crediting for passenger car scenarios 4, 5, and 6 (M_0 adjusted)

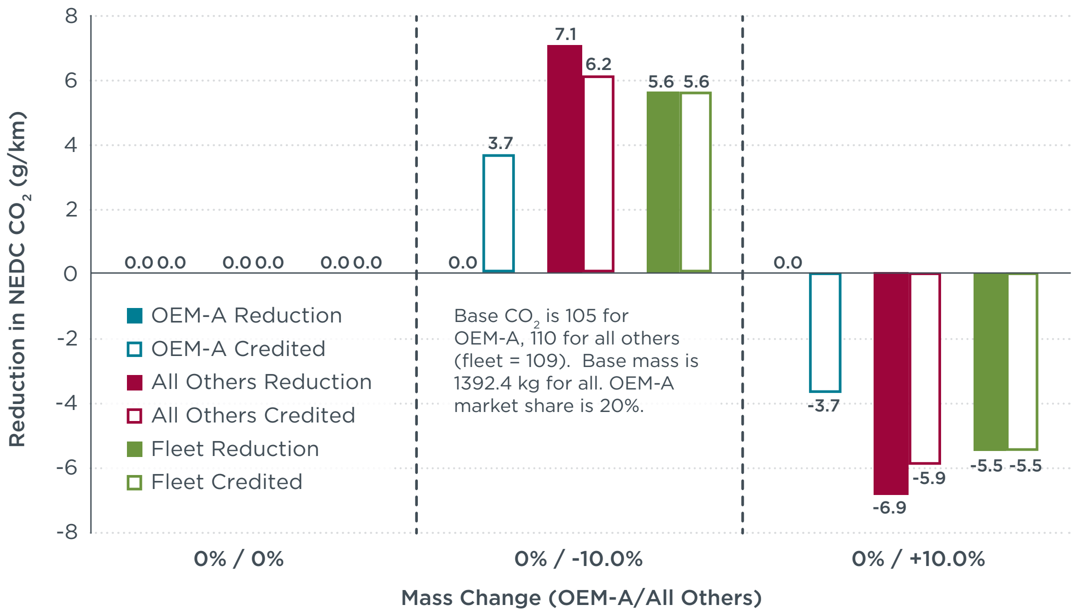


Figure A9. CO_2 crediting for passenger car scenarios 7, 8, and 9 (M_0 not adjusted)

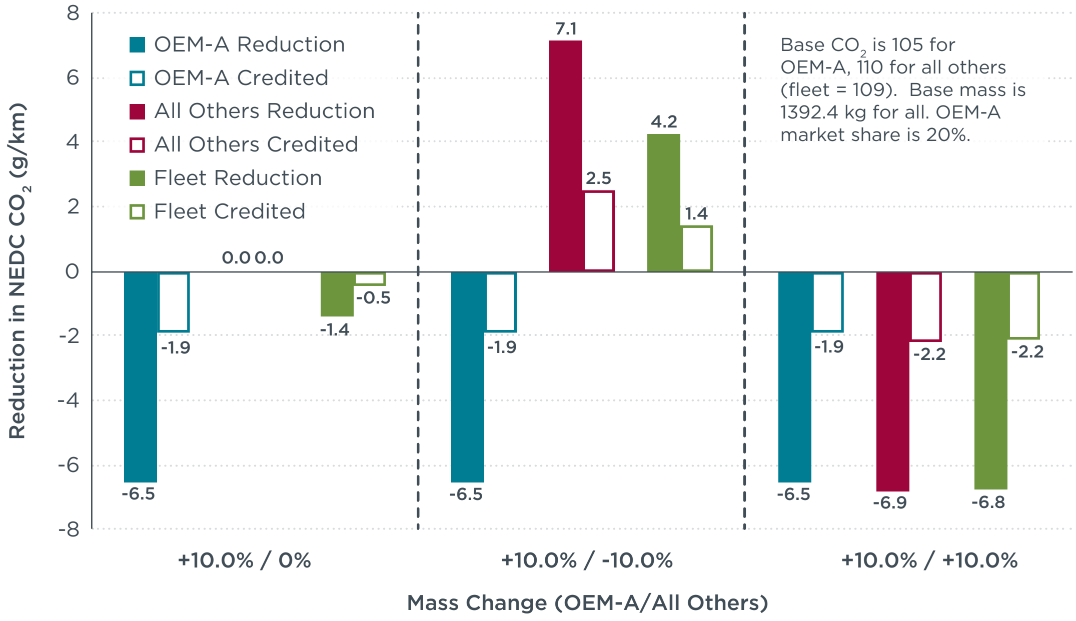


Figure A10. CO_2 crediting for passenger car scenarios 7, 8, and 9 (M_0 adjusted)

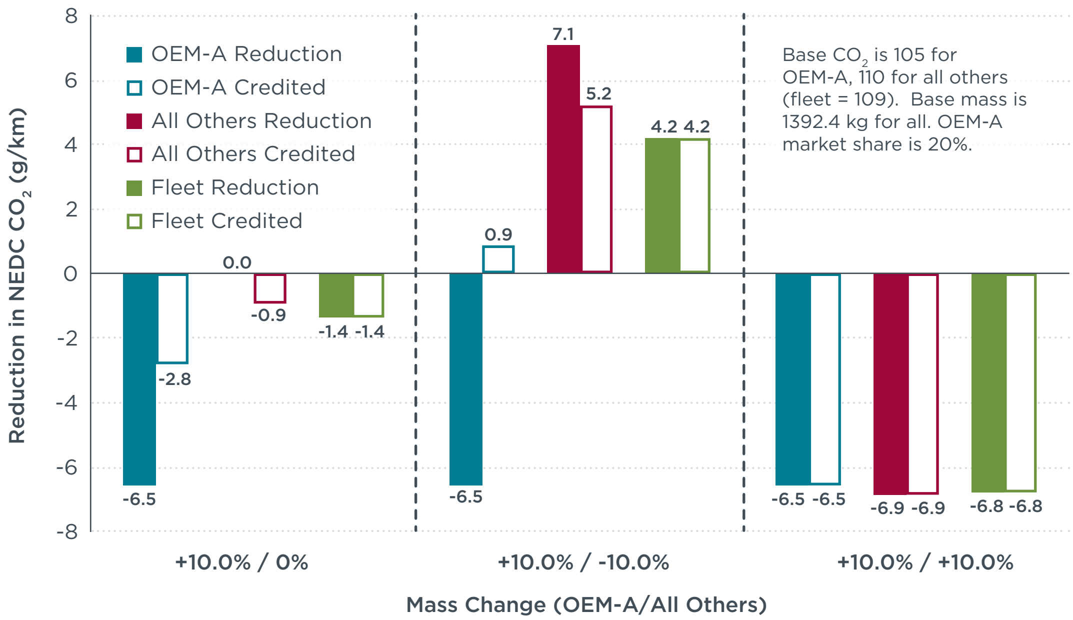


Figure A11. CO_2 crediting for LCV scenarios 1, 2, and 3 (M_0 not adjusted)

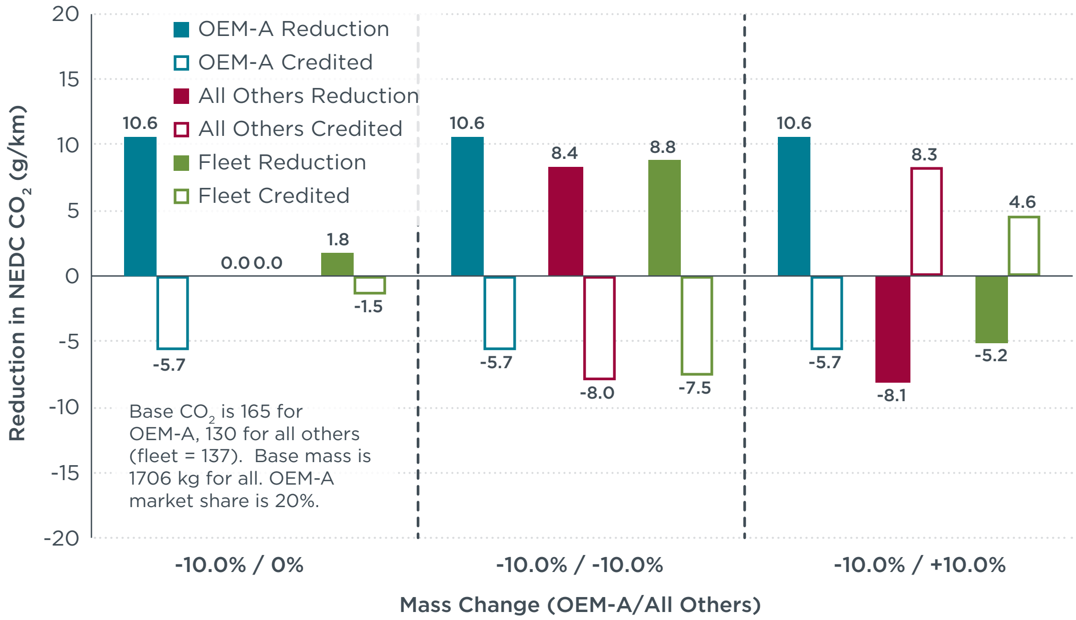


Figure A12. CO_2 crediting for LCV scenarios 1, 2, and 3 (M_0 adjusted)

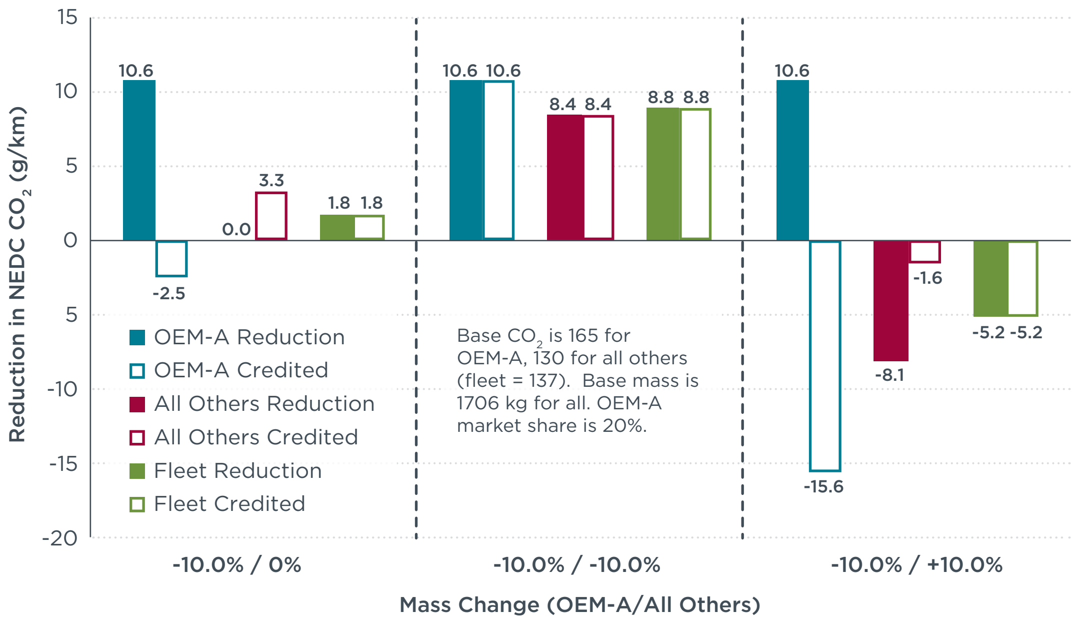


Figure A13. CO_2 crediting for LCV scenarios 4, 5, and 6 (M_0 not adjusted)

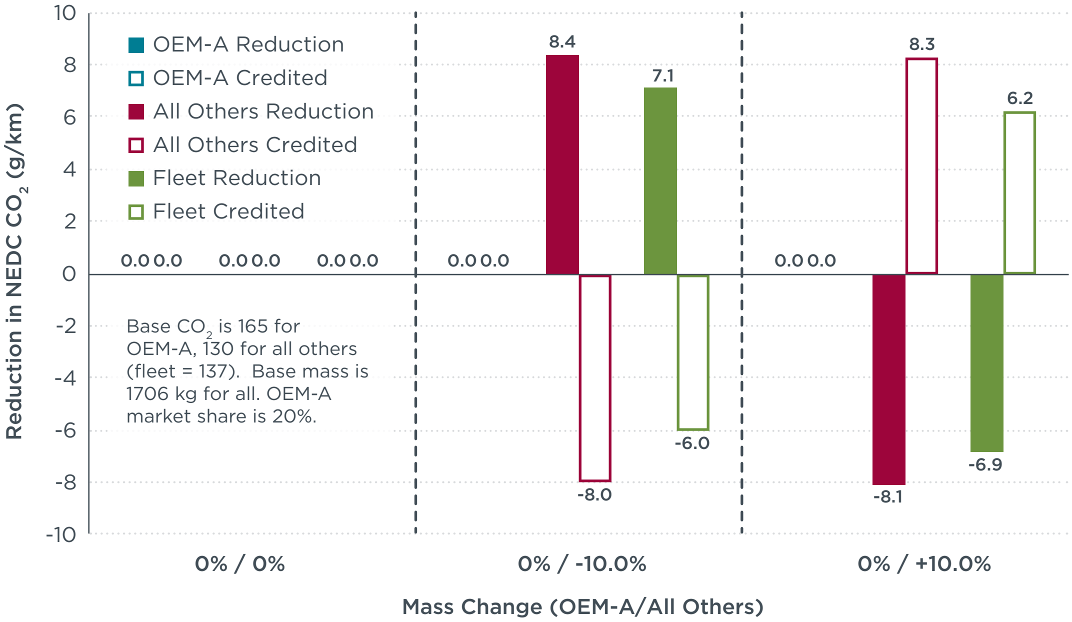


Figure A14. CO_2 crediting for LCV scenarios 4, 5, and 6 (M_0 adjusted)

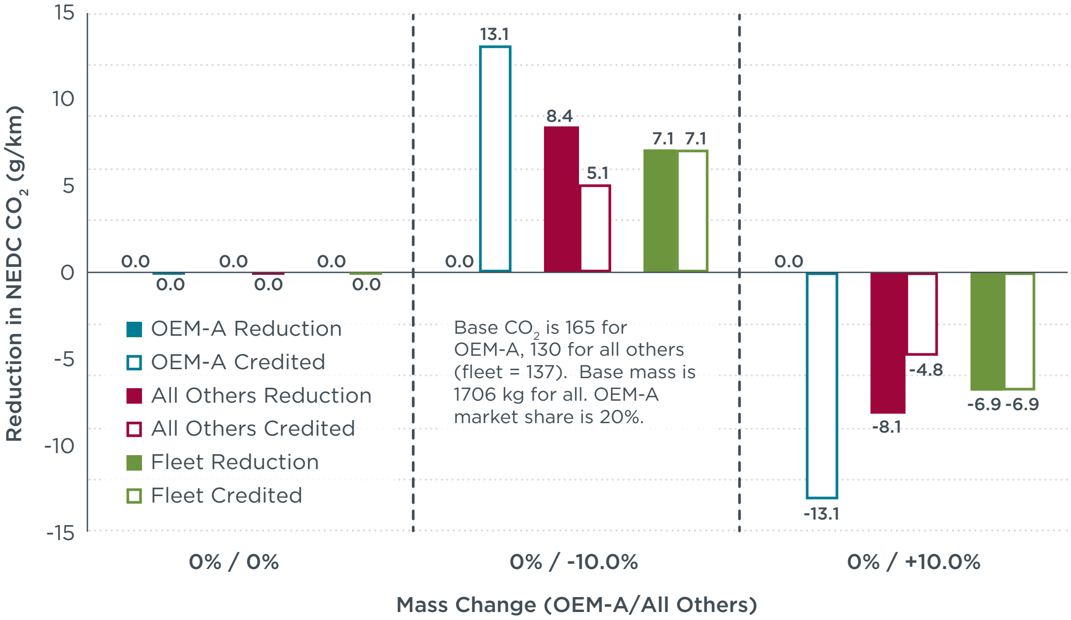


Figure A15. CO_2 crediting for LCV scenarios 7, 8, and 9 (M_0 not adjusted)

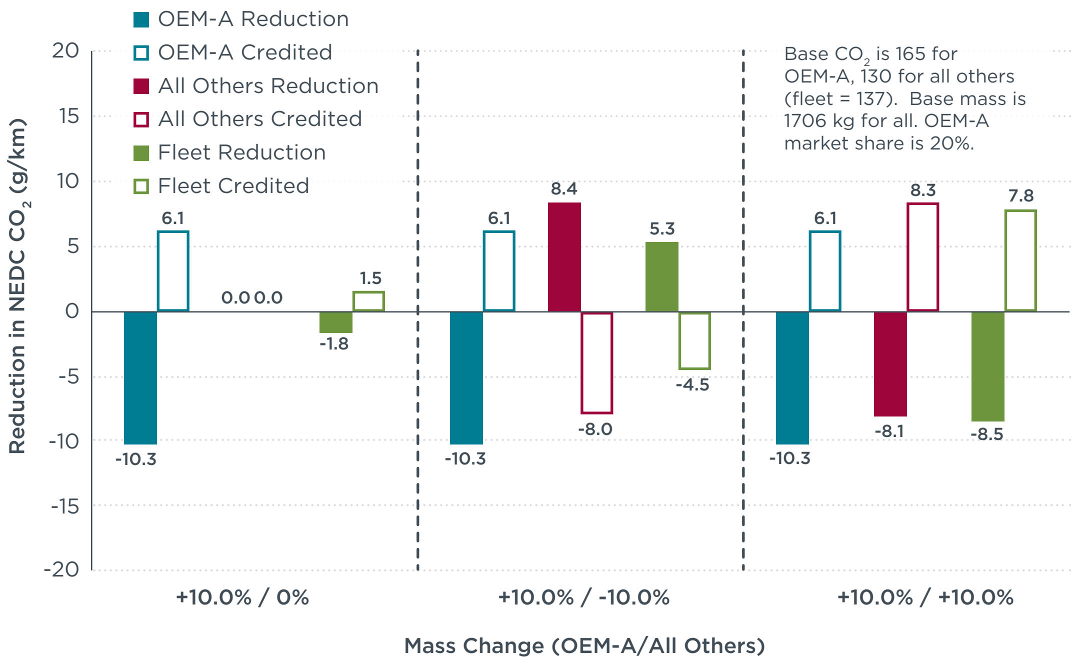
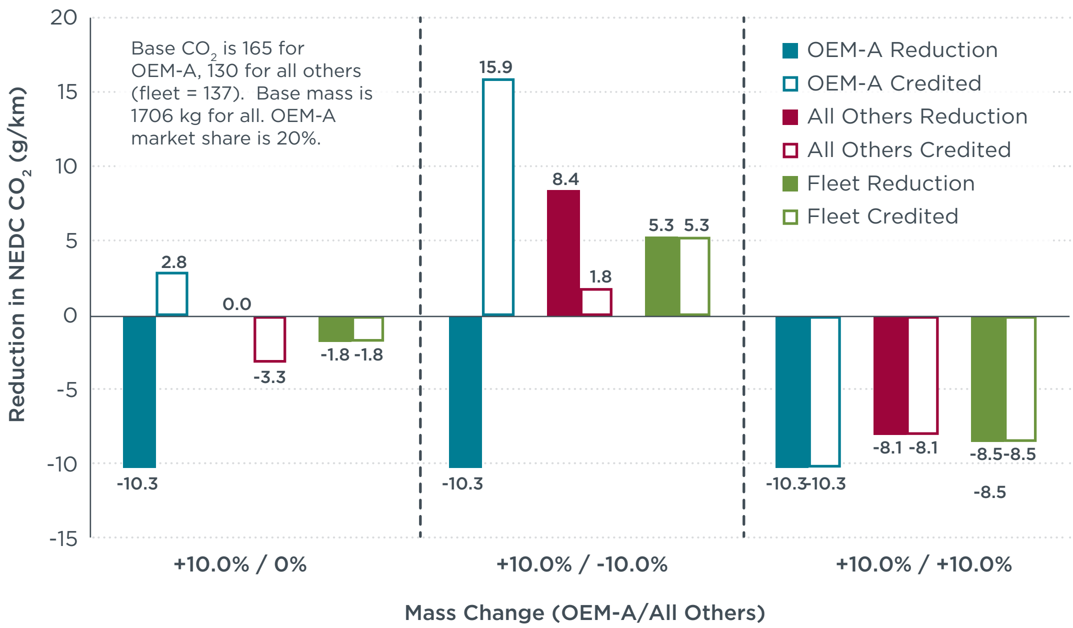


Figure A16. CO_2 crediting for LCV scenarios 7, 8, and 9 (M_0 adjusted)



manufacturers are assigned a CO_2 shortfall of 0.9 g/km, even though they have undertaken no actions to affect either their own or fleetwide CO_2 performance.

In passenger car scenario 8 (Table A4, Figures A9 and A10), OEM-A implements a 10% mass increase while all other manufacturers implement a 10% mass reduction. Without any adjustment in M_0, all manufacturers receive substantially discounted CO_2 credit. OEM-A moves only 1.9 g/km farther from its standard, despite increasing CO_2 by 6.5 g/km. All other manufacturers reduce CO_2 by 7.1 g/km, yet move only 2.5 g/km closer to their standard. On a fleetwide basis, CO_2 is reduced by 4.2 g/km, but the fleetwide compliance gap narrows by only 1.4 g/km. In all cases except that in which market shares and mass characteristics are such that the actions of OEM-A are exactly offset by the actions of all other manufacturers, an adjustment in M_0 should follow. After that adjustment is made, the CO_2 reduction credits for the fleet as a whole increase to 4.2 g/km to exactly match fleetwide CO_2 impacts. However, the credits for all other manufacturers, at 5.2 g/km, continue to lag the actual 7.1 g/km CO_2 reductions. This occurs because of the fact that adjusting M_0 on a fleetwide basis effectively credits a portion of the mass reduction efforts of all other manufacturers to OEM-A, resulting in the assignment of 2.8 g/km of CO_2 reduction to a manufacturer that actually increased mass, thus turning a 1.9 g/km increase in its compliance gap into a 0.9 g/km decrease.

In passenger car scenario 9 (Table A4, Figures A9 and A10), all manufacturers act in lockstep and increase mass by 10%. Without any adjustment in M_0, all manufacturers receive the benefits of a similar discounting of their mass-induced CO_2 increase. Because all manufacturers implement a 10% mass increase, the fleet as a whole also will exhibit the same increase and a corresponding adjustment in M_0 should follow. After that adjustment is made, the discounting of CO_2 increases for all manufacturers is eliminated in its entirety, such that the increase in each manufacturer's compliance gap is exactly equal to the mass-induced increase in CO_2. As was the case with the universal 10% mass reduction (scenario 2), this occurs only when all manufacturers undertake identical action. Under such conditions the apportioning of credits that is inherent in the M_0 adjustment process will be equitable to the actions actually undertaken by each manufacturer. This will not happen under any circumstances in which the actions of any single manufacturer differ from those of another, as they almost always will.

In summary, when OEM-A implements a 10% mass increase, the resulting compliance status impacts are directly dependent on the actions of other manufacturers. If they do nothing (scenario 7), OEM-A is penalized for only a portion of its CO_2 impacts, and all other manufacturers are penalized for doing nothing. If all other manufacturers decrease mass (scenario 8), OEM-A is the recipient of windfall CO_2 reduction credits whereas the credits actually generated by all other manufacturer actions are discounted. Only when all other manufacturers also increase mass by 10% (scenario 9) are the books balanced and all manufacturers treated equitably and penalized fully for their CO_2 impacts. Under this limited latter scenario, the EU regulatory structure becomes technology neutral.

In light commercial vehicle scenario 1 (Table A5, Figures A11 and A12), OEM-A implements a 10% mass reduction, reducing CO_2 by 10.6 g/km, while all others hold mass constant. Without any adjustment in M_0, OEM-A suffers a disbenefit from its 10.6 g/km CO_2 reduction by moving 5.7 g/km farther from its standard. This effect occurs for light commercial vehicles because the slope of the EU LCV standard is substantially greater than slope of the actual relationship between CO_2 and mass, which is to say that the standard changes more rapidly than actual CO_2. Because the actions of OEM-A affect the overall fleet in accordance with its market share, fleetwide CO_2 is reduced by 1.8 g/km and the fleet moves 1.5 g/km farther from its standard, for a constant M_0. However, because the OEM-A mass reduction also reduces overall fleetwide mass, a corresponding adjustment in M_0 should follow. After adjustment, the fleetwide CO_2 reduction credit properly increases to 1.8 g/km, commensurate with the fleetwide CO_2 reduction. However, the CO_2 standard impact for OEM-A increases by only 3.3 g/km such that OEM-A remains 2.5 g/km farther from its standard than before implementing the 10% mass reduction. Although the books are properly balanced from a fleetwide perspective, OEM-A continues to see a greater than 100% discount applied to its CO_2 reduction efforts. The reason is that adjusting M_0 on a fleetwide basis effectively credits a portion of the efforts of OEM-A to all manufacturers, treating the actions of OEM-A as a coordinated series of smaller actions by all manufacturers and averaging the actions of OEM-A over the entire fleet. Thus, OEM-A receives an additional CO_2 reduction credit exactly equal to that allocated to all manufacturers, 3.3 g/km. This reduction credit is a windfall for all other manufacturers because they have undertaken no CO_2 reduction actions under this scenario, yet receive a 3.3 g/km credit. In a particularly perverse outcome, OEM-A is penalized for reducing mass and the full credit for the CO_2 reductions resulting entirely from the actions of OEM-A is allocated among all other manufacturers.

In light commercial vehicle scenario 2 (Table A5, Figures A11 and A12), all manufacturers act in lockstep and implement a 10% mass reduction. Without any adjustment in M_0, all manufacturers receive a greater than 100% discounted CO_2 reduction credit, ending up with a larger compliance gap after reducing mass. However, because all manufacturers implement a 10% mass reduction, the fleet as a whole will also exhibit the same reduction and a corresponding adjustment in M_0 should follow. After that adjustment is made, the CO_2 reduction credits for all manufacturers increase to exactly match their individual CO_2 reductions. This occurs only when all manufacturers undertake the same actions. Under such conditions the apportioning of credits that is inherent in the M_0 adjustment process will be equitable to the actions actually undertaken by each manufacturer. This will not happen under any circumstances in which the actions of any single manufacturer differ from those of another, as they almost always will.

In light commercial vehicle scenario 3 (Table A5, Figures A11 and A12), OEM-A implements a 10% mass reduction, reducing CO_2 by 10.6 g/km, while all others increase mass by 10%. Without any adjustment in M_0, OEM-A receives a disbenefit from its 10.6 g/km CO_2 reduction, because of the excessive slope of the LCV standard, moving 5.7 g/km farther from its standard. Conversely, while the 10% mass increase implemented by all other manufacturers results in an 8.1 g/km increase in CO_2, these manufacturers move 8.3 g/km closer to their standard, once again because of the excessive slope of the LCV standard. On a fleetwide basis, the overall mass change generates a 5.2 g/km increase in CO_2, but the fleetwide compliance gap is reduced by 4.6 g/km. Given the overall change in mass, a corresponding adjustment in M_0 should follow. After such adjustment, the fleetwide CO_2 standard properly reflects an increased compliance gap of 5.2 g/km, commensurate with the fleetwide CO_2 change. However, the compliance gap for manufacturers increasing mass increases by only 1.6 g/km for an actual CO_2 increase of 8.1 g/km. This is because a portion of the net fleetwide mass increase is assigned to OEM-A despite the fact that OEM-A implemented a mass reduction. Instead of facing an increased compliance gap of 5.7 g/km, OEM-A finds itself 15.6 g/km farther from its standard. The mass increase undertaken by all other manufacturers has exacerbated an already perverse situation for OEM-A.

In summary, when OEM-A implements a 10% mass reduction, the resulting compliance status impacts are directly dependent on the actions of other manufacturers. If they do nothing (scenario 1), OEM-A gets a CO_2 reduction penalty while all other manufacturers receive a CO_2 reduction windfall. If all other manufacturers increase mass (scenario 3), they are penalized for only a small portion of their associated CO_2 increase and OEM-A absorbs the remainder, exacerbating the penalty absorbed when all other manufacturers held mass constant. Only when all other manufacturers also reduce mass by 10%

(scenario 2) are the books balanced and all manufacturers treated equitably and granted full credit for their CO_2 impacts. Under this limited latter scenario, the EU regulatory structure becomes technology neutral.

In light commercial vehicle scenario 4 (Table A6, Figures A13 and A14), all manufacturers hold mass constant. This is, of course, a bounding status quo case in which there are no CO_2 impacts or credits.

In light commercial vehicle scenario 5 (Table A6, Figures A13 and A14), OEM-A holds mass constant, while all other manufacturers implement a 10% mass reduction. This is the converse of scenario 1 and the impacts are entirely equivalent. Without any adjustment in M_0, all other manufactures reduce CO_2 by 8.4 g/km but move 8.0 g/km farther from their standard. Fleetwide CO_2 is reduced by 7.1 g/km but the fleet moves 6.0 g/km farther from its standard, for a constant M_0. Because all the other manufacturer mass reductions reduce overall fleetwide mass, a corresponding adjustment in M_0 should follow. After adjustment, the fleetwide CO_2 reduction credit properly increases to 7.1 g/km, commensurate with the fleetwide CO_2 reduction. The CO_2 reduction credit for all other manufacturers, however, is still shy of the actual reductions generated increasing from -8.0 g/km to +5.1 g/km. Although the books are properly balanced from a fleetwide perspective, all other manufacturers continue to see a discount applied to their CO_2 reduction efforts. The reason is that adjusting M_0 on a fleetwide basis effectively credits a portion of the all other manufacturer efforts to OEM-A. OEM-A receives a substantial windfall CO_2 reduction credit of 13.1 g/km, exactly equal in magnitude to that allocated to all other manufacturers in the M_0 adjustment process. Note that the windfall for OEM-A under this scenario is substantially larger than the windfall allocated to all other manufacturers under scenario 1 because of the larger market share assumed for all other manufacturers (80% versus 20% for OEM-A), which has the effect of creating a larger change in fleetwide mass, and thus a larger associated M_0 adjustment.

In light commercial vehicle scenario 6 (Table A6, Figures A13 and A14), OEM-A holds mass constant, while all other manufacturers implement a 10% mass increase. Without any adjustment in M_0, the 8.1 g/km increase in CO_2 that results from the actions of all other manufacturers actually moves them 8.3 g/km closer to their standard. On a fleetwide basis, the overall mass change generates a 6.9 g/km increase in CO_2, but the fleetwide compliance gap is reduced by 6.2 g/km. Given the overall change in mass, a corresponding adjustment in M_0 should follow. After such adjustment, the fleetwide CO_2 compliance gap properly increases by 6.9 g/km, commensurate with the fleetwide CO_2 change. However, the compliance gap for manufacturers increasing mass increases only by 4.8 g/km, for an actual CO_2 increase of 8.1 g/km. This is because a portion of the net fleetwide mass increase is assigned to OEM-A despite the fact that OEM-A held mass constant. OEM-A undertook no mass-related changes, yet finds itself 13.1 g/km farther from its standard.

In summary, when OEM-A holds mass constant, the resulting compliance status impacts remain directly dependent on the actions of other manufacturers. If all manufacturers hold mass constant (scenario 4), then OEM-A is unaffected. If all other manufacturers decrease mass (scenario 5), OEM-A receives a CO_2 reduction windfall while all other manufacturers get a discounted compliance credit. If all other manufacturers increase mass (scenario 6), they are penalized for only a portion of their associated CO_2 increase and OEM-A absorbs the remainder.

In light commercial vehicle scenario 7 (Table A7, Figures A15 and A16), OEM-A implements a 10% mass increase, increasing CO_2 by 10.3 g/km, while all others hold mass constant. Without any adjustment in M_0, OEM-A benefits from its 10.3 g/km CO_2 increase by moving 6.1 g/km closer to its standard. Because the actions of OEM-A affect the overall fleet in accordance with its market share, fleetwide CO_2 increases by 1.8 g/km and the fleet moves 1.5 g/km closer to its standard, for a constant M_0. However, because the OEM-A mass increase also increases overall fleetwide mass, a corresponding adjustment in M_0 should follow. After adjustment, the fleetwide CO_2 increase is properly credited at 1.8 g/km, but the CO_2 increase for OEM-A is still entirely offset, although the offset is reduced from a 6.1 g/km credit to a 2.8 g/km credit, as opposed to the 10.3 g/km increase in CO_2 generated. Although the books are properly balanced from a fleetwide perspective, OEM-A continues to receive a windfall for its CO_2 increasing actions. The reason is that adjusting M_0 on a fleetwide basis effectively credits a portion of the efforts of OEM-A to all manufacturers, treating the individual actions of OEM-A as a coordinated series of smaller actions undertaken by all manufacturers, averaging the actions of OEM-A over the entire fleet. Thus, all other manufacturers are assigned a CO_2 shortfall of 3.3 g/km, even though they have undertaken no actions to affect either their own or fleetwide CO_2 performance.

In light commercial vehicle scenario 8 (Table A7, Figures A15 and A16), OEM-A implements a 10% mass increase while all other manufacturers implement a 10% mass reduction. Without any adjustment in M_0, all other manufacturers receive substantially discounted CO_2 credit. OEM-A moves 6.1 g/km closer to its standard, despite increasing CO_2 by 10.3 g/km. All other manufacturers reduce CO_2 by 8.4 g/km, yet move 8.0 g/km farther from their standard. On a fleetwide basis, CO_2 is reduced by 5.3 g/km. However, the fleet compliance gap increases by 4.5 g/km. In all cases except that in which market shares and mass characteristics are such that the actions of OEM-A are exactly offset by the actions of all other manufacturers, an adjustment in M_0 should follow. After that adjustment is made, the CO_2 reduction credits for the fleet as a whole increase to 5.3 g/km to exactly match fleetwide CO_2 impacts. However, the credits for all other manufacturers, at 1.8 g/km, continue to lag actual CO_2 reductions observed, which amount to 8.4 g/km. This occurs due to the fact that adjusting M_0 on a fleetwide basis effectively credits a portion of the mass reduction efforts of all other manufacturers to OEM-A, resulting in the assignment of 9.8 g/km of CO_2 reduction to a manufacturer that actually increased mass, turning a 6.1 g/km reduction in its compliance gap into a 15.9 g/km reduction. Note that here again the substantial magnitude of the adjustments in the light commercial sector is due to the excessive slope of the EU LCV standard structure.

In light commercial vehicle scenario 9 (Table A7, Figures A15 and A16), all manufacturers act in lockstep and increase mass by 10%. Without any adjustment in M_0, all manufacturers receive the benefits of a similar discounting of their mass-induced CO_2 increase. Because all manufacturers implement a 10% mass increase, the fleet as a whole will also exhibit the same increase and a corresponding adjustment in M_0 should follow. After that adjustment is made, the discounting of CO_2 increases for all manufacturers is eliminated in its entirety, such that the increase in each manufacturer's compliance gap is exactly equal to the mass-induced increase in CO_2. As was the case with the universal 10% mass reduction (scenario 2), this occurs only when all manufacturers undertake the same actions. Under such conditions, the apportioning of credits that is inherent in the M_0 adjustment process will be equitable to the actions actually undertaken by each manufacturer. This will not happen under any circumstances in which the actions of any single manufacturer differ from those of another, as they almost always will.

In summary, when OEM-A implements a 10% mass increase, the resulting compliance status impacts are directly dependent on the actions of other manufacturers. If they do nothing, as in scenario 7, OEM-A is rewarded with a reduced compliance gap despite increasing its CO_2 emissions and all other manufacturers are penalized despite holding mass constant. If all other manufacturers decrease mass, as in scenario 8, OEM-A is the recipient of windfall CO_2 reduction credits, whereas the credits actually generated by the actions of all other manufacturers are discounted. Only when all other manufacturers also increase mass by 10% (scenario 9) are the books balanced and all manufacturers treated equitably and penalized fully for their CO_2 impacts. Under this limited latter scenario, the EU regulatory structure becomes technology neutral.

OVERALL SUMMARY

Although the specific credits or penalties imposed on any given manufacturer depend on a number of factors, such as the CO_2 emission levels and mass characteristics of the vehicles of all individual manufacturers, the mass changes implemented by those manufacturers, and their respective market shares, there are general trends that emerge from the EU M_0 adjustment process. In a declining mass environment, an individual manufacturer's most efficient action is to hold mass constant, in which case that manufacturer will receive a CO_2 windfall credit courtesy of the actions of others. In an increasing mass environment, an individual manufacturer's most efficient action is to increase mass at a rate commensurate with or greater than that of the overall trend. Although the manufacturer could limit its CO_2 penalty by holding mass constant or increasing mass at a rate below that of the trend, it also would lose any economic advantage associated with reducing the use of more expensive lightweight materials. The net effect of the range of possible interactions is one of great uncertainty, because internal manufacturer impacts depend on not only internal actions, but also on the actions of all other manufacturers. Uncertainty breeds inertia, greatly inhibiting the CO_2 reduction potential of lightweighting technology under the current regulatory structure in the EU.