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

METHODOLOGY AND SUMMARY OF COMPLIANCE COSTS FOR POTENTIAL EU CO_2 STANDARDS

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EXECUTIVE SUMMARY

This paper describes the results obtained and methodology employed by the ICCT to develop carbon dioxide (CO_2) cost curves for the European passenger car and light commercial vehicle (LCV, sometimes referred to as vans in the EU) fleet in the 2025–2030 time frame. Using the developed curves, compliance costs are estimated for a series of potential CO_2 standards. 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. (FEV, 2015). These data are combined with supplemental data 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). These individual class curves are then sales weighted to estimate fleet average compliance costs for a range of potential CO_2 standards.

Technology costs are estimated as high-volume production direct manufacturing costs (DMCs) 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 (ICMs) are applied to base-year direct manufacturing cost estimates. The applied learning and indirect cost factors are derived from the U.S. Environmental Protection Agency's (EPA's) technical support document for their 2017–2025 U.S. light-duty vehicle greenhouse gas (GHG) standards rulemaking. (EPA, 2012)

The employed simulation modeling data are limited in the scope of technology considered. Generally, these data focus on internal combustion engine (ICE) 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 CO_2 targets evaluated in this analysis. Such technology could include pure (i.e., no 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 "non ICE" technology are taken from a recently released ICCT study on the cost of such technology in Europe in the 2020–2030 time frame.[1] (ICCT, 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, such as vehicle mass reduction, either in whole or in part. In effect, the cost curves presented in this paper assume an underlying regulatory structure that is itself technology neutral, such as a fleet average flat standard or a vehicle size-based standard. The magnitude of cost increases associated with regulatory structures that discount the value of mass reduction technology will be investigated and published separately as an addendum to this paper.

Conceptually, construction of the EU cost curves is straightforward. First, CO_2 emissions and technology penetration are estimated for the baseline fleet, which constitutes the zero-cost baseline. These data are combined with CO_2 and associated 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

1 While the ICCT non-ICE 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 paragraphs that follow and in greater detail in the body of this paper.

are nuances, however, related to the integration of ICE and non-ICE data as required to meet some of the target CO_2 levels evaluated in this analysis. 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 non-ICE vehicles into the fleet, and this introduction is controlled not by the continuous introduction of new technology, but rather by continuously increasing non-ICE technology penetration. The continuous addition of technology cost is replaced by the continuous addition of ever greater non-ICE market shares. Thus, evaluation of the cost of attaining very low CO_2 levels is a two-step process consisting of first determining the cost associated with ICE technology and then determining the fraction of non-ICE vehicles (and their associated cost) required to further reduce CO_2 emissions to the desired level.[2]

For CO_2 levels requiring the introduction of non-ICE vehicles, this analysis assumes that such vehicles are distributed across vehicle classes in accordance with current class sales shares. In other words, non-ICE vehicles are allocated across all classes so that costs are *not* artificially minimized by assuming that non-ICE vehicles 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 non-ICE 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 non-ICE demand.

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 (while lower bound costs assume mass reduction cost savings when such savings are appropriate).

» 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

2 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 and non-ICE vehicles. 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 non-ICE vehicles are held constant for a given evaluation year. After all the component costs and CO_2 emission levels are determined for both ICE and non-ICE vehicles, CO_2 compliance cost estimation involves first determining (step one) the cost and CO_2 emissions available through the various ICE technology packages and then determining (step two) what level of non-ICE vehicle penetration (if any) is required to further reduce fleetwide emissions to the desired CO_2 target. Once the cost of a non-ICE vehicle is estimated, the non-ICE technology cost associated with attainment of various CO_2 levels becomes solely a function of market penetration.

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 non-ICE vehicles are based exclusively on ICCT estimates; upper bound estimates substitute (generally higher) U.S. National Research Council battery cost assumptions for those associated with the ICCT data.

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 non-ICE vehicles. The cost of ICE technology is generally reflected as an upwardly sloping exponential curve. The cost of increasing non-ICE 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 using only the vehicle simulation (i.e., ICE) data.

While this generalization always holds true, there is a degree of freedom associated with introducing non-ICE vehicles into the fleet that creates uncertainty with regard to the precise integration of ICE and non-ICE cost data. There is no requirement that a vehicle manufacturer exhaust all ICE technology before introducing non-ICE vehicles into the fleet. From a mathematical viewpoint, this means that there are an infinite number of ways in which the ICE and non-ICE cost data can be integrated. This analysis resolves this uncertainty by evaluating the integration of non-ICE vehicles under two scenarios. Under one scenario, the transition to non-ICE technology is assumed to take place only after all ICE technology has been exhausted.[3] Under the second scenario, the transition to non-ICE technology is assumed to take place at the point of cost optimization; i.e., when the marginal cost of non-ICE vehicles is less than the marginal cost of additional ICE technology.

The fact that the marginal cost of non-ICE vehicles can be lower than the marginal cost of additional ICE technology does *not* imply that non-ICE vehicles 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 this analysis, so they provide substantial CO_2 reductions over which to spread costs. While PHEV CO_2 emissions are non-zero, they still provide significant reductions. Non-ICE reductions are such that they can carry a cost-effective CO_2 reduction signal even while per-vehicle absolute costs are high. Because non-ICE vehicles enter the market starting from a zero market share, fleet-wide incremental cost impacts are initially modest as only a small fraction of vehicles are 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 the focus on vehicle technology costs (for both ICE and non-ICE vehicles) employed in this analysis does not equate to a full assessment of consumer impacts. This analysis focuses on vehicle procurement impacts only. Impacts on the total cost of ownership for both ICE and non-ICE vehicles would include offsetting savings due to reduced fuel use for ICE vehicles and alternative energy

3 Technology exhaustion as defined herein only refers to technology as reflected in the simulation modeling data employed in this analysis. It is virtually certain that continuing advancements (in combination with 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. 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 *in the context of this analysis*.

economics for non-ICE vehicles. Such life-cycle assessments can be developed from the vehicle technology cost estimates described herein, but are not considered in this paper.

Figures ES-1 and ES-2 present the derived passenger vehicle fleet average compliance cost curves for CO_2 targets measured over the New European Driving Cycle (NEDC) in 2020, 2025, and 2030. Figure ES-1 presents compliance costs for the ICE technology exhaustion scenario, while Figure ES-2 presents costs for the least-cost non-ICE transition scenario. While it is difficult to generalize the cost estimates in the absence of a specific CO_2 reduction target, the following conclusions can be drawn for the average EU market in the 2025–2030 time frame.

» Passenger vehicle NEDC standards as low as 60–70 g/km can be achieved with either no or only modest levels of non-ICE vehicle penetration.

» Given the current state of ICE technology, a passenger vehicle NEDC standard of 70 g/km can be attained by 2025 for between €1,000 and €2,000 per vehicle (2014€) with no (lower bound) or very modest (upper bound) non-ICE market penetration. Costs would be €200 to €500 per vehicle (2014€) lower under a least-cost non-ICE transition strategy.

» Passenger vehicle standards as low as 40 g/km can be achieved by 2030 for costs of between €1,300 and €3,000 per vehicle (2014€) under either the NEDC or Worldwide Harmonized Light Vehicles Test Procedures (WLTP) cycles (WLTP curves are shown in the body of the report); compliance with such standards is dominated by large non-ICE market shares.

Figure ES-1. NEDC CO_2 Costs for Passenger Vehicles (ICE Exhaustion Strategy)

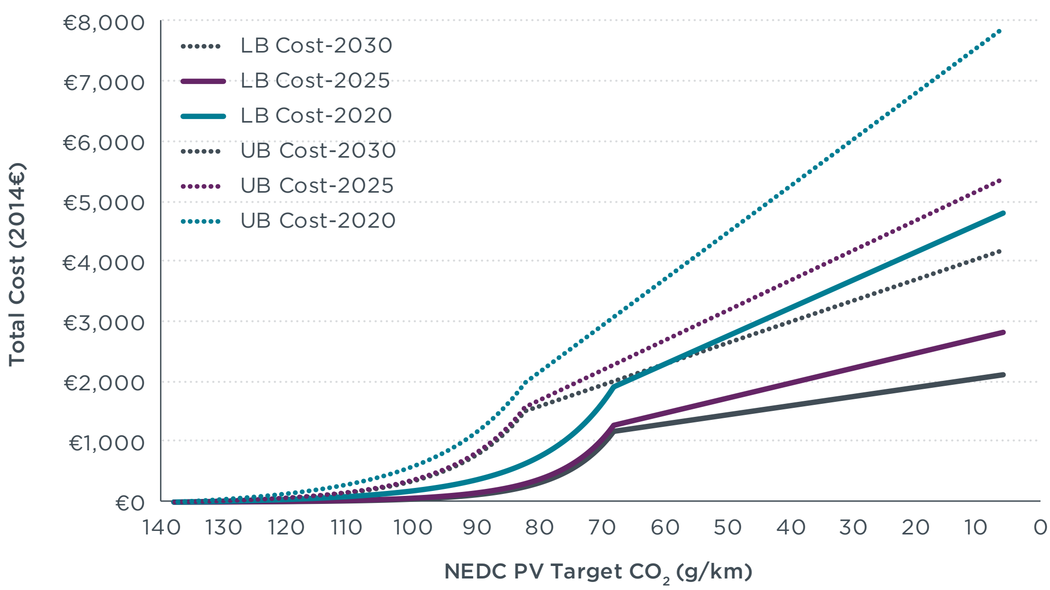
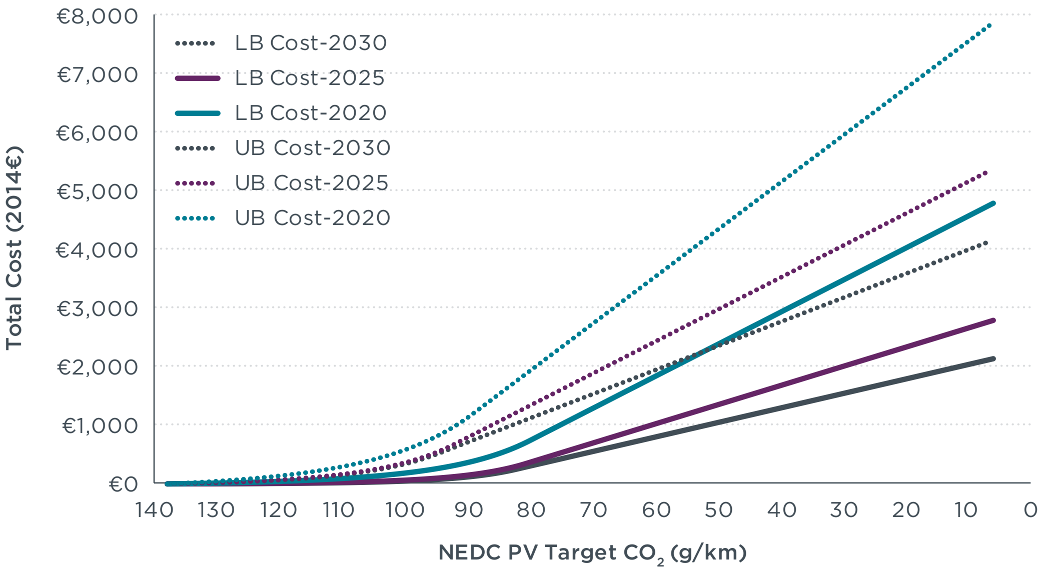


Figure ES-2. NEDC CO_2 Costs for Passenger Vehicles (Optimum Non-ICE Strategy)



There are a number of limitations to the approach and the presented cost curves that each likely results in an underestimate of ICE CO_2 reduction potential and an overestimate of reduction costs. These include:

- 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 (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 simulation modeling development, such as non-consideration of engine downsizing potential in mass reduction and hybrid technology simulations, non-consideration of the impacts of mass and 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 variable compression ratio (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 by 2030.
- All CO_2 emissions-reduction technology is evaluated on a constant performance basis. CO_2 emissions-reduction costs for reduced performance vehicles would be lower than costs estimated in this analysis.

Given these limitations, the cost curves presented in this paper are expected to be more reflective of the upper bound of actual future costs, and that the real costs for meeting potential CO_2 emission targets are likely to be lower.

1. INTRODUCTION

This paper describes the results obtained and methodology employed by the ICCT to develop carbon dioxide (CO_2) cost curves for the European passenger car and light commercial vehicle (LCV, sometimes referred to as vans in the EU) fleet in the 2025–2030 time frame. Using the developed curves, compliance costs are estimated for a series of potential CO_2 standards. With appropriate modification of assumptions, the methodology described in this report can be used to develop cost curves in other regions of the world. The primary CO_2 and associated technology cost data used in the development of the EU cost curves are from simulation modeling and bottom-up cost-estimation work performed for the ICCT by FEV, Inc. (FEV, 2015) These data, which for convenience are generally referred to as the *2015 FEV ICCT data* in this paper, are combined with supplemental data, as described below, 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). These individual class curves are then sales weighted to estimate fleet average compliance costs for a range of potential CO_2 standards. While this paper provides an overview of the FEV ICCT CO_2 and cost data, considerably more detail with regard to the methodologies employed by FEV to generate the data is available in the referenced FEV study report.

There are several limitations associated with the FEV cost data that necessitate the use of supplemental data sources for some technologies, and supplemental processing for cost curve development. 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. (ICCT, 2012a; ICCT, 2012b; ICCT, 2013; ICCT, 2014)

The methodology employed for the earlier ICCT cost curve analysis largely carries over to the work documented in this paper. This carryover includes, except as otherwise indicated, the earlier-developed mass reduction technology cost curves as well as the impact of differences in western and eastern European labor rates on technology costs.[4] For convenience, these data are generally referred to as the *2012 FEV ICCT data* in this paper.

The cost of rolling resistance and aerodynamic drag are based on relationships developed by the U.S. Environmental Protection Agency (EPA), as documented in that agency's technical support document for their 2017–2025 U.S. light-duty vehicle GHG standards rulemaking. (EPA, 2012) These secondary cost data are referred to as the *EPA cost data* in this paper.[5]

4 Costs in the previous FEV analysis were expressed in 2010/2011 euros. Costs in the current FEV analysis are expressed in 2014 euros. To convert the previous cost estimates to an equivalent 2014 basis, all earlier estimated costs were adjusted in accordance with the relationship between the 2010/2011 (taken as the average of 2010 and 2011) and the 2014 EU Consumer Price Index (CPI). The derived CPI adjustment is 5.7%; the specific multiplier being 1.0573 = 2014 CPI (117.7125) divided by 2010/2011 CPI (111.3354). EU CPI data are from the European Central Bank Statistical Data Warehouse (ECB, 2016), where annual indices are calculated as the average of component monthly indices.

5 While the EPA cost data represent high-volume production costs (analogous to FEV estimated costs), both temporal and geographic adjustments are required to render the EPA data consistent with the 2015 FEV ICCT data. Whereas the EPA data apply to the 2010 U.S. market, the 2015 FEV ICCT cost data apply to the EU market in the 2014 time frame. To convert U.S. cost data to their EU equivalents, detailed cost data for an identical technology system conversion, as prepared by FEV for the EPA (and the U.S. market), and separately (for the ICCT) for the EU market, were compared (EPA, 2009; FEV, 2012). The specific technology conversion

2015 FEV ICCT data costs are estimated as high-volume production direct manufacturing costs (DMCs) 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.[6] To properly estimate retail-level costs in future years, both learning effects and indirect cost multipliers (ICMs) are applied to base-year direct manufacturing 2015 FEV ICCT data cost estimates. Supplemental data for mass reduction technology costs (2012 FEV ICCT data) and aerodynamic drag and rolling resistance technology costs (EPA cost data) already include both learning and indirect cost multipliers for future-year retail-level cost evaluation. As described in more detail below, the applied learning and indirect cost factors are derived from the U.S. EPA's technical support document for their 2017–2025 U.S. light-duty vehicle greenhouse gas (GHG) standards rulemaking, the same reference used as the source of the supplemental EPA cost data. (EPA, 2012)

The 2015 FEV ICCT data are also limited in the scope of technology considered. Generally, these data focus on internal combustion engine (ICE) technology as extended through onboard-only charged hybrid electric vehicle (HEV) systems. For some of the CO_2 emission levels evaluated in this analysis, vehicle technology capable of reducing CO_2 below levels observed in the 2015 FEV ICCT data will be required to demonstrate compliance. Such technology could include pure (i.e., no ICE) battery electric vehicles (BEVs), off-board charging-capable (or plug-in) hybrid electric vehicles (PHEVs), or hydrogen fuel cell vehicles (FCVs). For convenience, this paper refers to the technologies included in the 2015 FEV ICCT data as "ICE" technology (which, as described, extends through onboard-only charged HEVs) and other CO_2 reduction options as "non ICE" technology. Except as otherwise indicated in the discussion that follows, cost estimates for non-ICE technology are generally taken from a recently released ICCT study on the cost of such technology in Europe in the 2020–2030 time frame. (ICCT, 2016) For convenience, these data are generally referred to as the *2016 ICCT non-ICE data* in this paper.

There are important issues that should be recognized when reviewing the cost curve data presented in this paper. First, unless otherwise indicated, the developed curves are strictly technology-based and do not consider the impacts associated with any

consisted of a baseline 2.4 liter, I4, 16-valve DOHC naturally aspirated gasoline engine with discrete variable valve timing converted to a 1.6 liter, I4, 16-valve DOHC turbocharged gasoline direct injection engine with discrete variable valve timing.

While the EPA cost data are expressed as 2010 U.S. dollars, the detailed system component data analyzed to develop the necessary U.S.-to-EU conversion are expressed in 2008 U.S. dollars (the EPA updated all technology costs to 2010 dollars when they developed their technical support document for the 2017–2025 U.S. GHG standards rulemaking) and 2010/2011 euros. To convert the detailed system component costs to the same 2010 basis used by the EPA for their rulemaking costs, component costs were adjusted in accordance with the relationship between the 2008 and the 2010 U.S. Consumer Price Index (CPI). The derived CPI adjustment is 1.3%; the specific multiplier being 1.0128 = 2010 CPI (218.0555) divided by 2008 CPI (215.3025). U.S. CPI data are from the U.S. Bureau of Labor Statistics (BLS, 2016), and represent U.S. city average, all urban consumer, non-seasonally adjusted data.

The ratio of the FEV ICCT (EU) cost data to the 2010-adjusted U.S. cost data for the referenced (identical) technology package reflect both an inherent adjustment of 2010 U.S. dollars to 2010/2011 euros and an inherent adjustment of costs from the U.S. to the EU market. The combined adjustment factor is calculated to be 0.8126, and is used to adjust all utilized EPA cost data to its 2010/2011 EU equivalent. However, the 2015 FEV ICCT cost data are expressed as 2014 euros. Thus, an additional conversion is required to express 2010-based EPA costs on an equivalent 2014 EU basis. The appropriate adjustment is derived through the relationship between the 2010/2011 (taken as the average of 2010 and 2011) and the 2014 EU Consumer Price Index (CPI). The derived CPI adjustment is 5.7%; the specific multiplier being 1.0573 = 2014 CPI (117.7125) divided by 2010/2011 CPI (111.3354). EU CPI data are from the European Central Bank Statistical Data Warehouse (ECB, 2016), where annual indices are calculated as the average of component monthly indices. The product of the U.S.-to-EU and EU 2010/2011-to-EU 2014 adjustments, 0.859 = 0.8126 times 1.0573, is used to convert all 2010-based EPA cost data to its 2014 EU market equivalent.

6 Total (retail-level) costs, as defined in this report, are exclusive of taxes.

potential regulatory structure that might be imposed to drive CO_2 emission reductions. For example, mass reduction technology is included in the cost curves on the basis of estimated technology impacts and costs. The fact that regulatory structures that discount the value of vehicle mass reduction—either in whole or in part, through mechanisms such as adjusting CO_2 standards for changes in vehicle mass—influence the cost-effectiveness of mass reduction technology is not generally considered. In effect, the cost curves presented in this paper are technology neutral and can be viewed as inherently assuming an underlying technology-neutral (e.g., a single standard or vehicle size-based) regulatory structure. Costs for structures that are not technology neutral will be higher. The potential magnitude of the cost increases associated with regulatory structures that discount the value of mass reduction technology will be investigated and published separately as an addendum to this paper.

Additionally, as stated above the presented cost curves are primarily based on costs developed on the basis of current design and manufacturing expectations. In effect, any unknown future advances in technology design are inherently discounted. To the extent that design advances occur, the presented cost curves will overstate CO_2 emissions reduction costs in the years following such advances. Thus, while the utilized cost estimates serve an important role in grounding future cost expectations, they also generally reflect a relatively pessimistic view of advances beyond current technology. Accordingly, the presented curves should be viewed as relatively conservative, such that future costs could be significantly lower than estimated in this paper.

The remaining sections of this paper detail the specific steps undertaken to develop the EU cost curves from the available CO_2 and technology cost data. Section 2 provides a brief summary of the 2015 FEV ICCT data. Section 3 discusses the costs assumed for road-load reduction technology. Section 4 presents the learning and indirect cost assumptions employed in this analysis. Sections 5 and 6 discuss test flexibility and performance-based adjustments that are applied (unless otherwise indicated) to the 2015 FEV ICCT CO_2 data. Section 7 discusses performance-based adjustments that are applied (unless otherwise indicated) to both the 2015 FEV ICCT data and the 2016 ICCT non-ICE data. Section 8 presents the approach employed to incorporate off-cycle CO_2 credits and associated costs into the analysis. Section 9 provides a brief summary of the 2016 ICCT non-ICE data and discusses the approaches employed to incorporate that data into this analysis. Section 10 discusses the methodology employed to estimate CO_2 emission rates for the 2016 ICCT non-ICE data. Section 11 discusses the methodology employed to adjust technology costs for differences between western and eastern EU vehicle production. Section 12 discusses the approach employed to estimate compliance costs for various target levels of CO_2, while Section 13 presents the derived compliance cost estimates. Section 14 provides a comparison of the compliance costs estimated in this analysis with corresponding estimates from an earlier 2012–2013 era analysis. Section 15 presents a discussion of how the presented compliance costs might be interpreted, along with a discussion of associated limitations. Finally, Section 16 presents definitions for the various abbreviations and acronyms that appear in this paper, while Section 17 provides a list of references.

2. SUMMARY OF 2015 FEV ICCT DATA

While the 2015 FEV ICCT data report referenced in Section 1 (FEV, 2015) should be consulted for further background, methodological, and analysis assumptions, this section presents a summary of the generated data. Table 1 provides an overview of the baseline vehicle characteristics associated with the simulation modeling underlying the 2015 FEV ICCT data, while Tables 2 through 11 present a summary of the evaluated technology packages and their associated CO_2 and cost impacts. Generally, baseline vehicles reflect 2014-era technology and were selected to reasonably reflect the average EU market of that era. The particular technologies included in the 2015 FEV ICCT data evaluation vary across vehicle class, fueling type, and any given technology package, but generally include engine downsizing, conversion from multi-port fuel injection (MPFI) to turbocharged direct injection (gasoline engines only), advanced valve controls, advanced turbocharging technology, advanced exhaust gas recirculation (EGR) techniques, friction-reduction strategies, VCR technology, advanced transmissions, a wide range of hybridization approaches (ranging from 12-volt start-stop to full parallel hybrid electric systems), and a range of road-load (mass, rolling resistance, and aerodynamic drag) reductions. With limited exceptions, CO_2 reduction technology is generally evaluated on a constant performance basis (relative to associated baseline vehicle performance).[7] Moreover, although the presented 2015 FEV ICCT data include CO_2 impact estimates for road-load-influencing mass, rolling resistance, and aerodynamic drag reduction technology, the associated costs of achieving the reductions were not estimated by FEV and are not included in the costs presented in Tables 2 through 11.[8]

Although the 2015 FEV ICCT data are based on detailed simulation modeling, it is important to recognize that there are specific limitations with regard to certain aspects of simulation development. Such limitations include:

- Simulations for mass reduction and hybrid technology do not incorporate engine downsizing. This results in performance improvements that were not fully analyzed or offset. Transmission gear ratios and shift strategy (for automatic transmission vehicles) were optimized in order to maximize benefits while equalizing performance to the maximum extent practical, but such optimization is not fully equivalent to accounting for either the CO_2 or cost impacts of constant performance-driven engine downsizing.
- The impacts of mass and load reduction on required constant performance hybrid system size and cost were not assessed.
- Improvements in hybrid battery power density were not considered and current hybrid battery specifications were used for hybrid cost assessments.
- CO_2 simulations on the New European Driving Cycle (NEDC) include flexibilities allowed for coastdown (road-load) determination, which are not allowed in the Worldwide Harmonized Light Vehicles Test Procedures (WLTP), as well as a lower test mass than utilized for the WLTP. Comparisons between the NEDC and WLTP CO_2 estimates in the 2015 FEV ICCT data are affected by the different loads, not just the test cycles.
- No increase in the gasoline engine compression ratio was included in the simulation analysis, except for the VCR and Miller cycle assessments.

It is expected that a complete accounting of these limitations would result in greater CO_2 reductions delivered at lower cost for a range of technology packages included in the 2015 FEV ICCT data.

7 The 2015 FEV ICCT data define constant vehicle performance in terms of constant power and constant top speed. This varies somewhat from the zero-to-96.6 kilometers per hour (60 miles per hour) acceleration performance constraint used in previous ICCT studies. Except as otherwise described in the sections that follow, no generalized adjustments have been made to normalize the 2015 FEV ICCT data to a constant acceleration performance basis.

8 Costs for road-load technologies are included in the cost analysis underlying this paper. Such costs were independently estimated as described in Section 3 that follows.

Table 1. 2015 FEV ICCT Baseline (2014 Era) Vehicle Characteristics

Vehicle Class		B Class	C Class	D Class	E Class	SUV	LCV
Diesel Vehicle Characteristics							
Displacement (liters)		1.4	1.6	2.0	3.0	3.0	2.2
Engine Configuration		I3	I4	I4	I6	I6	I4
Injection System		DI	DI	DI	DI	DI	DI
Turbocharged		Yes	Yes	Yes	Yes	Yes	Yes
Rated Engine Output (kW)		60	80	110	150	150	120
Valve Technology		Fixed	Fixed	Fixed	Fixed	Fixed	Fixed
Transmission		M5	M6	M6	A8	A8	M6
High-Pressure EGR		Uncooled	Uncooled	Cooled	Cooled	Cooled	Cooled
Low-Pressure EGR		Cooled	Cooled	n/a	n/a	n/a	n/a
Mass in Running Order (kg)		1,224	1,434	1,625	1,838	1,688	2,026
Idle-Off Technology		No	No	No	No	No	No
C_dA (m^2)		0.75	0.77	0.72	0.77	0.98	1.53
Rolling Resistance Coefficient	Tires	0.0102	0.0097	0.0098	0.0098	0.0096	0.0095
	Drivetrain	0.0017	0.0017	0.0017	0.0020	0.0028	0.0017
	Total	0.0119	0.0114	0.0116	0.0118	0.0124	0.0112
Gasoline Vehicle Characteristics							
Displacement (liters)		1.3	1.8	2.4	3.0	n/a	
Engine Configuration		I4	I4	V6	V6		
Injection System		MPFI	MPFI	MPFI	MPFI		
Turbocharged		No	No	No	No		
Rated Engine Output (kW)		65	95	135	180		
Valve Technology		DVVT	DVVT	DVVT	DVVT		
Transmission		M5	M5	A7	A7		
High-Pressure EGR		n/a	n/a	n/a	n/a		
Low-Pressure EGR		n/a	n/a	n/a	n/a		
Mass in Running Order (kg)		1,150	1,345	1,578	1,800		
Idle-Off Technology		No	No	No	No		
C_dA (m^2)		0.75	0.77	0.72	0.77		
Rolling Resistance Coefficient	Tires	0.0102	0.0097	0.0098	0.0098		
	Drivetrain	0.0017	0.0017	0.0017	0.0020		
	Total	0.0119	0.0114	0.0116	0.0118		

Table 2. 2015 FEV ICCT Data for B Class Diesel Vehicles

TP	Disp	Cyl	Eng	TC	VT	EGR	CR	Fr	HEV	XM	MR	RL	AT	CO_2	Cost[1]
BD1	1.40	3	DI	1V	F	UC	No	BL	No	M5	M0	RL0	PF2	103.6	0
BD2	1.40	3	DI	1V	F	UC	No	BL	SS	M5	M0	RL0	PF2	100.0	77
BD3	1.20	3	DI	1V	F	UC	No	BL	SS	M6	M0	RL0	PF2	102.3	96
BD4	1.20	3	DI	1V	F	UC	No	BL	SS	M6	M1	RL0	PF2	93.7	96
BD5	1.20	3	DI	1V	F	UC	No	BL	SS	M6	M2	RL0	PF2	85.7	96
BD6	1.20	3	DI	1V	F	UC	No	BL	SS	M6	M2	RL1	PF2	80.9	96
BD7	1.20	3	DI	1V	F	UC	No	BL	SS	M6	M2	RL2	PF2	77.0	96
BD8	1.20	3	DI	1V	F	UC	No	RF	SS	M6	M2	RL1	PF2	77.0	167
BD9	1.20	3	DI	1V	F	CB	No	RF	SS	M6	M2	RL1	PF2	76.3	206
BD10	1.20	3	DI	1V	Ex	CB	No	RF	SS	M6	M2	RL1	PF1	75.7	480
BD11	1.20	3	DI	1V	Ex	CB	No	RF	SS	M6	M0	RL1	PF1	89.8	480
BD12	1.20	3	DI	1V	F	CB	No	RF	P0	M6	M2	RL1	PF2	73.5	887

(1) Although FEV simulation modeling included (for some technology packages) CO_2 impacts due to changes in road-load influencing mass, rolling resistance, and aerodynamic drag, FEV did not estimate the costs associated with achieving such changes. As a result, technology packages that vary only with respect to their associated road loads will have identical FEV-estimated costs. The costs of road-load technology are estimated independently (as described in Section 3) and added, as appropriate, to the FEV-estimated costs tabulated here.

Key:
- TP = Technology Package with entries coded as class (B, C, D, E, S=SUV, L=LCV), fuel (D=Diesel, G=Gasoline), and package number;
- Disp = Engine Displacement (in liters);
- Cyl = Number of Cylinders;
- Eng = Engine Type (with entries of PFI=Port Fuel Injection or DI=Direct Injection);
- TC = Turbocharger Type (with entries of No=No Turbo, 1S=Single Stage Waste Gate Turbo, 2S=Two Stage Waste Gate Turbo, 1V=Single Stage Variable Geometry Turbo, and 2V=Two Stage Variable Geometry Turbo);
- VT = Valve Control Type (with entries of F=Fixed, Ex=Exhaust Cam Phasing, T=Dual Cam Phasing, TL=Dual Cam Phasing plus Variable Valve Lift, and TLM= Dual Cam Phasing plus Variable Valve Lift plus Miller Cycle Control);
- EGR = Exhaust Gas Recirculation (with entries of No=No EGR, UC=Uncooled High-Pressure/Cooled Low-Pressure EGR, CH= Cooled High-Pressure EGR, CL=Cooled High-Pressure EGR, CB=Cooled High- and Low-Pressure EGR, and D=Dedicated EGR);
- CR = Compression Ratio Technology (with entries of No=Fixed Compression Ratio and VR=Two Step VCR);
- FR = Engine Friction Technology (with entries of BL=Baseline Technology and RF=20% Friction Reduction);
- HEV = Hybrid Electric Technology (with entries of No=No Hybrid Technology, SS=12 Volt Start-Stop Technology, AS=12 Volt Advanced Start-Stop Technology, P0=48 Volt Belt Starter-Generator, and P2=Full Parallel P2 HEV);
- XM = Transmission Technology (with entries of M5=5-Speed Manual, M6=6-Speed Manual, A8=8-Speed Automatic, D7=7-Speed Dual Clutch, and DX=10-Speed Dual Clutch);
- MR = Mass Reduction (with entries of M0=Baseline Mass, M1=Nominal 10% Mass Reduction, and M2=Nominal 20% Mass Reduction);
- RL = Road Load (with entries RL0=Baseline Rolling Resistance and Aerodynamic Drag, RL1=25% Rolling Resistance Reduction and 10% Aerodynamic Drag Reduction, and RL2=35% Rolling Resistance Reduction and 20% Aerodynamic Drag Reduction);
- AT = Aftertreatment Technology (with entries 3W0=3-Way Catalyst, 3W1=3-Way Catalyst with Direct and Port Injection, 3W2=3-Way Catalyst with 350 Bar Direct Injection, 3W3=3-Way Catalyst with Piezo Injectors, 4W=4-Way Catalyst, PF1=Diesel Oxidation Catalyst and SCR-Coated Diesel Particulate Filter, and PF2=Lean NO_x Trap and Catalyzed Diesel Particulate Filter);
- CO_2 = Carbon Dioxide Emissions over the EU NEDC (in grams per kilometer);
- Cost = Incremental Cost Relative to the Baseline Technology Package (2014 Euros).

Table 3. 2015 FEV ICCT Data for C Class Diesel Vehicles

TP	Disp	Cyl	Eng	TC	VT	EGR	CR	Fr	HEV	XM	MR	RL	AT	CO_2	Cost[1]
CD1	1.60	4	DI	1V	F	UC	No	BL	No	M6	M0	RL0	PF2	114.9	0
CD2	1.60	4	DI	1V	F	UC	No	BL	SS	M6	M0	RL0	PF2	110.7	83
CD3	1.40	3	DI	1V	F	UC	No	BL	AS	D7	M0	RL0	PF2	99.8	433
CD4	1.40	3	DI	1V	F	UC	No	BL	AS	D7	M1	RL0	PF2	95.7	433
CD5	1.40	3	DI	1V	F	UC	No	BL	AS	D7	M2	RL0	PF2	90.2	433
CD6	1.40	3	DI	1V	F	UC	No	BL	AS	D7	M2	RL1	PF2	84.5	433
CD7	1.40	3	DI	1V	F	UC	No	BL	AS	D7	M2	RL2	PF2	80.4	433
CD8	1.40	3	DI	1V	F	UC	No	RF	AS	D7	M2	RL1	PF2	81.2	504
CD9	1.40	3	DI	1V	F	CB	VR	RF	AS	D7	M2	RL1	PF2	77.2	674
CD10	1.40	3	DI	1V	Ex	CB	VR	RF	AS	D7	M2	RL1	PF1	76.6	948
CD11	1.40	3	DI	1V	Ex	CB	VR	RF	AS	D7	M0	RL1	PF1	85.6	948
CD12	1.40	3	DI	1V	F	CB	No	RF	P0	D7	M2	RL1	PF2	76.5	1235

See Table 2 for note and key to abbreviations.

Table 4. 2015 FEV ICCT Data for D Class Diesel Vehicles

TP	Disp	Cyl	Eng	TC	VT	EGR	CR	Fr	HEV	XM	MR	RL	AT	CO_2	Cost[1]
DD1	2.00	4	DI	1V	F	CH	No	BL	No	M6	M0	RL0	PF1	122.4	0
DD2	2.00	4	DI	1V	F	CH	No	BL	SS	M6	M0	RL0	PF1	116.5	92
DD3	1.60	4	DI	1V	F	CH	No	BL	AS	DX	M0	RL0	PF1	116.2	602
DD4	1.60	4	DI	1V	F	CH	No	BL	AS	DX	M1	RL0	PF1	109.4	602
DD5	1.60	4	DI	1V	F	CH	No	BL	AS	DX	M2	RL0	PF1	104.0	602
DD6	1.60	4	DI	1V	F	CH	No	BL	AS	DX	M2	RL1	PF1	98.9	602
DD7	1.60	4	DI	1V	F	CH	No	BL	AS	DX	M2	RL2	PF1	94.7	602
DD8	1.60	4	DI	1V	F	CH	No	RF	AS	DX	M2	RL1	PF1	95.4	675
DD9	1.60	4	DI	1V	Ex	CH	No	RF	AS	DX	M2	RL1	PF1	94.9	712
DD10	1.60	4	DI	1V	Ex	CB	VR	RF	AS	DX	M2	RL1	PF1	89.1	968
DD11	1.60	4	DI	1V	Ex	CB	VR	RF	AS	DX	M0	RL1	PF1	99.1	968
DD12	1.60	4	DI	1V	Ex	CB	No	RF	P2	DX	M2	RL1	PF1	80.8	2682

(1) Although FEV simulation modeling included (for some technology packages) CO_2 impacts due to changes in road-load influencing mass, rolling resistance, and aerodynamic drag, FEV did not estimate the costs associated with achieving such changes. As a result, technology packages that vary only with respect to their associated road loads will have identical FEV-estimated costs. The costs of road-load technology are estimated independently (as described in Section 3) and added, as appropriate, to the FEV-estimated costs tabulated here.

Key:
- TP = Technology Package with entries coded as class (B, C, D, E, S=SUV, L=LCV), fuel (D=Diesel, G=Gasoline), and package number;
- Disp = Engine Displacement (in liters);
- Cyl = Number of Cylinders;
- Eng = Engine Type (with entries of PFI=Port Fuel Injection or DI=Direct Injection);
- TC = Turbocharger Type (with entries of No=No Turbo, 1S=Single Stage Waste Gate Turbo, 2S=Two Stage Waste Gate Turbo, 1V=Single Stage Variable Geometry Turbo, and 2V=Two Stage Variable Geometry Turbo);
- VT = Valve Control Type (with entries of F=Fixed, Ex=Exhaust Cam Phasing, T=Dual Cam Phasing, TL=Dual Cam Phasing plus Variable Valve Lift, and TLM= Dual Cam Phasing plus Variable Valve Lift plus Miller Cycle Control);
- EGR = Exhaust Gas Recirculation (with entries of No=No EGR, UC=Uncooled High-Pressure/Cooled Low-Pressure EGR, CH= Cooled High-Pressure EGR, CL=Cooled High-Pressure EGR, CB=Cooled High- and Low-Pressure EGR, and D=Dedicated EGR);
- CR = Compression Ratio Technology (with entries of No=Fixed Compression Ratio and VR=Two Step VCR);
- FR = Engine Friction Technology (with entries of BL=Baseline Technology and RF=20% Friction Reduction);
- HEV = Hybrid Electric Technology (with entries of No=No Hybrid Technology, SS=12 Volt Start-Stop Technology, AS=12 Volt Advanced Start-Stop Technology, P0=48 Volt Belt Starter-Generator, and P2=Full Parallel P2 HEV);
- XM = Transmission Technology (with entries of M5=5-Speed Manual, M6=6-Speed Manual, A8=8-Speed Automatic, D7=7-Speed Dual Clutch, and DX=10-Speed Dual Clutch);
- MR = Mass Reduction (with entries of M0=Baseline Mass, M1=Nominal 10% Mass Reduction, and M2=Nominal 20% Mass Reduction);
- RL = Road Load (with entries RL0=Baseline Rolling Resistance and Aerodynamic Drag, RL1=25% Rolling Resistance Reduction and 10% Aerodynamic Drag Reduction, and RL2=35% Rolling Resistance Reduction and 20% Aerodynamic Drag Reduction);
- AT = Aftertreatment Technology (with entries 3W0=3-Way Catalyst, 3W1=3-Way Catalyst with Direct and Port Injection, 3W2=3-Way Catalyst with 350 Bar Direct Injection, 3W3=3-Way Catalyst with Piezo Injectors, 4W=4-Way Catalyst, PF1=Diesel Oxidation Catalyst and SCR-Coated Diesel Particulate Filter, and PF2=Lean NO_x Trap and Catalyzed Diesel Particulate Filter);
- CO_2 = Carbon Dioxide Emissions over the EU NEDC (in grams per kilometer);
- Cost = Incremental Cost Relative to the Baseline Technology Package (2014 Euros).

Table 5. 2015 FEV ICCT Data for E Class Diesel Vehicles

TP	Disp	Cyl	Eng	TC	VT	EGR	CR	Fr	HEV	XM	MR	RL	AT	CO_2	Cost[1]
ED1	3.00	6	DI	1V	F	CH	No	BL	No	A8	M0	RL0	PF1	151.5	0
ED2	3.00	6	DI	1V	F	CH	No	BL	SS	A8	M0	RL0	PF1	142.6	87
ED3	2.00	4	DI	2V	F	CH	No	BL	AS	DX	M0	RL0	PF1	131.3	-29
ED4	2.00	4	DI	2V	F	CH	No	BL	AS	DX	M1	RL0	PF1	125.0	-29
ED5	2.00	4	DI	2V	F	CH	No	BL	AS	DX	M2	RL0	PF1	119.0	-29
ED6	2.00	4	DI	2V	F	CH	No	BL	AS	DX	M2	RL1	PF1	112.7	-29
ED7	2.00	4	DI	2V	F	CH	No	BL	AS	DX	M2	RL2	PF1	108.2	-29
ED8	2.00	4	DI	2V	F	CH	No	RF	AS	DX	M2	RL1	PF1	108.5	44
ED9	2.00	4	DI	2V	Ex	CH	No	RF	AS	DX	M2	RL1	PF1	108.2	81
ED10	2.00	4	DI	2V	Ex	CB	VR	RF	AS	DX	M2	RL1	PF1	101.4	372
ED11	2.00	4	DI	2V	Ex	CB	VR	RF	AS	DX	M0	RL1	PF1	113.3	372
ED12	2.00	4	DI	2V	Ex	CB	No	RF	P2	DX	M2	RL1	PF1	90.5	2168

See Table 4 for note and key to abbreviations.

Table 6. 2015 FEV ICCT Data for Diesel Sport Utility Vehicles

TP	Disp	Cyl	Eng	TC	VT	EGR	CR	Fr	HEV	XM	MR	RL	AT	CO_2	Cost[1]
SD1	3.00	6	DI	1V	F	CH	No	BL	No	A8	M0	RL0	PF1	153.9	0
SD2	3.00	6	DI	1V	F	CH	No	BL	SS	A8	M0	RL0	PF1	145.0	87
SD3	2.00	4	DI	2V	F	CH	No	BL	AS	DX	M0	RL0	PF1	133.9	-29
SD4	2.00	4	DI	2V	F	CH	No	BL	AS	DX	M1	RL0	PF1	128.4	-29
SD5	2.00	4	DI	2V	F	CH	No	BL	AS	DX	M2	RL0	PF1	122.7	-29
SD6	2.00	4	DI	2V	F	CH	No	BL	AS	DX	M2	RL1	PF1	116.5	-29
SD7	2.00	4	DI	2V	F	CH	No	BL	AS	DX	M2	RL2	PF1	111.3	-29
SD8	2.00	4	DI	2V	F	CH	No	RF	AS	DX	M2	RL1	PF1	112.0	44
SD9	2.00	4	DI	2V	Ex	CH	No	RF	AS	DX	M2	RL1	PF1	111.2	81
SD10	2.00	4	DI	2V	Ex	CB	VR	RF	AS	DX	M2	RL1	PF1	104.4	372
SD11	2.00	4	DI	2V	Ex	CB	VR	RF	AS	DX	M0	RL1	PF1	114.9	372
SD12	2.00	4	DI	2V	Ex	CB	No	RF	P2	DX	M2	RL1	PF1	95.6	2168

(1) Although FEV simulation modeling included (for some technology packages) CO_2 impacts due to changes in road-load influencing mass, rolling resistance, and aerodynamic drag, FEV did not estimate the costs associated with achieving such changes. As a result, technology packages that vary only with respect to their associated road loads will have identical FEV-estimated costs. The costs of road-load technology are estimated independently (as described in Section 3) and added, as appropriate, to the FEV-estimated costs tabulated here.

Key:
- TP = Technology Package with entries coded as class (B, C, D, E, S=SUV, L=LCV), fuel (D=Diesel, G=Gasoline), and package number;
- Disp = Engine Displacement (in liters);
- Cyl = Number of Cylinders;
- Eng = Engine Type (with entries of PFI=Port Fuel Injection or DI=Direct Injection);
- TC = Turbocharger Type (with entries of No=No Turbo, 1S=Single Stage Waste Gate Turbo, 2S=Two Stage Waste Gate Turbo, 1V=Single Stage Variable Geometry Turbo, and 2V=Two Stage Variable Geometry Turbo);
- VT = Valve Control Type (with entries of F=Fixed, Ex=Exhaust Cam Phasing, T=Dual Cam Phasing, TL=Dual Cam Phasing plus Variable Valve Lift, and TLM= Dual Cam Phasing plus Variable Valve Lift plus Miller Cycle Control);
- EGR = Exhaust Gas Recirculation (with entries of No=No EGR, UC=Uncooled High-Pressure/Cooled Low-Pressure EGR, CH= Cooled High-Pressure EGR, CL=Cooled High-Pressure EGR, CB=Cooled High- and Low-Pressure EGR, and D=Dedicated EGR);
- CR = Compression Ratio Technology (with entries of No=Fixed Compression Ratio and VR=Two Step VCR);
- FR = Engine Friction Technology (with entries of BL=Baseline Technology and RF=20% Friction Reduction);
- HEV = Hybrid Electric Technology (with entries of No=No Hybrid Technology, SS=12 Volt Start-Stop Technology, AS=12 Volt Advanced Start-Stop Technology, P0=48 Volt Belt Starter-Generator, and P2=Full Parallel P2 HEV);
- XM = Transmission Technology (with entries of M5=5-Speed Manual, M6=6-Speed Manual, A8=8-Speed Automatic, D7=7-Speed Dual Clutch, and DX=10-Speed Dual Clutch);
- MR = Mass Reduction (with entries of M0=Baseline Mass, M1=Nominal 10% Mass Reduction, and M2=Nominal 20% Mass Reduction);
- RL = Road Load (with entries RL0=Baseline Rolling Resistance and Aerodynamic Drag, RL1=25% Rolling Resistance Reduction and 10% Aerodynamic Drag Reduction, and RL2=35% Rolling Resistance Reduction and 20% Aerodynamic Drag Reduction);
- AT = Aftertreatment Technology (with entries 3W0=3-Way Catalyst, 3W1=3-Way Catalyst with Direct and Port Injection, 3W2=3-Way Catalyst with 350 Bar Direct Injection, 3W3=3-Way Catalyst with Piezo Injectors, 4W=4-Way Catalyst, PF1=Diesel Oxidation Catalyst and SCR-Coated Diesel Particulate Filter, and PF2=Lean NO_x Trap and Catalyzed Diesel Particulate Filter);
- CO_2 = Carbon Dioxide Emissions over the EU NEDC (in grams per kilometer);
- Cost = Incremental Cost Relative to the Baseline Technology Package (2014 Euros).

Table 7. 2015 FEV ICCT Data for Light Commercial Diesel Vehicles

TP	Disp	Cyl	Eng	TC	VT	EGR	CR	Fr	HEV	XM	MR	RL	AT	CO_2	Cost[1]
LD1	2.20	4	DI	1V	F	CH	No	BL	No	M6	M0	RL0	PF1	171.5	0
LD2	2.20	4	DI	1V	F	CH	No	BL	SS	M6	M0	RL0	PF1	165.5	95
LD3	1.80	4	DI	2V	F	CH	No	BL	AS	DX	M0	RL0	PF1	157.3	746
LD4	1.80	4	DI	2V	F	CH	No	BL	AS	DX	M1	RL0	PF1	151.9	746
LD5	1.80	4	DI	2V	F	CH	No	BL	AS	DX	M2	RL0	PF1	145.6	746
LD6	1.80	4	DI	2V	F	CH	No	BL	AS	DX	M2	RL1	PF1	138.0	746
LD7	1.80	4	DI	2V	F	CH	No	BL	AS	DX	M2	RL2	PF1	130.4	746
LD8	1.80	4	DI	2V	F	CH	No	RF	AS	DX	M2	RL1	PF1	133.7	819
LD9	1.80	4	DI	2V	Ex	CH	No	RF	AS	DX	M2	RL1	PF1	133.3	856
LD10	1.80	4	DI	2V	Ex	CB	VR	RF	AS	DX	M2	RL1	PF1	124.9	1119
LD11	1.80	4	DI	2V	Ex	CB	VR	RF	AS	DX	M0	RL1	PF1	136.6	1119
LD12	1.80	4	DI	2V	Ex	CB	No	RF	P2	DX	M2	RL1	PF1	116.9	3123

See Table 6 for note and key to abbreviations.

Table 8. 2015 FEV ICCT Data for B Class Gasoline Vehicles

TP	Disp	Cyl	Eng	TC	VT	EGR	CR	Fr	HEV	XM	MR	RL	AT	CO_2	Cost[1]
BG1	1.30	4	PFI	No	T	No	No	BL	No	M5	M0	RL0	3W0	138.8	0
BG2	1.30	4	PFI	No	T	No	No	BL	SS	M5	M0	RL0	3W0	131.2	73
BG3	1.00	3	DI	1S	T	No	No	BL	No	M5	M0	RL0	3W0	118.5	262
BG4	1.00	3	DI	1S	T	No	No	BL	SS	M5	M0	RL0	3W0	112.7	335
BG5	0.80	3	DI	1S	T	No	No	BL	SS	M6	M1	RL0	3W2	104.0	381
BG6	0.80	3	DI	1S	T	No	No	BL	SS	M6	M2	RL0	3W2	98.4	381
BG7	0.80	3	DI	1S	T	No	No	BL	SS	M6	M2	RL1	3W2	92.5	381
BG8	0.80	3	DI	1S	T	No	No	BL	SS	M6	M2	RL2	3W2	87.7	381
BG9	0.80	3	DI	1S	T	No	No	RF	SS	M6	M2	RL1	3W2	88.5	458
BG10	0.80	3	DI	1S	TL	No	No	RF	SS	M6	M2	RL1	3W2	86.8	543
BG11	0.80	3	DI	1S	TLM	No	No	RF	SS	M6	M2	RL1	3W2	81.8	543
BG12	0.80	3	DI	1S	TL	CL	No	RF	SS	M6	M2	RL1	3W2	84.7	636
BG13	0.80	3	DI	1S	TLM	CL	No	RF	SS	M6	M2	RL1	3W2	80.7	636
BG14	0.80	3	DI	1S	TLM	CL	No	RF	SS	D7	M2	RL1	3W2	77.8	1142
BG15	0.80	3	DI	1S	TLM	CL	No	RF	SS	M6	M0	RL1	3W2	90.0	636
BG16	0.80	3	DI	1S	TLM	CL	No	RF	P0	D7	M2	RL1	3W2	74.1	1832

(1) Although FEV simulation modeling included (for some technology packages) CO_2 impacts due to changes in road-load influencing mass, rolling resistance, and aerodynamic drag, FEV did not estimate the costs associated with achieving such changes. As a result, technology packages that vary only with respect to their associated road loads will have identical FEV-estimated costs. The costs of road-load technology are estimated independently (as described in Section 3) and added, as appropriate, to the FEV-estimated costs tabulated here.

Key:
- TP = Technology Package with entries coded as class (B, C, D, E, S=SUV, L=LCV), fuel (D=Diesel, G=Gasoline), and package number;
- Disp = Engine Displacement (in liters);
- Cyl = Number of Cylinders;
- Eng = Engine Type (with entries of PFI=Port Fuel Injection or DI=Direct Injection);
- TC = Turbocharger Type (with entries of No=No Turbo, 1S=Single Stage Waste Gate Turbo, 2S=Two Stage Waste Gate Turbo, 1V=Single Stage Variable Geometry Turbo, and 2V=Two Stage Variable Geometry Turbo);
- VT = Valve Control Type (with entries of F=Fixed, Ex=Exhaust Cam Phasing, T=Dual Cam Phasing, TL=Dual Cam Phasing plus Variable Valve Lift, and TLM= Dual Cam Phasing plus Variable Valve Lift plus Miller Cycle Control);
- EGR = Exhaust Gas Recirculation (with entries of No=No EGR, UC=Uncooled High-Pressure/Cooled Low-Pressure EGR, CH= Cooled High-Pressure EGR, CL=Cooled High-Pressure EGR, CB=Cooled High- and Low-Pressure EGR, and D=Dedicated EGR);
- CR = Compression Ratio Technology (with entries of No=Fixed Compression Ratio and VR=Two Step VCR);
- FR = Engine Friction Technology (with entries of BL=Baseline Technology and RF=20% Friction Reduction);
- HEV = Hybrid Electric Technology (with entries of No=No Hybrid Technology, SS=12 Volt Start-Stop Technology, AS=12 Volt Advanced Start-Stop Technology, P0=48 Volt Belt Starter-Generator, and P2=Full Parallel P2 HEV);
- XM = Transmission Technology (with entries of M5=5-Speed Manual, M6=6-Speed Manual, A8=8-Speed Automatic, D7=7-Speed Dual Clutch, and DX=10-Speed Dual Clutch);
- MR = Mass Reduction (with entries of M0=Baseline Mass, M1=Nominal 10% Mass Reduction, and M2=Nominal 20% Mass Reduction);
- RL = Road Load (with entries RL0=Baseline Rolling Resistance and Aerodynamic Drag, RL1=25% Rolling Resistance Reduction and 10% Aerodynamic Drag Reduction, and RL2=35% Rolling Resistance Reduction and 20% Aerodynamic Drag Reduction);
- AT = Aftertreatment Technology (with entries 3W0=3-Way Catalyst, 3W1=3-Way Catalyst with Direct and Port Injection, 3W2=3-Way Catalyst with 350 Bar Direct Injection, 3W3=3-Way Catalyst with Piezo Injectors, 4W=4-Way Catalyst, PF1=Diesel Oxidation Catalyst and SCR-Coated Diesel Particulate Filter, and PF2=Lean NO_x Trap and Catalyzed Diesel Particulate Filter);
- CO_2 = Carbon Dioxide Emissions over the EU NEDC (in grams per kilometer);
- Cost = Incremental Cost Relative to the Baseline Technology Package (2014 Euros).

Table 9. 2015 FEV ICCT Data for C Class Gasoline Vehicles

TP	Disp	Cyl	Eng	TC	VT	EGR	CR	Fr	HEV	XM	MR	RL	AT	CO_2	Cost[1]
CG1	1.80	4	PFI	No	T	No	No	BL	No	M5	M0	RL0	3W0	170.2	0
CG2	1.80	4	PFI	No	T	No	No	BL	SS	M5	M0	RL0	3W0	159.9	79
CG3	1.40	4	DI	1S	T	No	No	BL	No	M5	M0	RL0	3W0	141.5	402
CG4	1.40	4	DI	1S	T	No	No	BL	SS	M5	M0	RL0	3W0	133.7	481
CG5	1.00	3	DI	1S	T	No	No	BL	SS	M6	M1	RL0	3W2	118.0	410
CG6	1.00	3	DI	1S	T	No	No	BL	SS	M6	M2	RL0	3W2	111.5	410
CG7	1.00	3	DI	1S	T	No	No	BL	SS	M6	M2	RL1	3W2	105.8	410
CG8	1.00	3	DI	1S	T	No	No	BL	SS	M6	M2	RL2	3W2	100.2	410
CG9	1.00	3	DI	1S	T	No	No	BL	SS	M6	M0	RL0	3W2	125.1	410
CG10	1.00	3	DI	1S	T	No	No	BL	AS	D7	M2	RL1	3W2	97.4	904
CG11	1.00	3	DI	1S	T	No	No	RF	AS	D7	M2	RL1	3W2	91.6	981
CG12	1.00	3	DI	1S	TL	No	No	RF	AS	D7	M2	RL1	3W2	90.0	1066
CG13	1.00	3	DI	2S	TLM	No	No	RF	AS	D7	M2	RL1	3W2	86.0	1244
CG14	1.00	3	DI	2S	TL	CL	VR	RF	AS	D7	M2	RL1	3W2	85.6	1457
CG15	1.00	3	DI	2S	TLM	CL	No	RF	AS	D7	M2	RL1	3W2	85.2	1347
CG16	1.00	3	DI	2S	TLM	CL	No	RF	AS	D7	M0	RL1	3W2	95.0	1347
CG17	0.80	3	DI	2S	TL	CL	No	RF	AS	D7	M2	RL1	3W2	88.7	1323
CG18	1.00	3	DI	2S	TLM	CL	No	RF	P0	D7	M2	RL1	3W2	82.1	2041
CG19	0.80	3	DI	2S	TL	CL	No	RF	P0	D7	M2	RL1	3W2	83.8	2017

(1) Although FEV simulation modeling included (for some technology packages) CO_2 impacts due to changes in road-load influencing mass, rolling resistance, and aerodynamic drag, FEV did not estimate the costs associated with achieving such changes. As a result, technology packages that vary only with respect to their associated road loads will have identical FEV-estimated costs. The costs of road-load technology are estimated independently (as described in Section 3) and added, as appropriate, to the FEV-estimated costs tabulated here.

Key:
- TP = Technology Package with entries coded as class (B, C, D, E, S=SUV, L=LCV), fuel (D=Diesel, G=Gasoline), and package number;
- Disp = Engine Displacement (in liters);
- Cyl = Number of Cylinders;
- Eng = Engine Type (with entries of PFI=Port Fuel Injection or DI=Direct Injection);
- TC = Turbocharger Type (with entries of No=No Turbo, 1S=Single Stage Waste Gate Turbo, 2S=Two Stage Waste Gate Turbo, 1V=Single Stage Variable Geometry Turbo, and 2V=Two Stage Variable Geometry Turbo);
- VT = Valve Control Type (with entries of F=Fixed, Ex=Exhaust Cam Phasing, T=Dual Cam Phasing, TL=Dual Cam Phasing plus Variable Valve Lift, and TLM= Dual Cam Phasing plus Variable Valve Lift plus Miller Cycle Control);
- EGR = Exhaust Gas Recirculation (with entries of No=No EGR, UC=Uncooled High-Pressure/Cooled Low-Pressure EGR, CH= Cooled High-Pressure EGR, CL=Cooled High-Pressure EGR, CB=Cooled High- and Low-Pressure EGR, and D=Dedicated EGR);
- CR = Compression Ratio Technology (with entries of No=Fixed Compression Ratio and VR=Two Step VCR);
- FR = Engine Friction Technology (with entries of BL=Baseline Technology and RF=20% Friction Reduction);
- HEV = Hybrid Electric Technology (with entries of No=No Hybrid Technology, SS=12 Volt Start-Stop Technology, AS=12 Volt Advanced Start-Stop Technology, P0=48 Volt Belt Starter-Generator, and P2=Full Parallel P2 HEV);
- XM = Transmission Technology (with entries of M5=5-Speed Manual, M6=6-Speed Manual, A8=8-Speed Automatic, D7=7-Speed Dual Clutch, and DX=10-Speed Dual Clutch);
- MR = Mass Reduction (with entries of M0=Baseline Mass, M1=Nominal 10% Mass Reduction, and M2=Nominal 20% Mass Reduction);
- RL = Road Load (with entries RL0=Baseline Rolling Resistance and Aerodynamic Drag, RL1=25% Rolling Resistance Reduction and 10% Aerodynamic Drag Reduction, and RL2=35% Rolling Resistance Reduction and 20% Aerodynamic Drag Reduction);
- AT = Aftertreatment Technology (with entries 3W0=3-Way Catalyst, 3W1=3-Way Catalyst with Direct and Port Injection, 3W2=3-Way Catalyst with 350 Bar Direct Injection, 3W3=3-Way Catalyst with Piezo Injectors, 4W=4-Way Catalyst, PF1=Diesel Oxidation Catalyst and SCR-Coated Diesel Particulate Filter, and PF2=Lean NO_x Trap and Catalyzed Diesel Particulate Filter);
- CO_2 = Carbon Dioxide Emissions over the EU NEDC (in grams per kilometer);
- Cost = Incremental Cost Relative to the Baseline Technology Package (2014 Euros).

Table 10. 2015 FEV ICCT Data for D Class Gasoline Vehicles

TP	Disp	Cyl	Eng	TC	VT	EGR	CR	Fr	HEV	XM	MR	RL	AT	CO_2	Cost[1]
DG1	2.40	6	PFI	No	T	No	No	BL	No	A8	M0	RL0	3W0	183.0	0
DG2	2.40	6	PFI	No	T	No	No	BL	SS	A8	M0	RL0	3W0	166.8	70
DG3	1.80	4	DI	1S	T	No	No	BL	No	A8	M0	RL0	3W3	163.6	-410
DG4	1.80	4	DI	1S	T	No	No	BL	SS	A8	M0	RL0	3W3	150.2	-340
DG5	1.40	4	DI	1S	T	No	No	BL	AS	DX	M1	RL0	3W1	130.2	-212
DG6	1.40	4	DI	1S	T	No	No	BL	AS	DX	M2	RL0	3W1	124.0	-212
DG7	1.40	4	DI	1S	T	No	No	BL	AS	DX	M2	RL1	3W1	118.0	-212
DG8	1.40	4	DI	1S	T	No	No	BL	AS	DX	M2	RL2	3W1	111.7	-212
DG9	1.40	4	DI	1S	T	No	No	BL	AS	DX	M0	RL0	3W1	136.4	-212
DG10	1.40	4	DI	1S	T	No	No	RF	AS	DX	M2	RL1	3W1	112.9	-133
DG11	1.40	4	DI	1S	TL	No	No	RF	AS	DX	M2	RL1	3W1	110.8	-23
DG12	1.40	4	DI	2S	TLM	No	No	RF	AS	DX	M2	RL1	3W1	105.8	177
DG13	1.40	4	DI	2S	TL	CL	VR	RF	AS	DX	M2	RL1	3W1	104.4	434
DG14	1.40	4	DI	2S	TLM	CL	No	RF	AS	DX	M2	RL1	3W1	104.6	293
DG15	1.40	4	DI	2S	TLM	CL	No	RF	AS	DX	M0	RL1	3W1	116.2	293
DG16	1.80	4	DI	1S	T	D	No	RF	AS	DX	M2	RL1	3W1	112.9	66
DG17	1.00	3	DI	2S	TL	CL	No	RF	AS	DX	M2	RL1	3W1	107.7	43
DG18	1.40	4	DI	2S	TLM	CL	No	RF	P2	DX	M2	RL1	3W1	95.1	2163
DG19	1.00	3	DI	2S	TL	CL	No	RF	P2	DX	M2	RL1	3W1	98.5	1913

(1) Although FEV simulation modeling included (for some technology packages) CO_2 impacts due to changes in road load influencing mass, rolling resistance, and aerodynamic drag, FEV did not estimate the costs associated with achieving such changes. As a result, technology packages that vary only with respect to their associated road loads will have identical FEV-estimated costs. The costs of road load technology are estimated independently (as described in Section 3) and added, as appropriate, to the FEV-estimated costs tabulated here.

Key:
- TP = Technology Package with entries coded as class (B, C, D, E, S=SUV, L=LCV), fuel (D=Diesel, G=Gasoline), and package number;
- Disp = Engine Displacement (in liters);
- Cyl = Number of Cylinders;
- Eng = Engine Type (with entries of PFI=Port Fuel Injection or DI=Direct Injection);
- TC = Turbocharger Type (with entries of No=No Turbo, 1S=Single Stage Waste Gate Turbo, 2S=Two Stage Waste Gate Turbo, 1V=Single Stage Variable Geometry Turbo, and 2V=Two Stage Variable Geometry Turbo);
- VT = Valve Control Type (with entries of F=Fixed, Ex=Exhaust Cam Phasing, T=Dual Cam Phasing, TL=Dual Cam Phasing plus Variable Valve Lift, and TLM= Dual Cam Phasing plus Variable Valve Lift plus Miller Cycle Control);
- EGR = Exhaust Gas Recirculation (with entries of No=No EGR, UC=Uncooled High-Pressure/Cooled Low-Pressure EGR, CH= Cooled High-Pressure EGR, CL=Cooled High-Pressure EGR, CB=Cooled High- and Low-Pressure EGR, and D=Dedicated EGR);
- CR = Compression Ratio Technology (with entries of No=Fixed Compression Ratio and VR=Two Step VCR);
- FR = Engine Friction Technology (with entries of BL=Baseline Technology and RF=20% Friction Reduction);
- HEV = Hybrid Electric Technology (with entries of No=No Hybrid Technology, SS=12 Volt Start-Stop Technology, AS=12 Volt Advanced Start-Stop Technology, P0=48 Volt Belt Starter-Generator, and P2=Full Parallel P2 HEV);
- XM = Transmission Technology (with entries of M5=5-Speed Manual, M6=6-Speed Manual, A8=8-Speed Automatic, D7=7-Speed Dual Clutch, and DX=10-Speed Dual Clutch);
- MR = Mass Reduction (with entries of M0=Baseline Mass, M1=Nominal 10% Mass Reduction, and M2=Nominal 20% Mass Reduction);
- RL = Road Load (with entries RL0=Baseline Rolling Resistance and Aerodynamic Drag, RL1=25% Rolling Resistance Reduction and 10% Aerodynamic Drag Reduction, and RL2=35% Rolling Resistance Reduction and 20% Aerodynamic Drag Reduction);
- AT = Aftertreatment Technology (with entries 3W0=3-Way Catalyst, 3W1=3-Way Catalyst with Direct and Port Injection, 3W2=3-Way Catalyst with 350 Bar Direct Injection, 3W3=3-Way Catalyst with Piezo Injectors, 4W=4-Way Catalyst, PF1=Diesel Oxidation Catalyst and SCR-Coated Diesel Particulate Filter, and PF2=Lean NO_x Trap and Catalyzed Diesel Particulate Filter);
- CO_2 = Carbon Dioxide Emissions over the EU NEDC (in grams per kilometer);
- Cost = Incremental Cost Relative to the Baseline Technology Package (2014 Euros).

Table 11. 2015 FEV ICCT Data for E Class Gasoline Vehicles

TP	Disp	Cyl	Eng	TC	VT	EGR	CR	Fr	HEV	XM	MR	RL	AT	CO_2	Cost[1]
EG1	3.00	6	PFI	No	T	No	No	BL	No	A8	M0	RL0	3W0	213.6	0
EG2	3.00	6	PFI	No	T	No	No	BL	SS	A8	M0	RL0	3W0	194.2	79
EG3	2.00	4	DI	1S	T	No	No	BL	No	A8	M0	RL0	3W3	183.5	-378
EG4	2.00	4	DI	1S	T	No	No	BL	SS	A8	M0	RL0	3W3	168.9	-299
EG5	1.60	4	DI	1V	T	No	No	BL	AS	DX	M1	RL0	4W	147.5	-128
EG6	1.60	4	DI	1V	T	No	No	BL	AS	DX	M2	RL0	4W	140.3	-128
EG7	1.60	4	DI	1V	T	No	No	BL	AS	DX	M2	RL1	4W	132.5	-128
EG8	1.60	4	DI	1V	T	No	No	BL	AS	DX	M2	RL2	4W	126.3	-128
EG9	1.60	4	DI	1V	T	No	No	BL	AS	DX	M0	RL0	4W	154.2	-128
EG10	1.60	4	DI	1V	T	No	No	RF	AS	DX	M2	RL1	4W	127.1	-49
EG11	1.60	4	DI	1V	TL	No	No	RF	AS	DX	M2	RL1	4W	125.0	61
EG12	1.60	4	DI	2S	TLM	No	No	RF	AS	DX	M2	RL1	4W	119.9	165
EG13	1.60	4	DI	2S	TL	CL	VR	RF	AS	DX	M2	RL1	4W	116.9	446
EG14	1.60	4	DI	2S	TLM	CL	No	RF	AS	DX	M2	RL1	4W	118.9	297
EG15	1.60	4	DI	2S	TLM	CL	No	RF	AS	DX	M0	RL1	4W	132.8	297
EG16	2.40	4	DI	1S	T	D	No	RF	AS	DX	M2	RL1	4W	134.6	260
EG17	1.20	3	DI	2S	TL	CL	No	RF	AS	DX	M2	RL1	4W	121.8	138
EG18	1.60	4	DI	2S	TLM	CL	No	RF	P2	DX	M2	RL1	4W	106.6	2275
EG19	1.20	3	DI	2S	TL	CL	No	RF	P2	DX	M2	RL1	4W	110.7	2116

(1) Although FEV simulation modeling included (for some technology packages) CO_2 impacts due to changes in road-load influencing mass, rolling resistance, and aerodynamic drag, FEV did not estimate the costs associated with achieving such changes. As a result, technology packages that vary only with respect to their associated road loads will have identical FEV-estimated costs. The costs of road-load technology are estimated independently (as described in Section 3) and added, as appropriate, to the FEV-estimated costs tabulated here.

Key:
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- Eng = Engine Type (with entries of PFI=Port Fuel Injection or DI=Direct Injection);
- TC = Turbocharger Type (with entries of No=No Turbo, 1S=Single Stage Waste Gate Turbo, 2S=Two Stage Waste Gate Turbo, 1V=Single Stage Variable Geometry Turbo, and 2V=Two Stage Variable Geometry Turbo);
- VT = Valve Control Type (with entries of F=Fixed, Ex=Exhaust Cam Phasing, T=Dual Cam Phasing, TL=Dual Cam Phasing plus Variable Valve Lift, and TLM= Dual Cam Phasing plus Variable Valve Lift plus Miller Cycle Control);
- EGR = Exhaust Gas Recirculation (with entries of No=No EGR, UC=Uncooled High-Pressure/Cooled Low-Pressure EGR, CH= Cooled High-Pressure EGR, CL=Cooled High-Pressure EGR, CB=Cooled High- and Low-Pressure EGR, and D=Dedicated EGR);
- CR = Compression Ratio Technology (with entries of No=Fixed Compression Ratio and VR=Two Step VCR);
- FR = Engine Friction Technology (with entries of BL=Baseline Technology and RF=20% Friction Reduction);
- HEV = Hybrid Electric Technology (with entries of No=No Hybrid Technology, SS=12 Volt Start-Stop Technology, AS=12 Volt Advanced Start-Stop Technology, P0=48 Volt Belt Starter-Generator, and P2=Full Parallel P2 HEV);
- XM = Transmission Technology (with entries of M5=5-Speed Manual, M6=6-Speed Manual, A8=8-Speed Automatic, D7=7-Speed Dual Clutch, and DX=10-Speed Dual Clutch);
- MR = Mass Reduction (with entries of M0=Baseline Mass, M1=Nominal 10% Mass Reduction, and M2=Nominal 20% Mass Reduction);
- RL = Road Load (with entries RL0=Baseline Rolling Resistance and Aerodynamic Drag, RL1=25% Rolling Resistance Reduction and 10% Aerodynamic Drag Reduction, and RL2=35% Rolling Resistance Reduction and 20% Aerodynamic Drag Reduction);
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- CO_2 = Carbon Dioxide Emissions over the EU NEDC (in grams per kilometer);
- Cost = Incremental Cost Relative to the Baseline Technology Package (2014 Euros).

3. ROAD-LOAD COST ESTIMATES

As indicated above, the 2015 FEV ICCT data include CO_2 impacts for mass, rolling resistance, and aerodynamic drag road-load reduction technologies, but do not include associated cost impacts. As discussed in Section 1, the costs for these technologies were estimated using supplemental data sources, namely 2012 FEV ICCT data for mass reduction technology and EPA cost data for rolling resistance and aerodynamic drag technology. Extensive documentation exists for both data sources, as referenced in Section 1 (FEV, 2013; EPA, 2012), so only summary data are presented in this report.

Figures 1 and 2 present the mass reduction cost curves utilized to estimate the mass reduction costs associated with all 2015 FEV ICCT technology packages that include such technology. These curves were generated as a critical component of a 2012 cost analysis performed by FEV for the ICCT and are used without changes to support this analysis.[9] Figure 1 presents Direct Manufacturing Cost (DMC) curves, while Figure 2 presents Total (retail-level) Cost (TC) curves. WEU signifies costs based on western EU (WEU) labor rates and manufacturing costs. EEU signifies costs based on eastern EU (EEU) labor rates and manufacturing costs.

Table 12 presents the cost assumptions used to estimate rolling resistance and aerodynamic drag reduction costs associated with all 2015 FEV ICCT technology packages that include such technology. These data are extracted from the EPA cost data, as referenced in Section 1 above (EPA, 2012), and used without change except as follows. First, the data are updated to 2014 euros as described in Section 1. Second, the data have been expanded to address reductions greater than those explicitly treated in the EPA cost data. The EPA cost data for rolling resistance and aerodynamic drag reduction are directly applicable for reductions up to 20%. This is adequate to estimate all aerodynamic drag costs for the 2015 FEV ICCT data, but that data includes technology packages that consider rolling resistance reductions of 25% or 35%. To estimate the cost of such reductions, this analysis assumes that the cost per % reduction in the road-load parameter increases at the same rate as costs explicitly estimated by the EPA for reductions "up to 10%" and "between 10% and 20%." In other words, the difference between the "between 10% and 20%" costs and the "up to 10%" costs is added to the "between 10% and 20%" costs to derive the "between 20% and 30%" costs, and is added to the "between 20% and 30%" costs to derive the "between 30% and 40%" costs. These calculations are performed for the base cost year (as defined in the EPA cost data) and costs for other years are developed using the same learning and ICM assumptions used by the EPA for the "between 10% and 20%" reduction technology. Section 4 discusses learning and ICM assumptions for all evaluated 2015 FEV ICCT data.

9 The only exception being that costs were updated to 2014 euros (for consistency with 2015 FEV ICCT data) as discussed in Section 1.

Figure 1. Mass Reduction Technology Direct Manufacturing Cost Curves (2014€)

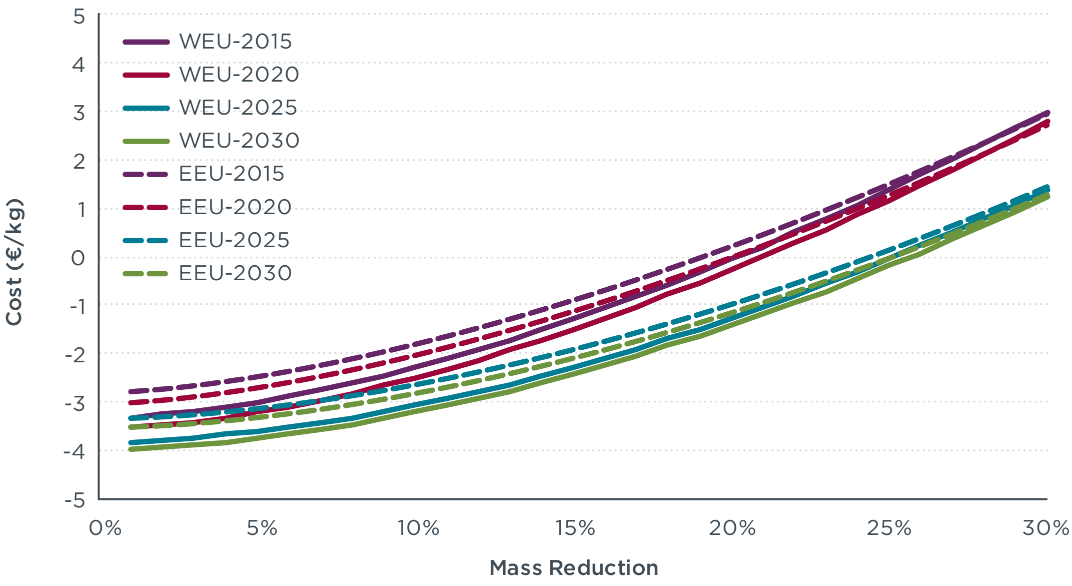


Figure 2. Mass Reduction Technology Total Cost Curves (2014€)

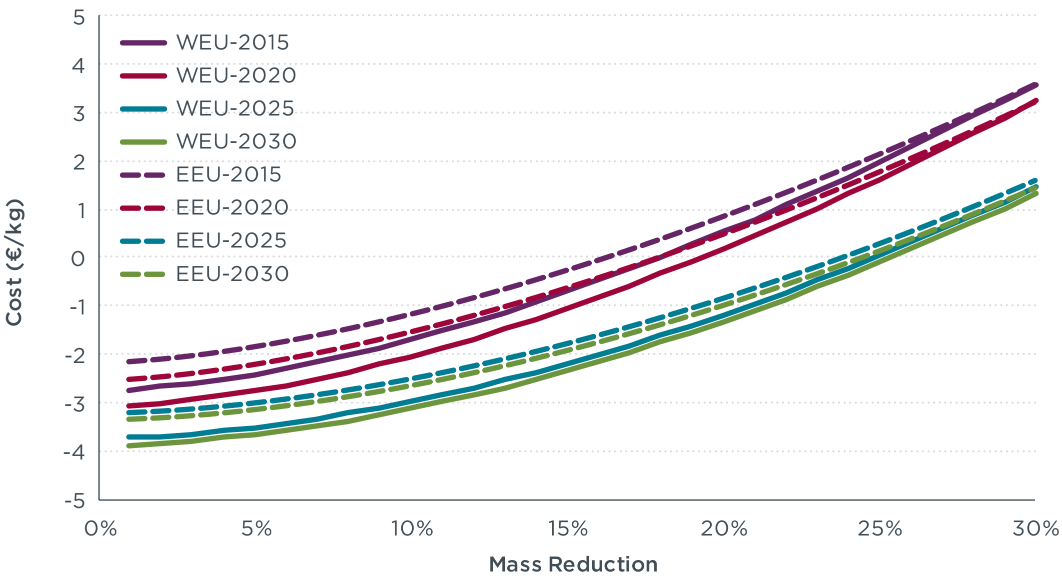


Table 12. Rolling Resistance and Aerodynamic Drag Reduction Costs (2014€ per % Reduction)

Year	LRR0-1	LRR1-2	LRR2-3	LRR3-4	LRR0-1	LRR1-2	LRR2-3	LRR3-4
	Direct Manufacturing Cost				Total Cost			
2015	0.41	4.76	8.83	12.91	0.51	5.48	10.21	14.94
2016	0.41	4.76	8.83	12.91	0.51	5.48	10.21	14.94
2017	0.41	4.76	8.83	12.91	0.51	5.48	10.21	14.94
2018	0.41	4.76	8.83	12.91	0.51	5.48	10.21	14.94
2019	0.41	3.72	6.91	10.10	0.49	4.45	8.30	12.14
2020	0.41	3.72	6.91	10.10	0.49	4.45	8.30	12.14
2021	0.41	2.89	5.38	7.86	0.49	3.62	6.74	9.86
2022	0.41	2.80	5.19	7.59	0.49	3.52	6.55	9.59
2023	0.41	2.70	5.01	7.33	0.49	3.42	6.37	9.32
2024	0.41	2.61	4.84	7.07	0.49	3.32	6.19	9.06
2025	0.41	2.52	4.67	6.83	0.49	3.07	5.72	8.37
2026	0.41	2.43	4.51	6.59	0.49	2.98	5.55	8.13
2027	0.41	2.37	4.40	6.43	0.49	2.92	5.45	7.97
2028	0.41	2.31	4.30	6.28	0.49	2.87	5.34	7.82
2029	0.41	2.26	4.20	6.13	0.49	2.81	5.24	7.67
2030	0.41	2.21	4.10	5.99	0.49	2.76	5.14	7.52

Year	AD0-1	AD1-2	AD2-3	AD3-4	AD0-1	AD1-2	AD2-3	AD3-4
	Direct Manufacturing Cost				Total Cost			
2015	3.39	10.17	16.95	23.73	4.21	14.11	24.01	33.91
2016	3.29	9.87	16.44	23.02	4.11	13.79	23.47	33.15
2017	3.22	9.67	16.12	22.56	4.04	13.59	23.12	32.65
2018	3.16	9.48	15.79	22.11	3.98	13.38	22.78	32.17
2019	3.10	9.29	15.48	21.67	3.75	13.19	22.44	31.69
2020	3.03	9.10	15.17	21.24	3.68	12.99	22.11	31.22
2021	2.97	8.92	14.86	20.81	3.62	12.80	21.78	30.77
2022	2.91	8.74	14.57	20.39	3.56	12.62	21.47	30.32
2023	2.86	8.57	14.28	19.99	3.50	12.43	21.16	29.88
2024	2.80	8.39	13.99	19.59	3.45	12.25	20.85	29.45
2025	2.74	8.23	13.71	19.20	3.39	11.11	18.91	26.71
2026	2.71	8.14	13.57	19.00	3.36	11.03	18.77	26.50
2027	2.69	8.06	13.44	18.81	3.34	10.94	18.62	26.30
2028	2.66	7.98	13.30	18.63	3.31	10.86	18.48	26.10
2029	2.63	7.90	13.17	18.44	3.28	10.78	18.34	25.90
2030	2.61	7.82	13.04	18.25	3.25	10.70	18.20	25.71

LRR0-1 = 0–10% Rolling Resistance Reduction,
LRR1-2 = 10–20% Rolling Resistance Reduction (Incremental to LRR0-1)
LRR2-3 = 20–30% Rolling Resistance Reduction (Incremental to LRR0-1 and LRR1-2), and
LRR3-4 = 30–40% Rolling Resistance Reduction (Incremental to LRR0-1, LRR1-2, and LRR2-3).
AD0-1 = 0–10% Aerodynamic Drag Reduction,
AD1-2 = 10–20% Aerodynamic Drag Reduction (Incremental to AD0-1),
AD2-3 = 20–30% Aerodynamic Drag Reduction (Incremental to AD0-1 and AD1-2), and
AD3-4 = 30–40% Aerodynamic Drag Reduction (Incremental to AD0-1, AD1-2, and AD2-3).

Example direct manufacturing cost calculation for a (hypothetical) 35% rolling resistance reduction in 2030:

Cost = (LRR0-1)(10) + (LRR1-2)(10) + (LRR2-3)(10) + (LRR3-4)(5)

= (0.41)(10) + (2.21)(10) + (4.10)(10) + (5.99)(5) = 97.15 euros

Cost calculations for total costs, other percentage reductions, other evaluation years, and analogous aerodynamic drag reductions are identical.

4. LEARNING AND INDIRECT COSTS

With the exception of VCR technology, 2015 FEV ICCT data are presented as 2014-specific DMCs, assuming high-volume production. For VCR technology, DMCs are also as expected under high-volume production, but for a base year of 2025 instead of 2014.[10] To ensure consistency, all costs estimated through supplemental data sources have been converted to equivalent 2014 euros using the price index data discussed in Section 1. Because this analysis estimates costs for a series of future years, it is necessary to extrapolate the 2014 (or 2025 in the case of VCR technology) costs to the desired alternative evaluation years. This is accomplished using learning curves derived from the U.S. EPA's technical support document for their 2017–2025 U.S. light-duty vehicle GHG standards rulemaking, the same reference used as the source of the supplemental EPA cost data. (EPA, 2012) Indirect cost multipliers, also derived from the EPA technical support document, are applied to given DMC data to estimate total (retail-level) costs.

The EPA data include a series of learning curves and ICM levels that generally vary with the current state of development and complexity of an associated given technology. Tables 13 and 14 provide a summary of the EPA learning curve and ICM data, respectively. Tables 15a and 15b present the various learning curve and ICM technology assignments employed by the EPA for their light-duty vehicle GHG analysis. The "Assignment Key" field included in Tables 15a and 15b is not sourced to the EPA analysis, but is instead an arbitrary construct used in this analysis to relate an EPA analysis technology to a technology included in the 2015 FEV ICCT data.

While the reader is referred to the referenced EPA document (EPA, 2012) for detailed information, the basic functionality of the learning curve and ICM data is as follows.

$$DMC_{EY} = DMC_{BY} \times LF_{EY}$$

$$IC_{EY} = (DMC_{BY} \times ICM_{EY,NonWarranty}) + (DMC_{EY} \times ICM_{EY,Warranty})$$

$$TC_{EY} = DMC_{EY} + IC_{EY}$$

Where: DMC = Direct Manufacturing Cost,
EY = Evaluation Year,
BY = Base Year,
LF = Learning Factor (see Table 13),
IC = Indirect Cost,
ICM = Indirect Cost Multiplier (see Table 14),
NonWarranty = Non-Warranty ICM (see Table 14),
Warranty = Warranty ICM (see Table 14), and
TC = Total (Retail-Level) Cost

Direct manufacturing costs for a given evaluation year are a function of base-year DMC and an associated learning factor. Evaluation year total costs are a function of base-year DMC, evaluation year DMC, and evaluation year indirect-cost multipliers. Generally, technologies that are either currently marketed or moderately evolutionary in nature relative to current technology are characterized as low complexity with only minor learning potential. Longer-term technologies are assigned higher-complexity ICMs and greater learning potential in accordance with their still-developing nature.

10 FEV applies a differential base year to VCR technology due to concerns that the technology is not sufficiently mature to currently support high-volume production. Although other technologies may or may not yet be produced in high volume, they are considered sufficiently mature to do so should demand dictate. FEV does not believe that this is the case for VCR technology and thus qualifies their associated cost estimates as applicable only to a future year (in this case, 2025).

Table 13. EPA Learning Curve Data

Year	Learning Curve Number							
	6	11	12	16	19	21	24	25
2010	1.00000	1.06281	1.16450	1.56250	3.05176	1.23765	1.56250	1.00000
2011	1.00000	1.03093	1.12957	1.56250	3.05176	1.20052	1.56250	1.00000
2012	1.00000	1.00000	1.09568	1.56250	3.05176	1.16450	1.56250	1.00000
2013	1.00000	0.97000	1.06281	1.56250	3.05176	1.12957	1.56250	1.00000
2014	1.00000	0.94090	1.03093	1.25000	2.44141	1.09568	1.25000	1.00000
2015	1.00000	0.91267	1.00000	1.00000	2.44141	1.06281	1.25000	1.00000
2016	1.00000	0.88529	0.97000	1.00000	1.95313	1.03093	1.00000	1.00000
2017	1.00000	0.86759	0.95060	0.97000	1.95313	1.00000	1.00000	1.00000
2018	1.00000	0.85024	0.93159	0.94090	1.56250	0.97000	0.97000	1.00000
2019	1.00000	0.83323	0.91296	0.91267	1.56250	0.94090	0.94090	0.80000
2020	1.00000	0.81657	0.89470	0.88529	1.25000	0.91267	0.91267	0.80000
2021	1.00000	0.80023	0.87680	0.85873	1.25000	0.88529	0.88529	0.64000
2022	1.00000	0.78423	0.85927	0.83297	1.25000	0.85873	0.85873	0.62080
2023	1.00000	0.76855	0.84208	0.80798	1.25000	0.84156	0.83297	0.60218
2024	1.00000	0.75317	0.82524	0.78374	1.25000	0.82473	0.80798	0.58411
2025	1.00000	0.73811	0.80874	0.76023	1.00000	0.80823	0.78374	0.56659
2026	1.00000	0.73073	0.80065	0.74503	0.97000	0.79207	0.76807	0.54959
2027	1.00000	0.72342	0.79264	0.73013	0.94090	0.77623	0.75271	0.53860
2028	1.00000	0.71619	0.78472	0.71552	0.91267	0.76847	0.73765	0.52783
2029	1.00000	0.70903	0.77687	0.70121	0.88529	0.76078	0.72290	0.51727
2030	1.00000	0.70194	0.76910	0.68719	0.85873	0.75317	0.70844	0.50692

Table 14. EPA Indirect Cost Multipliers

Technology Complexity	Near Term		Long Term	
	Warranty	Non-Warranty	Warranty	Non-Warranty
Low	0.0120	0.2300	0.0050	0.1870
Medium	0.0446	0.3427	0.0310	0.2587
High1	0.0650	0.4990	0.0320	0.3140
High2	0.0740	0.6960	0.0490	0.4480

Table 15a. EPA Technology-Specific Learning and ICM Assignments

Technology Description	Assignment Key	Learning Curve	ICM Complexity	Near-Term End Year	DMC Base Year
Low-Friction Lubricant	LFLube	6	Low	2018	2010
Engine Friction Reduction 1: 3 Cylinder	EFR1-3	6	Low	2018	2010
Engine Friction Reduction 2: 3 Cylinder	EFR2-3	6	Low	2024	2010
Engine Friction Reduction 1: 4 Cylinder	EFR1-4	6	Low	2018	2010
Engine Friction Reduction 2: 4 Cylinder	EFR2-4	6	Low	2024	2010
Engine Friction Reduction 1: 6 Cylinder	EFR1-6	6	Low	2018	2010
Engine Friction Reduction 2: 6 Cylinder	EFR2-6	6	Low	2024	2010
Engine Friction Reduction 1: 8 Cylinder	EFR1-8	6	Low	2018	2010
Engine Friction Reduction 2: 8 Cylinder	EFR2-8	6	Low	2024	2010
Cylinder Deactivation: 6 Cylinder	DeAct-6	11	Low	2018	2015
Cylinder Deactivation: 8 Cylinder	DeAct-8	11	Low	2018	2015
Intake Cam Phasing: Inline Engine	ICPinline	12	Low	2018	2015
Intake Cam Phasing: Overhead Cam V Engine	ICPohcV	12	Low	2018	2015
Intake Cam Phasing: Overhead Valve V Engine	ICPohvV	12	Low	2018	2015
Coupled Cam Phasing: Inline Engine	CCPinline	12	Low	2018	2015
Coupled Cam Phasing: Overhead Cam V Engine	CCPohcV	12	Low	2018	2015
Coupled Cam Phasing: Overhead Valve V Engine	CCPohvV	12	Low	2018	2015
Dual Cam Phasing: Inline Engine	DCPinline	12	Medium	2018	2015
Dual Cam Phasing: Overhead Cam V Engine	DCPohcV	12	Medium	2018	2015
Dual Cam Phasing: Overhead Valve V Engine	DCPohvV	12	Medium	2018	2015
Discrete Variable Valve Lift: 4 Cylinder	DVVL-4	12	Medium	2018	2015
Discrete Variable Valve Lift: 6 Cylinder	DVVL-6	12	Medium	2018	2015
Discrete Variable Valve Lift: 8 Cylinder	DVVL-8	12	Medium	2018	2015
Continuous Variable Valve Lift: I4	CVVL-4	12	Medium	2018	2015
Continuous Variable Valve Lift: OHC-V6	CVVL-c6	12	Medium	2018	2015
Continuous Variable Valve Lift: OHC-V8	CVVL-c8	12	Medium	2018	2015
Continuous Variable Valve Lift: OHV-V6	CVVL-v6	12	Medium	2018	2015
Continuous Variable Valve Lift: OHV-V8	CVVL-v8	12	Medium	2018	2015
Stoichiometric Gasoline Direct Injection: I3/I4	sGDI-IL	11	Medium	2018	2012
Stoichiometric Gasoline Direct Injection: V6	sGDI-V6	11	Medium	2018	2012
Stoichiometric Gasoline Direct Injection: V8	sGDI-V8	11	Medium	2018	2012
18-Bar Turbocharging: Inline Engine	TC18	11	Medium	2018	2012
18-Bar Turbocharging: V Engine	TC18	11	Medium	2018	2012
24-Bar Turbocharging: Inline Engine	TC24	11	Medium	2024	2012
24-Bar Turbocharging: V Engine	TC24	11	Medium	2024	2012
27-Bar Turbocharging: Inline Engine	TC27	11	Medium	2024	2012
27-Bar Turbocharging: V Engine	TC27	11	Medium	2024	2012
Engine Downsizing	DSize	11	Medium	2018	2012
Engine Downsizing without Learning (1)	DSizeX	6	Medium	2018	2012
Cooled EGR	CoolEGR	11	Medium	2024	2012
Advanced Diesel	AdvDsl	11	Medium	2018	2012
Advanced Shift Logic 1	ASL1	21	Medium	2018	2015
Advanced Shift Logic 2	ASL2	21	Medium	2024	2017
Early Torque Converter Lockup	ETCLU	12	Low	2018	2015
High-Efficiency Gearbox	HEGbox	21	Low	2024	2017
6-Speed Automatic Transmission	A6	11	Low	2018	2012
8-Speed Automatic Transmission	A8	11	Medium	2018	2012
6-Speed Dual Dry Clutch Automated Manual Transmission	6DCT-dry	11	Medium	2018	2012
6-Speed Dual Wet Clutch Automated Manual Transmission	6DCT-wet	11	Medium	2018	2012

(1) "Manufactured" from EPA downsizing technology data (DSize) to eliminate learning effect on downsized engine savings.

Table 15b. EPA Technology-Specific Learning and ICM Assignments

Technology Description	Assignment Key	Learning Curve	ICM Complexity	Near-Term End Year	DMC Base Year
8-Speed Dual Dry Clutch Automated Manual Transmission	8DCT-dry	11	Medium	2024	2012
8-Speed Dual Wet Clutch Automated Manual Transmission	8DCT-wet	11	Medium	2024	2012
6-Speed Manual Transmission	M6	12	Low	2018	2012
Electric/Electrohydraulic Power Steering	EPS	12	Low	2018	2015
Improved Accessories 1	IAcc1	12	Low	2018	2015
Improved Accessories 2	IAcc2	12	Low	2018	2015
12-Volt Start-Stop: Small & Medium Car	12VSS-sc	16	Medium	2018	2015
12-Volt Start-Stop: Large Car & Small/ Large MPV	12VSS-lc	16	Medium	2018	2015
12-Volt Start-Stop: Truck	12VSS-trk	16	Medium	2018	2015
Integrated Motor Assist/Integrated Starter Generator	IMA/ISG	16	High1	2018	2015
Powersplit HEV: Battery	PSHEVb	24	High1	2018	2017
Powersplit HEV: Non-Battery Components	PSHEVnb	11	High1	2018	2015
2 Mode HEV: Battery	2MHEVb	24	High1	2018	2025
2 Mode HEV: Non-Battery Components	2MHEVnb	11	High1	2018	2012
P2 HEV: Battery	P2HEVb	24	High1	2024	2017
P2 HEV: Non-Battery Components	P2HEVnb	11	High1	2018	2012
PHEV: Battery	PHEVb	19	High2	2024	2025
PHEV: Non-Battery Components	PHEVnb	11	High1	2018	2012
EV: Battery	EVb	19	High2	2024	2025
EV: Non-Battery Components	EVnb	21	High2	2024	2017
Mild HEV/Belt Starter Generator: Battery	MHEVb	24	High1	2024	2017
Mild HEV/Belt Starter Generator: Non-Battery Components	MHEVnb	11	Medium	2018	2012
In-Home EV Charger	Charger	19	High1	2024	2025
In-Home EV Charger Installation Labor	ChargerIL	6	None	2099	2025
Low Rolling Resistance Tires 1	LRR1	6	Low	2018	2010
Low Rolling Resistance Tires 2	LRR2	25	Low	2024	2021
Low-Drag Brakes	LDBrakes	6	Low	2018	2010
Secondary Axel Disconnect	SAX	12	Low	2018	2015
Aerodynamic Drag Reduction 1	Aero1	12	Low	2018	2015
Aerodynamic Drag Reduction 2	Aero2	12	Medium	2024	2015
Mass Reduction, Through 15%	MR1	21	Low	2018	2017
Mass Reduction, 15% Through 25%	MR2	21	Medium	2024	2017
Mass Reduction, Greater Than 25%	MR3	21	High1	2024	2017
VCR (2)	VCR	19	High2	2024	2025
Baseline ICE Engine (3)	BaseICE	6	Low	2010	2010

(2) "Manufactured" based on least advanced learning, highest-complexity ICM with a base year of 2025 to fit 2015 FEV ICCT data analysis.
(3) "Manufactured" based on mature learning, low-complexity ICM to fit the ICE engine elimination credit of the 2016 ICCT non-ICE costing analysis.

2015 FEV ICCT data include base-year DMC. The requisite learning factor and ICMs are derived from the EPA light-duty GHG technical support document. Thus, each of the 2015 FEV ICCT technologies must be mapped to one of the EPA technologies presented in Tables 15a and 15b. This does not mean that the 2015 FEV ICCT data are replaced by the EPA data in any way, simply that the learning- and indirect-cost functions employed by the EPA are applied to the independent 2015 FEV ICCT data.

In most cases, there is a one-to-one relationship between 2015 FEV ICCT and EPA technologies. However, this is not always the case. The specific mapping assignments employed in this analysis are as follows:

Engine downsizing: Engine downsizing costs in the 2015 FEV ICCT data are disaggregated into three components, a direct injection component, a turbocharging component, and a downsizing component. This disaggregation is performed using detailed data presented in the 2015 FEV ICCT data report so that there is no loss in precision. Not all technology packages that consider downsizing will include all three components. Diesel downsizing packages, for example, include zero direct injection and zero turbocharging costs, while gasoline downsizing packages generally include all three components. Because a zero-cost component will evaluate to zero regardless of the learning curve and ICMs assumed, there is no error introduced by assigning a universal mapping function to these data regardless of whether one, two, or three non-zero costs are applicable. For the direct injection component, this analysis uses learning curve and ICM assignment key sGDI-IL (stoichiometric gasoline direct injection for an inline engine) as delineated in Table 15a. Some of the baseline engines are V configuration engines, but all downsized engines are inline. The turbocharging cost component is mapped to the EPA TC27 learning curve and ICM data. Finally, the downsizing cost component is mapped to the DSizeX learning curve and ICM data.

Turbocharger technology: Turbocharger technology that is included in the 2015 FEV ICCT data independent of engine downsizing is also mapped to the EPA TC27 learning curve and ICM data. Some of the less-advanced turbocharger options reflected in the 2015 FEV ICCT data may well be of a lesser complexity than TC27 EPA technology, but the use of a TC27 mapping ensures that indirect costs are not reduced prematurely (through the use of an extended "near term" ICM definition). Other than the near-term definition, all EPA learning and ICM data for turbocharger technology are identical.

Valvetrain technology: Valvetrain technology included in the 2015 FEV ICCT data is mapped to DVVL-4, DVVL-6, or ICPinline EPA learning curve and ICM data. The DVVL-4 and DVVL-6 assignments are applied to gasoline inline and V configuration valvetrain technology, respectively, while the ICPinline assignment is applied to diesel valvetrain technology. For gasoline vehicles, the 2015 FEV ICCT data include both cam phasing (dual) and lift technology implemented both independently and in combination. The EPA has separate timing and lift technologies, but the learning and ICM data for dual cam phasing is identical to that for valve lift technology, so there is no error associated with assigning both to the same EPA lift key. For diesel vehicles, the 2015 FEV ICCT data include an exhaust cam phaser, while the EPA data are applicable to an intake phaser. However, the underlying phaser technology is identical, so there is no error in assigning intake learning and ICM profiles to exhaust technology.

EGR technology: The 2015 FEV ICCT data includes various cooled exhaust gas recirculation (EGR) configurations as well as dedicated EGR technology. All are mapped to EPA CoolEGR learning curve and ICM data. Functionally, the dedicated EGR system is more complex and includes supercharger and aftercooler technology, but because EPA's learning and ICM factors for advanced turbocharger technology (EPA does not include supercharging as a separate technology) are identical to those of cooled EGR technology, application of the cooled EGR learning and ICM data introduces no error.

Friction reduction technology: Friction reduction costs in the 2015 FEV ICCT data are disaggregated into two components, an internal engine friction component and a cooling system component. This disaggregation is performed using detailed data presented in the 2015 FEV ICCT data report so that there is no loss in precision. The engine friction component cost is mapped to the EPA EFR2-3, EFR2-4, or EFR2-6 learning curve and ICM data in accordance with whether the applicable technology package is associated with a 3-, 4-, or 6-cylinder engine, respectively. The cooling system component is mapped to the EPA IAcc2 learning curve and ICM data.

Hybridization technology: Hybridization costs in the 2015 FEV ICCT data are disaggregated into two components, a battery system component and a "non battery" system component, the latter of which includes all costs except those associated with the battery. This disaggregation is performed using detailed data presented in the 2015 FEV ICCT data report so that there is no loss in precision. Not all technology packages that consider hybridization will include a battery cost. Start-stop systems include only "non battery" costs. However, because a zero-cost component will evaluate to zero regardless of the learning curve and ICMs assumed, there is no error introduced by assigning a universal mapping function to these data regardless of whether one or both costs are applicable. Start-stop system costs are mapped to 12VSS-sc (Classes B and C), 12VSS-lc (Classes D, E, and SUV), or 12VSS-trk (LCVs) learning curve and ICM data. P0 system costs are mapped to MHEVb and MHEVnb learning curves and ICM data for battery and non-battery costs, respectively. P2 system costs are mapped to P2HEVb and P2HEVnb learning curves and ICM data for battery and non-battery costs, respectively.

Transmission technology: The 2015 FEV ICCT data includes various transmission configurations. Six-speed manual transmission costs are mapped to the EPA M6 learning curve and ICM data. Seven- and 10-speed dual-clutch automated manual transmission costs are respectively mapped to EPA 8DCT-dry and 8DCT-wet learning curve and ICM data. Although the number of included gears is not identical in this mapping, the complexity of the technology is equivalent so there is no introduced error.

VCR technology: The 2015 FEV ICCT data include several technology packages that incorporate VCR technology. No equivalent data are available in the EPA learning and ICM dataset. VCR technology also differs from other technology in the 2015 FEV ICCT dataset in that it assumes a base DMC year of 2025 (as compared with 2014 for the other evaluated technology). A set of EPA-equivalent learning and ICM data were developed by assigning a technology complexity and learning potential equal to that of EV battery technology (which will result in substantially higher DMCs for years prior to 2025 and assignment of the highest ICMs associated with the EPA data). In other words, this analysis assigns conservatively high costs to VCR technology.

Aftertreatment technology: The 2015 FEV ICCT data include technology packages that include various improved aftertreatment technologies. As with VCR technology, the EPA learning and ICM dataset includes no equivalent technology. The 2015 FEV ICCT data include gasoline aftertreatment costs in the engine downsizing costs, but there is no mechanism included in the associated report with which to disaggregate the cost data. Thus gasoline aftertreatment costs are inherently assigned the same learning and ICM data as described above for engine downsizing technology. Diesel aftertreatment costs are reported separately in the 2015 FEV ICCT data and are mapped to EPA CoolEGR learning and ICM data (relatively flat learning with a medium-complexity ICM). The use of the CoolEGR assignment key is not intended to imply any relationship between EGR and aftertreatment technology, but simply serves as a reasonable complexity-based surrogate for aftertreatment-specific learning and ICM assumptions.

Supplemental data sources were utilized to estimate mass reduction technology costs (2012 FEV ICCT data) and aerodynamic drag and rolling resistance technology costs (EPA cost data). As presented in Section 3 above, both data sources explicitly include learning and ICMs for future year retail-level cost evaluation. The aerodynamic drag and rolling resistance technology cost data are derived from the same EPA reference (EPA, 2012) as the learning curve and ICM data presented in this section, so both are internally consistent. The mass reduction learning and ICM data were also derived in the 2012 FEV ICCT data analysis from the same source. No additional processing of the learning and indirect cost assumptions for either is required.

5. TEST FLEXIBILITY ADJUSTMENTS TO FEV CO_2 ESTIMATES

In September 2015, the ICCT and Element Energy Limited released a study on the differential between test cycle CO_2 and CO_2 emitted during real-world driving. (EEL, 2015) This study identified a range of contributions that lead to substantial differences between certification (i.e., test cycle) and real-world emissions. Some of these contributions are due to differences in vehicle operations, but others result from flexibilities inherent in the certification procedures, including road-load simulation and equipment-optimization parameters. These latter flexibilities result in certification emissions from a given vehicle being lower than *emissions from that same vehicle tested over the same test cycle* using more realistic road-load and operational equipment settings. This difference accrues to the vehicle manufacturer as "windfall" CO_2 emission reductions and to the extent such reductions are not reflected in the 2015 FEV ICCT data, the CO_2 emissions reported for vehicle technology packages in that dataset will be higher than emissions from those same technology packages when tested by manufacturers during certification.

In their vehicle simulation work, FEV took advantage of the same test flexibilities available to vehicle manufacturers under current testing procedures.[11] They did this for both the NEDC and WLTP test cycles. However, the ICCT and Element Energy work finds that the impacts of test flexibility are expected to increase over time, so that future flexibility impacts will exceed those considered by FEV in their 2015 work. It is perhaps important to emphasize that the ICCT and Element Energy work explicitly investigates the difference between certification and real-world emissions, not the difference between certification emissions in one year versus another. However, this latter metric can be extracted from the ICCT and Element Energy data by taking the ratio of two certification to real-world metrics. Because the *real-world* emissions of a given vehicle do not change with test-cycle or changing test-cycle flexibility, the impacts of flexibility on *certification* emissions can be readily isolated through the relationship between two ICCT and Element Energy ratios as follows:

11 While a complete discussion of such flexibilities is outside the scope of this paper, allowances related to beneficial tire selection and inflation, beneficial road-load determination conditions, beneficial vehicle test weight (excluding beneficially specified optional equipment), beneficial vehicle conditioning, and beneficial test and test equipment tolerances are among the various mechanisms that allow vehicle manufacturers to minimize test-specific CO_2 emissions.

$$\text{IF } RW_1 = RW_2, \frac{RW_1}{Test_1} \times \frac{Test_2}{RW_2} \times \frac{Test_2}{Test_1}$$

Where: RW_1 = Real-World Emissions under Test Cycle 1,
RW_2 = Real-World Emissions under Test Cycle 2,
$Test_1$ = Test-Cycle Emissions under Test Cycle 1, and
$Test_2$ = Test-Cycle Emissions under Test Cycle 2.

Using this approach and evaluating the ICCT and Element Energy data *only* for those portions of the real-world to certification emissions differential traceable to road-load and dynamometer parameters, the following real-world to certification differentials are calculated:

NEDC in 2014: 1.2682
NEDC in 2020: 1.3299
WLTP in 2020: 1.0930
WLTP in 2025: 1.1632

The test flexibilities reflected in the 2015 FEV ICCT data are consistent with those of the 2014 NEDC and 2020 WLTP ratios. So by 2020, the expected increase in NEDC test flexibility (for constant real-world emissions) will result in 2020 NEDC emissions being about 4.6% lower than 2014 NEDC emissions (1.2682/1.3299). In other words, the *identical technology package* will garner 4.6% lower emissions in 2020 (over the NEDC) than it did in 2014. For the WLTP, 2025 emissions are expected to be about 6.0% lower than those in 2020 (1.0930/1.1632).

To properly account for this evolution, this analysis (unless otherwise indicated) adjusts 2015 FEV ICCT data for CO_2 emissions over the NEDC downward by 4.6% for all evaluation years after 2019. Downward adjustments for evaluation years between 2014 and 2020 are based on linear interpolation between no adjustment in 2014 and a 4.6% adjustment in 2020. Similarly (unless otherwise indicated), 2015 FEV ICCT data for CO_2 emissions over the WLTP are adjusted downward by 6.0% for all evaluation years after 2024. Downward adjustments for evaluation years between 2020 and 2025 are based on linear interpolation between no adjustment in 2020 and a 6.0% adjustment in 2025.

6. PERFORMANCE-BASED ADJUSTMENTS TO FEV CO_2 ESTIMATES

As indicated above, the 2015 FEV ICCT data are generally developed on the basis of constant performance.[12] There are, however, two exceptions. First, engine downsizing was not implemented in conjunction with performance-improving P2 hybrid technology. Second (and similarly), engine downsizing was also not implemented in conjunction with energy demand-reducing mass reduction technology. In an effort to address these omissions, this analysis investigated methods to implement adjustments to the 2015 FEV ICCT CO_2 data for technology packages that include either P2 hybridization or mass reduction. A successful adjustment methodology was ultimately developed for mass reduction, but no satisfactory approach was derived to adjust the CO_2 estimates for P2 hybridization technology. Therefore, unless otherwise indicated, this analysis implements adjustments to the 2015 FEV ICCT CO_2 data only for technology packages that include mass reduction. Despite a failure to develop a reliable adjustment for hybridization technology, we continue to believe that CO_2 reduction beyond that reflected in the 2015 FEV ICCT data for such technology is appropriate. It is simply not reflected in this analysis.

12 Defined as constant power and top speed.

The biggest impediments to the derivation of a hybridization adjustment are the transmission adjustments (e.g., modified gear ratios and shift schedule) that are included in the 2015 FEV ICCT hybrid technology packages in lieu of downsizing. Such adjustments must be "factored out" of the 2015 FEV ICCT data to implement a reliable downsizing adjustment. An estimate of the engine downsizing potential and associated CO_2 impacts due to hybridization was developed using a CO_2 technology data visualization tool (DVT), an interactive database developed by Ricardo Inc., as an integral component of vehicle-simulation modeling performed by that organization for the ICCT in 2012. (Ricardo, 2012; Ricardo, 2013) The DVT allows CO_2 emissions to be estimated for a user-selected set of input parameters, including vehicle class, vehicle architecture, engine technology, transmission technology, engine displacement, final drive ratio, rolling resistance characteristics, aerodynamic drag characteristics, test weight, engine efficiency, and electric drive motor size. However, adjusting the DVT impact estimates for the effects of the transmission tuning inherent in the 2015 FEV ICCT data requires knowledge of the incremental effects of such tuning, and such data are not available. In the absence of these data and the associated risk of "over adjusting" the 2015 FEV ICCT hybrid technology impact estimates, it was decided to simply retain such estimates at their reported values. Until data become available with which to untangle the transmission tuning and hybrid technology effects, the hybrid technology packages included in the 2015 FEV ICCT data are likely to underestimate associated CO_2 reductions.

Engine downsizing adjustments for vehicle mass reduction technology are derived from the physical equations of motion. Given a specified vehicle (i.e., a vehicle with defined mass, rolling resistance, aerodynamic drag, and accessory load characteristics) and a specified driving cycle, it is possible to precisely calculate the tractive energy required for the vehicle to execute the driving cycle. The ratio of such energy requirements for changes in any of the vehicle specifications—in this case mass—can be taken as a direct indicator of changes in associated fuel consumption (and, by extension, CO_2 emissions). Such an approach inherently assumes that engine displacement changes with the changing vehicle specification and that the secondary effects of such changes (e.g., cylinder volume to surface area ratio) are reasonably small relative to the primary energy demand effect. It is reasonable to expect that such an assumption is valid for the modest mass changes evaluated in this analysis.

Because the relationship between the various road-load parameters (i.e., mass, rolling resistance, and aerodynamic drag) varies across vehicles, it is appropriate to evaluate the energy impact effect over a range of vehicles. For this analysis, the effects for six vehicles ranging from a small B class vehicle to a large pickup truck were evaluated for mass reductions of both 10% and 20%. The results of this evaluation indicated an expected change in CO_2 emissions of 0.645 (0.59–0.69)% and 0.574 (0.51–0.62)% per % change in vehicle mass for vehicles executing the NEDC and WLTP cycles, respectively. Because these effects reflect the impact of both mass reduction and engine downsizing, they cannot be applied directly to the 2015 FEV ICCT data, because those data already include the mass reduction impacts. Moreover, because the mass reductions reflected in the 2015 FEV ICCT data are variable with regard to their magnitude, the derived adjustment factor must be continuous in nature so that it can be applied to specific technology packages in accordance with the specific mass reductions associated with each. To generalize the CO_2 effects of mass reduction as reflected in the 2015 FEV ICCT 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 % change in vehicle mass for vehicles executing the NEDC, WLTP low road-load, and WLTP high road-load cycles, respectively.

Using the derived relations, a generalized adjustment for the omitted effect of engine downsizing can be developed. The adjustment is mathematically expressed as follows:

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

Where: AdjFac = CO_2 Multiplier,
PerPct = Change in CO_2 per % Change in Mass,
Physics = Effect Based on the Physics of Motion,
Modeled = Effect Observed in the 2015 FEV ICCT Data, and
PctMassRed = % Change in Mass.

While this analysis evaluates the function on a continuous basis in accordance with the specific mass reduction (if any) associated with a given technology package, the derived CO_2 multipliers for a 10% mass reduction are 0.980, 0.989, and 0.987 for the NEDC, WLTP low road-load, and WLTP high road-load cycles, respectively. The respective derived multipliers for a 20% mass reduction are 0.958, 0.976, and 0.972. Nominally, these reflect the ranges included in the 2015 FEV ICCT data (actual changes can vary by a few % based on the mass effects of other included technologies), so that total CO_2 adjustments generally range from 1% to 2% for the nominal 10% reductions and 2% to 4% for the nominal 20% reductions.

Finally, this analysis will ultimately be augmented with scenarios that exclude mass reduction technology as a viable CO_2 compliance strategy (to simulate the maximum effect on compliance costs of regulatory structures that vary CO_2 standards with mass). For such analysis scenarios, the average mass effect inherent in the 2015 FEV ICCT data will be utilized to "factor out" the simulated CO_2 effects of mass reduction. The adjustment is mathematically expressed as follows:

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

Where: AdjFac = CO_2 Multiplier,
PerPct = Change in CO_2 per % Change in Mass,
Modeled = Effect Observed in the 2015 FEV ICCT Data, and
PctMassRed = % Change in Mass.

As with the physics of motion adjustment, this analysis evaluates the function on a continuous basis in accordance with the specific mass reduction (if any) associated with a given technology package. However, 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 2015 FEV ICCT data, so that total CO_2 adjustments generally are about 5% for the nominal 10% reductions and 10% for the nominal 20% reductions.

It is important to note that all of the CO_2 adjustments are "average" in nature. The majority of the technology packages included in the 2015 FEV ICCT database consist of multiple varying technologies, so that the precise effects of any one specific technology cannot be isolated. Thus, while this analysis applies average factors to adjust or eliminate the effects of a given technology (specifically, engine downsizing and mass reduction), the actual effects may be moderately different so that the adjustments, although reasonably accurate, are not precise.

7. PERFORMANCE-BASED ADJUSTMENTS TO FEV AND NON-ICE COST ESTIMATES

Costs are estimated in the 2015 FEV ICCT and the 2016 ICCT non-ICE data by assigning 100% of the cost of technology to CO_2 reduction. However, there are both co-benefits and other market drivers for many technologies that also reduce CO_2. Such co-benefits include improved performance, reduced noise, improved handling, improved braking, enhanced safety, and increased durability. For example, turbocharged direct injection (gasoline) and hybridization (gasoline and diesel) boost low-end torque performance, which is considered an attractive benefit by most consumers. Diesel engines possess inherent low-end torque benefits as well, but all 2015 FEV ICCT diesel data are incremental to a diesel baseline so that there is no significant performance enhancement associated with the diesel engine technology evaluated. This analysis conservatively estimates the following torque benefits for evaluated technologies (actual co-benefits may be much higher as evidenced by the popularity of turbocharged gasoline direct injection engines):

- Turbocharged gasoline direct injection: 5%
- Onboard-only charged full hybrid: 5%
- PHEVs with less than 40 kW motor/battery: 5%
- Other PHEVs: 10%
- BEVs: 10%
- FCVs: 10%

Similarly, the automated shifting capability of dual-clutch transmission technology offers significant performance benefits. In keeping with the conservative nature of costing assumptions, this analysis assumes only a 5% co-benefit value. Electric drive technology can significantly reduce noise. While the degree of reduction is dependent on the all-electric range (AER) of the technology, a conservative estimate of the value of the noise benefit might be zero for full onboard-only charged HEVs, but 5% for PHEVs and 10% for BEVs and FCVs. Mass reduction technology leads to substantial handling and braking benefits. While the value of such benefits can be equally substantial, this analysis conservatively assigns only a 10% co-benefit value. Finally, both PHEV and BEVs offer a home-refueling benefit. While the value of this benefit is more uncertain, it is reasonable to assume a marginal co-benefit value of 5%.

Combining the various co-benefits yields net CO_2 cost fractions of:

- Turbocharged gasoline direct injection: 95%
- Onboard-only charged full hybrid: 95%
- PHEVs with less than 40 kW motor/battery: 85%
- Other PHEVs: 80%
- BEVs: 75%
- FCVs: 80%
- Vehicle mass reduction: 90%
- Dual-clutch automated manual transmission: 95%

Unless otherwise indicated, this analysis adjusts the technology costs estimated in the 2015 FEV ICCT data and the 2016 ICCT non-ICE data by the indicated fractions. For example, the CO_2 reduction cost of turbocharged gasoline direct-injection technology is taken as 95% of the 2015 FEV ICCT data cost. Generally, as discussed above, we believe the adjustments to be conservative. For example, a comparative study on EU

CO_2 reduction potential discounted costs for technologies such as variable valve timing, variable valve lift, dual-clutch automated manual transmissions, and both mild and full onboard-only charged HEVs by a full 25% (as compared with either zero or 5% in this analysis). (TNO, 2006) These effects are further exemplified by the now-common practice for manufacturers to market the "more fun to drive" characteristics of advanced technology vehicles.[13]

8. OFF-CYCLE CO_2 REDUCTION CREDITS

The 2015 FEV ICCT data include no consideration of off-cycle CO_2 reduction credits available to vehicle manufacturers under the current EU NEDC-based requirements and expected to be available under the forthcoming WLTP-based requirements. Off-cycle technology reduces vehicle engine energy demand by either reducing the amount of energy required to perform a function or deriving the required energy from a secondary source (e.g., solar, heat recovery). In either case, the engine would have to provide the equivalent energy in the absence of the off-cycle technology. It is this equivalent energy savings that constitute off-cycle credits.

A recent report developed by Ricardo-AEA for the EU Directorate-General for Climate Action included emissions benefit and cost estimates for 21 off-cycle technologies. (Ricardo, 2015) Specific evaluated technologies were: LED lighting, solar roof cooling, solar roof battery charging, engine compartment encapsulation, radar adaptive braking, a high-efficiency alternator, improved air-conditioning systems, a heat pump, an EV heat pump, active seat ventilation, advanced cruise control, solar glazing, eco-roll/coasting, active engine and transmission warmup, active aerodynamics (3–5% drag reduction), tire pressure monitoring systems, a fuel-quality sensor, model-based control of engine and aftertreatment systems, a cold storage evaporator, heat storage, and localized air-conditioning. Ricardo-AEA also considered the off-cycle benefits of six additional technologies but could not quantify reliable cost estimates.[14]

This analysis utilized the benefit and cost estimates for 20 of the 21 Ricardo-AEA off-cycle technologies to estimate the costs of off-cycle emissions credits and their effect on compliance costs for various levels of CO_2 standards. The only omitted technology was an EV heat pump because that technology is specific to non-ICE vehicles, which are credited with zero CO_2 emissions under current (and presumed future) compliance policy. For each technology, Ricardo-AEA estimated the % reduction in *real-world* CO_2 emissions and the cost (both DMC and TC) of the technology in 2015, 2020, 2025, and 2030. This analysis rank ordered the 20 technologies, from most to least cost-effective, in terms of 2030 DMC per % CO_2 reduction. The technologies were then aggregated into 20 technology packages, starting with a stand-alone package for the most cost-effective technology and then layering less and less cost-effective technologies, so that technology package two consisted of the two most cost-effective technologies, package three consisted of the three most cost-effective technologies, etc.

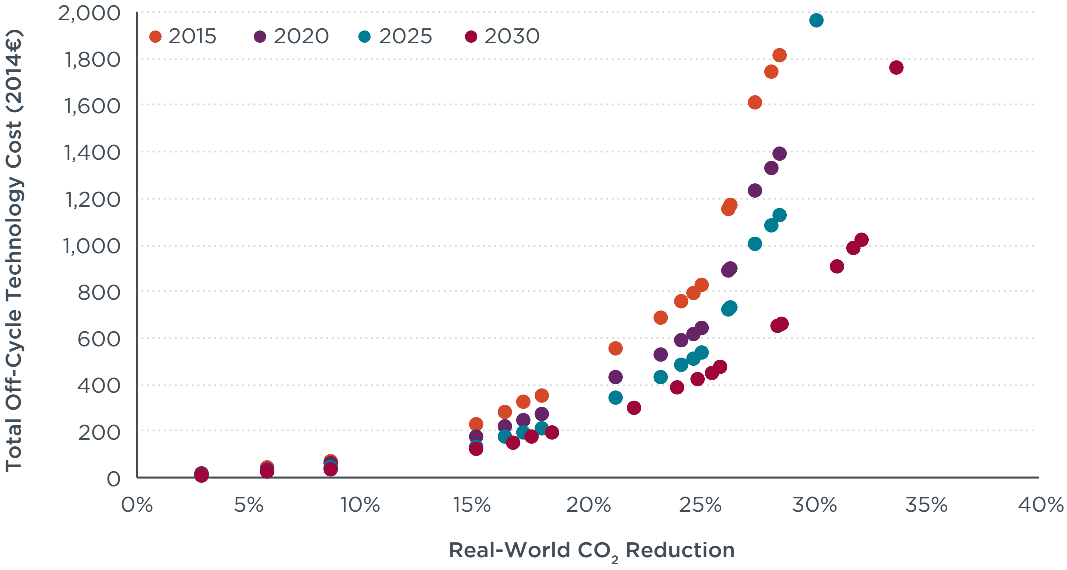
As shown in Figure 3, this results in a pseudo cost curve for off-cycle technology. The fact that Figure 3 does not present the resulting data as continuous functions is deliberate as the

13 See, for example, from Ford, "The available EcoBoost engines combine three different technologies—turbocharging, direct injection and twin independent variable cam timing (Ti-VCT)—designed to enhance performance." (Ford, 2016) Or from Hyundai, "Ioniq gives you the power of choice. Each model, all-electric, hybrid, and plug-in hybrid, is based on a dedicated vehicle platform designed to enhance efficiency, comfort, and handling. Plus, our Blue Drive® technology gives you lower pollution and higher performance." (Hyundai, 2016) Or from Toyota, "What if you found a vehicle that had style, was fun to drive, and had excellent efficiency? What if you didn't have to choose between good for all and good for you? Prius Prime encompasses this vision, where a vehicle can be as inspiring to the human spirit as it is mindful of the world around us." (Toyota, 2016) These are but a sampling of the myriad indicators of the performance marketing associated with advanced technology vehicles.

14 The six technologies were an improved power steering pump, GPS battery management, regenerative shock absorbers, solar reflective paint, GPS routing, and a second level of active aerodynamics (an additional 3–5% drag reduction beyond an initial 3–5% drag reduction).

data are treated as discrete options in this analysis. It should be recognized that the Ricardo-AEA data are developed at a vehicle class-specific level of detail. Figure 3 specifically depicts cost estimates for the lower-medium-car segment, but similar data is available for small cars, upper-medium cars, large cars, small LCVs, medium LCVs, and large LCVs. It should also be recognized that the cost axis in Figure 3 is capped to improve readability for lower-cost options. The data actually extend to €6,192, €4,648, €3,546 and €2,965 at 32, 32, 32, and 35.4% CO_2 reductions in 2015, 2020, 2025, and 2030, respectively.

Figure 3. Off-Cycle Technology Package Benefits and Costs (2014€, Lower-Medium Car)



For this analysis, the Ricardo-AEA classes are mapped to 2015 FEV ICCT data classes as follows. The 2015 FEV ICCT B, C, D, E, and SUV class data are mapped to Ricardo-AEA small car, lower-medium car, upper-medium car, large car, and large car data, respectively. The 2015 FEV ICCT LCV class data are mapped to an aggregate of the three Ricardo-AEA LCV classes. The three Ricardo-AEA LCV segments are aggregated using assumed market shares of 10%, 29%, and 61% for small, medium, and large LCVs, as reported in Figure 2.5 of the referenced Ricardo-AEA source document (Ricardo, 2015). Data for evaluation years other than 2015, 2020, 2025, and 2030 are based on linear interpolation between the two nearest bounding years.

Currently, NEDC requirements cap off-cycle emissions credits at seven grams per kilometer. To evaluate the cost of off-cycle credits for differing levels of emission standards, it is necessary to generalize the Ricardo-AEA data. Because fuel input energy (and, by extension, CO_2 emissions) for a given load decline as vehicle and engine efficiency increase, the absolute benefit of off-cycle technology declines with increasing on-cycle efficiency. In effect, as on-cycle efficiency increases, off-cycle technology provides constant *relative* and decreasing *absolute* benefits. In other words, the absolute benefit of a constant percentage reduction declines as vehicle and engine efficiency increases. This is perhaps easiest to understand when one considers that the amount of fuel input energy required to perform whatever function off-cycle technology is displacing will decrease as the conversion efficiency of fuel energy increases. The "value" of a static off-cycle technology declines as on-cycle efficiency increases. So, as CO_2 standards become more stringent (forcing increases in vehicle and/or engine efficiency), it will take progressively more off-cycle technology to generate a constant seven gram per kilometer credit. Because current NEDC requirements are silent on whether the seven gram credit cap is based on NEDC-equivalent or real-world equivalent emissions, there is some ambiguity in the mechanism required to generalize the Ricardo-AEA off-cycle data.

Generally, for a given certification test procedure (such as the NEDC), real-world (RW) emissions are higher than certification (C) emissions, but RW scales with C (i.e., $RW_1 = XC_1$ and $RW_2 = XC_2$) so that RW_2/RW_1 equals C_2/C_1 and a Y percentage reduction in RW equals a Y percentage reduction in C. Under such conditions, the fractional emissions level required to get a specific absolute off-cycle emission-reduction credit (Z) is equal to either (RW-Z)/RW or (C-Z)/C. The NEDC rules do not appear to explicitly make the requisite distinction as to which situation actually applies. For a non-unity scaling factor X, a Z gram real-world credit would generate an equivalent Z/X gram certification reduction, while a Z gram certification credit would require an equivalent XZ gram real-world reduction.

Because the Ricardo off-cycle data are in percentage terms and that effect is constant (i.e. independent of X) for both RW and C, either credit option can be assumed. While the more "correct" solution would be to require NEDC equivalence in the calculation of Z (i.e., Z as applied to C equals Z as calculated for RW divided by the scaling factor X). Because the NEDC rules mention no such adjustment, one can assume that Z applies to either a RW base or a C base. Either assumption can be used to generalize the Ricardo percentage reductions for a given NEDC standard, but the net result is two somewhat different emission-reduction requirements (and, therefore, somewhat different compliance costs). Regardless, the basic generalization approach is the same. Namely, because the Ricardo reductions are in RW percentage terms and (assuming off-cycle emission credits are cost-effective to seven grams) the given NEDC standards would be "with the off cycle" credit applied, the desired relationship between these two parameters is "what RW percentage reduction is required to generate a specific absolute (seven-gram) NEDC off-cycle credit given a variable NEDC standard with the credit in place."

Assuming the following definitions:
RWPR = Percentage Reduction in RW CO_2 Required to Generate a Z Gram NEDC Credit.
RW_1 = Real-World CO_2 Emissions without an Off-Cycle Credit.
RW_2 = Real-World CO_2 Emissions with an Off-Cycle Credit.
C_1 = NEDC CO_2 without an Off-Cycle Credit.
C_2 = NEDC CO_2 with an Off-Cycle Credit.
$RW_1 = (X)C_1.$
$RW_2 = (X)C_2.$

$RWPR = 1 - (RW_2/RW_1)$, where RWPR is expressed as a positive for reductions (consistent with the Ricardo-AEA data).

The RWPR required to generate a Z gram RW credit is:

$$RW_2 = RW_1 - Z$$

$$\text{so, } RWPR = 1 - \frac{RW_2}{(RW_1)} = 1 - \frac{RW_2}{(RW_2 + Z)} = 1 - \frac{XC_2}{(XC_2 + Z)}$$

And the RWPR required to generate a Z gram C credit is:

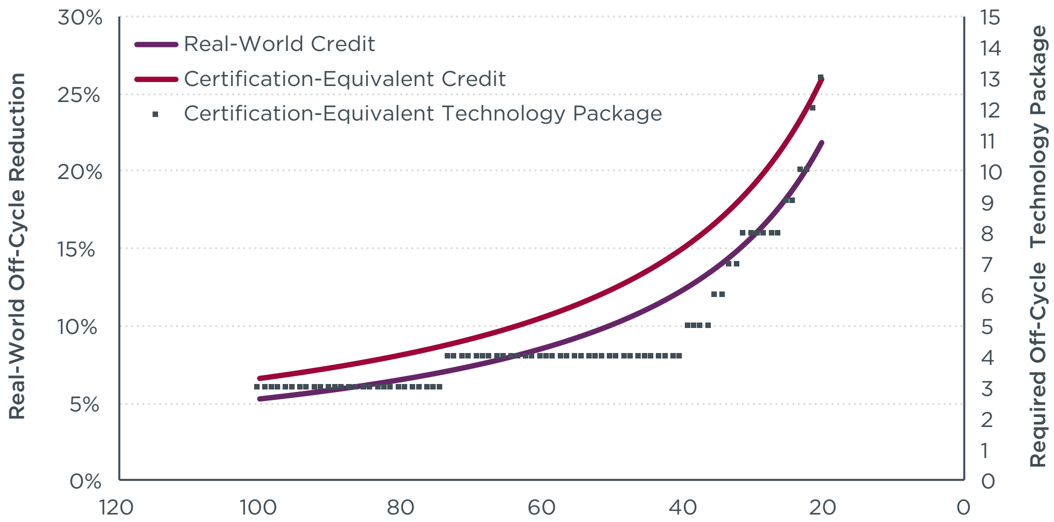
$$C_2 = C_1 - Z$$

$$\text{so, } RWPR = 1 - \frac{RW_2}{(RW_1)} = 1 - \frac{XC_2}{(XC_1)} = 1 - \frac{C_2}{(C_1)} = 1 - \frac{C_2}{(C_2 + Z)}$$

Only when X equals unity (i.e., RW emissions equal certification emissions) are the two RWPR expressions identical. NEDC rules do not explicitly mention a scaling factor X, but they do cite the NEDC as the applicable driving cycle reference and thus may implicitly assume an X factor for benefits derived using alternative cycles. For this reason, this analysis assumes that Z applies to the "certification side." The certification side Z option requires larger (and thus more costly) off-cycle reductions for a given Z (seven grams in this analysis), so it is more conservative than the RW Z option and thus more appropriate given the described uncertainty in NEDC specifications.

Figure 4 graphically depicts the generalized off-cycle credit algorithm employed in this analysis. Note that the figure depicts the differential between the RW emission reductions required to generate a seven-gram-per-kilometer certification credit using both the RW and certification-side crediting algorithms. As indicated, the certification-side algorithm always requires greater RW emission reductions because the seven-gram credit explicitly includes a correction for the difference between RW emissions and certification emissions. *Both approaches are depicted solely for illustrative purposes, the higher certification-equivalent reductions are used without exception in the analysis*. The figure also presents the off-cycle technology package required to generate the necessary emission reductions and, as indicated, the packages are treated discretely in that they must provide at least the required emission reductions. If one package does not provide the requisite reduction, the next package is selected regardless of the magnitude of excess reduction it may provide. Once the necessary off-cycle package for a given certification standard is identified, the appropriate costs are taken from the Ricardo-AEA data in accordance with the specific vehicle class and evaluation year. The required on-cycle emission standard is then adjusted upward by seven grams to determine the cost of required on-cycle technology. Total compliance cost equals the sum of on- and off-cycle technology cost.

Figure 4. Off-Cycle Technology Package Selection for Seven-Gram Credit



9. 2016 ICCT NON-ICE DATA

As indicated in Section 1, cost estimates for non-ICE technology are generally taken from a recently released ICCT study on the cost of such technology in Europe in the 2020–2030 time frame. (ICCT, 2016) These data, generally referred to as the *2016 ICCT non-ICE data* in this paper, include a full set of direct manufacturing cost estimates (relative to a baseline current-era ICE vehicle) for a range of battery-only electric vehicles (BEVs), a range of plug-in hybrid electric vehicles (PHEVs), and hydrogen fuel cell vehicles (FCVs). Evaluated BEVs consist of vehicles with an all-electric range (AER) of 100, 150, 200, and 300 miles, while evaluated PHEVs consist of vehicles with an AER of 10, 20, 30, 40, and 60 miles.[15] 2016 ICCT non-ICE data include DMC estimates for 2015, 2020, 2025, and 2030. Estimates

15 AERs are expressed in miles rather than kilometers to reflect current convention and allow direct comparison with the referenced 2016 ICCT non-ICE data source document (ICCT, 2016). The 2016 ICCT non-ICE data is explicitly developed such that the named AER for the various considered PHEVs is the NEDC AER. In other words, BEV-100, BEV-150, BEV-200, BEV-300, PHEV-10, PHEV-20, PHEV-30, PHEV-40, and PHEV-60 vehicles have, by definition, an NEDC AER of 100, 150, 200, 300, 10, 20, 30, 40, and 60 miles, respectively (160.93, 241.40, 321.87, 482.80, 16.09, 32.19, 48.28, 64.37, and 96.56 kilometers).

for other years are derived through interpolation. Total (retail-level) costs were estimated by applying appropriate indirect cost multipliers taken from the same EPA reference materials used to estimate ICE technology costs (EPA, 2012; as described above). The specific multipliers used are discussed further below. Finally, the 2016 ICCT non-ICE data are only directly applicable to a class C vehicle, so that cost estimates for other classes were derived as part of this analysis (as described in the paragraphs that follow).

It is also important to recognize that the 2016 ICCT non-ICE data focus solely on vehicle technology costs. The data do not include either non-ICE infrastructure costs or offsetting savings due to such influences as differential electricity and petroleum fuel costs that might reduce the total cost of ownership of non-ICE vehicles. Assessments of such issues can be developed from the vehicle technology cost estimates described in this paper, but are not considered herein.

To derive non-ICE costs for vehicles other than class C vehicles, 2015 FEV ICCT data for P2 HEVs was analyzed to derive independent scaling factors for batteries and motors.[16] Essentially, the relationship between P2 HEV battery and motor costs across classes is assumed to provide a reasonable indicator of the cost relationship for those same components across non-ICE classes. Unfortunately, the 2015 FEV ICCT data does not include P2 technology in every vehicle class. As a result, the size and cost of P2 technology in both the B and C classes had to first be estimated. This was accomplished by first investigating the relationships between P2 battery capacity and ICE power and P2 motor power and ICE power for those classes for which the 2016 FEV ICCT data included P2 HEV technology (classes D, E, and SUV). The LCV class was excluded due to unique commercial vehicle design differences, but this poses no problems because the 2016 FEV ICCT data explicitly includes P2 technology for the LCV class, from which a scaling factor can be calculated directly. Using the derived capacity/power relationships, the battery and motor sizes for class B and C P2 systems can be estimated from the ICE power characteristics of each class. The relationships between battery capacity and cost and motor power and cost (as reflected in the 2015 FEV ICCT data) were then derived to estimate the costs associated with the battery and motor sizes derived for the B and C classes. All costs were then normalized to the C class cost (as that is the class for which costs are explicitly estimated in the 2016 ICCT non-ICE data). Non-ICE battery costs are assumed to scale with P2 battery costs and the costs for all non-battery components for non-ICEs are assumed to scale with P2 motor costs. The fuel cell stack and hydrogen storage components for FCVs are treated as "batteries" in this calculation. Table 16 summarizes the resulting scaling factors.

Table 16. Class-Specific Scaling Factors for Non-ICE Costs

Vehicle Fuel	Vehicle Class	ICE Power (kW)	P2 HEV Battery (kW-hr)	P2 HEV Motor (kW)	Battery Cost Scaler	Non-Battery Cost Scaler
Diesel	B	60	0.8	28	0.9649	0.9630
	C	80	0.9	31	1.0000	1.0000
	D	110	1.1	35	1.0702	1.0504
	E	150	1.3	40	1.1404	1.1109
	SUV	150	1.3	40	1.1404	1.1109
	LCV	120	1.8	45	1.3158	1.1739
Gasoline	B	65	0.8	28	0.9649	0.9630
	C	95	0.9	31	1.0000	1.0000
	D	135	1.1	35	1.0702	1.0504
	E	180	1.3	40	1.1404	1.1109

P2 data for all classes except B and C are from 2015 FEV ICCT data. P2 data for classes B and C are estimated from P2 data for other vehicle classes and class B and C ICE characteristics.

16 A P2 HEV is a dual clutch, single motor, parallel design HEV.

Table 17 summarizes the raw 2016 ICCT non-ICE data (prior to scaling by vehicle class), broken down into three component categories, battery costs, non-battery costs, and cost credits due to the elimination of the baseline ICE engine. As indicated, these costs are expressed as DMC and must thus be converted into total (retail-level) costs prior to use in CO_2 compliance cost estimation. The approach used to estimate indirect costs is identical to that employed for ICE engines as discussed in Section 4 above. No learning curve data are assigned because the 2016 ICCT non-ICE data include DMC estimates for evaluation years between 2015 and 2030 (with DMC for intervening years determined through interpolation). Table 18 lists the ICM assignment keys employed for the various non-ICE cost components. For convenience, Table 18 also includes the specific ICM parameters associated with the assigned keys, but those parameters are identical to those previously presented in Table 15b as derived from the EPA's technical support materials for their 2017–2025 light-duty vehicle GHG standards. (EPA, 2012) Table 19 depicts the nominal total cost estimates that result from application of the indicated ICMs to the 2016 ICCT non-ICE DMC data. Nominal costs are those estimated prior to the application of either vehicle class cost-scaling or performance-based cost adjustments. As described in Section 7, performance-based costs adjustments for both ICE and non-ICE vehicles are applied in this analysis (unless otherwise indicated). The specific adjustments for non-ICE vehicles (expressed as the fraction of cost allocated to CO_2 reduction) are as follows:

» PHEVs with less than 40 kW motor/battery: 85%

» Other PHEVs: 80%

» BEVs: 75%

» FCVs: 80%

Table 17. Non-ICE DMC for Class C Vehicles (2014€)

Year	BEV-100	BEV-150	BEV-200	BEV-300	PHEV-10	PHEV-20	PHEV-30	PHEV-40	PHEV-60	FCV
Battery Costs										
2015	6,000€	9,000€	12,000€	18,000€	891€	1,782€	2,706€	3,597€	5,280€	23,674€
2020	3,888€	5,832€	7,776€	11,664€	667€	1,264€	1,919€	2,551€	3,744€	16,987€
2025	2,527€	3,791€	5,054€	7,582€	416€	831€	1,262€	1,678€	2,462€	9,144€
2030	1,750€	2,624€	3,499€	5,249€	315€	630€	956€	1,271€	1,866€	6,179€
Non-Battery Costs										
2015	2,810€	2,810€	2,810€	2,810€	2,110€	2,110€	2,110€	2,110€	2,110€	2,678€
2020	2,271€	2,750€	2,750€	2,750€	1,786€	1,786€	1,786€	1,786€	1,786€	2,087€
2025	2,004€	2,725€	2,725€	2,725€	1,637€	1,637€	1,637€	1,637€	1,637€	1,831€
2030	1,779€	1,925€	1,925€	1,925€	1,500€	1,500€	1,500€	1,500€	1,500€	1,618€
Credit Due to Elimination of ICE Engine (1)										
2015	-3,160€	-3,160€	-3,160€	-3,160€	0€	0€	0€	0€	0€	-3,160€
2020	-3,160€	-3,160€	-3,160€	-3,160€	0€	0€	0€	0€	0€	-3,160€
2025	-3,160€	-3,160€	-3,160€	-3,160€	0€	0€	0€	0€	0€	-3,160€
2030	-3,160€	-3,160€	-3,160€	-3,160€	0€	0€	0€	0€	0€	-3,160€
Total DMC										
2015	5,650€	8,650€	11,650€	17,650€	3,001€	3,892€	4,816€	5,707€	7,390€	23,193€
2020	2,999€	5,422€	7,366€	11,254€	2,453€	3,049€	3,704€	4,336€	5,530€	15,914€
2025	1,372€	3,356€	4,619€	7,147€	2,052€	2,468€	2,899€	3,314€	4,099€	7,815€
2030	368€	1,389€	2,264€	4,013€	1,815€	2,130€	2,456€	2,771€	3,366€	4,637€

(1) A small credit should also accrue to PHEVs due to their ability to utilize a downsized internal combustion engine. Because such credit was not estimated in the referenced 2016 ICCT non-ICE data (ICCT, 2016), it is also not included in the analysis for this paper. Generally, however, the magnitude of the credit (100 to 200 euros) is minor compared with the total DMC for PHEVs.

Table 18. Non-ICE ICM Data

Cost	BEV-100	BEV-150	BEV-200	BEV-300	PHEV-10	PHEV-20	PHEV-30	PHEV-40	PHEV-60	FCV
ICM Assignment Keys										
Battery	EVb	EVb	EVb	EVb	PHEVb	PHEVb	PHEVb	PHEVb	PHEVb	EVb
NonBatt	EVnb	EVnb	EVnb	EVnb	PHEVnb	PHEVnb	PHEVnb	PHEVnb	PHEVnb	EVnb
Credit	BaseICE	BaseICE	BaseICE	BaseICE	BaseICE	BaseICE	BaseICE	BaseICE	BaseICE	BaseICE
ICM Complexity										
Battery	High2	High2	High2	High2	High2	High2	High2	High2	High2	High2
NonBatt	High2	High2	High2	High2	High1	High1	High1	High1	High1	High2
Credit	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
ICM Near-Term End Year										
Battery	2024	2024	2024	2024	2024	2024	2024	2024	2024	2024
NonBatt	2024	2024	2024	2024	2018	2018	2018	2018	2018	2024
Credit	2010	2010	2010	2010	2010	2010	2010	2010	2010	2010
DMC Base Year										
Battery	2025	2025	2025	2025	2025	2025	2025	2025	2025	2025
NonBatt	2017	2017	2017	2017	2012	2012	2012	2012	2012	2017
Credit	2010	2010	2010	2010	2010	2010	2010	2010	2010	2010

Battery costs are those related to the battery system for BEVs and PHEVs or, for FCVs, the hydrogen storage and fuel cell stack.
NonBatt (non-battery) costs are those related to components other than the battery system.
Credit "costs" are those related to the elimination of the base ICE engine.

Table 19. Non-ICE Total Costs (Prior to Any Adjustment) for Class C Vehicles (2014€)

Year	BEV-100	BEV-150	BEV-200	BEV-300	PHEV-10	PHEV-20	PHEV-30	PHEV-40	PHEV-60	FCV
2015	9,260€	13,495€	17,596€	25,799€	4,546€	5,792€	7,085€	8,331€	10,685€	32,600€
2016	8,690€	12,801€	16,676€	24,425€	4,429€	5,612€	6,846€	8,037€	10,286€	31,036€
2017	8,121€	12,108€	15,756€	23,051€	4,312€	5,431€	6,608€	7,743€	9,887€	29,473€
2018	7,551€	11,415€	14,836€	21,677€	4,194€	5,251€	6,370€	7,449€	9,488€	27,909€
2019	6,982€	10,721€	13,915€	20,304€	3,626€	4,619€	5,680€	6,704€	8,637€	26,346€
2020	6,412€	10,028€	12,995€	18,930€	3,511€	4,441€	5,444€	6,412€	8,240€	24,782€
2021	6,063€	9,584€	12,405€	18,047€	3,426€	4,317€	5,273€	6,194€	7,934€	23,043€
2022	5,713€	9,140€	11,815€	17,165€	3,341€	4,194€	5,101€	5,976€	7,628€	21,303€
2023	5,364€	8,696€	11,225€	16,283€	3,257€	4,070€	4,929€	5,757€	7,322€	19,563€
2024	5,014€	8,253€	10,635€	15,401€	3,172€	3,946€	4,757€	5,539€	7,016€	17,824€
2025	3,281€	6,015€	7,906€	11,690€	2,974€	3,596€	4,241€	4,863€	6,038€	12,936€
2026	3,071€	5,602€	7,412€	11,032€	2,924€	3,525€	4,149€	4,750€	5,885€	12,269€
2027	2,860€	5,189€	6,918€	10,375€	2,875€	3,455€	4,056€	4,636€	5,731€	11,603€
2028	2,650€	4,777€	6,424€	9,717€	2,826€	3,384€	3,964€	4,522€	5,578€	10,936€
2029	2,439€	4,364€	5,929€	9,060€	2,776€	3,314€	3,871€	4,409€	5,424€	10,269€
2030	2,229€	3,951€	5,435€	8,403€	2,727€	3,243€	3,779€	4,295€	5,271€	9,602€

Because all of the PHEV motors associated with the 2016 ICCT non-ICE data exceed 40 kW, only the latter three adjustments are applied. Table 20 depicts the resulting performance-adjusted total cost estimates for a Class C non-ICE vehicle.

Finally, the 2016 ICCT non-ICE data are based on aggressive battery cost reductions between now and 2030. While such costs are generally reflective of the current state of industry development and industry leader planning, it is possible that average industry costs may be higher, especially if assumed cost reductions are delayed due to bottlenecks in supply chain expansion and logistics, or if raw material costs rise. As discussed in Section 12 below, this analysis estimates potential CO_2 compliance costs under two sets of assumptions, designed to reflect lower and upper bound costs. Given the sensitivity of non-ICE costs to battery development economics, the analysis adjusts the battery cost assumptions inherent in the 2016 ICCT non-ICE data to reflect the less aggressive development assumptions reported in a 2013 U.S. National Research Council (NRC) study that investigated the costs of transition to alternative vehicle power trains. (NRC, 2013) Table 21 presents the basic battery cost assumptions of the 2016 ICCT non-ICE data and the 2013 NRC data, along with the associated adjustment factors used to derive adjusted non-ICE costs that are included in the upper bound compliance cost estimates of this analysis.[17]

Table 20. Non-ICE Total Costs for Class C Vehicles after Performance Adjustment (2014€)

Year	BEV-100	BEV-150	BEV-200	BEV-300	PHEV-10	PHEV-20	PHEV-30	PHEV-40	PHEV-60	FCV
2015	6,945€	10,121€	13,197€	19,349€	3,637€	4,634€	5,668€	6,665€	8,548€	26,080€
2016	6,518€	9,601€	12,507€	18,319€	3,543€	4,490€	5,477€	6,430€	8,228€	24,829€
2017	6,091€	9,081€	11,817€	17,289€	3,449€	4,345€	5,287€	6,194€	7,909€	23,578€
2018	5,664€	8,561€	11,127€	16,258€	3,356€	4,201€	5,096€	5,959€	7,590€	22,328€
2019	5,236€	8,041€	10,436€	15,228€	2,901€	3,695€	4,544€	5,363€	6,910€	21,077€
2020	4,809€	7,521€	9,746€	14,197€	2,809€	3,553€	4,356€	5,130€	6,592€	19,826€
2021	4,547€	7,188€	9,304€	13,536€	2,741€	3,454€	4,218€	4,955€	6,347€	18,434€
2022	4,285€	6,855€	8,861€	12,874€	2,673€	3,355€	4,081€	4,781€	6,103€	17,042€
2023	4,023€	6,522€	8,419€	12,212€	2,605€	3,256€	3,943€	4,606€	5,858€	15,651€
2024	3,761€	6,189€	7,976€	11,551€	2,538€	3,157€	3,806€	4,431€	5,613€	14,259€
2025	2,461€	4,511€	5,930€	8,767€	2,379€	2,877€	3,393€	3,890€	4,830€	10,349€
2026	2,303€	4,202€	5,559€	8,274€	2,340€	2,820€	3,319€	3,800€	4,708€	9,816€
2027	2,145€	3,892€	5,188€	7,781€	2,300€	2,764€	3,245€	3,709€	4,585€	9,282€
2028	1,987€	3,583€	4,818€	7,288€	2,260€	2,707€	3,171€	3,618€	4,462€	8,749€
2029	1,829€	3,273€	4,447€	6,795€	2,221€	2,651€	3,097€	3,527€	4,340€	8,215€
2030	1,672€	2,964€	4,076€	6,302€	2,181€	2,595€	3,023€	3,436€	4,217€	7,682€

Table 21. Non-ICE Battery Cost Assumptions (€/kW-hr, 2014€)

Year (1)	2016 ICCT non-ICE Data			2013 NRC Data (2)			Adjustment Factors		
	BEV	PHEV	FCV	BEV	PHEV	FCV	BEV	PHEV	FCV
2015	250€	330€	630€	280€	360€	770€	1.12	1.09	1.22
2020	180€	260€	490€	220€	300€	550€	1.22	1.15	1.12
2025	130€	190€	420€	200€	260€	430€	1.54	1.37	1.02
2030	100€	160€	350€	160€	210€	360€	1.60	1.31	1.03

(1) Cost estimates for intervening years are determined through interpolation.
(2) The raw 2013 NRC data is expressed in U.S. dollars and is converted to euros using the same factor (0.79 euros per dollar) used for such conversions in the 2016 ICCT non-ICE data report (ICCT, 2016).

17 The 2013 NRC data include both midrange ("ambitious but reasonable") and optimistic ("potentially attainable, but will require greater successes") estimates. The optimistic estimates are utilized in this analysis.

Table 22 summarizes the upper bound non-ICE DMC data (prior to scaling by vehicle class), broken down into three component categories: battery costs (from the 2013 NRC study), non-battery costs, and cost credits due to the elimination of the baseline ICE engine. These data correspond to those presented in Table 17, as used for lower bound non-ICE cost analysis. Table 23 depicts the nominal upper bound non-ICE total cost estimates that result from application of ICMs to the upper bound non-ICE DMC data. These data correspond to those presented in Table 19, as used for lower bound non-ICE cost analysis. The ICM data used for upper bound cost estimation is identical to that presented in Table 18, as used for lower (and upper) bound non-ICE cost analysis. Table 24 presents the performance-adjusted upper bound non-ICE total cost estimates for a Class C non-ICE vehicle. These data correspond to those presented in Table 20, as used for lower bound non-ICE cost analysis, and rely on the identical performance adjustments applied to the lower bound cost-estimation data. Note, however, that the upper bound performance-adjusted cost estimates presented in Table 24 are provided for comparative purposes only as the performance adjustments are not used for upper bound cost estimation in this analysis (as discussed in Section 12 below).

Table 22. Non-ICE Upper Bound DMC for Class C Vehicles (2014€)

Year	BEV-100	BEV-150	BEV-200	BEV-300	PHEV-10	PHEV-20	PHEV-30	PHEV-40	PHEV-60	FCV
Battery Costs										
2015	6,720€	10,080€	13,440€	20,160€	972€	1,944€	2,952€	3,924€	5,760€	28,935€
2020	4,752€	7,128€	9,504€	14,256€	770€	1,458€	2,214€	2,943€	4,320€	19,067€
2025	3,888€	5,832€	7,776€	11,664€	569€	1,137€	1,727€	2,296€	3,370€	9,361€
2030	2,799€	4,199€	5,599€	8,398€	413€	827€	1,255€	1,669€	2,449€	6,355€
Non-Battery Costs										
2015	2,810€	2,810€	2,810€	2,810€	2,110€	2,110€	2,110€	2,110€	2,110€	2,678€
2020	2,271€	2,750€	2,750€	2,750€	1,786€	1,786€	1,786€	1,786€	1,786€	2,087€
2025	2,004€	2,725€	2,725€	2,725€	1,637€	1,637€	1,637€	1,637€	1,637€	1,831€
2030	1,779€	1,925€	1,925€	1,925€	1,500€	1,500€	1,500€	1,500€	1,500€	1,618€
Credit Due to Elimination of ICE Engine (1)										
2015	-3,160€	-3,160€	-3,160€	-3,160€	0€	0€	0€	0€	0€	-3,160€
2020	-3,160€	-3,160€	-3,160€	-3,160€	0€	0€	0€	0€	0€	-3,160€
2025	-3,160€	-3,160€	-3,160€	-3,160€	0€	0€	0€	0€	0€	-3,160€
2030	-3,160€	-3,160€	-3,160€	-3,160€	0€	0€	0€	0€	0€	-3,160€
Total DMC										
2015	6,370€	9,730€	13,090€	19,810€	3,082€	4,054€	5,062€	6,034€	7,870€	28,454€
2020	3,863€	6,718€	9,094€	13,846€	2,555€	3,244€	4,000€	4,729€	6,106€	17,994€
2025	2,732€	5,397€	7,341€	11,229€	2,205€	2,774€	3,364€	3,932€	5,006€	8,033€
2030	1,418€	2,964€	4,363€	7,163€	1,913€	2,326€	2,755€	3,168€	3,949€	4,813€

(1) A small credit should also accrue to PHEVs due to their ability to utilize a downsized internal combustion engine. Because such credit was not estimated in the referenced 2016 ICCT non-ICE data (ICCT, 2016), it is also not included in the analysis for this paper. Generally, however, the magnitude of the credit (100 to 200 euros) is minor compared with the total DMC for PHEVs.

Table 23. Non-ICE Upper Bound Total Costs (Prior to Any Adjustment) for Class C Vehicles (2014€)

Year	BEV-100	BEV-150	BEV-200	BEV-300	PHEV-10	PHEV-20	PHEV-30	PHEV-40	PHEV-60	FCV
2015	10,980€	16,075€	21,037€	30,960€	4,740€	6,179€	7,672€	9,112€	11,832€	38,402€
2016	10,442€	15,428€	20,179€	29,679€	4,627€	6,006€	7,445€	8,832€	11,453€	36,155€
2017	9,903€	14,781€	19,320€	28,398€	4,515€	5,832€	7,217€	8,552€	11,075€	33,908€
2018	9,365€	14,134€	18,462€	27,117€	4,402€	5,659€	6,990€	8,273€	10,696€	31,661€
2019	8,826€	13,487€	17,604€	25,836€	3,838€	5,034€	6,311€	7,541€	9,866€	29,415€
2020	8,287€	12,840€	16,745€	24,555€	3,727€	4,863€	6,085€	7,264€	9,490€	27,168€
2021	8,045€	12,557€	16,369€	23,993€	3,654€	4,763€	5,950€	7,094€	9,255€	25,028€
2022	7,802€	12,273€	15,992€	23,431€	3,580€	4,663€	5,814€	6,924€	9,021€	22,888€
2023	7,559€	11,989€	15,616€	22,869€	3,506€	4,564€	5,679€	6,754€	8,786€	20,749€
2024	7,316€	11,705€	15,239€	22,306€	3,432€	4,464€	5,544€	6,585€	8,551€	18,609€
2025	5,319€	9,070€	11,981€	17,801€	3,203€	4,054€	4,937€	5,788€	7,396€	13,262€
2026	5,043€	8,560€	11,356€	16,948€	3,142€	3,961€	4,810€	5,628€	7,175€	12,587€
2027	4,767€	8,049€	10,731€	16,095€	3,081€	3,867€	4,682€	5,469€	6,953€	11,911€
2028	4,491€	7,539€	10,106€	15,242€	3,020€	3,774€	4,555€	5,309€	6,732€	11,236€
2029	4,215€	7,028€	9,482€	14,388€	2,959€	3,680€	4,428€	5,149€	6,511€	10,561€
2030	3,940€	6,518€	8,857€	13,535€	2,899€	3,587€	4,301€	4,989€	6,289€	9,885€

Table 24. Non-ICE Upper Bound Total Costs for Class C Vehicles after Performance Adjustment (2014€)

Year	BEV-100	BEV-150	BEV-200	BEV-300	PHEV-10	PHEV-20	PHEV-30	PHEV-40	PHEV-60	FCV
2015	8,235€	12,056€	15,778€	23,220€	3,792€	4,944€	6,138€	7,290€	9,465€	30,721€
2016	7,831€	11,571€	15,134€	22,259€	3,702€	4,805€	5,956€	7,066€	9,162€	28,924€
2017	7,427€	11,086€	14,490€	21,299€	3,612€	4,666€	5,774€	6,842€	8,860€	27,127€
2018	7,023€	10,601€	13,846€	20,338€	3,522€	4,527€	5,592€	6,618€	8,557€	25,329€
2019	6,620€	10,116€	13,203€	19,377€	3,070€	4,027€	5,048€	6,033€	7,893€	23,532€
2020	6,216€	9,630€	12,559€	18,416€	2,982€	3,890€	4,868€	5,811€	7,592€	21,734€
2021	6,033€	9,417€	12,277€	17,995€	2,923€	3,810€	4,760€	5,675€	7,404€	20,023€
2022	5,851€	9,205€	11,994€	17,573€	2,864€	3,731€	4,652€	5,539€	7,216€	18,311€
2023	5,669€	8,992€	11,712€	17,151€	2,805€	3,651€	4,543€	5,404€	7,029€	16,599€
2024	5,487€	8,779€	11,429€	16,730€	2,746€	3,571€	4,435€	5,268€	6,841€	14,887€
2025	3,989€	6,803€	8,985€	13,351€	2,562€	3,243€	3,950€	4,631€	5,917€	10,610€
2026	3,782€	6,420€	8,517€	12,711€	2,514€	3,169€	3,848€	4,503€	5,740€	10,069€
2027	3,575€	6,037€	8,048€	12,071€	2,465€	3,094€	3,746€	4,375€	5,563€	9,529€
2028	3,368€	5,654€	7,580€	11,431€	2,416€	3,019€	3,644€	4,247€	5,386€	8,989€
2029	3,162€	5,271€	7,111€	10,791€	2,368€	2,944€	3,542€	4,119€	5,209€	8,448€
2030	2,955€	4,888€	6,643€	10,151€	2,319€	2,870€	3,441€	3,991€	5,031€	7,908€

10. NON-ICE CO_2 DATA

The 2016 ICCT non-ICE data does not include associated CO_2 emission estimates. For BEVs and FCVs, such data are relatively straightforward as such vehicles emit no CO_2 during vehicle operation. While CO_2 is produced and emitted during the generation of electricity used to recharge BEVs and during the manufacture and distribution of hydrogen used to refuel FCVs, current regulatory programs treat such vehicles as zero emission vehicles. It is not certain that such allowances will continue indefinitely, but this analysis assumes that such treatment will continue through at least 2030 and thus treats all BEVs and FCVs as having zero CO_2 emissions. PHEVs, however, will emit CO_2 when the internal combustion engine is running and must be treated accordingly.

There are three factors that must be estimated to derive net PHEV emission rates. These consist of the emission rate during electric-only operation, the emission rate during internal combustion engine operation, and the fraction of time the internal combustion engine is operating. As with BEVs and FEVs, this analysis assumes a zero emission rate during electric-only operation. The emission rate during internal combustion engine operation is assumed to be equivalent to that of a P2 HEV. Finally, various regulatory functions have been derived to estimate the fraction of time the internal combustion engine is operating, and this analysis uses those functions directly to estimate this parameter for both the NEDC and WLTP driving cycles.

P2 HEV emission rates are taken directly from the 2016 FEV ICCT data for class D, E, SUV, and LCV vehicles. However, as described above, P2 HEV technology packages were not simulated for either class B or C vehicles. Thus P2 HEV-equivalent emission rates for these two classes had to be derived from available 2016 FEV ICCT data. As described in Section 9, P2 HEV battery and motor sizes for class B and C vehicles were estimated on the basis of P2 HEV and ICE power ratios for the various P2 HEVs explicitly simulated in the 2016 FEV ICCT data. Thus, it is reasonable to expect that the *relative* emission impact associated with P2 HEV technology in those classes would be equivalent to that observed for the P2 HEVs explicitly simulated in the 2016 FEV ICCT data. Based on this assumption, the percentage emission impact observed (individually) for class D diesel and gasoline P2 HEVs relative to their respective baseline class D ICE vehicles was taken as an estimate of the percentage emission impact that would be observed for class B and C vehicles had P2 HEV technology been explicitly considered. Applying this factor to baseline CO_2 estimates for class B and C ICE vehicles results in an estimate of P2 HEV-equivalent emission rates for these same classes. These derived estimates were used to represent the CO_2 emission rate during internal combustion engine operation for class B and C PHEVs.

The fraction of time that PHEVs operate as electric-only vehicles is generally termed the "utility factor" and is a function of both the AER of a vehicle and the driving cycle over which it operates. Of course, by definition the fraction of time that the internal combustion engine of a PHEV is operating is unity minus the utility factor. Thus, once the utility factor is known, the net emission rate for a PHEV is:

$$ER_{net} = (UF)(ER_{el}) + (1\text{-}UF)(ER_{ice})$$

Where: ER_{net} = Net PHEV Emission Rate,
ER_{el} = PHEV Emission Rate During Electric-Only Operation,
ER_{ice} = PHEV Emission Rate During ICE Operation, and
UF = PHEV Utility Factor.

For the NEDC, the utility factor is defined as the ratio of the AER to the AER+25, where the AER is expressed in kilometers. The 2016 ICCT non-ICE data is explicitly developed such that the named AER for the various considered PHEVs is the NEDC AER. In other words, PHEV-10, PHEV-20, PHEV-30, PHEV-40, and PHEV-60 vehicles have, by definition, an NEDC AER of 10, 20, 30, 40, and 60 miles, respectively (16.09, 32.19, 48.28, 64.37, and 96.56 kilometers). Accordingly, the NEDC utility factors for these specific PHEVs are 0.3916, 0.5628, 0.6588, 0.7203, and 0.7943. Figure 5 presents the NEDC utility factor function graphically.

Considerable work has been performed in the EU to quantify the utility factor for the WLTP cycle. This analysis relies directly on the work reported in a recent technical support document for the EU's WLTP development effort. (Riemersma, 2015) That document expresses the WLTP utility factor function as:

$$UF = 1 - e^{-\left(\sum_{j=1}\left(Cj \times \left(\frac{AER}{d}\right)^{j}\right)\right)}$$

Where: UF = PHEV Utility Factor,

C = Power Series Coefficients as follows:

C_1	=	26.25,
C_2	=	-38.94,
C_3	=	-631.05,
C_4	=	5964.83,
C_5	=	-25094.60,
C_6	=	60380.21,
C_7	=	-87517.16,
C_8	=	75513.77,
C_9	=	-35748.77,
C_{10}	=	7154.94,

AER = PHEV All-Electric Range, and

d = Normalization Distance = 800 kilometers.

Figure 6 graphically depicts this WLTP utility factor function. To evaluate the WLTP utility factor function for the specific PHEVs included in the 2016 ICCT non-ICE data, it is necessary to know the WLTP AERs for each. The referenced WLTP technical support document (Riemersma, 2015; page 134) assumes that the WLTP AER is equal to 75% of the NEDC AER. An energy analysis for the NEDC and WLTP based on the physical equations of motion suggests that the WLTP AER might be as high as 83% of the NEDC AER. Figure 6 includes comparative utility factor functions based on the NEDC regulatory approach of the ratio of NEDC AER to NEDC AER+25 (AER in km) plotted in terms of WLTP-equivalent AER for both of the potential AER equivalency estimates. As indicated, all three functions result in reasonably similar utility factors, with the WLTP-specific function indicating lower utility at lower AERs, but higher utility for AERs above about 30–40 kilometers. Because the 75% AER relation provides lower WLTP AER estimates and thus lower utility factors and higher net PHEV emissions, this analysis uses the 75% AER factor in conjunction with the WLTP-specific utility factor curve to derive WLTP utility factors for each of the PHEVs included in the 2016 ICCT non-ICE data. The resulting utility factors are: 0.3198, 0.5246, 0.6572, 0.7447, and 0.8453 for PHEV-10, PHEV-20, PHEV-30, PHEV-40, and PHEV-60 vehicles, respectively (with WLTP AERs of 12.07, 24.14, 36.21, 48.28, and 72.42 kilometers).

Given the derived NEDC and WLTP utility factors, net emission rates for all PHEVs over both driving cycles can be readily calculated from their all-electric emission rates (zero) and their ICE operational emission rates (P2 HEV equivalent). Table 25 presents the resulting CO_2 emission rates assumed in this analysis for all 2016 ICCT non-ICE vehicles.

Figure 5. NEDC PHEV Utility Factor Function

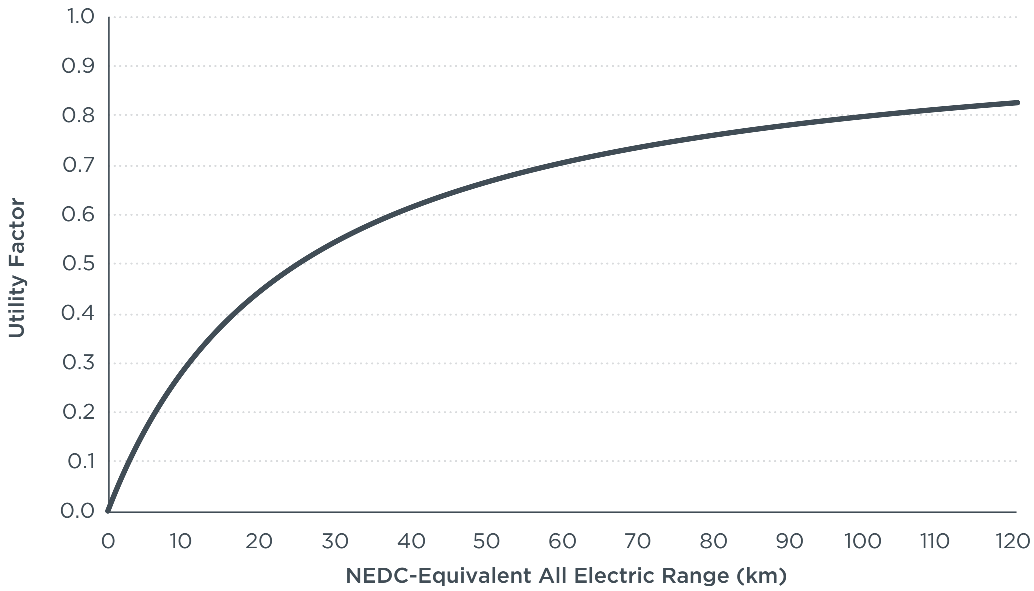


Figure 6. WLTP PHEV Utility Factor Function

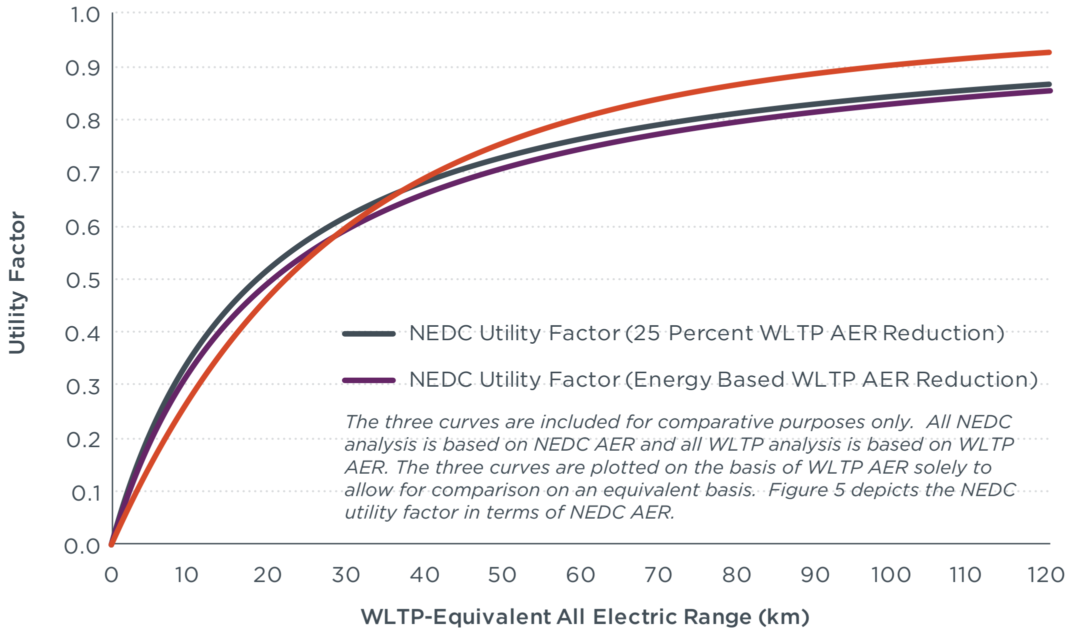


Table 25. Non-ICE CO_2 Emission Rates

Vehicle Fuel	Vehicle Class	BEV 100	BEV 150	BEV 200	BEV 300	PHEV 10	PHEV 20	PHEV 30	PHEV 40	PHEV 60	FCV
NEDC Cycle											
Diesel	B	0.0	0.0	0.0	0.0	37.7	27.1	21.2	17.3	12.8	0.0
	C	0.0	0.0	0.0	0.0	41.8	30.1	23.5	19.2	14.1	0.0
	D	0.0	0.0	0.0	0.0	44.6	32.0	25.0	20.5	15.1	0.0
	E	0.0	0.0	0.0	0.0	49.8	35.8	27.9	22.9	16.8	0.0
	SUV	0.0	0.0	0.0	0.0	52.6	37.8	29.5	24.2	17.8	0.0
	LCV	0.0	0.0	0.0	0.0	64.5	46.3	36.2	29.7	21.8	0.0
Gasoline	B	0.0	0.0	0.0	0.0	39.7	28.5	22.2	18.2	13.4	0.0
	C	0.0	0.0	0.0	0.0	48.6	34.9	27.3	22.4	16.4	0.0
	D	0.0	0.0	0.0	0.0	52.3	37.6	29.3	24.0	17.7	0.0
	E	0.0	0.0	0.0	0.0	58.6	42.1	32.9	27.0	19.8	0.0
WLTP Cycle											
Diesel	B	0.0	0.0	0.0	0.0	54.3	38.0	27.4	20.4	12.4	0.0
	C	0.0	0.0	0.0	0.0	58.1	40.6	29.3	21.8	13.2	0.0
	D	0.0	0.0	0.0	0.0	61.5	43.0	31.0	23.1	14.0	0.0
	E	0.0	0.0	0.0	0.0	66.5	46.4	33.5	24.9	15.1	0.0
	SUV	0.0	0.0	0.0	0.0	72.6	50.7	36.6	27.3	16.5	0.0
	LCV	0.0	0.0	0.0	0.0	95.5	66.7	48.1	35.8	21.7	0.0
Gasoline	B	0.0	0.0	0.0	0.0	57.5	40.2	29.0	21.6	13.1	0.0
	C	0.0	0.0	0.0	0.0	67.0	46.8	33.7	25.1	15.2	0.0
	D	0.0	0.0	0.0	0.0	71.0	49.6	35.8	26.7	16.2	0.0
	E	0.0	0.0	0.0	0.0	79.2	55.3	39.9	29.7	18.0	0.0

11. GEOGRAPHIC COST CONSIDERATIONS

All cost estimates associated with the 2015 FEV ICCT data are based on WEU labor rates and production costs. As an integral component of the work associated with the 2012 FEV ICCT data, FEV developed cost estimates for both WEU and EEU labor rates and production costs. This work is documented in the reference material cited in Section 1 for the 2012 FEV ICCT data (most specifically ICCT, 2014). Because the mass reduction cost curves for this analysis were taken directly from the 2012 FEV ICCT data, explicit versions based on WEU and EEU costs are available and were used without change in this analysis (save an identical adjustment to both to convert from 2010/11 euros to 2014 euros as described in Section 1). However, a geographic adjustment is required to estimate EEU equivalent costs for the 2015 FEV ICCT data and EEU costs for the secondary EPA cost data for rolling resistance and aerodynamic drag technology.

Because the 2015 FEV ICCT data and secondary EPA cost data provide no information on the differential cost impact of WEU and EEU production, a generalized method was developed to estimate such impacts. This method relies on a comparison of detailed and computationally consistent U.S., WEU, and EEU cost estimates for an *identical* technology system conversion. All three cost estimates were prepared by FEV, with the U.S. data being prepared for the EPA and the corresponding EU data (both western and eastern) being prepared for the ICCT. The specific technology package compared consisted of the conversion of a baseline 2.4-liter, I4, 16-valve, DOHC naturally aspirated gasoline engine with discrete variable valve timing to a 1.6-liter, I4, 16-valve, DOHC, turbocharged gasoline direct injection with discrete variable valve timing. From this comparison, a scaler was developed to adjust costs for the U.S. market to their EU market equivalents, and from the WEU market to its EEU equivalent.

The resulting U.S.-to-WEU cost adjustment factor is calculated to be 0.8126. The corresponding U.S.-to-EEU cost adjustment factor is 0.6805, so that the western-to-eastern EU cost adjustment factor is 0.8374. For this analysis, total EU production is split into its WEU and EEU components to develop a single weighted cost adjustment to reflect the combined EU. This weighting is performed separately for passenger and LCVs. For passenger cars, the WEU production share is estimated to be 77%, while that for LCVs is estimated to be 91% . Both are based on 2015 data published by the European Automobile Manufacturers Association (ACEA, 2016). These shares result in a net 2016 FEV ICCT cost adjustment factor of 0.9626 for passenger cars [(0.77×1)+(0.23×0.8374)] and 0.9854 for LCVs [(0.91×1)+(0.09×0.8374)]. All compliance cost calculations performed for this analysis reflect these geographic cost adjustments.

12. COST CURVE CONSTRUCTION APPROACH

Conceptually, construction of the EU cost curves is straightforward. Zero-cost baseline CO_2 data are combined with CO_2 and associated 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.[18] However, assemblage of the associated data includes nuances that must be addressed, especially with regard to the integration of ICE and non-ICE data as required to meet some of the target CO_2 levels evaluated in this analysis. Technology cost curves per se are really only developed for ICE data as these data reflect the cost of reducing CO_2 through the continuous application of technology. However, there is a maximum level of CO_2 reduction that can be attained through the technologies *included in the 2015 FEV ICCT data*. That level of reduction places a floor on the potential CO_2 standards that can be achieved through evaluation of the ICE cost curves directly.[19] Attainment of lower CO_2 targets requires the introduction of non-ICE vehicles into the fleet, and this introduction is controlled not by the continuous introduction of technology, but rather by increasing technology penetration. The continuous addition of technology cost is replaced by the continuous addition of ever-greater non-ICE market shares. Thus, evaluation of the cost of attaining CO_2 levels below the floor attainable with ICE technology alone is a two step process consisting of first determining the cost associated with ICE technology and then determining the fraction of non-ICE vehicles (and their associated cost) required to further reduce CO_2 emissions to the desired level.

18 Of course, the "zero cost" assigned to the baseline technology packages is a relative assignment. Obviously, current technology is not free. However, the *incremental* cost of baseline technology is zero relative to the *incremental* cost that would be incurred under any program requiring reduction in CO_2 emissions from current (baseline) levels.

19 It is important to note that this floor exists solely in the context of the 2015 FEV ICCT data. Although the study underlying these data considers a wide range of ICE technologies, it is not exhaustive, nor does it foresee potential future improvements in the effectiveness of the technologies that are evaluated. Consideration of either will continue to expand the levels of CO_2 reduction possible with ICE technology. Only *in the limited context of this study* do we define the limit of ICE technology as the CO_2 estimates associated with the most advanced technology included in the 2015 FEV ICCT data. A similar future study or a current study considering more advanced (and expensive) technologies than those included in the 2015 FEV ICCT data will almost assuredly demonstrate expanded CO_2 reduction capacity for ICE technology.

Independent ICE cost curves are developed for nine passenger vehicle classes (diesel vehicle classes B, C, D, E, and SUV, and gasoline vehicle classes B, C, D, and E) and a separate diesel LCV class. As described in Sections 9 and 10 above, non-ICE data are also evaluated at this same class level. For passenger vehicles, individual vehicle class estimates are sales weighted to determine overall fleet CO_2 levels using 2014 EU sales data as compiled in an ICCT internal database. (ICCT, 2015) The analysis assumes constant sales shares throughout the evaluation period 2015–2030. The employed sales shares are:

Diesel B Class	7.0%
Diesel C Class	24.5%
Diesel D Class	7.0%
Diesel E Class	3.0%
Diesel SUV Class	15.0%
Gasoline B Class	25.0%
Gasoline C Class	17.5%
Gasoline D Class	1.0%
Gasoline E Class	0.0%

For standards that require the introduction of non-ICE vehicles, the analysis requires that non-ICE vehicles are distributed across vehicle classes in accordance with the class sales shares. In other words, non-ICE vehicles are allocated across all classes so that costs are *not* artificially minimized by assuming that non-ICE vehicles 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 non-ICE demand. 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 non-ICE demand. In a compromise between consumer utility, required market penetration (CO_2 declines with increasing AER), and cost, the analysis assumes that PHEVs with an NEDC AER of 40 miles will be the preferred PHEV solution. Thus, non-ICE costs estimated for class D and larger vehicles do *not* represent a least-cost solution.

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 2015 FEV ICCT 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. The 2012 FEV ICCT data estimate that a substantial level of mass reduction (approximately 20% from baseline) can be achieved at a net negative cost as discussed in Section 3 above. Lower bound cost estimates assume such savings, while upper bound cost estimates treat all negative mass reduction costs as zero. Both lower and upper bound cost estimates assume increasingly large positive mass reduction costs as reductions increase beyond the cost savings levels estimated in the 2012 FEV ICCT data.

The lower bound estimates also include both test flexibility exploitation and performance-based CO_2 adjustments (as discussed in Sections 5 and 6 above); upper bound estimates include neither. Similarly, the lower bound estimates include performance-based technology cost adjustments (as discussed in Section 7 above); upper bound estimates do not. Lower bound estimates also include off-cycle technology credits (as discussed in Section 8 above); while upper bound estimates do not. Finally, lower bound estimates are based on 2016 ICCT non-ICE battery costs; upper bound estimates are based on 2013 NRC battery cost assumptions (as discussed in Section 9 above). Table 26 summarizes the different characteristics of the lower and upper bound cost estimates.

Table 26. Lower and Upper Bound Scenario Differential Analysis Parameters

Analysis Parameter	Lower Bound Estimates	Upper Bound Estimates	For More Information
Mass Reduction Cost Savings	Allowed	Treated as Zero (1)	Section 3
Test Flexibility Exploitation	Allowed	Not Allowed	Section 5
Performance-Based CO_2 Adjustments	Implemented	Not Implemented	Section 6
Performance-Based Cost Adjustments	Implemented	Not Implemented	Section 7
Off-Cycle Technology Credits	Included	Not Included	Section 8
Non-ICE Battery Costs	2016 ICCT Data	2013 NRC Data	Section 9

(1) As discussed in Section 3, cost savings are possible for some level of mass reduction. Lower bound cost estimates assume such savings, while upper bound cost estimates treat all negative mass reduction costs as zero. Both lower and upper bound cost estimates assume increasingly large positive mass reduction costs as reductions increase.

13. DERIVED CO_2 COMPLIANCE COSTS

As discussed in Section 12, 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 non-ICE vehicles. The cost of ICE technology is generally reflected as an upwardly sloping exponential curve. The cost of increasing non-ICE market penetration is a linear function (because the underlying non-ICE vehicle cost is constant for a given vehicle class and driving cycle in a given evaluation year) 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% non-ICE market penetration.[20]

While these generalizations always hold true, there is a degree of freedom associated with introducing non-ICE vehicles into the fleet that creates uncertainty with regard to the integration of ICE and non-ICE cost data. There is no requirement that a vehicle manufacturer must exhaust all ICE technology before introducing non-ICE vehicles into the fleet. From a mathematical viewpoint, this means that there are an infinite number of ways in which the ICE and non-ICE cost data can be integrated. Figure 7 provides a graphic illustration of this infinite potential.[21] The black curve illustrates a cost-integration strategy wherein all ICE technology is exhausted prior to the introduction of non-ICE vehicles.[22] The red line illustrates the effective opposite, where no additional ICE technology (beyond that inherent in the baseline fleet) is introduced, and instead only non-ICE vehicles are used to drive CO_2 reduction. Between these two extremes lie an infinite number of alternative transitional possibilities that generally include some additional ICE technology followed by further CO_2 reductions driven by non-ICE vehicles. Figure 7 depicts three such alternatives;

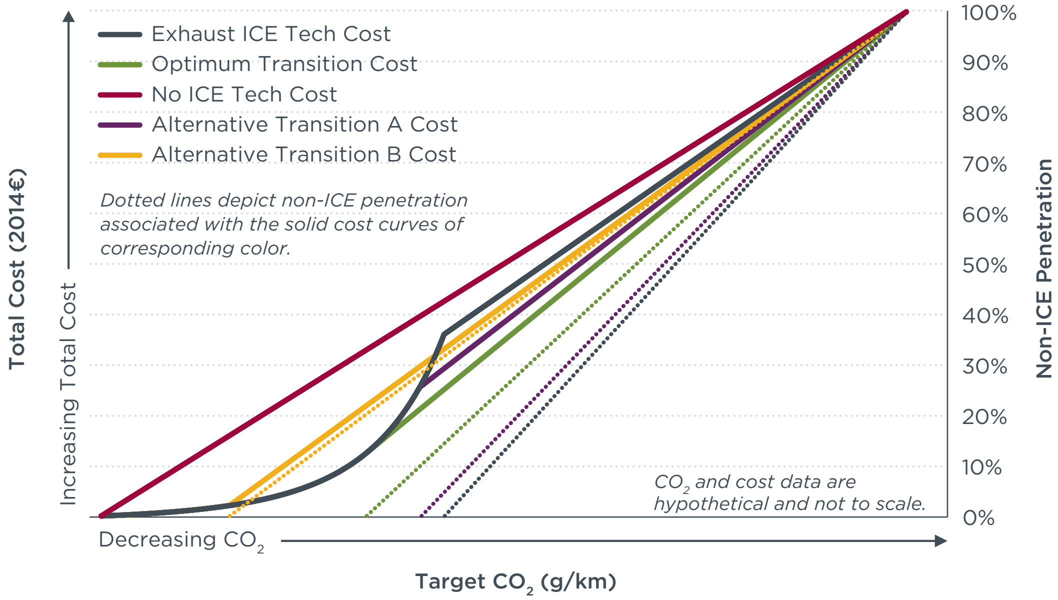
20 As discussed in Section 12, the analysis assumes that BEV-100 vehicles will be used to satisfy any non-ICE demand for B and C class vehicles. For all larger vehicle classes, the analysis assumes that BEVs will not be practical in the time frame considered and that PHEVs will be employed to satisfy any non-ICE demand. In a compromise between consumer utility, required market penetration (CO_2 declines with increasing AER), and cost, the analysis assumes that PHEVs with an NEDC AER of 40 miles will be the preferred PHEV solution.

21 Note that the CO_2 and cost axes of Figure 7 have been intentionally generalized to avoid any inference that the illustrated relations are specific to any given vehicle, driving cycle, or evaluation year. Specific CO_2 values and costs are not relevant; only the illustrative difference between costs at any given CO_2 level is important.

22 The solid lines of Figure 7 depict costs for a given level of CO_2. The dotted lines depict the non-ICE market penetrations associated with the corresponding solid cost curves.

one (graphed in violet) that shows a transition to non-ICE technology only marginally prior to the exhaustion of ICE technology, one (graphed in gold) that shows a transition to non-ICE technology well before the exhaustion of ICE technology, and one (graphed in green) that shows a transition to non-ICE technology about midway between the other alternatives. Any number of additional similar curves can be drawn, each of which transitions from a different point on the (black) ICE technology exhaustion curve.

Figure 7. CO_2 Cost Effects of Transition between ICE and Non-ICE Vehicles



One (and only one) of the infinite possible transitional alternatives has special significance, in that it transitions from ICE technology to non-ICE 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 non-ICE vehicles to the fleet is cheaper than adding more expensive ICE technologies. In Figure 7, that curve is depicted as the green (optimum transition) curve. In mathematical terms, the appropriate transition point is determined by comparing the rate of change of the slope (i.e., the derivative) of the ICE cost curve (which represents the marginal ICE technology cost at any given level of CO_2) with the derivative of the non-ICE cost curve (which represents the marginal non-ICE technology cost at any given level of CO_2). The CO_2 level at which the derivatives of the two curves are equal is the point at which a least-cost solution would dictate transitioning from the ICE cost curve to the non-ICE cost curve. Because the 100% non-ICE market penetration cost is fixed (i.e., independent of the point of transition away from ICE technology) for any given set of analysis conditions, the least-cost transition point can be easily identified visually as the tangent to the ICE technology cost curve that extends through the 100% non-ICE market penetration point (as exemplified by the green curve in Figure 7). Identifying this transition point mathematically requires a recursive solution as the slope of the non-ICE market penetration curve varies with the transition point from the ICE technology curve, and appropriate formulations have been undertaken in this analysis to identify the least-cost transition point for all evaluated cost curves.

Despite the ability to identify the least-cost transition point, this 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* (given the constraints associated with the 2015 FEV ICCT data) non-ICE market penetration. The resulting cost curve is exemplified by the black curve in Figure 7. 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 non-ICE market introduction. With this strategy, hereafter referred to as the Non-ICE Strategy, transition occurs when the marginal cost of non-ICE vehicles is less than the marginal cost of additional ICE technology. The resulting curve is exemplified by the green curve in Figure 7. Note that, between these two approaches, there can be substantial differences in the estimated CO_2 compliance costs for small non-ICE 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 non-ICE vehicles approaches 100% (because cost at this limit is independent of the point of ICE technology transition). This is exemplified by the large, but continually declining, difference in compliance costs between the black and green curves of Figure 7 as the two approaches transition away from ICE technology.

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

Nevertheless, this analysis retains the two strategy compliance cost approach for two primary reasons. First, the 2016 ICCT non-ICE data include vehicle technology costs only. Costs associated with overcoming market barriers to widespread non-ICE introduction (e.g., availability of a supporting infrastructure) are not considered, and 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 non-ICE market penetration shifts can occur over a similarly limited time frame. Because the 2016 ICCT non-ICE data imply substantial cost reductions between 2015 and 2030, it is likely that the costs associated with facilitating large non-ICE market penetrations in one year (say 2030) will require significantly more expensive non-ICE investments in earlier years. For these reasons, this analysis presents compliance cost data for both ICE technology exhaustion and least-cost non-ICE transition CO_2 reduction strategies.

It is also important to recognize that the focus on vehicle technology costs (for both ICE and non-ICE vehicles) employed in this analysis does not equate to a full assessment of consumer impacts. This analysis focuses on vehicle procurement impacts only. Impacts on the total cost of ownership for both ICE and non-ICE vehicles would include offsetting savings due to reduced fuel use for ICE vehicles and alternative energy economics for non-ICE vehicles. Such life-cycle assessments can be developed from the vehicle technology cost estimates described herein, but are not considered in this paper.

Figures 8a and 8b present passenger vehicle fleet average compliance cost curves for CO_2 targets measured over the NEDC in 2020, 2025, and 2030. Figure 8a presents compliance costs for an ICE technology exhaustion strategy, while Figure 8b presents costs for a least-cost non-ICE transition strategy. Figures 9a and 9b present corresponding data for LCVs. Figures 10 (10a and 10b) and 11 (11a and 11b) present corresponding data for passenger and LCVs as measured over the WLTP cycle. As discussed above (and in Section 12), 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 non-ICE vehicles 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% non-ICE market penetration.

Figure 8a. NEDC CO_2 Costs for Passenger Vehicles (ExhICE Strategy)

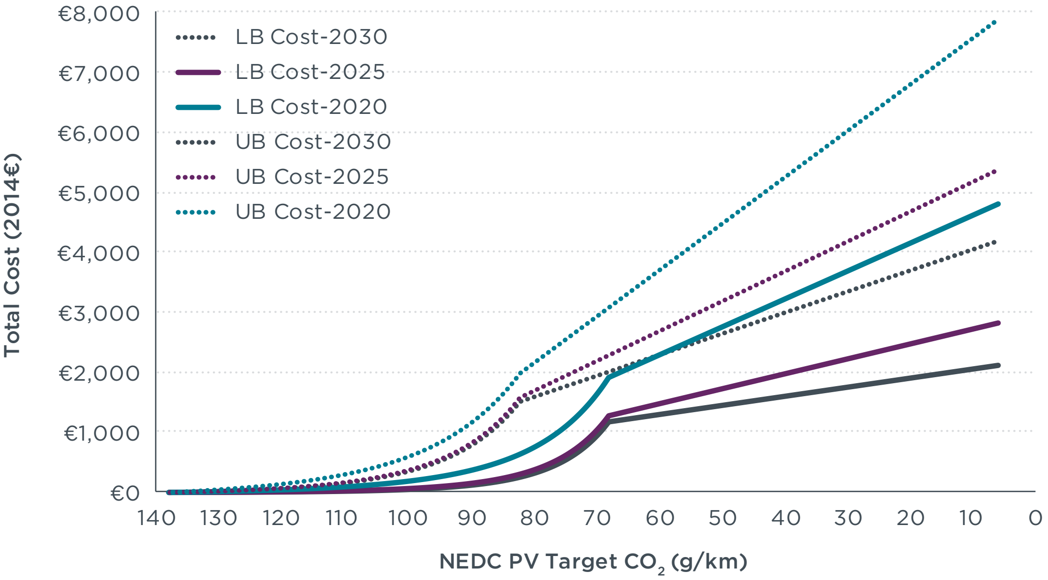


Figure 8b. NEDC CO_2 Costs for Passenger Vehicles (Non-ICE Strategy)

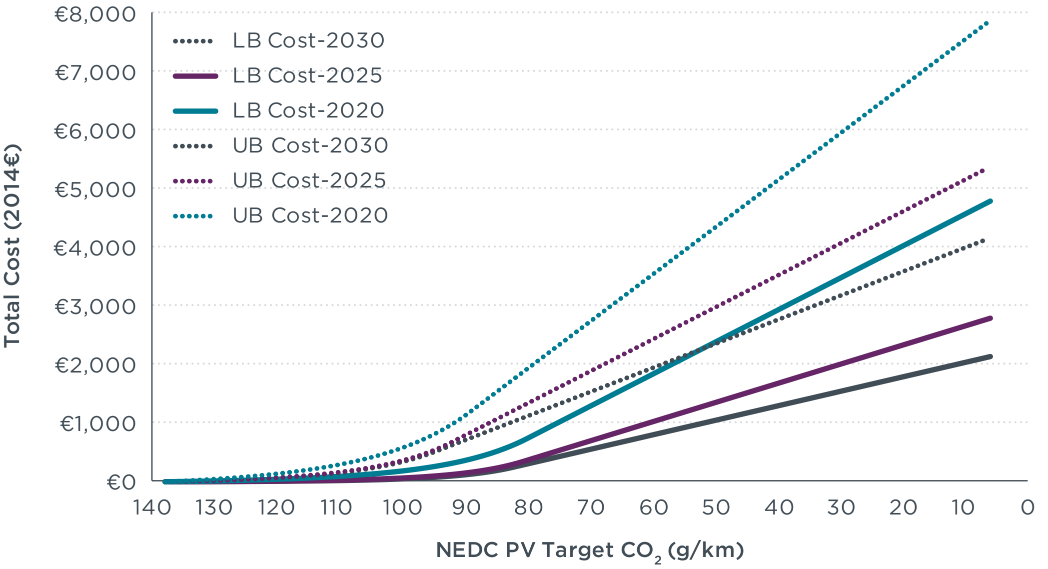


Figure 9a. NEDC CO_2 Costs for Light Commercial Vehicles (ExhICE Strategy)

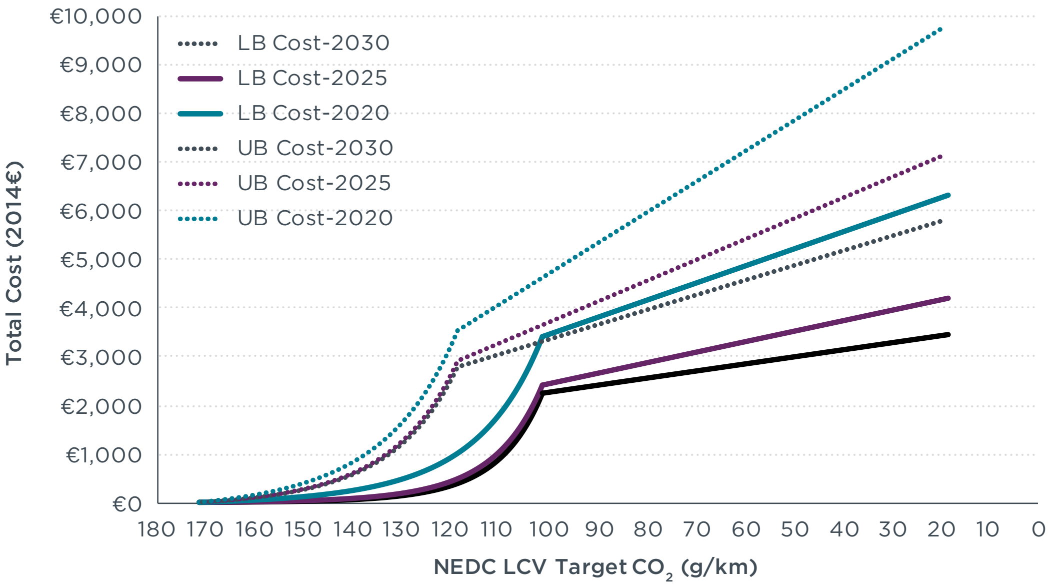


Figure 9b. NEDC CO_2 Costs for Light Commercial Vehicles (Non-ICE Strategy)

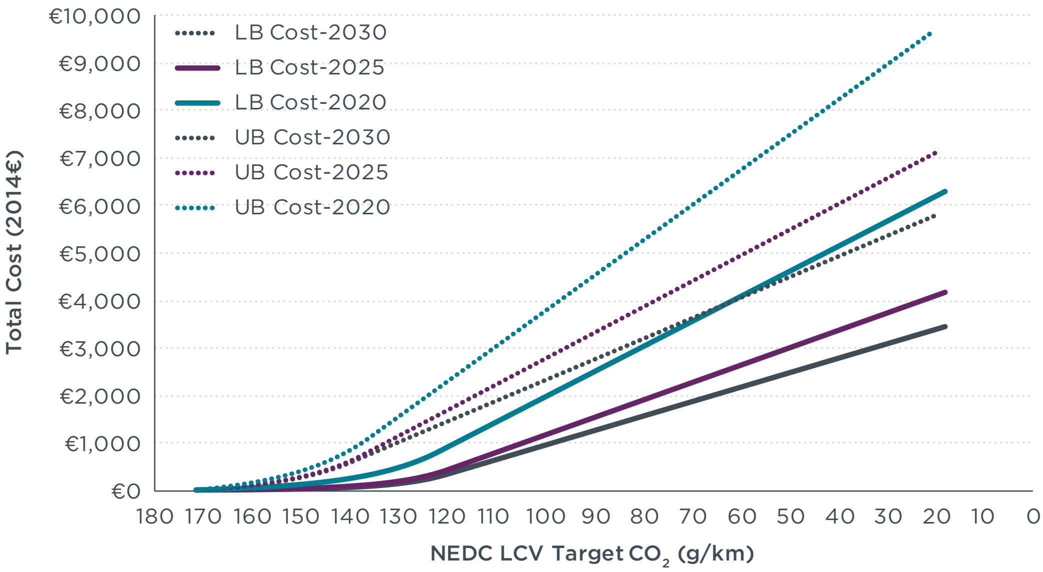


Figure 10a. WLTP CO_2 Costs for Passenger Vehicles (ExhICE Strategy)

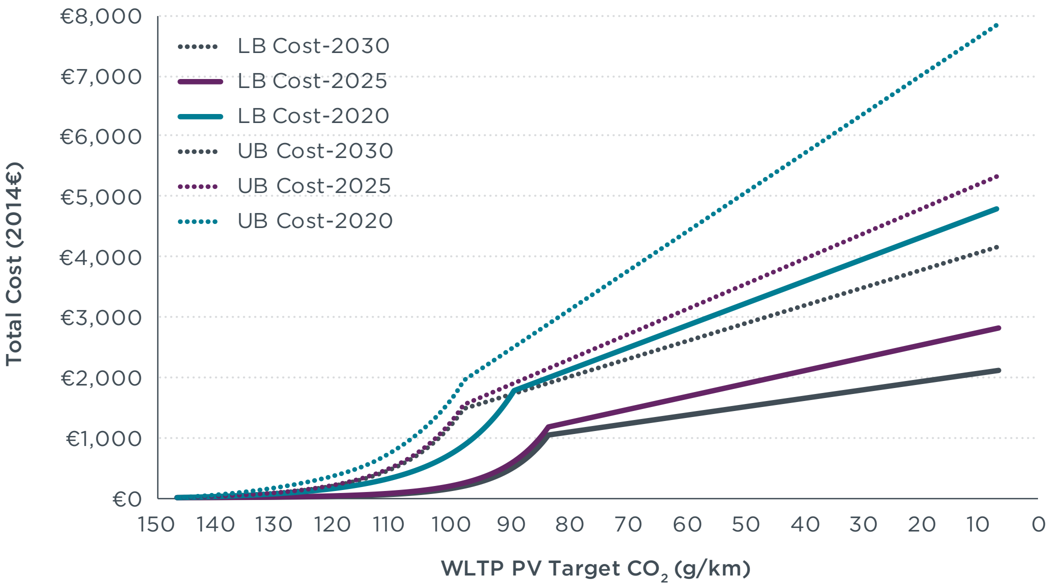


Figure 10b. WLTP CO_2 Costs for Passenger Vehicles (Non-ICE Strategy)

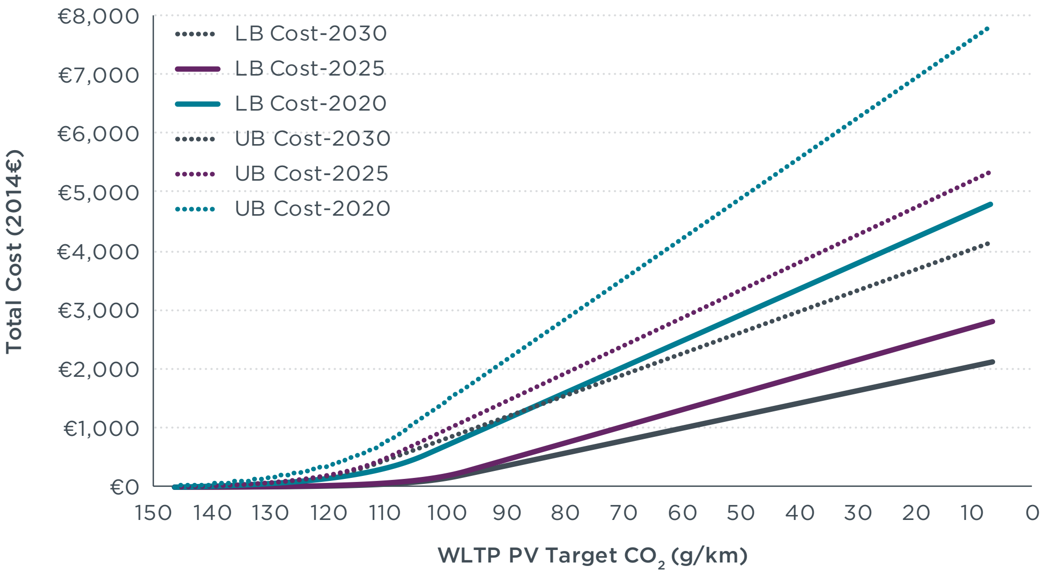


Figure 11a. WLTP CO_2 Costs for Light Commercial Vehicles (ExhICE Strategy)

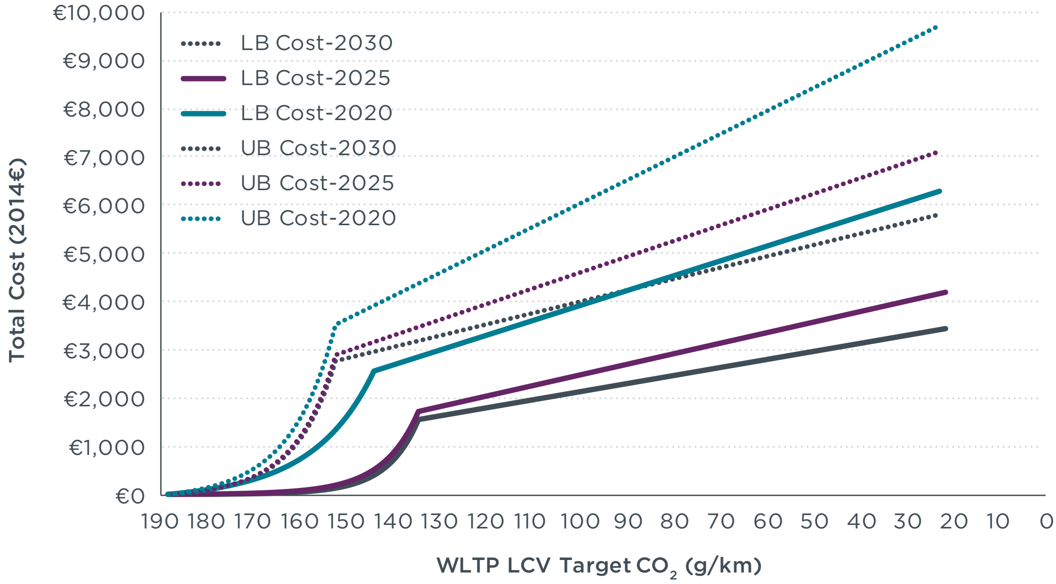
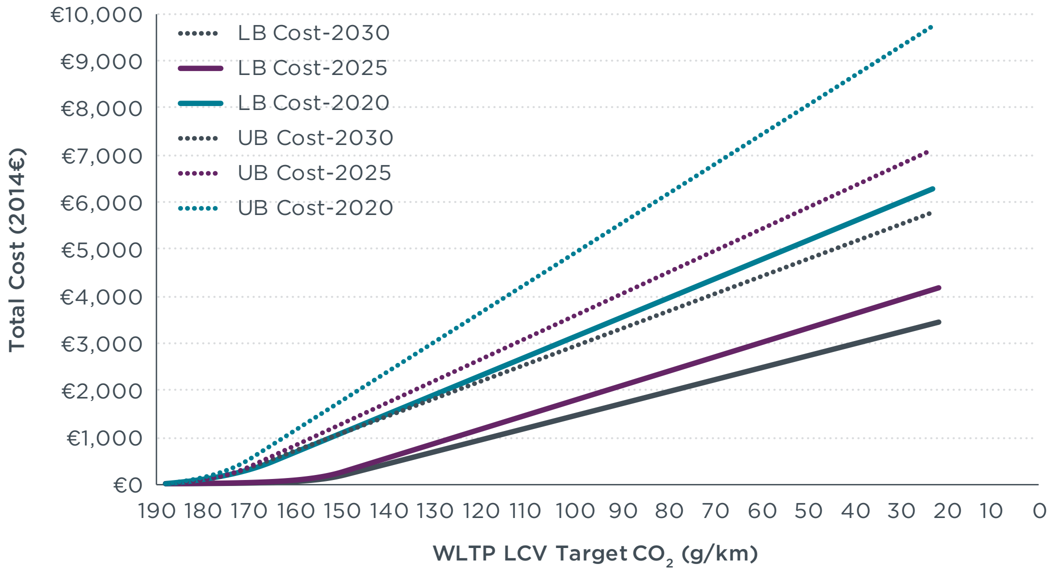


Figure 11b. WLTP CO_2 Costs for Light Commercial Vehicles (Non-ICE Strategy)



Note that zero CO_2 is theoretically attainable for B and C class vehicles because this analysis assumes that all associated non-ICE market penetration in these classes is satisfied by BEVs (which the analysis also assumes are treated as zero CO_2 vehicles through 2030). Zero CO_2 is not attainable for the larger vehicle classes, where non-ICE market demand is satisfied entirely by PHEVs.[23] Because LCVs are treated as a single class in the 2015 FEV ICCT data, this analysis apportions non-ICE market share data for the class into BEV and PHEV components using assumed market shares of 10%, 29%, and 61% for small, medium, and large LCVs, as reported in Section 8 of this

23 The CO_2 reduction cost-effectiveness of non-ICE vehicles is largely dependent on the cost-effectiveness of reductions achievable through ICE technology (because the CO_2 reduction delivered by non-ICEs declines as ICE reduction effectiveness increases). Moreover, this dependence is both time- and class-specific. Nevertheless, a relative view of the cost-effectiveness of the various non-ICE alternatives can be gleaned through a look at the fleet average CO_2 reduction such technology would deliver from a baseline CO_2 level of 70 g/km (roughly the level of CO_2 cost-effectively achievable by ICE passenger vehicles on the NEDC) in 2030. Expressed in terms of euros per g/km, non-ICE cost-effectiveness (based on 2016 ICCT non-ICE data) equals 23€, 42€, 57€, and 88€ for BEV-100, BEV-150, BEV-200, and BEV-300 vehicles; 84€, 67€, 66€, 68€, and 75€ for PHEV-10, PHEV-20, PHEV-30, PHEV-40, and PHEV-60 vehicles; and 108€ for fuel cell vehicles.

document and Figure 2.5 of the Ricardo-AEA source document referenced in that section (Ricardo, 2015). BEVs are assumed to satisfy non-ICE demand in the 39% market share associated with small and medium LCVs, while PHEVs are assumed to satisfy non-ICE demand in the remaining 61% of the LCV market.

The simplifying assumption employed in this analysis of constant BEV-100 non-ICE makeup in the B and C classes results in some "fuzziness" with regard to both the cost and CO_2 reduction associated with *very large* (i.e., approaching 100%) non-ICE market penetrations *in these classes*. On a fleet average basis, this fuzziness is substantially offset because homogeneous PHEV-40 penetration is assumed for all other passenger car classes (where some penetration of less-expensive BEV-100 or BEV-150 technology can reasonably be expected). For modest non-ICE penetrations (i.e., in the range of 30–40%), analysis assumptions will be precise, but that precision will progressively diminish as penetration increases. There is essentially an infinite mix of non-ICE technology that can be used to satisfy very low CO_2 standards. Moreover, unlike the constraint employed in this analysis wherein non-ICE penetration is implemented across classes in proportion with class-specific market shares, non-ICE technology can, in practice, be preferentially employed in less-expensive vehicle classes. A detailed market study outside the scope of this analysis would be required to estimate manufacturer-specific non-ICE response to very low CO_2 standards (below about 50 g/km NEDC), but a rough estimate of the potential fuzziness associated with fleet average compliance costs can be derived by substituting alternative non-ICE penetration assumptions for those employed in this analysis. For example, an assumption of 30% BEV-100, 40% PHEV-20, and 30% PHEV-30 non-ICEs across all classes would alter 100% non-ICE penetration costs as follows:

» 100% non-ICE penetration costs for passenger cars would *increase* under analysis lower bound assumptions by 270 euros (about 13%).
» 100% non-ICE penetration costs for passenger cars would *decrease* under analysis upper bound assumptions by 321 euros (about 8%).
» Potential attainable CO_2 levels would increase from 6 g/km to 20 g/km due to the replacement of BEVs in the B and C classes with non-zero CO_2 PHEVs.

Such effects (for this alternative non-ICE scenario) would scale from zero at 30% non-ICE penetration to the full estimated effect at 100% non-ICE penetration.[24]

Because the rightmost non-ICE portion of the curves depicted in Figures 8 through 11 is a linear function of non-ICE market penetration (as measured against the CO_2 level associated with ICE technology at the point of transition to non-ICE vehicles), non-ICE market penetration can be plotted alongside each cost curve. However, because the CO_2 level at which non-ICE penetration begins is evaluation-year dependent (as test flexibility impacts are assumed to vary by year), it is difficult to include such plots on Figures 8 through 11 that include multiple evaluation years. Therefore, similar figures are also shown for each evaluation year (2020, 2025, and 2030) individually, with each showing both CO_2 costs and associated non-ICE market penetration. Figures 12 through 15 present data for 2030, Figures 16 through 19 present data for 2025, and Figures 20 through 23 present data for 2020. All are analogous to Figures 8 through 11, but are restricted to a single evaluation year.

As discussed in Section 12, fleet average passenger vehicle cost curves are developed on the basis of class-specific market shares. The class-specific CO_2 compliance costs

24 Note that LCVs are treated as a single class for which, like fleet average passenger vehicles, both cost and CO_2 estimates are based on a mix of BEVs and PHEVs. Thus, LCV estimates are subject to the same modest level of precision uncertainty for a 100% non-ICE penetration scenario as passenger vehicles.

underlying the developed fleet average characteristics can, of course, also be presented. Due to the large number of associated figures (nine vehicle classes by three evaluation years by two test cycles), the class-specific data are presented separately in Appendices 1 through 6. Appendices 1 through 3 present class-specific data for the NEDC in 2030, 2025, and 2020, respectively, while Appendices 4 through 6 present class-specific data for the WLTP cycle in those same respective years. Note that to constrain the number of included graphics, the class-specific data included in Appendices 1 through 6 are presented solely in terms of the ICE technology exhaustion strategy. However, as mentioned above, the corresponding curves associated with a least-cost non-ICE transition strategy can be visualized as the tangent from the presented cost curves that runs through the 100% non-ICE market penetration point.

Figure 12a. 2030 NEDC CO_2 Costs for Passenger Vehicles (ExhICE Strategy)

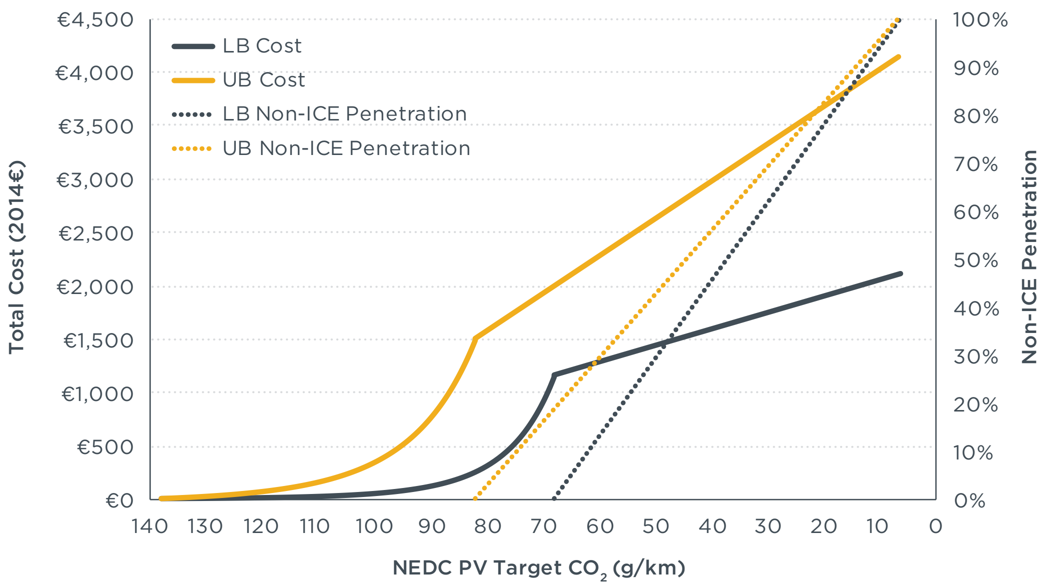


Figure 12b. 2030 NEDC CO_2 Costs for Passenger Vehicles (Non-ICE Strategy)

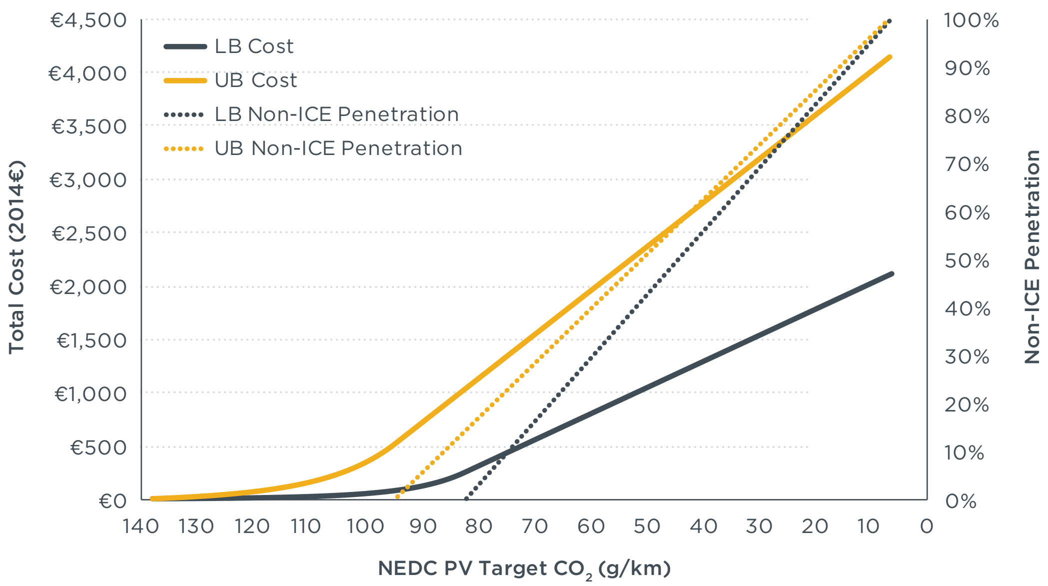


Figure 13a. 2030 NEDC CO_2 Costs for Light Commercial Vehicles (ExhICE Strategy)

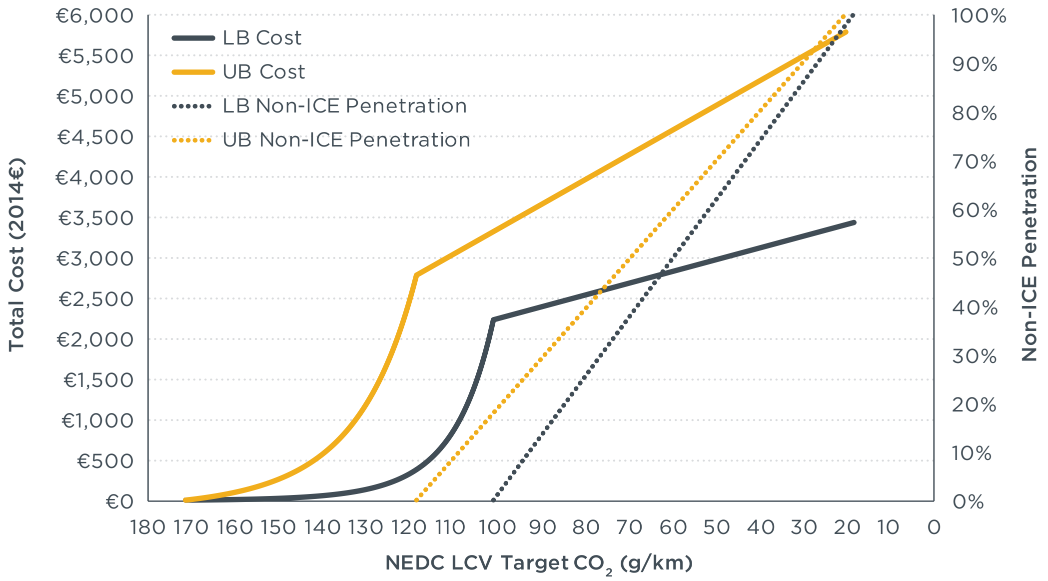


Figure 13b. 2030 NEDC CO_2 Costs for Light Commercial Vehicles (Non-ICE Strategy)

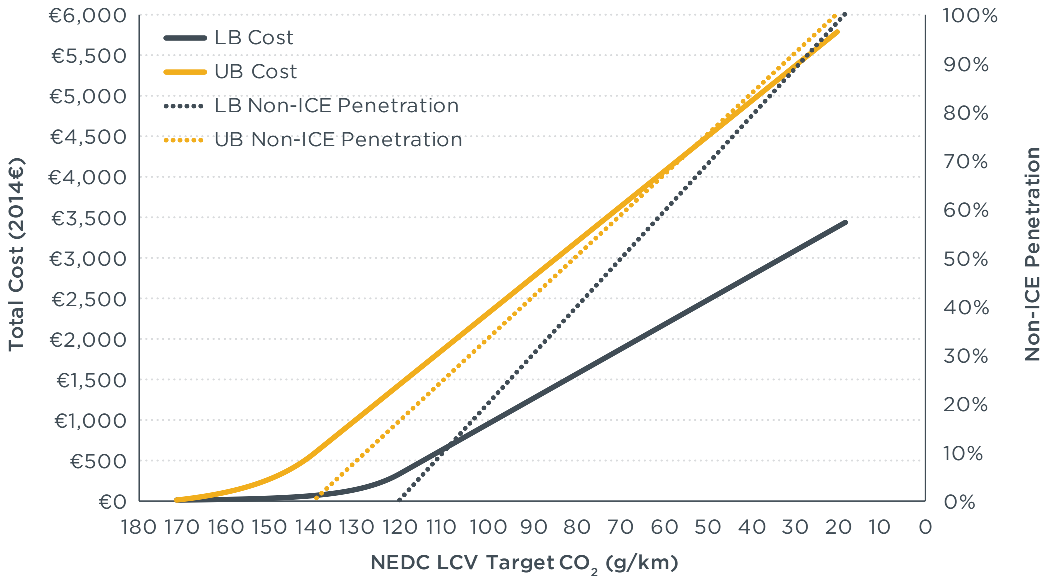


Figure 14a. 2030 WLTP CO_2 Costs for Passenger Vehicles (ExhICE Strategy)

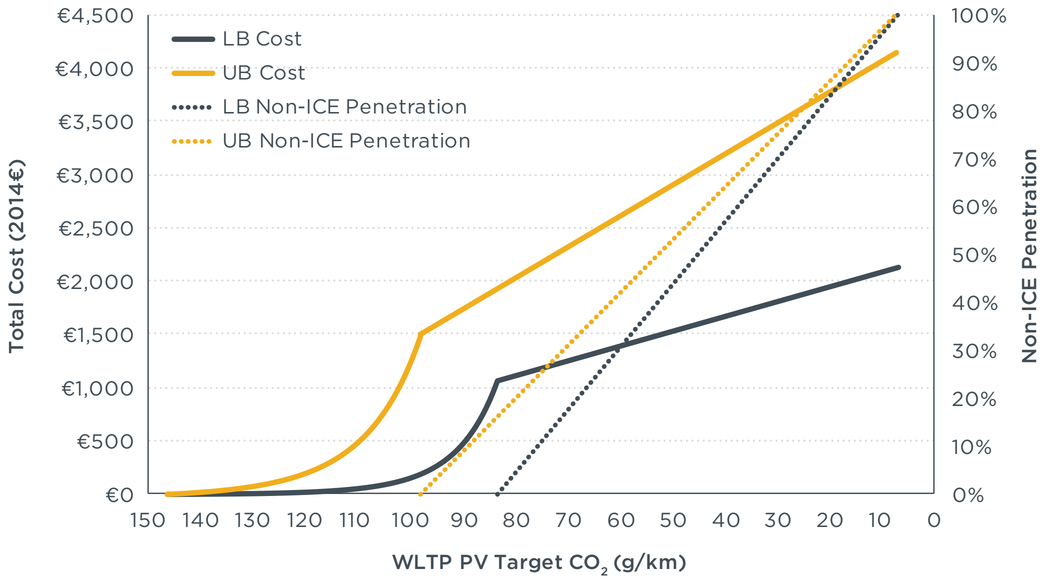


Figure 14b. 2030 WLTP CO_2 Costs for Passenger Vehicles (Non-ICE Strategy)

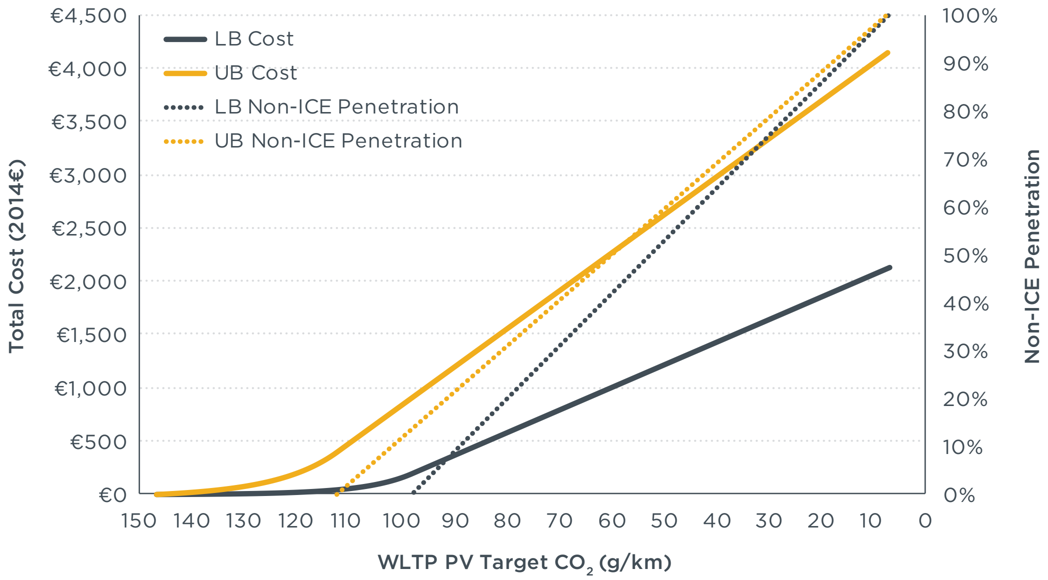


Figure 15a. 2030 WLTP CO_2 Costs for Light Commercial Vehicles (ExhICE Strategy)

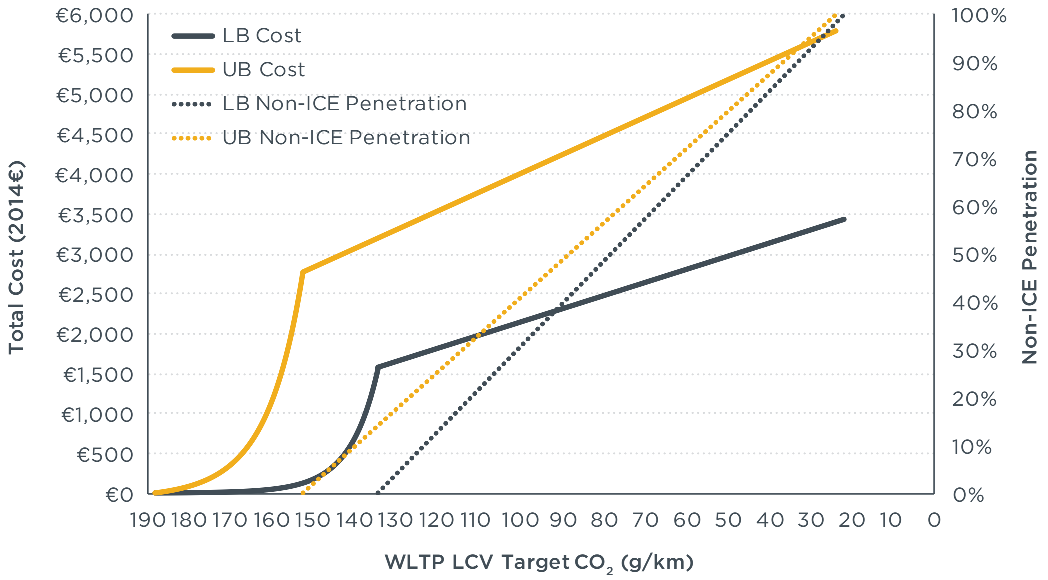


Figure 15b. 2030 WLTP CO_2 Costs for Light Commercial Vehicles (Non-ICE Strategy)

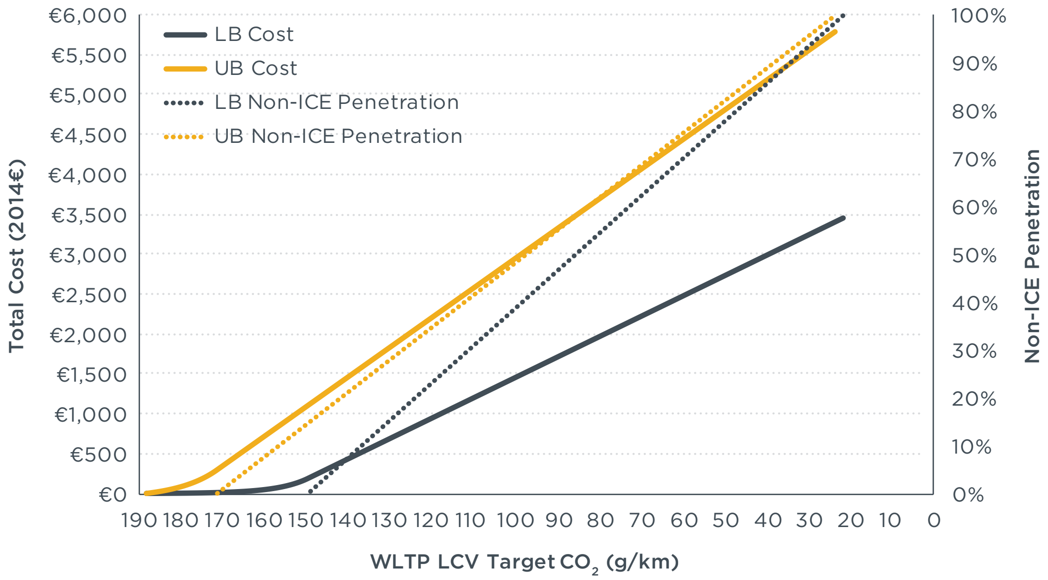


Figure 16a. 2025 NEDC CO_2 Costs for Passenger Vehicles (ExhICE Strategy)

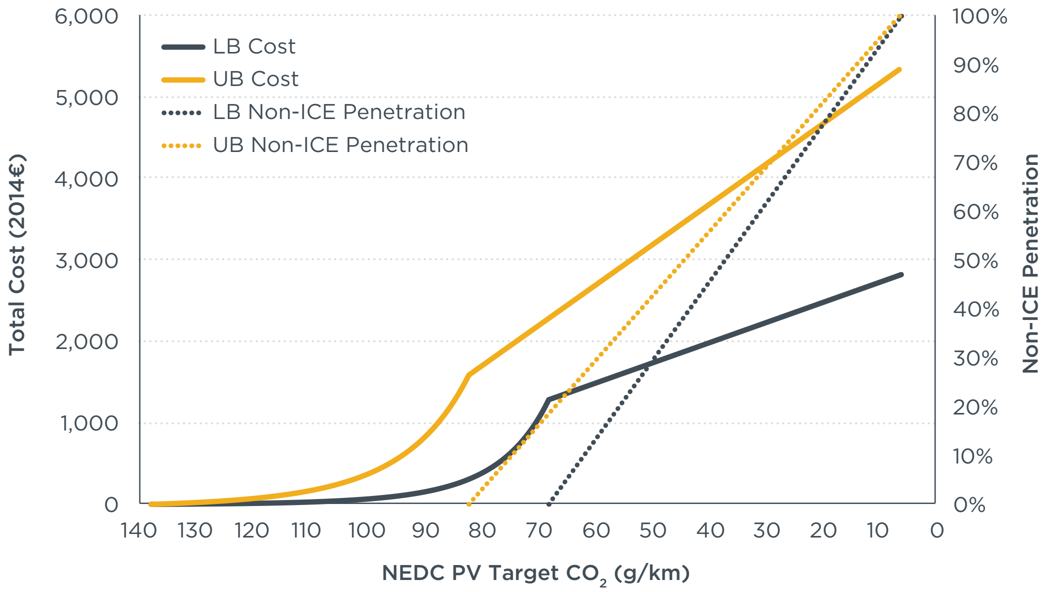


Figure 16b. 2025 NEDC CO_2 Costs for Passenger Vehicles (Non-ICE Strategy)

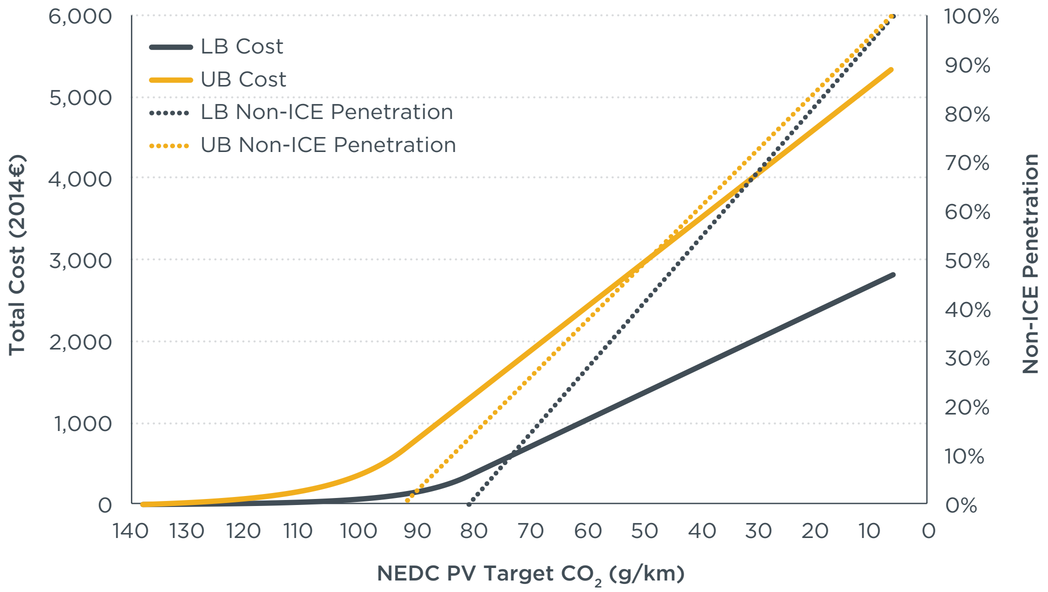


Figure 17a. 2025 NEDC CO_2 Costs for Light Commercial Vehicles (ExhICE Strategy)

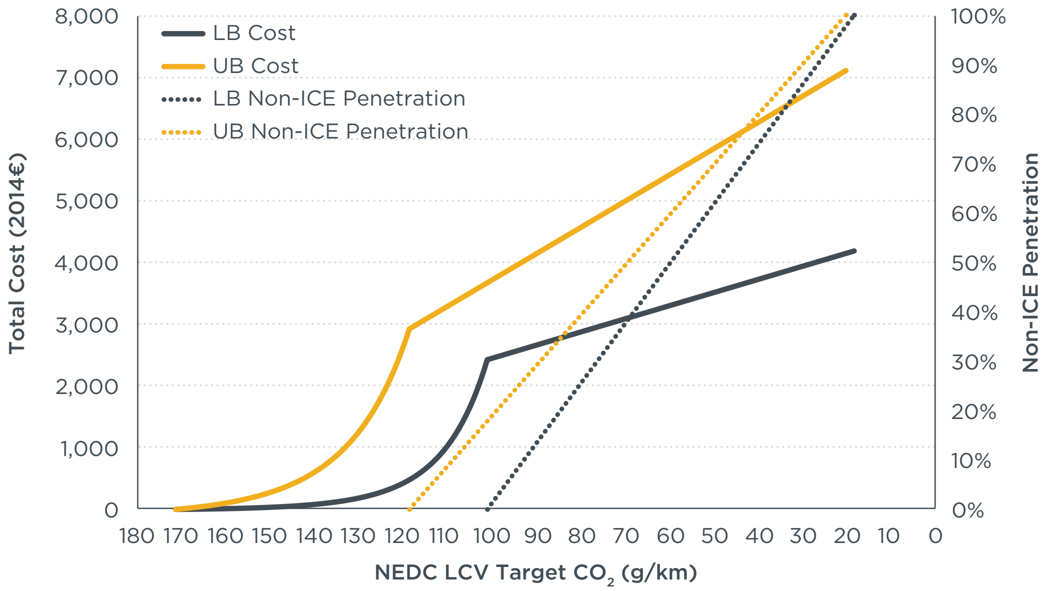


Figure 17b. 2025 NEDC CO_2 Costs for Light Commercial Vehicles (Non-ICE Strategy)

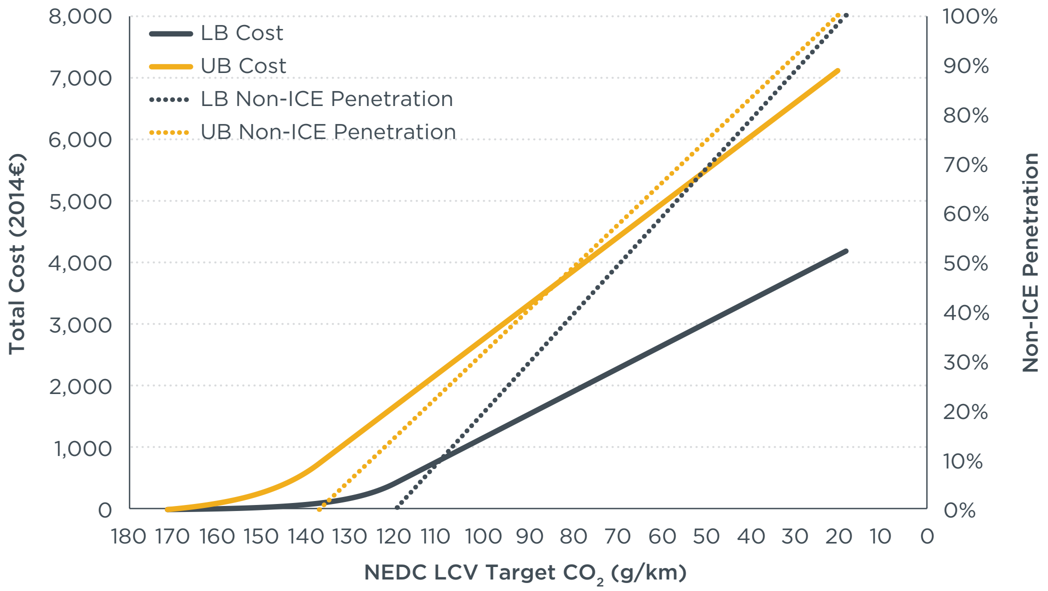


Figure 18a. 2025 WLTP CO_2 Costs for Passenger Vehicles (ExhICE Strategy)

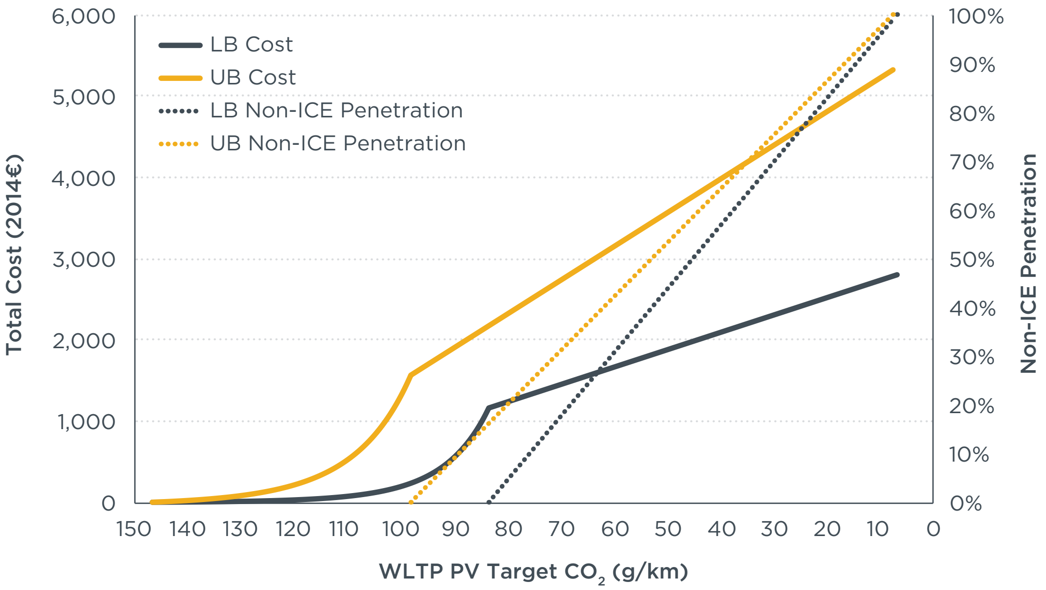


Figure 18b. 2025 WLTP CO_2 Costs for Passenger Vehicles (Non-ICE Strategy)

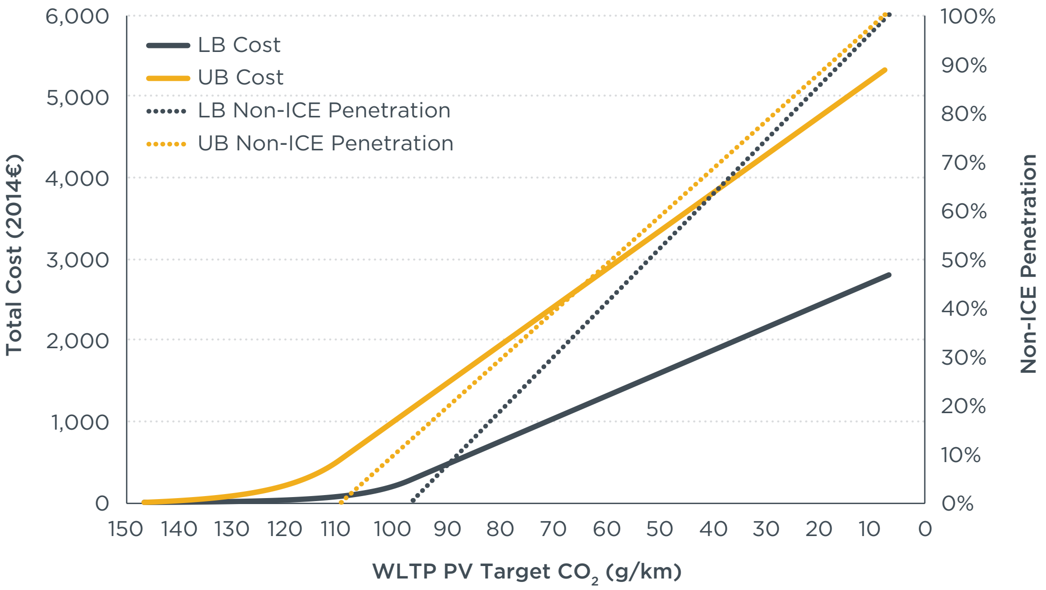


Figure 19a. 2025 WLTP CO_2 Costs for Light Commercial Vehicles (ExhICE Strategy)

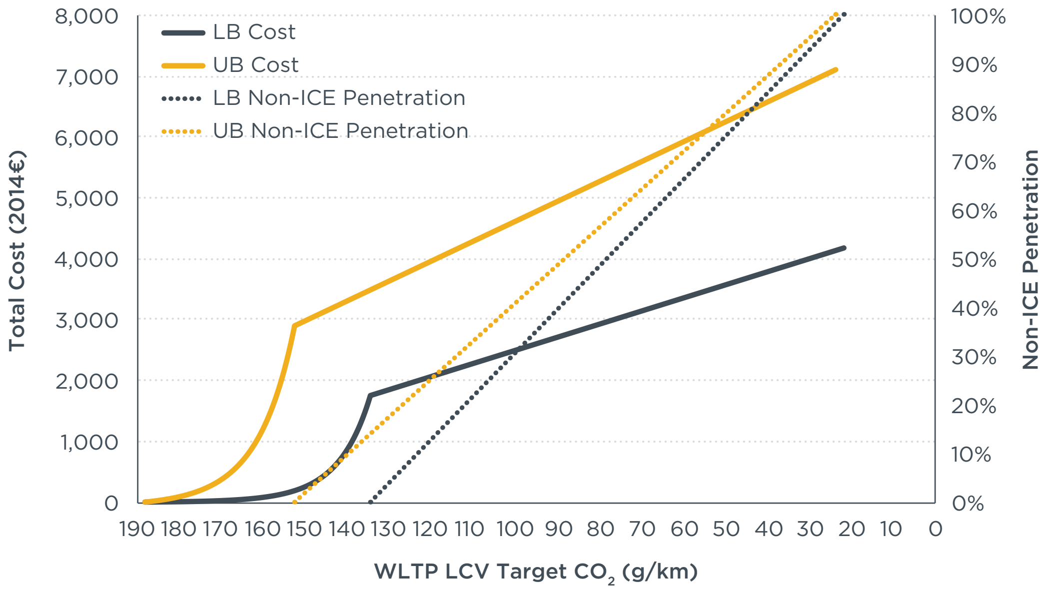


Figure 19b. 2025 WLTP CO_2 Costs for Light Commercial Vehicles (Non-ICE Strategy)

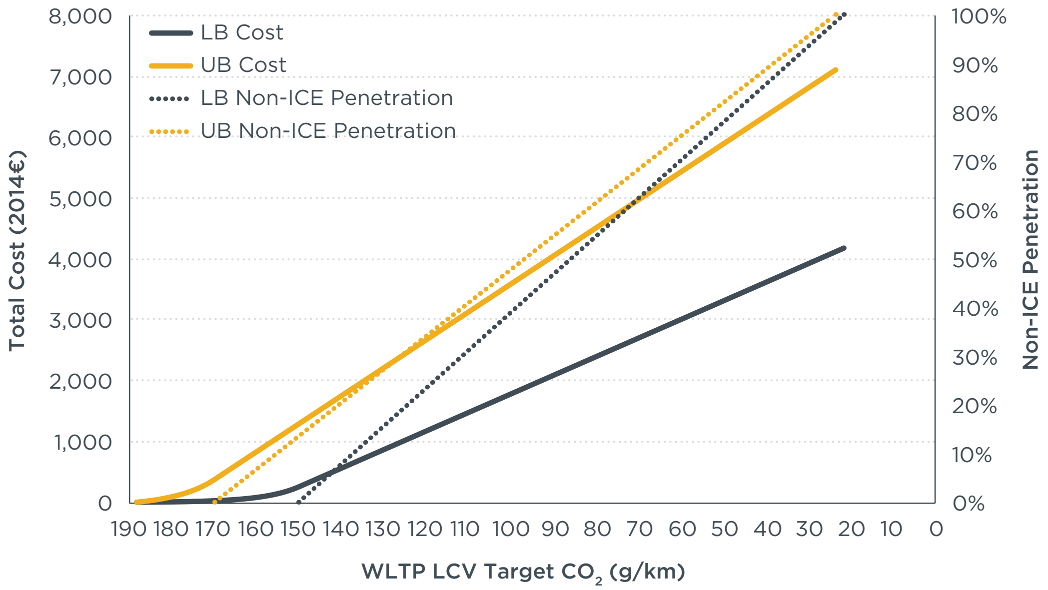


Figure 20a. 2020 NEDC CO_2 Costs for Passenger Vehicles (ExhICE Strategy)

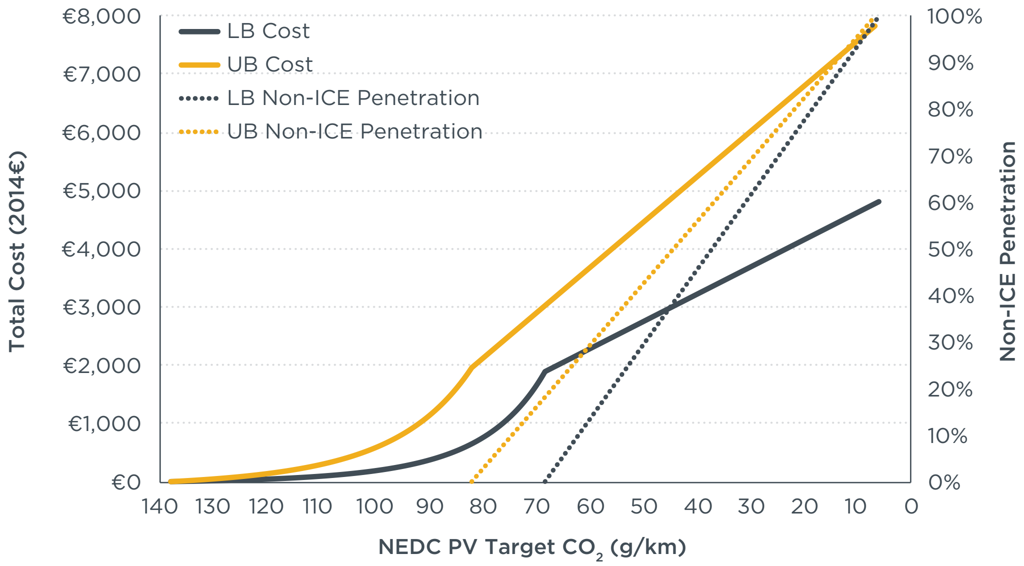


Figure 20b. 2020 NEDC CO_2 Costs for Passenger Vehicles (Non-ICE Strategy)

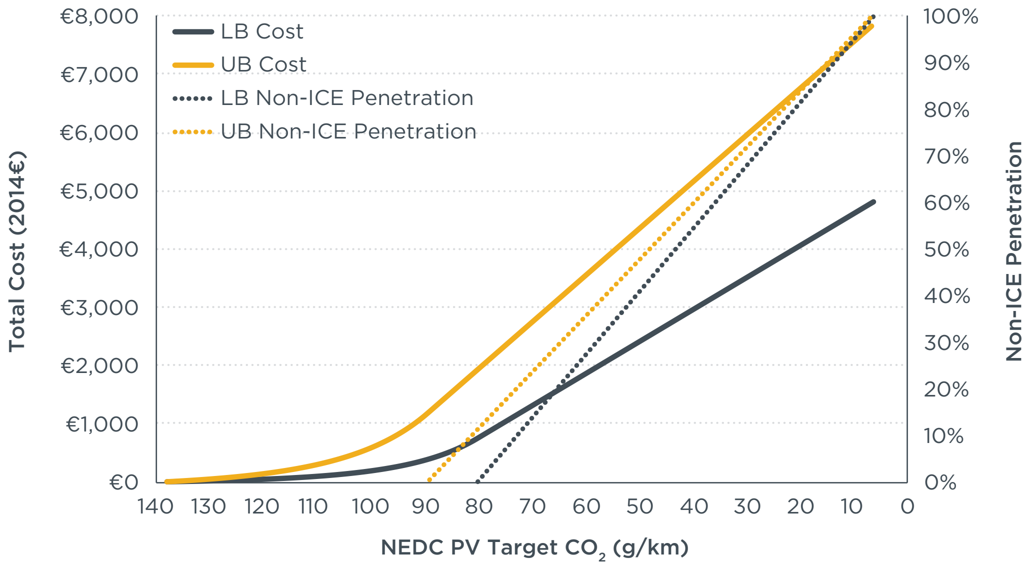


Figure 21a. 2020 NEDC CO_2 Costs for Light Commercial Vehicles (ExhICE Strategy)

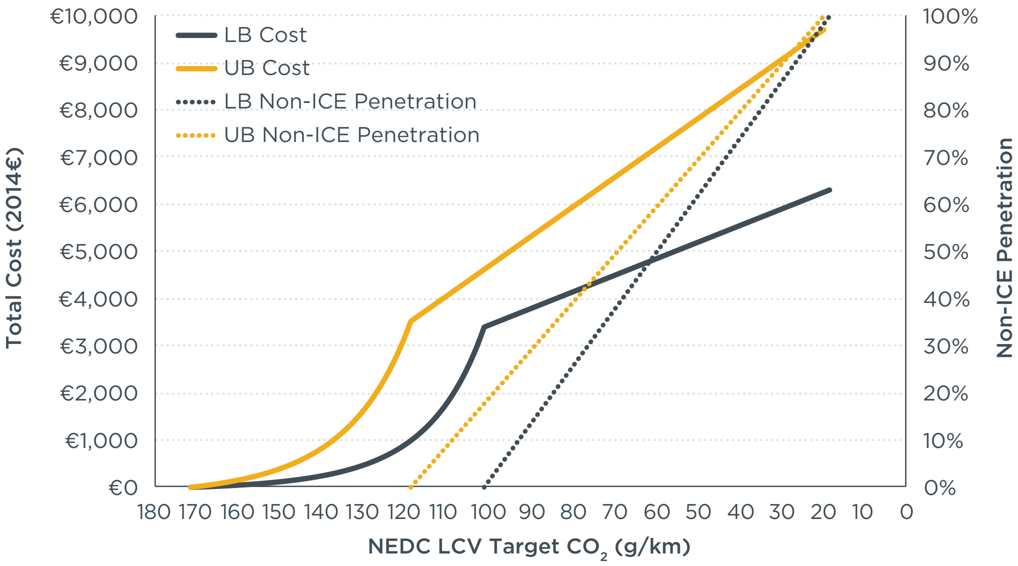


Figure 21b. 2020 NEDC CO_2 Costs for Light Commercial Vehicles (Non-ICE Strategy)

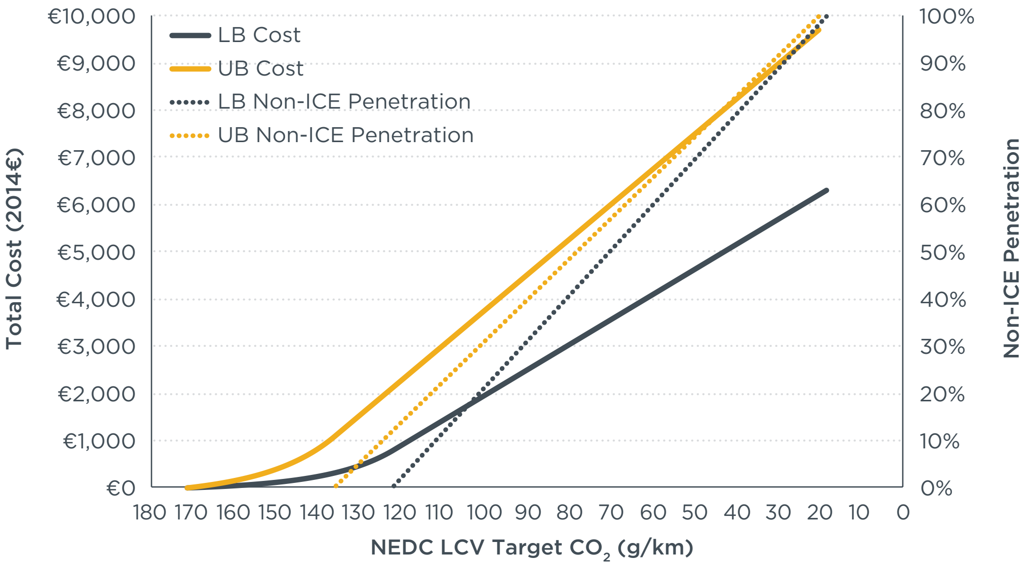


Figure 22a. 2020 WLTP CO_2 Costs for Passenger Vehicles (ExhICE Strategy)

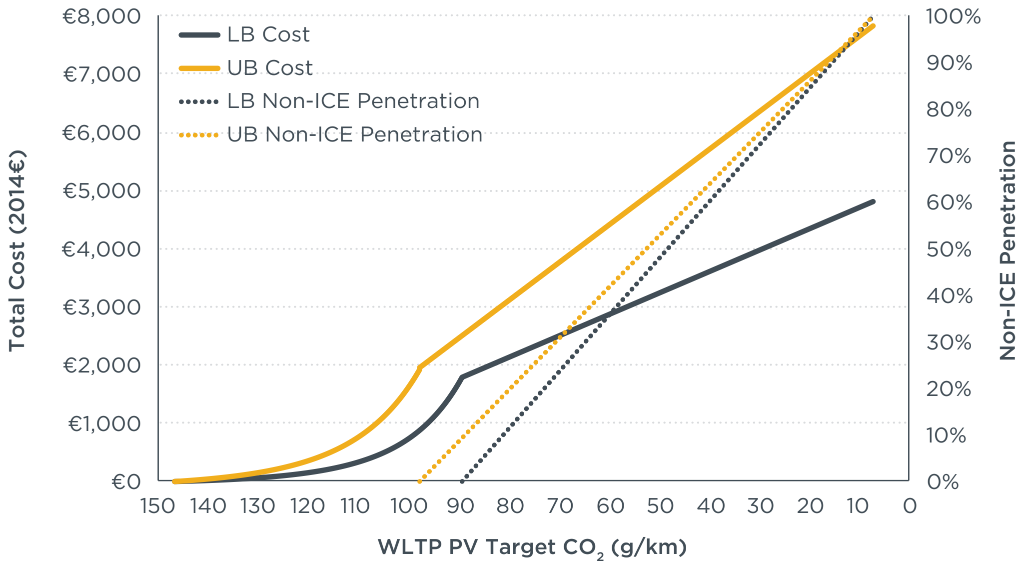


Figure 22b. 2020 WLTP CO_2 Costs for Passenger Vehicles (Non-ICE Strategy)

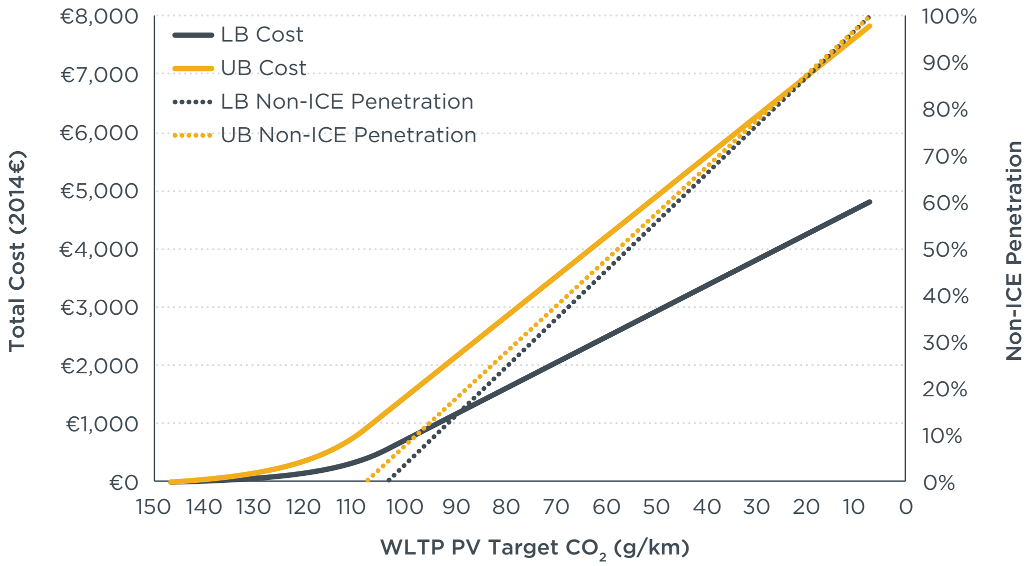


Figure 23a. 2020 WLTP CO_2 Costs for Light Commercial Vehicles (ExhICE Strategy)

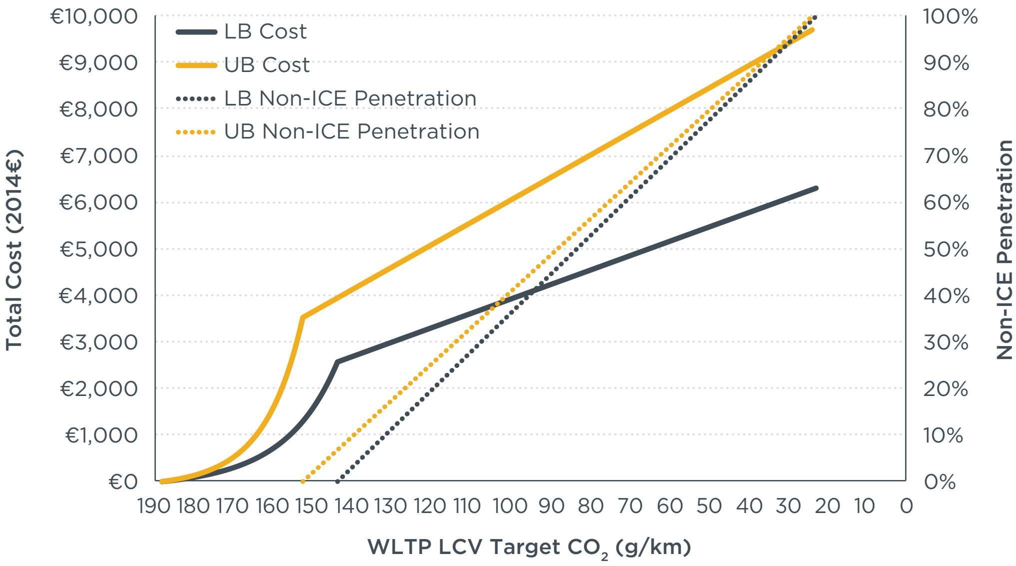
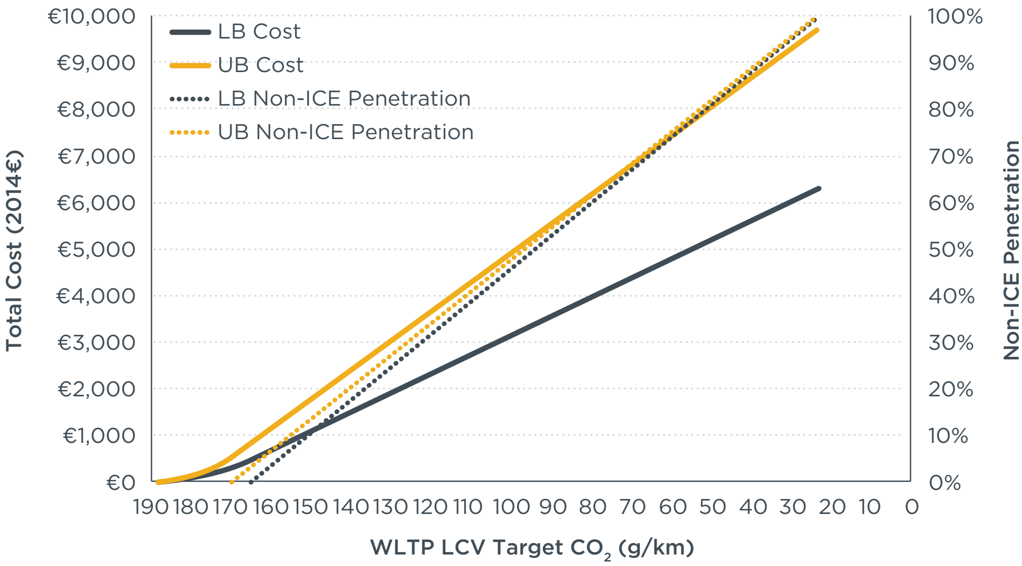


Figure 23b. 2020 WLTP CO_2 Costs for Light Commercial Vehicles (Non-ICE Strategy)



While the effects of potential cost savings are somewhat muted on a fleet average basis due to the averaging of positive and negative costs, there are several instances where class-specific costs (as shown in Appendices 1 through 6) are negative for a range of CO_2 levels. This is true even for upper bound cost estimates, albeit to a lesser degree than is the case for lower bound estimates. There are two basic drivers of cost savings. First, as discussed in Sections 3 and 12, there are a range of mass reductions for which the 2012 FEV ICCT data estimate a cost savings. Such savings do not affect upper bound cost estimates, but they can be significant contributors to net savings associated with lower bound estimates. Because mass reduction costs increase rapidly with mass reduction level, the largest net savings tend to be associated with reductions of about 10%, but lesser negative costs are observed through mass reductions of about 20% (such negative costs are treated as zero in developing upper bound cost estimates). The second negative cost driver, which affects both lower and upper bound cost estimates, is engine downsizing. Savings are generally modest, but can be significant in cases where cylinders are dropped and most especially in cases where V configuration baseline engines are replaced with inline engines of reduced cylinder count (as is the case with class D and E gasoline vehicles). Because both technologies can be applied to baseline engines, the left-hand end of affected ICE cost curves can be significantly below zero. Strictly speaking, there is a step change in cost (from zero) associated with the technologies that drive this leftmost data point, but this is not shown on the presented cost curves as a matter of convenience.

14. COMPARISON WITH PREVIOUS CO_2 COMPLIANCE COSTS

As mentioned earlier, the ICCT performed similar cost curve development work in 2012 and 2013 using vehicle simulation data and technology cost developed by Ricardo and FEV, respectively (ICCT, 2012a; ICCT, 2012b; ICCT, 2013; and ICCT, 2014). This analysis is not only independent of but also not directly comparable to that previous work for any number of reasons, including the fact that the previous work did not consider the potential impacts of non-ICE vehicle technology, the previous work did not include a number of the detailed cost and CO_2 adjustments considered in this analysis, and baseline vehicle characteristics as well as specific analysis parameters differ between the two analyses. Nevertheless, it is possible to undertake a basic comparison of the cost estimates developed for the 95 g/km passenger vehicle and 147 g/km LCV standards that were the focus of the previous work.

With mass reduction technology considered (as is the case with this analysis), the previous cost curve analysis predicted incremental total (retail-level) costs in 2020 of €1,036 for a 95 g/km passenger vehicle NEDC standard and €402 for a 147 g/km LCV NEDC standard. Note that these costs differ somewhat from those published for the 2012 and 2013 analysis due to the fact that several adjustments have been applied to normalize the parameters of the previous analysis with those of the current analysis. First, the previous analysis published only direct manufacturing costs, while costs in this analysis are expressed in terms of total retail-level costs.[25] Total compliance costs from the previous analytical work were extracted from unpublished support materials used to produce the referenced report documents, and are entirely consistent with the published direct manufacturing costs. Second, the baseline CO_2 levels of the two analyses are slightly different, with the previous analysis assuming baseline passenger and LCV CO_2 of 140 g/km and 180 g/km, respectively, as compared with 138 and 172 g/km for this analysis. The incremental costs associated with reducing passenger and LCV CO_2 by 2 and 8 g/km, respectively, have been subtracted from the CO_2 compliance costs estimated in the previous work to put both analyses on a common CO_2 baseline. Third, the estimates for the previous analysis are for the WEU, whereas those for this analysis reflect a production-weighted average of WEU and EEU costs.[26] To eliminate this inconsistency, previous analysis passenger and LCV costs have been multiplied

25 At the time the 2012/2013 ICCT cost curve analysis was performed, the ICCT had commissioned a separate study to evaluate potential differences between indirect costs in the U.S. and EU. Because that study was not completed until after the 2012/2013 cost curves were developed, those curves focused solely on direct manufacturing costs. The EU indirect cost study was completed in late 2013 and found that retail-to-direct manufacturing costs in the EU were 7% higher than those in the U.S. on a sales-weighted average basis (with individual manufacturers showing ratios ranging from 1% lower to 15% higher). However, the study also found that the U.S. EPA's approach to estimating indirect costs resulted in an overestimate of such costs in the 2025 time frame, generally on the order of 10–25%. Given these offsetting findings, it was decided to retain the U.S. indirect cost multipliers without change in this analysis. This may result in a modest overestimate of retail-level costs.

26 For passenger vehicles, 77% western and 23% eastern EU costs. For LCVs, 91% western and 9% EEU costs.

by 0.963 and 0.985, respectively (see Section 11 for a discussion of these factors). Finally, estimates from the previous work were multiplied by a factor of 1.057 to convert 2010/2011 euros to the 2014 euro basis associated with this analysis (see Section 1 for a derivation of the euro adjustment factor).

As shown in Table 27, the CO_2 compliance cost estimates for this analysis predict incremental costs in 2020 of between €261 (lower bound) and €807 (upper bound) for a 95 g/km passenger vehicle NEDC standard, and incremental costs in 2020 of between €146 (lower bound) and €506 (upper bound) for a 147 g/km LCV NEDC standard. These compare with the incremental cost estimates of €1,036 for a 95 g/km passenger vehicle standard and €402 for a 147 g/km LCV standard from the previous study. The most direct comparison is between the previous and current upper bound estimates as these are more consistent with regard to analytical assumptions than are the previous and current lower bound estimates. Current upper bound estimates for passenger vehicles are about 22% lower than the previous cost estimates, while those for LCVs are about 26% higher. Lower bound cost estimates are about 75% lower for passenger vehicles and 64% lower for LCVs.

Table 27. Comparison of Current and Previous Retail-Level Compliance Cost Estimates (2014€)

Analysis Scenario	2012/2013 Analysis	This Analysis	
		Lower Bound Estimate	Upper Bound Estimate
NEDC Passenger Vehicle Standard of 95 g/km	€ 1,036	€ 261	€ 807
NEDC LCV Standard of 147 g/km	€ 402	€ 146	€ 506

Thus, this analysis estimates that, even under worst-case conditions, compliance costs should be roughly similar to those estimated in the previous work, but will likely be substantially lower.

That estimated compliance costs have decreased over the three-year interval between the two analyses is not surprising, given ongoing ICE technology development and associated cost reductions. Significant advancements in technologies such as 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 non-hybrid vehicles, VCR operation, and 48-volt hybrid systems have been observed and are expected to continue.

15. 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. Based on the derived curves, compliance costs at the retail level can be estimated for a wide range of potential CO_2 standards. Table 28 summarizes lower and upper bound cost estimates for both passenger and LCVs, assuming a compliance strategy that relies on the exhaustion of ICE technology prior to the widespread introduction of non-ICE vehicles. Table 29 summarizes corresponding estimates for a least-cost compliance strategy that assumes the introduction of non-ICE vehicles as soon as their onboard technology is more cost-effective (from a CO_2 standpoint) than alternative ICE technology. While it is difficult to generalize the cost estimates in the absence of a specific CO_2 reduction target, the following conclusions can be drawn for the average EU market in the 2025–2030 time frame.

» Passenger vehicle NEDC standards as low as 60–70 g/km can be achieved with either no or only modest levels of non-ICE vehicle penetration (see Table 28).

» Given the current state of ICE technology, a passenger vehicle NEDC standard of 70 g/km can be attained by 2025 for between €1,000 and €2,000 per vehicle (2014€) with no (lower bound) or very modest (upper bound) non-ICE market penetration. Costs would be €200 to €500 per vehicle (2014€) lower under a least-cost non-ICE transition strategy (see Tables 28 and 29).

Table 28. Summary of Retail Compliance Costs for Various CO_2 Targets (ExhICE Strategy)

CO_2 Target (g/km)	Total Cost (2014€) to Achieve in:				non-ICE Market Share at:	
	2025		2030			
	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Passenger Vehicles over the NEDC						
80	€ 300	€ 1,650	€ 250	€ 1,550	0%	3%
70	€ 1,000	€ 2,150	€ 900	€ 1,900	0%	16%
60	€ 1,450	€ 2,650	€ 1,300	€ 2,250	13%	29%
50	€ 1,700	€ 3,150	€ 1,450	€ 2,600	29%	42%
40	€ 1,950	€ 3,650	€ 1,600	€ 2,950	45%	56%
Passenger Vehicles over the WLTP Cycle						
80	€ 1,250	€ 2,300	€ 1,100	€ 2,000	5%	20%
70	€ 1,450	€ 2,750	€ 1,250	€ 2,300	18%	31%
60	€ 1,650	€ 3,150	€ 1,400	€ 2,600	31%	42%
50	€ 1,900	€ 3,550	€ 1,550	€ 2,900	44%	53%
40	€ 2,100	€ 3,950	€ 1,650	€ 3,200	57%	64%
LCVs over the NEDC						
120	€ 450	€ 2,650	€ 350	€ 2,500	0%	0%
110	€ 1,050	€ 3,300	€ 900	€ 3,050	0%	9%
100	€ 2,450	€ 3,700	€ 2,250	€ 3,350	1%	19%
90	€ 2,650	€ 4,100	€ 2,400	€ 3,650	13%	29%
80	€ 2,850	€ 4,550	€ 2,550	€ 3,950	26%	39%
70	€ 3,100	€ 4,950	€ 2,700	€ 4,250	38%	49%
60	€ 3,300	€ 5,400	€ 2,850	€ 4,550	50%	59%
50	€ 3,500	€ 5,800	€ 3,000	€ 4,850	62%	70%
40	€ 3,700	€ 6,250	€ 3,150	€ 5,200	74%	80%
LCVs over the WLTP Cycle						
120	€ 2,050	€ 3,950	€ 1,800	€ 3,550	13%	25%
110	€ 2,300	€ 4,300	€ 2,000	€ 3,750	22%	33%
100	€ 2,500	€ 4,600	€ 2,150	€ 4,000	31%	41%
90	€ 2,700	€ 4,950	€ 2,300	€ 4,250	40%	49%
80	€ 2,900	€ 5,250	€ 2,500	€ 4,450	48%	56%
70	€ 3,150	€ 5,600	€ 2,650	€ 4,700	57%	64%
60	€ 3,350	€ 5,900	€ 2,800	€ 4,950	66%	72%
50	€ 3,550	€ 6,250	€ 2,950	€ 5,150	75%	80%
40	€ 3,800	€ 6,550	€ 3,150	€ 5,400	84%	87%

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 above) to direct manufacturing costs to derive total retail-level cost estimates.

Table 29. Summary of Retail Compliance Costs for Various CO_2 Targets(Non-ICE Strategy)

CO_2 Target (g/km)	Total Cost (2014€) to Achieve in:				non-ICE Market Share at:	
	2025		2030			
	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Passenger Vehicles over the NEDC						
80	€ 300	€ 1,350	€ 250	€ 1,100	4%	17%
70	€ 650	€ 1,900	€ 500	€ 1,550	17%	28%
60	€ 1,000	€ 2,450	€ 750	€ 1,950	30%	39%
50	€ 1,300	€ 2,950	€ 1,000	€ 2,350	43%	51%
40	€ 1,650	€ 3,500	€ 1,250	€ 2,750	56%	62%
Passenger Vehicles over the WLTP Cycle						
80	€ 700	€ 1,900	€ 500	€ 1,550	20%	31%
70	€ 1,000	€ 2,400	€ 750	€ 1,900	31%	40%
60	€ 1,250	€ 2,850	€ 950	€ 2,250	42%	50%
50	€ 1,550	€ 3,350	€ 1,150	€ 2,600	53%	59%
40	€ 1,850	€ 3,800	€ 1,400	€ 3,000	64%	69%
LCVs over the NEDC						
120	€ 450	€ 1,700	€ 350	€ 1,450	0%	17%
110	€ 800	€ 2,200	€ 650	€ 1,900	10%	25%
100	€ 1,150	€ 2,750	€ 950	€ 2,300	20%	33%
90	€ 1,550	€ 3,300	€ 1,250	€ 2,750	30%	42%
80	€ 1,900	€ 3,850	€ 1,550	€ 3,200	40%	50%
70	€ 2,250	€ 4,400	€ 1,850	€ 3,600	49%	58%
60	€ 2,650	€ 4,950	€ 2,150	€ 4,050	59%	67%
50	€ 3,000	€ 5,450	€ 2,450	€ 4,500	69%	75%
40	€ 3,400	€ 6,000	€ 2,800	€ 4,900	79%	83%
LCVs over the WLTP Cycle						
120	€ 1,150	€ 2,650	€ 950	€ 2,200	23%	35%
110	€ 1,500	€ 3,150	€ 1,200	€ 2,600	31%	42%
100	€ 1,800	€ 3,600	€ 1,450	€ 2,950	39%	48%
90	€ 2,100	€ 4,050	€ 1,700	€ 3,300	47%	55%
80	€ 2,400	€ 4,500	€ 1,950	€ 3,700	54%	62%
70	€ 2,700	€ 4,950	€ 2,200	€ 4,050	62%	69%
60	€ 3,000	€ 5,400	€ 2,450	€ 4,450	70%	75%
50	€ 3,300	€ 5,900	€ 2,700	€ 4,800	78%	82%
40	€ 3,600	€ 6,350	€ 3,000	€ 5,200	86%	89%

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 above) to direct manufacturing costs to derive total retail-level cost estimates.

» For numerically identical passenger vehicle standards the WLTP will require a cost premium of €500 to €1,000 per vehicle (2014€) for standards requiring no or modest non-ICE market penetrations, but that premium will decline as non-ICE market shares increase because non-ICE vehicles are credited with very low CO_2 under either driving cycle (see Tables 28 and 29). The cost premium ultimately declines to zero at 100% non-ICE market penetration (although the standards attainable through PHEV technology are cycle dependent due to cycle-specific AER influences).

- Passenger vehicle standards as low as 40 g/km can be achieved by 2030 for costs of between €1,300 and €3,000 per vehicle (2014€) under either the NEDC or WLTP cycles, as compliance with such standards is dominated by large non-ICE market shares.
- LCV NEDC standards as low as 90–100 g/km can be achieved with either no or only modest levels of non-ICE vehicle penetration (see Table 28).
- Under an ICE technology exhaustion strategy, a LCV NEDC standard of 110 g/km in 2025 will cost approximately between €1,000 and €3,000 per vehicle (2014€), while a 90 g/km standard in 2025 will cost between €2,500 and €4,000 per vehicle (2014€). Costs would be €250 to €1,000 per vehicle (2014€) lower under a least-cost non-ICE transition strategy (see Tables 28 and 29).
- For numerically identical LCV standards the WLTP will require a cost premium of €1,000 to €1,500 per vehicle (2014€) for standards requiring no or modest non-ICE market penetrations, but that premium will decline (ultimately to zero) as non-ICE market shares increase because non-ICE vehicles are credited with very low CO_2 under either driving cycle (see Tables 28 and 29).
- LCV standards as low as 40 g/km can be achieved by 2030 for costs of between €3,000 and €5,500 per vehicle (2014€) under either the NEDC or WLTP cycles, as compliance with such standards is dominated by large non-ICE market shares.

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. Additionally, as described in Section 1 above, the developed compliance costs are technology neutral and do not consider the impacts associated with any potential regulatory structure that might discount the value of any CO_2 reduction technology. Mass reduction technology is included in the developed cost curves, so that regulatory structures that discount the value of vehicle mass reduction—either in whole or in part—will impose greater compliance costs than estimated herein. The potential magnitude of the cost increases associated with regulatory structures that discount the value of mass reduction technology will be investigated and published separately as an addendum to this paper.

Limitations to the approach and the presented cost curves include:

- 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 (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. FEV calls this more conservative approach a "should cost" assessment, in that it is based on what should be the cost of a technology *that already exists today* if it is mass-produced in high volume, without any changes to a design that reflects current knowledge. This is different than a "could cost" assessment that considers what could be the cost of a technology if it is optimized over time through product redesigns that take advantage of evolving knowledge. A good example of this differential approach is P2 hybrid electric vehicle technology. Currently, the P2 electric motor and transmission are produced as two separate units. With larger volumes, it is likely that manufacturers will invest in a redesign of the technology to integrate the electric motor and transmission into a single unit, which will reduce manufacturing costs. This likely redesign of the technology, as well as potential similar impacts for other evaluated technology, is not taken into account for the current cost assessment presented in this paper. Thus, while the "should cost" approach employed for this paper adds an important "ground truth" validation to the presented cost estimates, it also results in the assignment of a zero probability to the cost value of future technology advances. To the extent that such design advances occur, the presented cost curves will overstate CO_2 emission-reduction costs in the years following such advances.

» Specific limitations with respect to FEV's simulation development, including non-consideration of engine downsizing potential in mass reduction and hybrid technology simulations, non-consideration of the impacts of mass and 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,[27] 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 would have an impact on fleet average compliance costs—as gasoline vehicle compliance costs are generally lower than those for diesel vehicles. A detailed assessment of this effect will be presented in a subsequent addendum to this paper.

» 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 bound of actual future costs, and that the real costs for meeting potential CO_2 emission targets are likely to be lower than indicated above. This is supported by the comparison of projected costs from this analysis with those of the ICCT's previous (2012/2013) cost curve analysis (as discussed in Section 14 above). The substantial cost reductions that have occurred in the three years since the earlier analysis illustrate the continuing potential for major technology development and cost reduction in the future.

27 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 non-hybrid vehicles, VCR operation, and 48-volt hybrid systems. Even the first Li-ion battery application was less than 10 years ago.

16. ABBREVIATIONS AND ACRONYMS

ACEA	European Automobile Manufacturers' Association
AD	Aerodynamic Drag
AER	All-Electric Range
AT	Aftertreatment Technology
A7	Seven Speed Automatic Transmission
A8	Eight Speed Automatic Transmission
BD	Class B Diesel Vehicle
BG	Class B Gasoline Vehicle
BEV	Battery Electric Vehicle (with the battery being the sole energy source)
BEV-xxx	BEV with an AER of xxx as measured over the NEDC
CD	Class C Diesel Vehicle
C_d	Coefficient of Drag
C_dA	Coefficient of Drag × Vehicle Frontal Area
CG	Class C Gasoline Vehicle
CO_2	Carbon Dioxide
CPI	Consumer Price Index
DCT	Dual Clutch (Automated Manual) Transmission
DD	Class D Diesel Vehicle
DG	Class D Gasoline Vehicle
DI	Direct Injection
DMC	Direct Manufacturing Cost
DOHC	Dual Overhead Cam Configuration
DVT	Ricardo Data Visualization Tool
DVVT	Discrete Variable Valve Timing
ED	Class E Diesel Vehicle
EG	Class E Gasoline Vehicle
EPA	U.S. Environmental Protection Agency
EGR	Exhaust Gas Recirculation
EU	European Union
EEU	Eastern European Union
ExhICE Strategy	Compliance strategy wherein ICE technology is exhausted before non-ICE vehicles are introduced
FCV	Hydrogen Fuel Cell Vehicle (with the fuel cell being the sole energy source)
FEV	FEV Consulting GmbH
g	Gram(s)
GPS	Global Positioning System
HEV	Hybrid Electric Vehicle (without off-board charging capability)

hr	Hour
ICCT	International Council on Clean Transportation
ICE	Internal Combustion Engine
ICM	Indirect Cost Multiplier
I4	Four-Cylinder Inline Configuration Engine
kg	Kilogram(s)
km	Kilometer(s)
kW	Kilowatt(s)
l	Liter(s)
LB	Lower Bound
LCV	Light Commercial Vehicle
LCVD	LCV Class Diesel Vehicle
LED	Light-Emitting Diode
Li-ion	Lithium Ion Battery Technology
LRR	Lower (Reduced) Rolling Resistance
m^2	Square Meters
MPFI	Multi-Port Fuel Injection
mph	Miles per Hour
M5	Five-Speed Manual Transmission
M6	Six-Speed Manual Transmission
NEDC	New European Driving Cycle
Non-ICE Strategy	Compliance strategy wherein non-ICE vehicles are introduced as soon as they are more cost-effective from a CO_2 reduction standpoint than alternative ICE technology
n/a	Not Applicable
NonBatt	Non-Battery
non-ICE	Without an ICE, meaning PHEVs, BEVs, and FCVs
NRC	U.S. National Research Council
PHEV	Plug-In Hybrid Electric Vehicle (with off-board charging capability)
PHEV-xxx	PHEV with an AER of xxx as measured over the NEDC
P2	P2 Configuration (parallel two-clutch single motor) HEV
SUV	Sport Utility Vehicle
SUVD	SUV Class Diesel Vehicle
TC	Total (Retail Level) Cost
UB	Upper Bound
U.S.	United States
V6	Six-Cylinder V-Configuration Engine
WEU	Western European Union
WLTP	Worldwide Harmonized Light Vehicles Test Procedure
8DCT	Eight-Speed Dual Clutch (Automated Manual) Transmission

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APPENDIX 1

Passenger Vehicle Class-Specific CO_2 Compliance Costs over the NEDC in 2030

All presented cost curves are for an ICE technology exhaustion strategy. Corresponding curves for a least-cost non-ICE transition strategy can be derived as the tangent line from the ICE technology cost curve that passes through the 100% non-ICE market penetration data point.

Figure A1-1. 2030 CO_2 Costs for Class B Diesel Passenger Vehicles over the NEDC

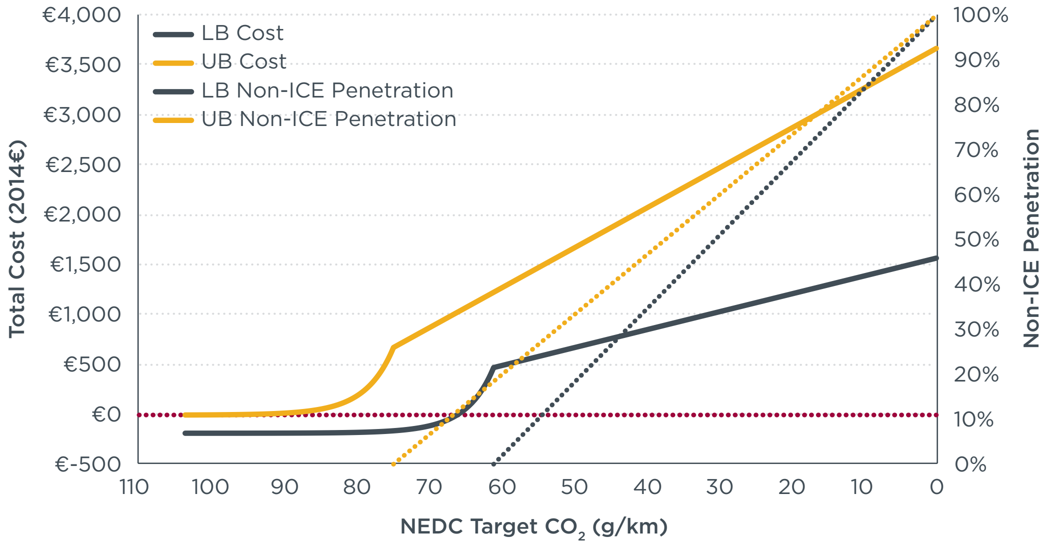


Figure A1-2. 2030 CO_2 Costs for Class C Diesel Passenger Vehicles over the NEDC

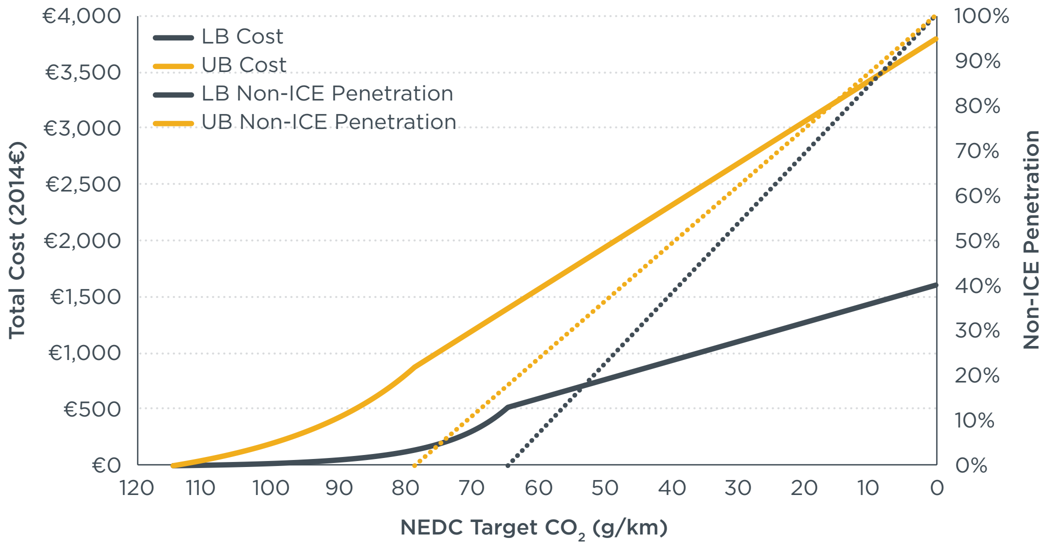


Figure A1-3. 2030 CO_2 Costs for Class D Diesel Passenger Vehicles over the NEDC

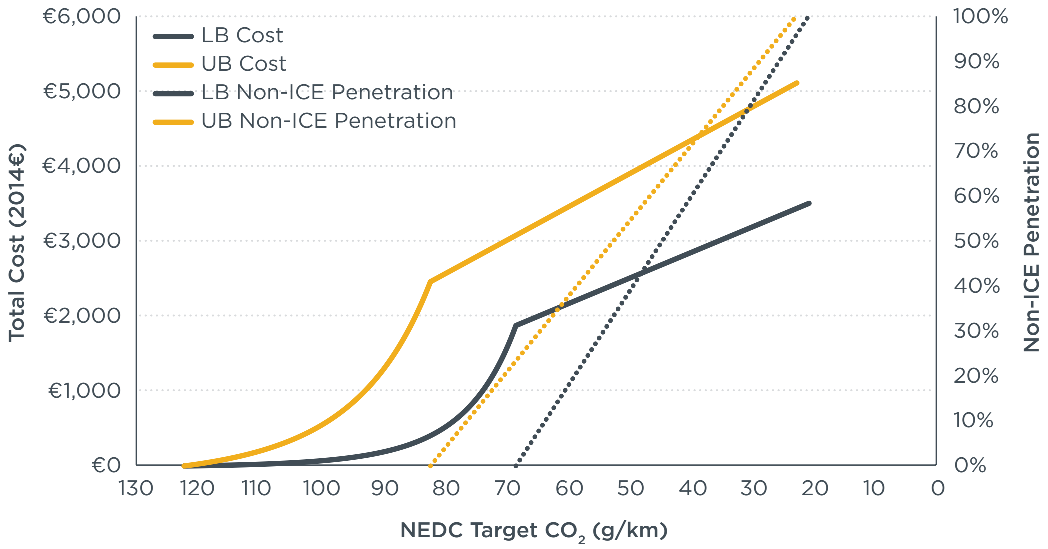


Figure A1-4. 2030 CO_2 Costs for Class E Diesel Passenger Vehicles over the NEDC

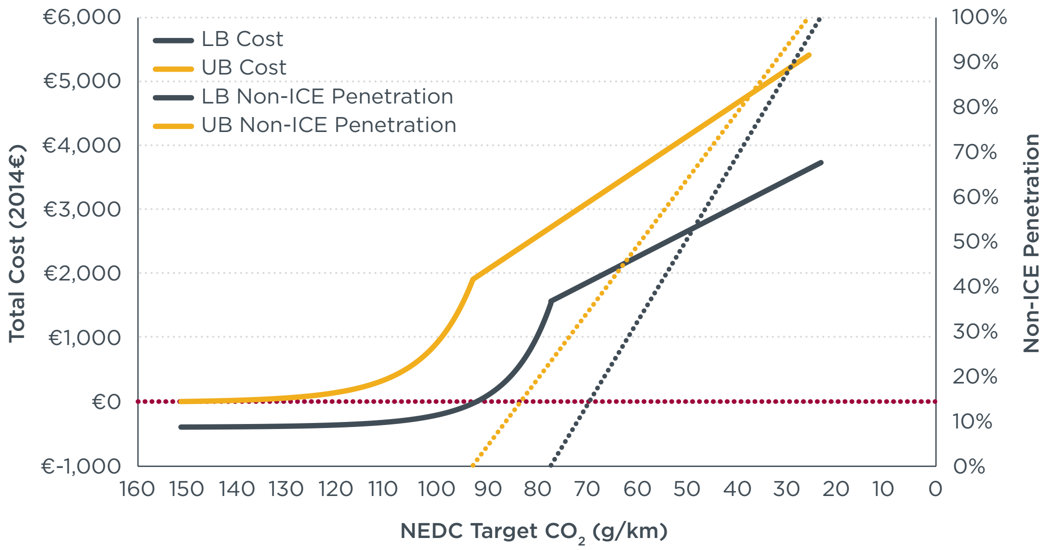


Figure A1-5. 2030 CO_2 Costs for Diesel SUV Passenger Vehicles over the NEDC

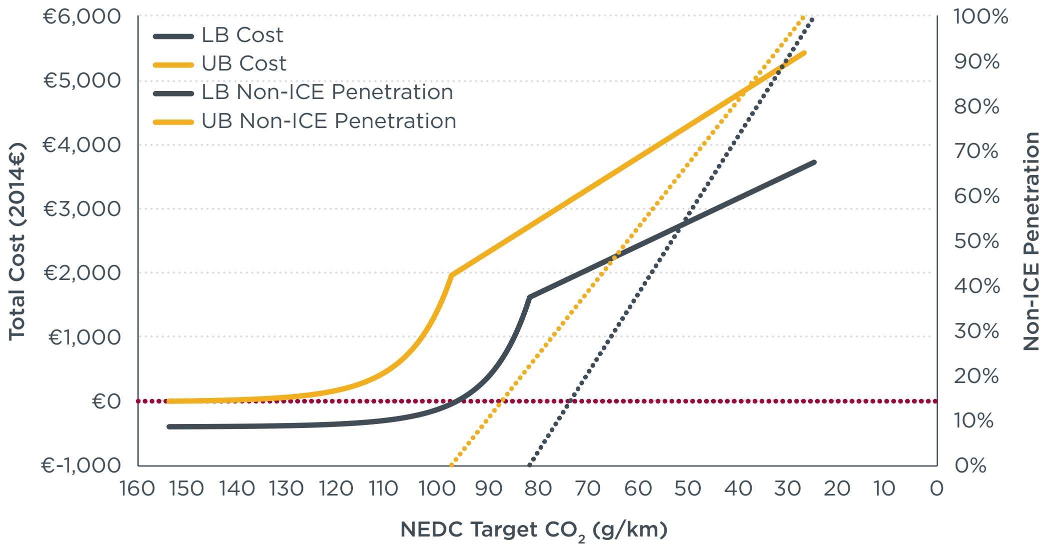


Figure A1-6. 2030 CO_2 Costs for Class B Gasoline Passenger Vehicles over the NEDC

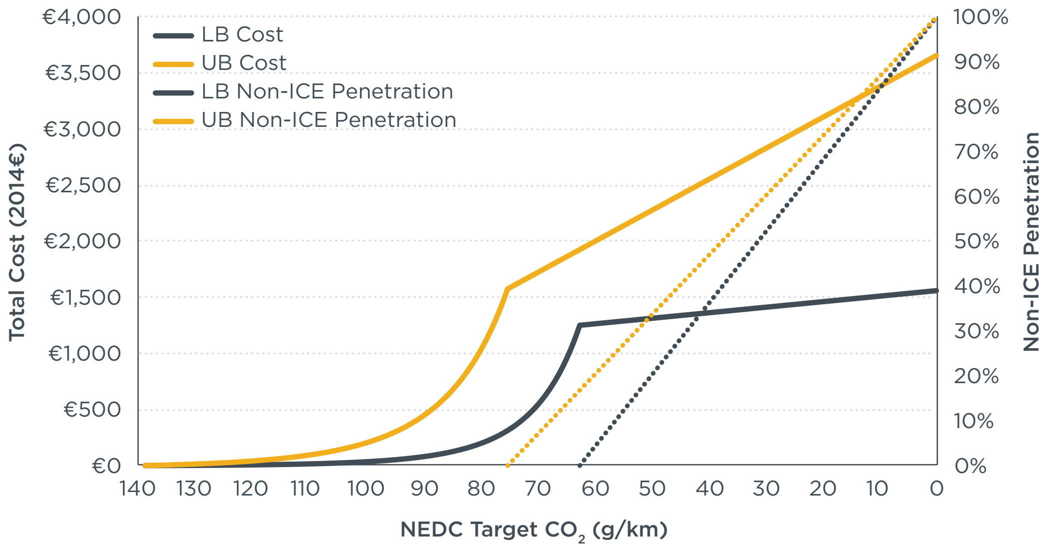


Figure A1-7. 2030 CO_2 Costs for Class C Gasoline Passenger Vehicles over the NEDC

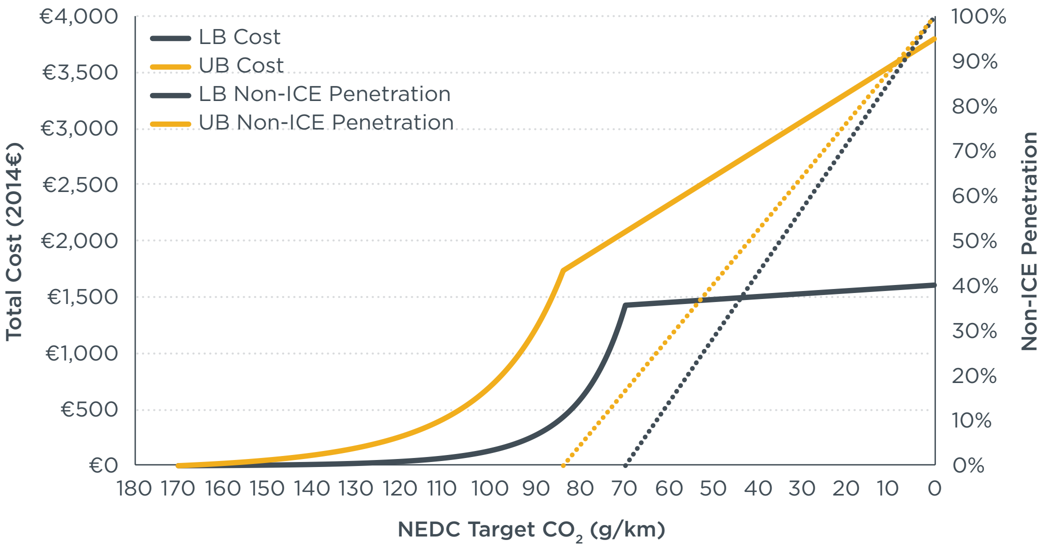


Figure A1-8. 2030 CO_2 Costs for Class D Gasoline Passenger Vehicles over the NEDC

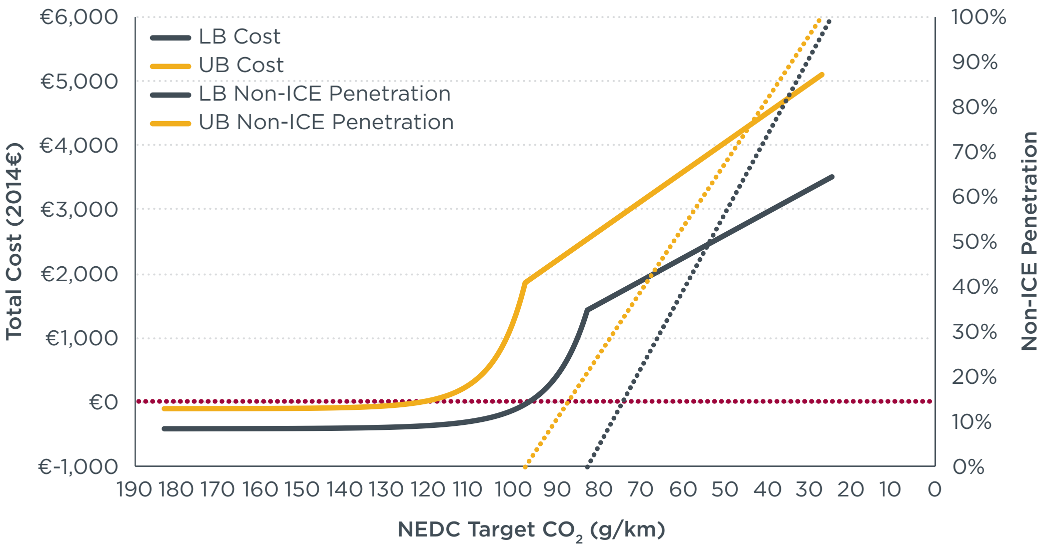
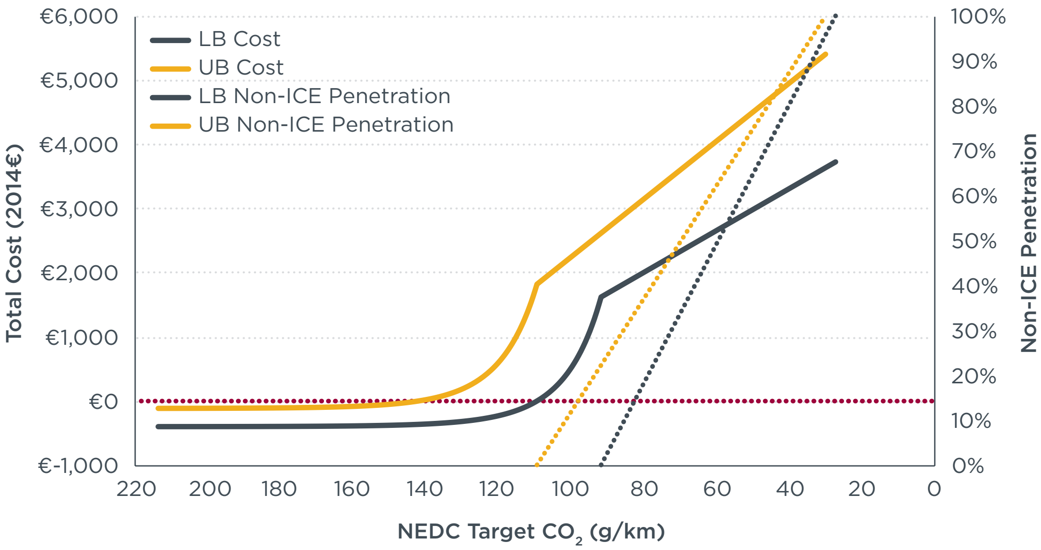


Figure A1-9. 2030 CO_2 Costs for Class E Gasoline Passenger Vehicles over the NEDC



APPENDIX 2

Passenger Vehicle Class-Specific CO_2 Compliance Costs over the NEDC in 2025

All presented cost curves are for an ICE technology exhaustion strategy. Corresponding curves for a least-cost non-ICE transition strategy can be derived as the tangent line from the ICE technology cost curve that passes through the 100% non-ICE market penetration data point.

Figure A2-1. 2025 CO_2 Costs for Class B Diesel Passenger Vehicles over the NEDC

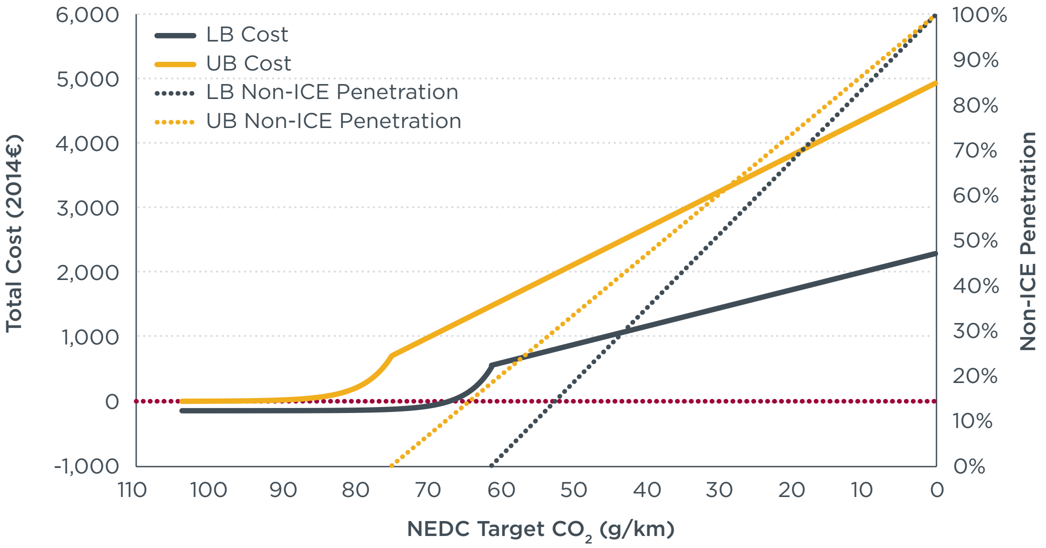


Figure A2-2. 2025 CO_2 Costs for Class C Diesel Passenger Vehicles over the NEDC

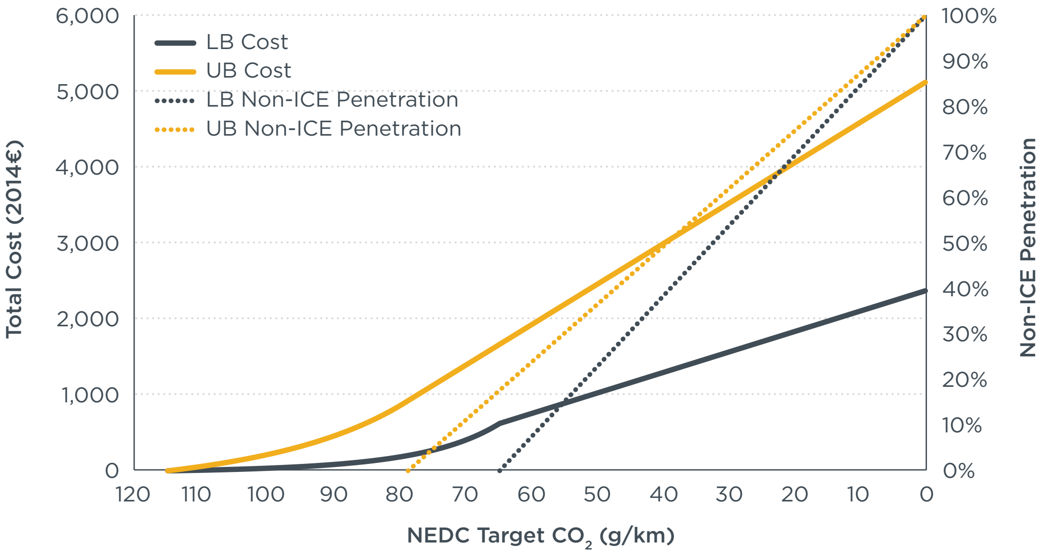


Figure A2-3. 2025 CO_2 Costs for Class D Diesel Passenger Vehicles over the NEDC

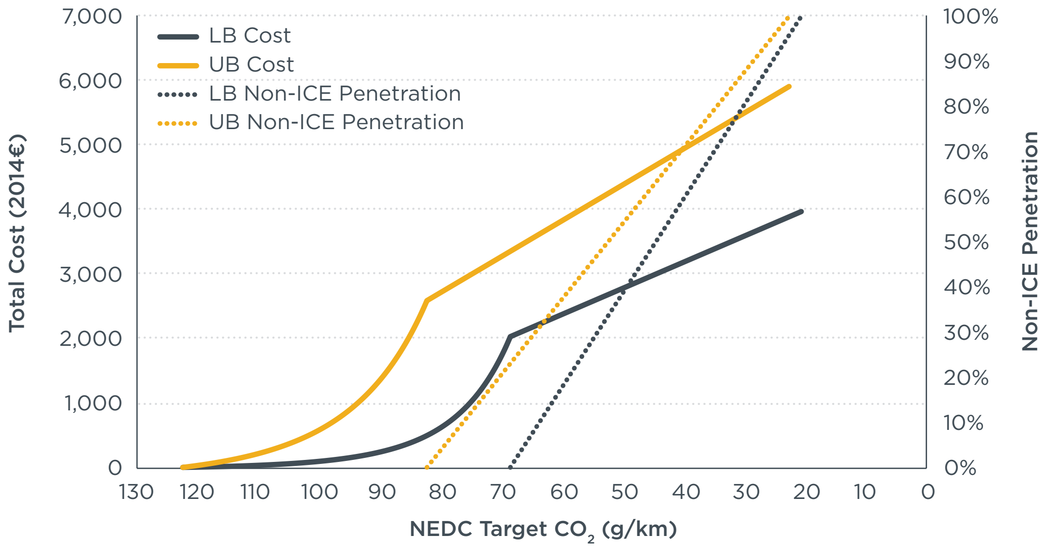


Figure A2-4. 2025 CO_2 Costs for Class E Diesel Passenger Vehicles over the NEDC

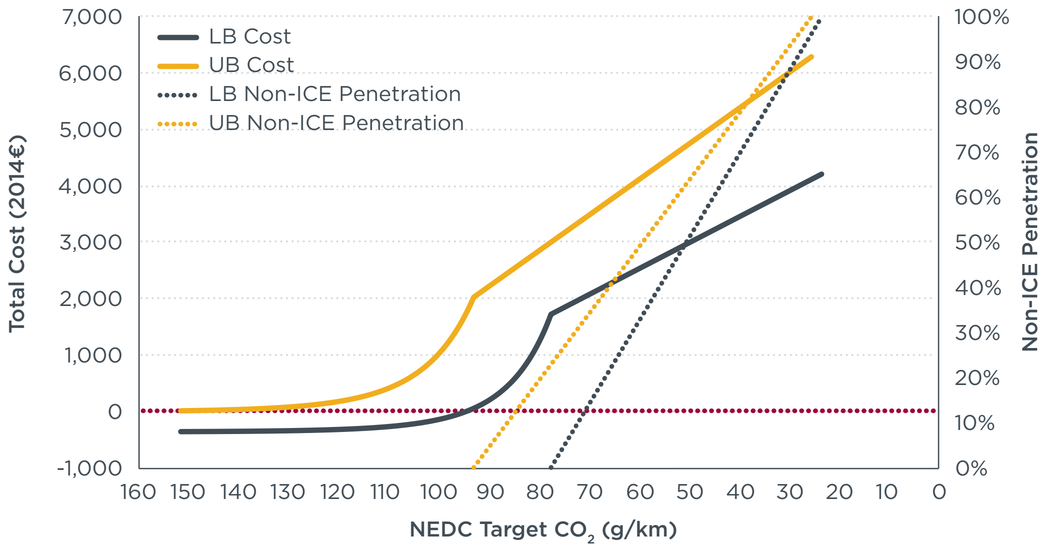


Figure A2-5. 2025 CO_2 Costs for Diesel SUV Passenger Vehicles over the NEDC

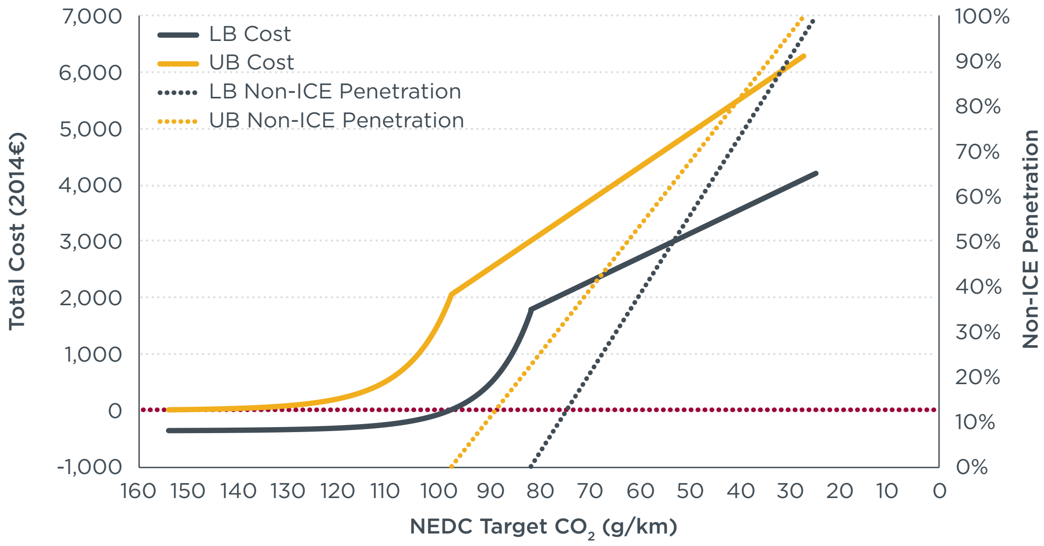


Figure A2-6. 2025 CO_2 Costs for Class B Gasoline Passenger Vehicles over the NEDC

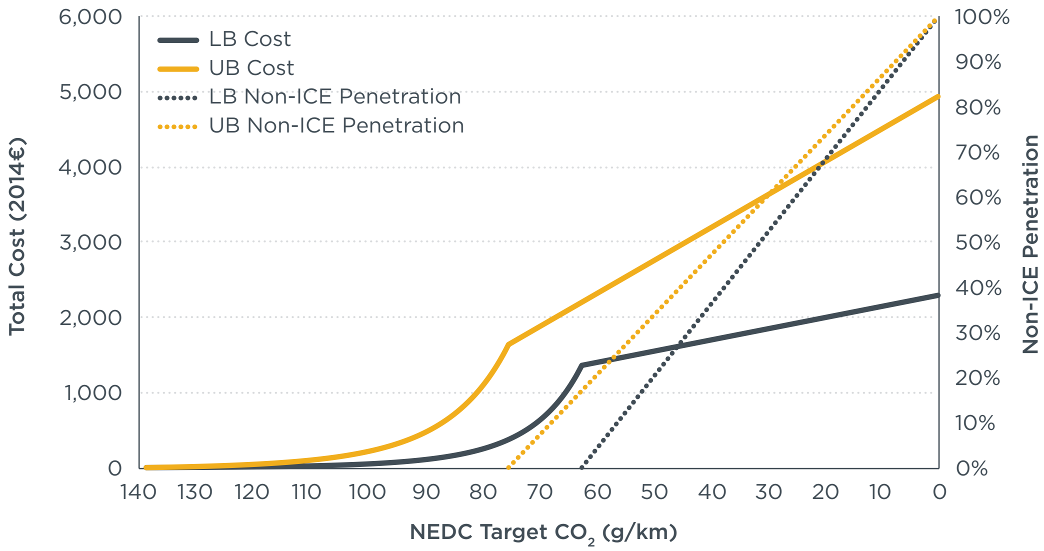


Figure A2-7. 2025 CO_2 Costs for Class C Gasoline Passenger Vehicles over the NEDC

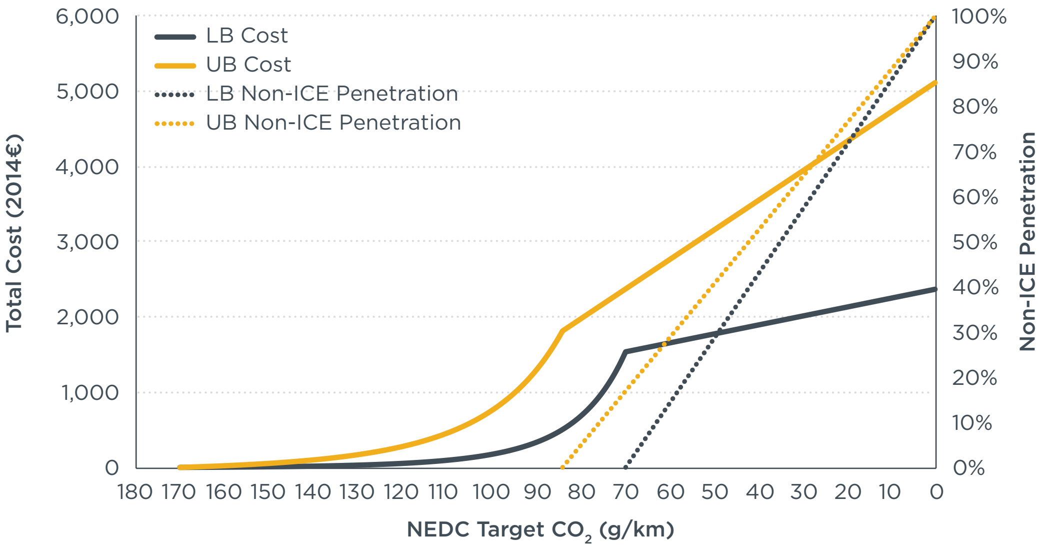


Figure A2-8. 2025 CO_2 Costs for Class D Gasoline Passenger Vehicles over the NEDC

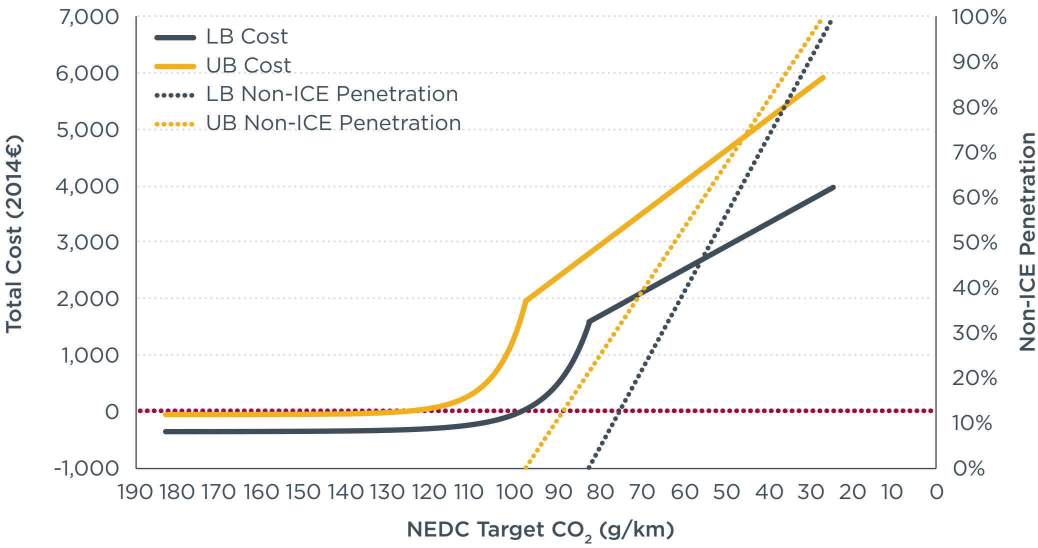
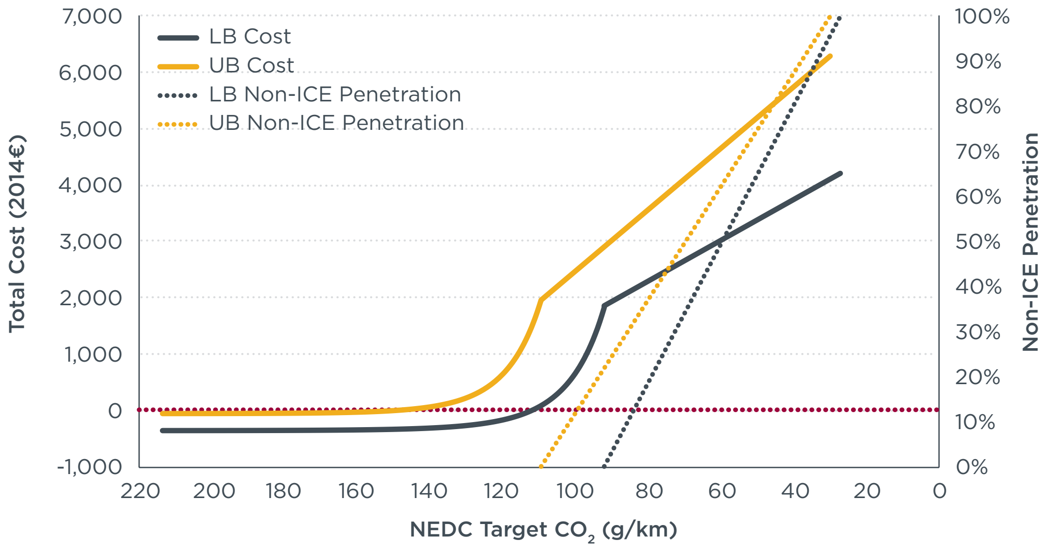


Figure A2-9. 2025 CO_2 Costs for Class E Gasoline Passenger Vehicles over the NEDC



APPENDIX 3

Passenger Vehicle Class-Specific CO_2 Compliance Costsover the NEDC in 2020

All presented cost curves are for an ICE technology exhaustion strategy. Corresponding curves for a least-cost non-ICE transition strategy can be derived as the tangent line from the ICE technology cost curve that passes through the 100% non-ICE market penetration data point.

Figure A3-1. 2020 CO_2 Costs for Class B Diesel Passenger Vehicles over the NEDC

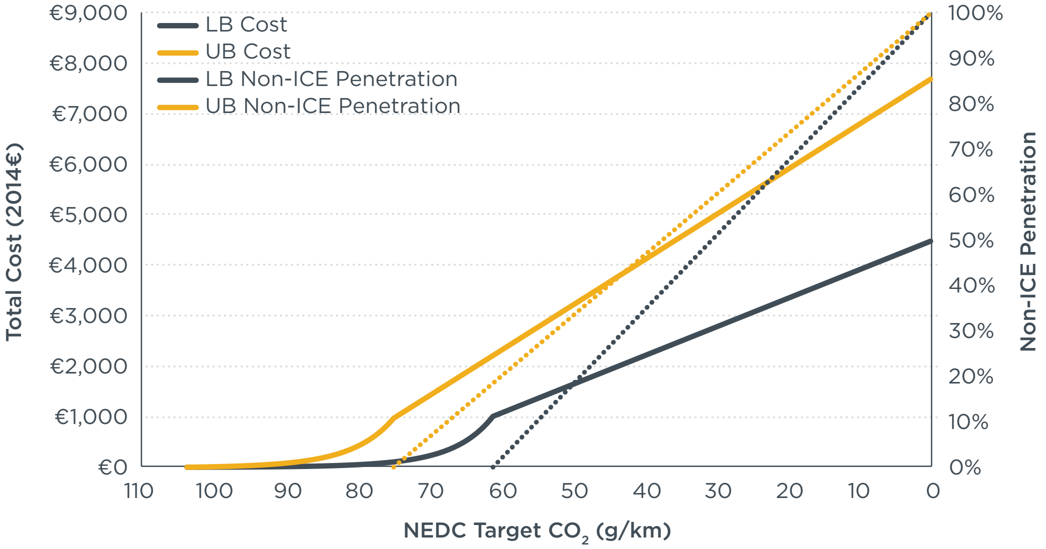


Figure A3-2. 2020 CO_2 Costs for Class C Diesel Passenger Vehicles over the NEDC

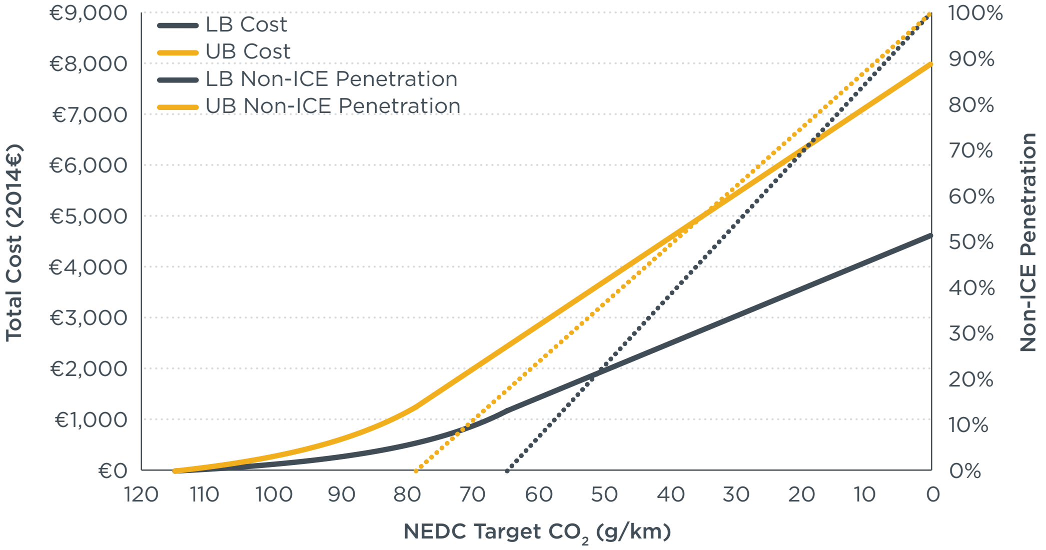


Figure A3-3. 2020 CO_2 Costs for Class D Diesel Passenger Vehicles over the NEDC

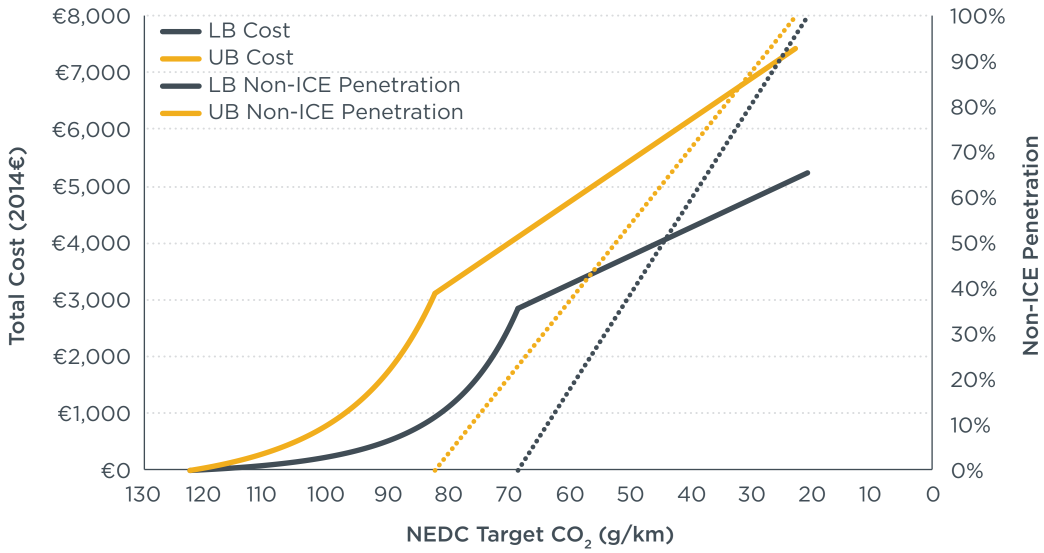


Figure A3-4. 2020 CO_2 Costs for Class E Diesel Passenger Vehicles over the NEDC

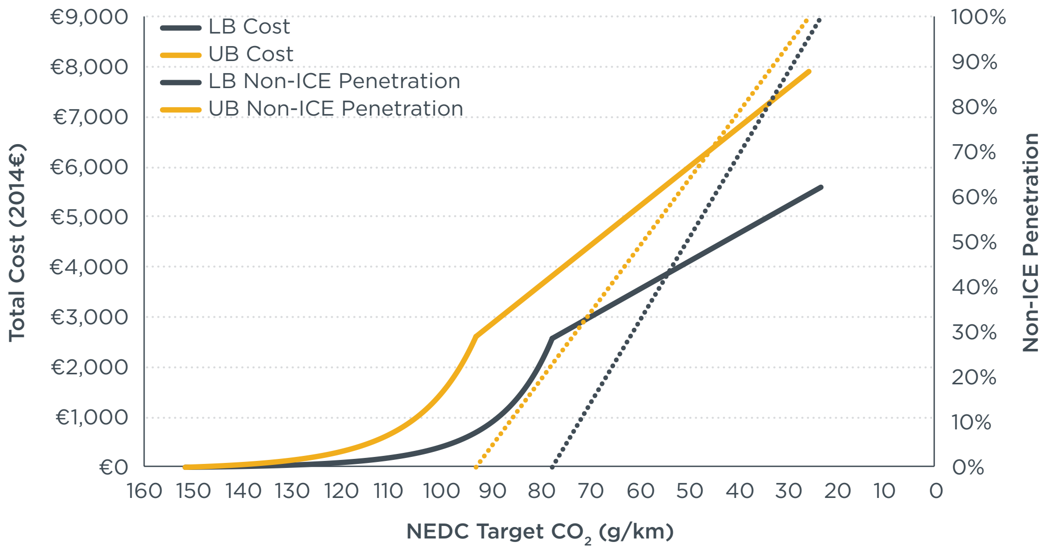


Figure A3-5. 2020 CO_2 Costs for Diesel SUV Passenger Vehicles over the NEDC

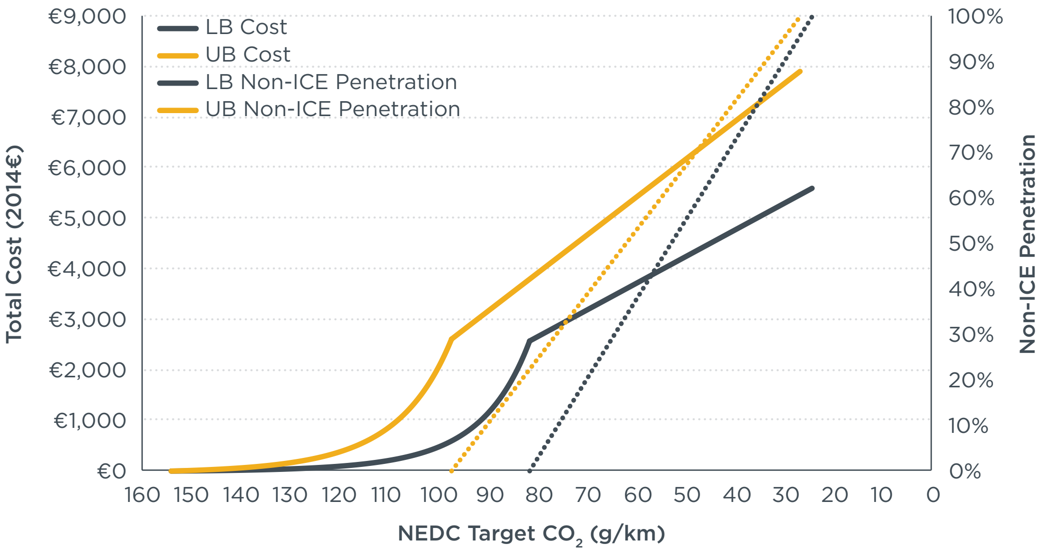


Figure A3-6. 2020 CO_2 Costs for Class B Gasoline Passenger Vehicles over the NEDC

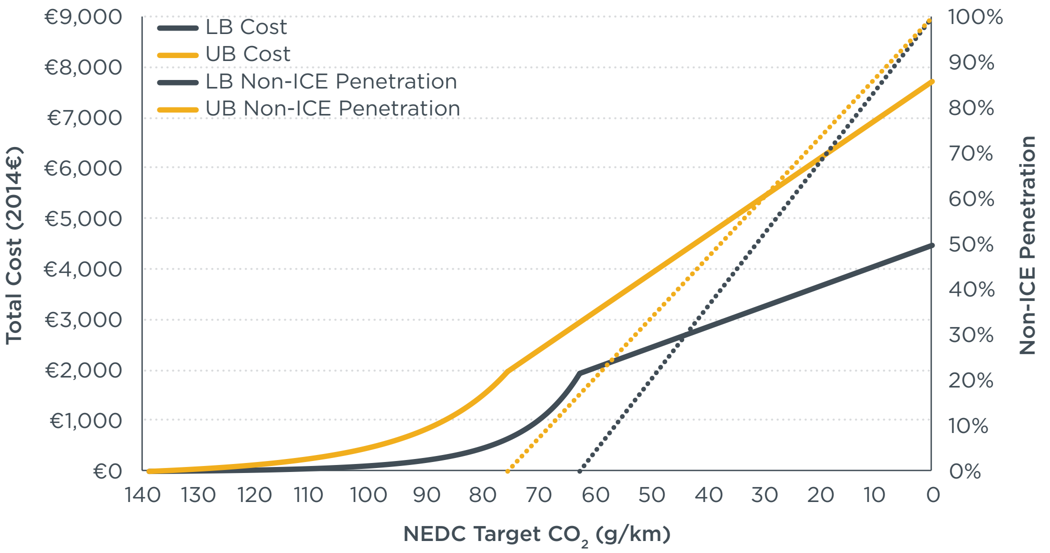


Figure A3-7. 2020 CO_2 Costs for Class C Gasoline Passenger Vehicles over the NEDC

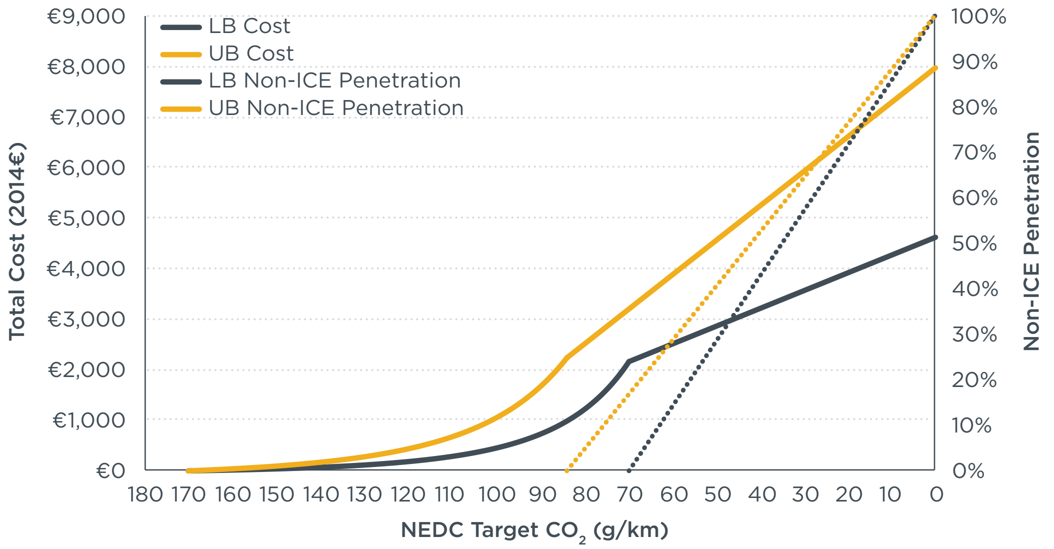


Figure A3-8. 2020 CO_2 Costs for Class D Gasoline Passenger Vehicles over the NEDC

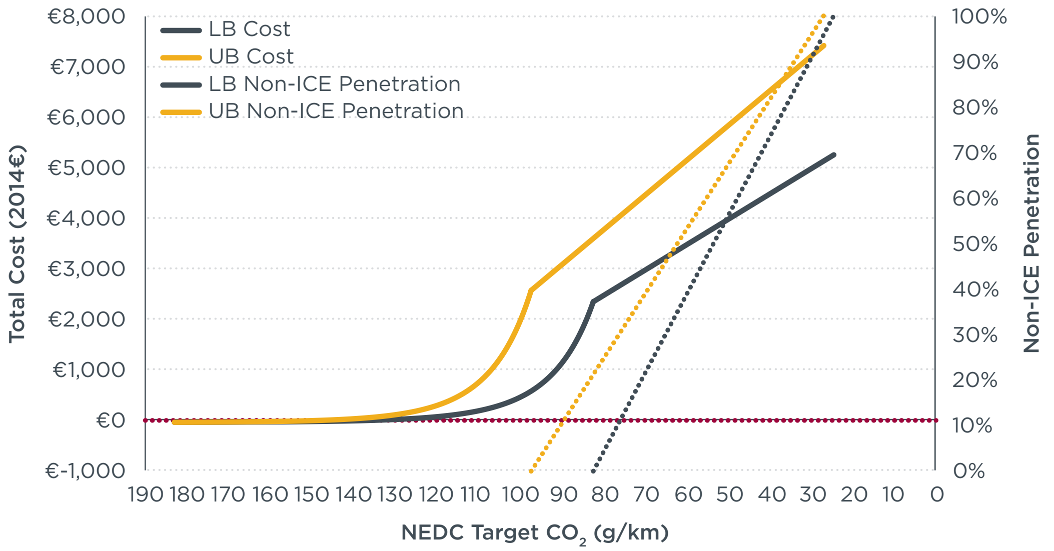
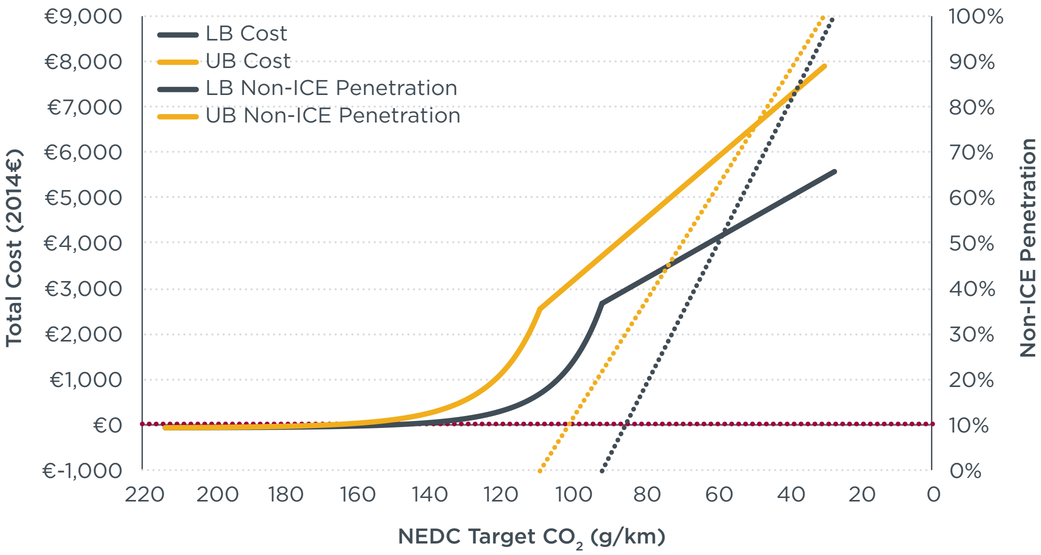


Figure A3-9. 2020 CO_2 Costs for Class E Gasoline Passenger Vehicles over the NEDC



APPENDIX 4

Passenger Vehicle Class-Specific CO_2 Compliance Costs over the WLTP in 2030

All presented cost curves are for an ICE technology exhaustion strategy. Corresponding curves for a least-cost non-ICE transition strategy can be derived as the tangent line from the ICE technology cost curve that passes through the 100% non-ICE market penetration data point.

Figure A4-1. 2030 CO_2 Costs for Class B Diesel Passenger Vehicles over the WLTP

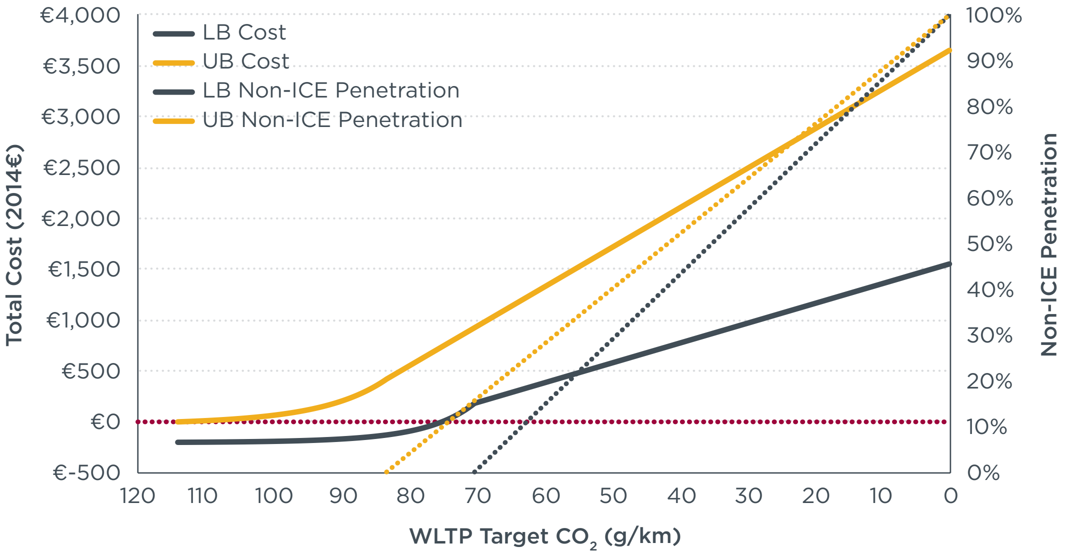


Figure A4-2. 2030 CO_2 Costs for Class C Diesel Passenger Vehicles over the WLTP

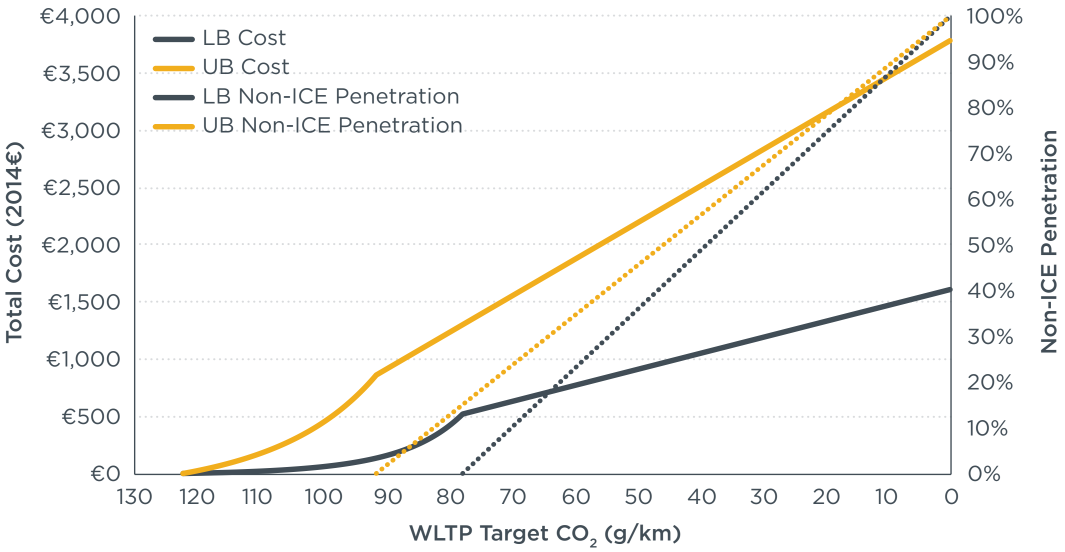


Figure A4-3. 2030 CO_2 Costs for Class D Diesel Passenger Vehicles over the WLTP

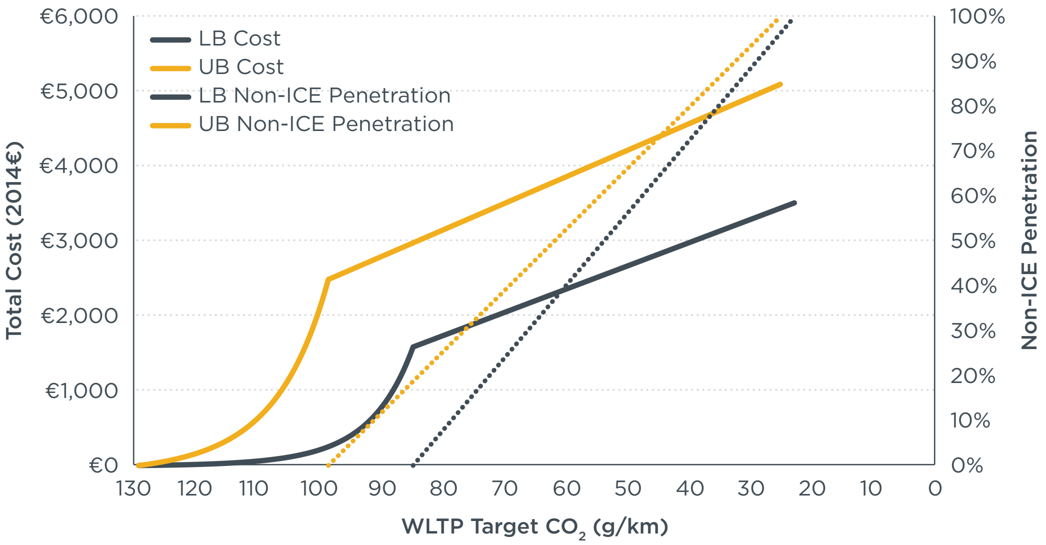


Figure A4-4. 2030 CO_2 Costs for Class E Diesel Passenger Vehicles over the WLTP

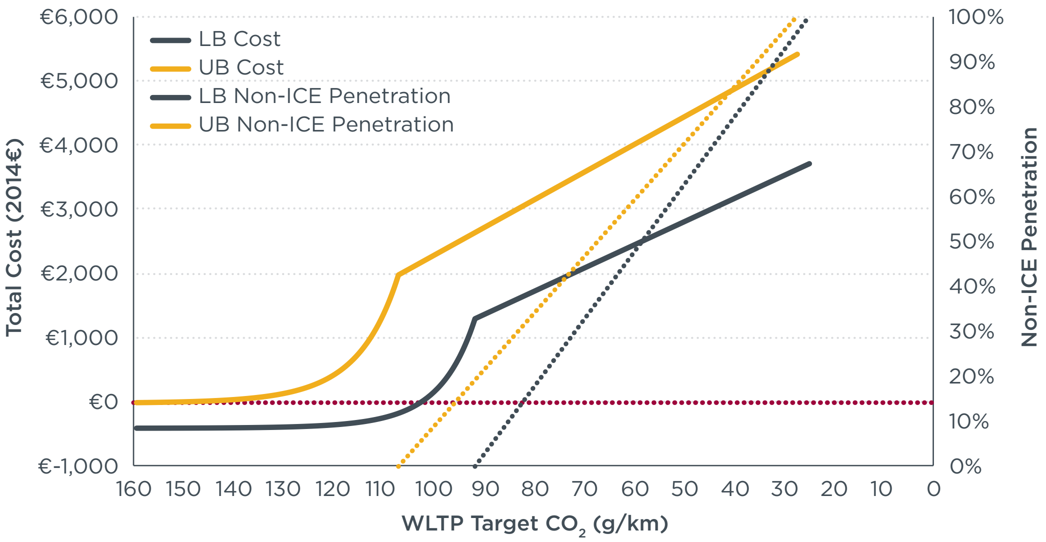


Figure A4-5. 2030 CO_2 Costs for Diesel SUV Passenger Vehicles over the WLTP

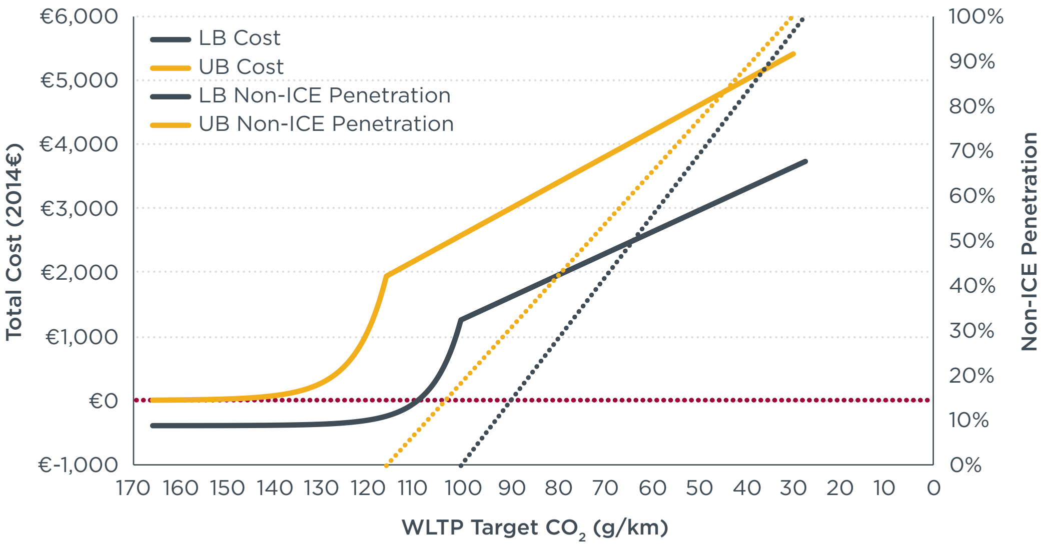


Figure A4-6. 2030 CO_2 Costs for Class B Gasoline Passenger Vehicles over the WLTP

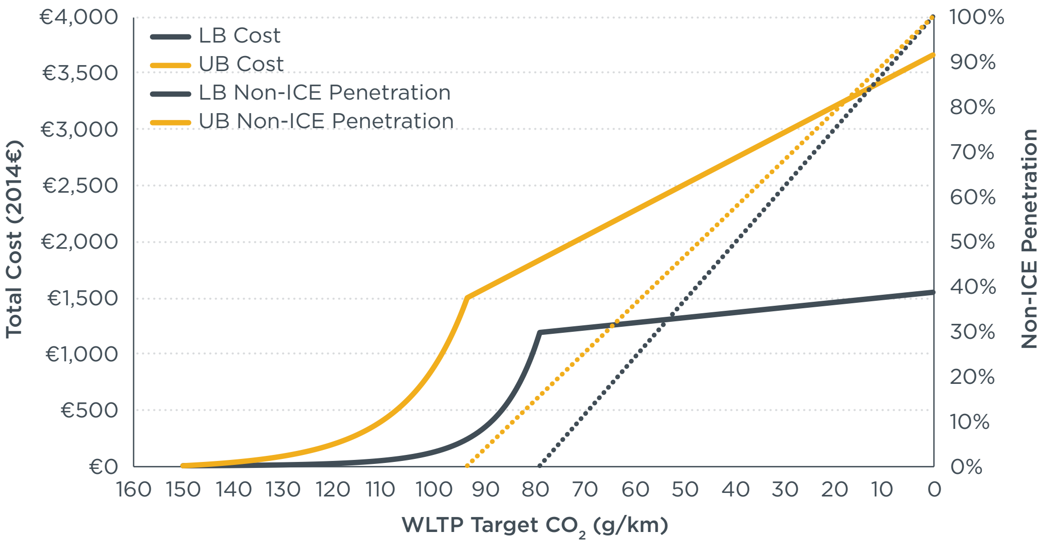


Figure A4-7. 2030 CO_2 Costs for Class C Gasoline Passenger Vehicles over the WLTP

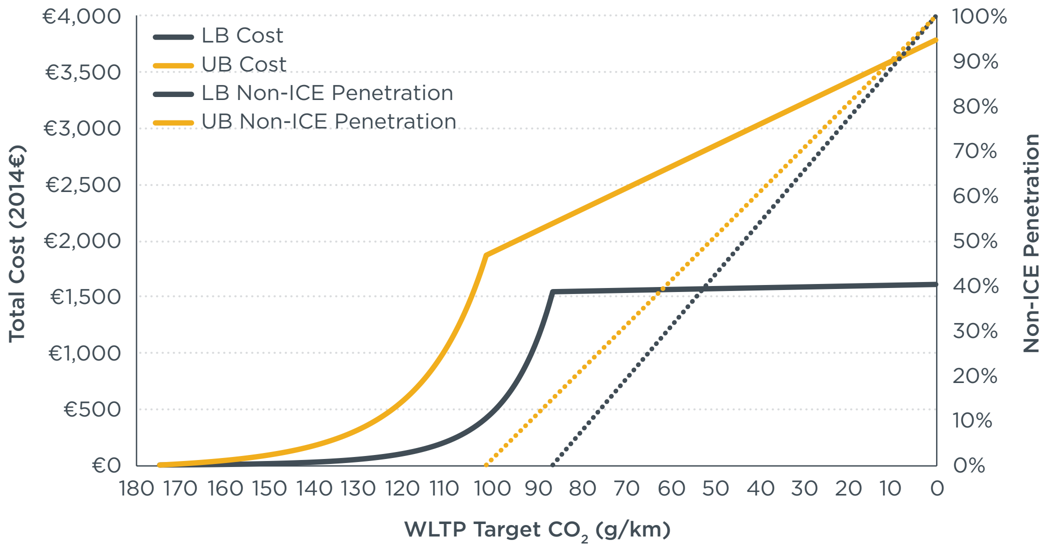


Figure A4-8. 2030 CO_2 Costs for Class D Gasoline Passenger Vehicles over the WLTP

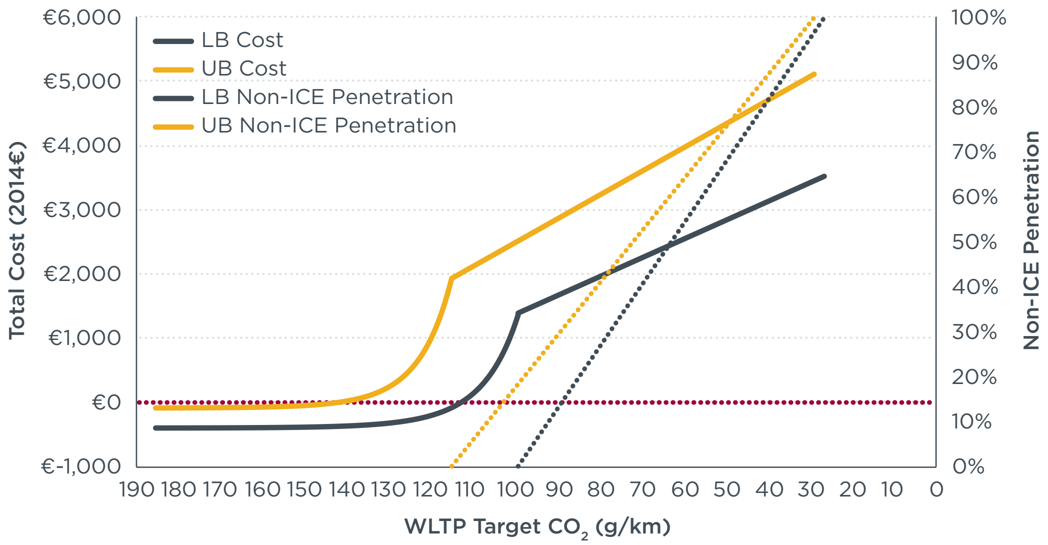
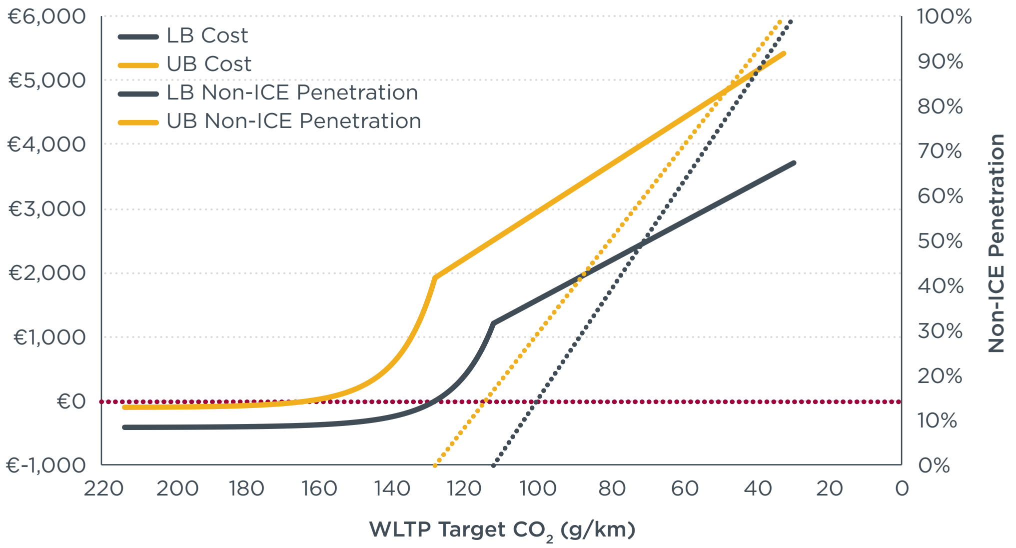


Figure A4-9. 2030 CO_2 Costs for Class E Gasoline Passenger Vehicles over the WLTP



APPENDIX 5

Passenger Vehicle Class-Specific CO_2 Compliance Costs over the WLTP in 2025

All presented cost curves are for an ICE technology exhaustion strategy. Corresponding curves for a least-cost non-ICE transition strategy can be derived as the tangent line from the ICE technology cost curve that passes through the 100% non-ICE market penetration data point.

Figure A5-1. 2025 CO_2 Costs for Class B Diesel Passenger Vehicles over the WLTP

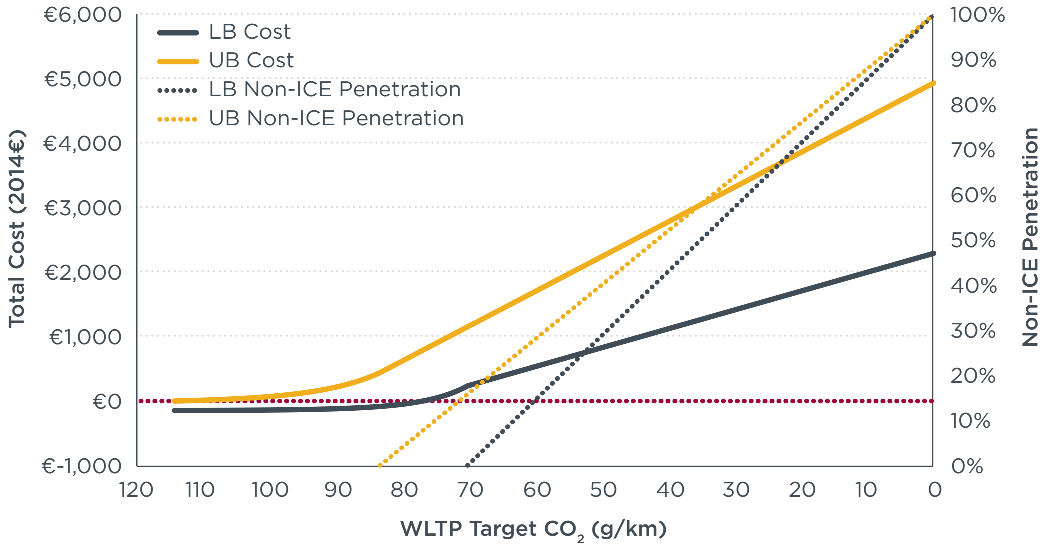


Figure A5-2. 2025 CO_2 Costs for Class C Diesel Passenger Vehicles over the WLTP

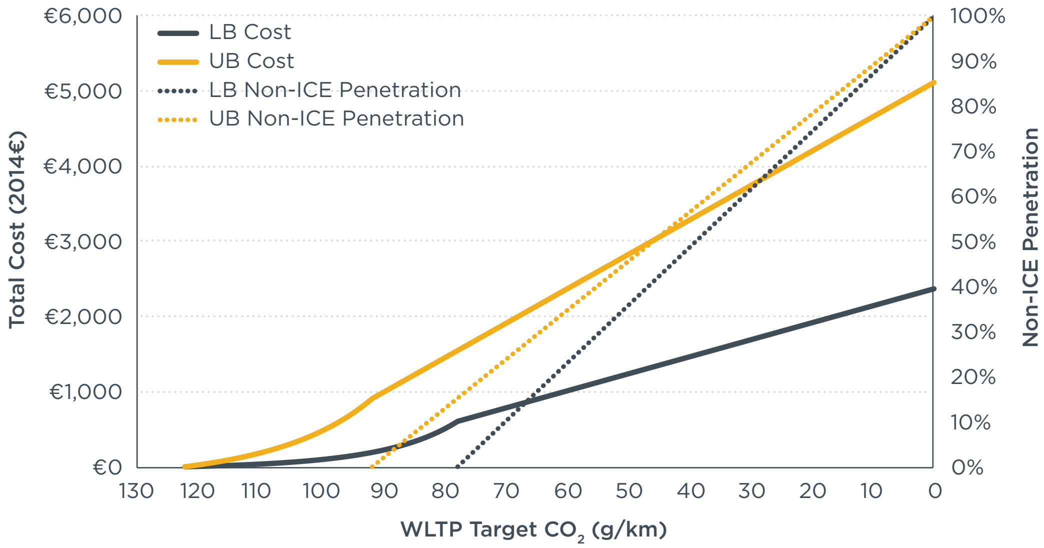


Figure A5-3. 2025 CO_2 Costs for Class D Diesel Passenger Vehicles over the WLTP

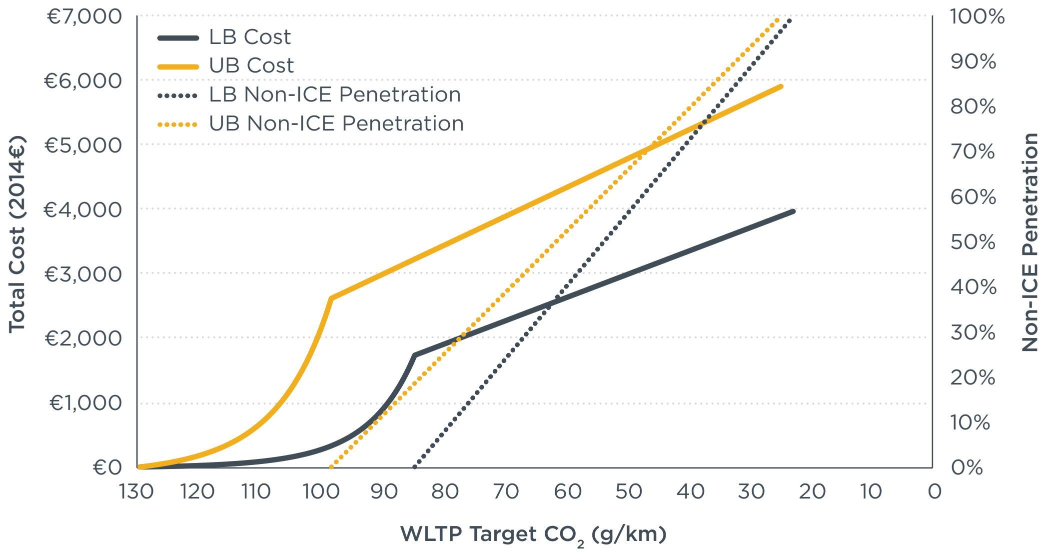


Figure A5-4. 2025 CO_2 Costs for Class E Diesel Passenger Vehicles over the WLTP

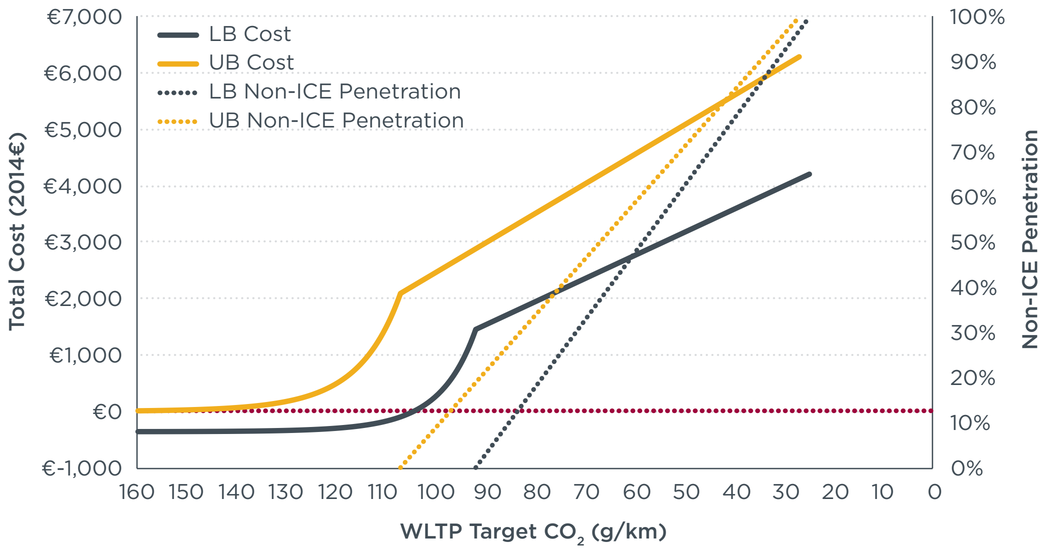


Figure A5-5. 2025 CO_2 Costs for Diesel SUV Passenger Vehicles over the WLTP

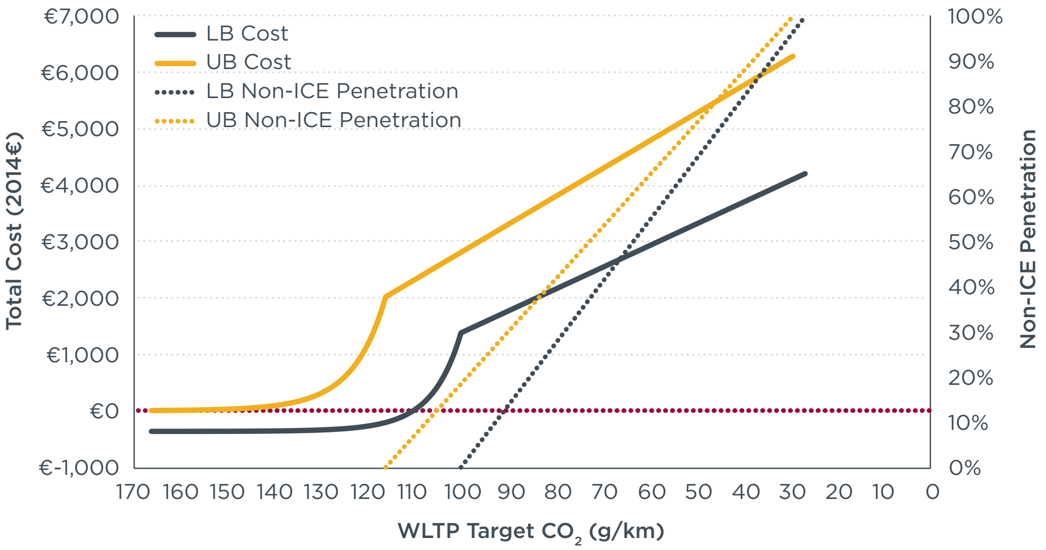


Figure A5-6. 2025 CO_2 Costs for Class B Gasoline Passenger Vehicles over the WLTP

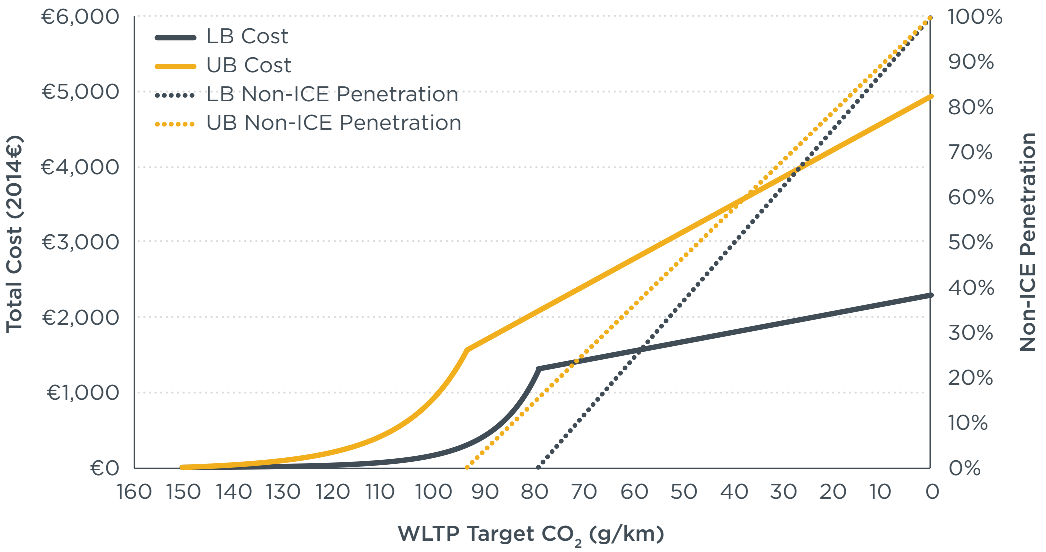


Figure A5-7. 2025 CO_2 Costs for Class C Gasoline Passenger Vehicles over the WLTP

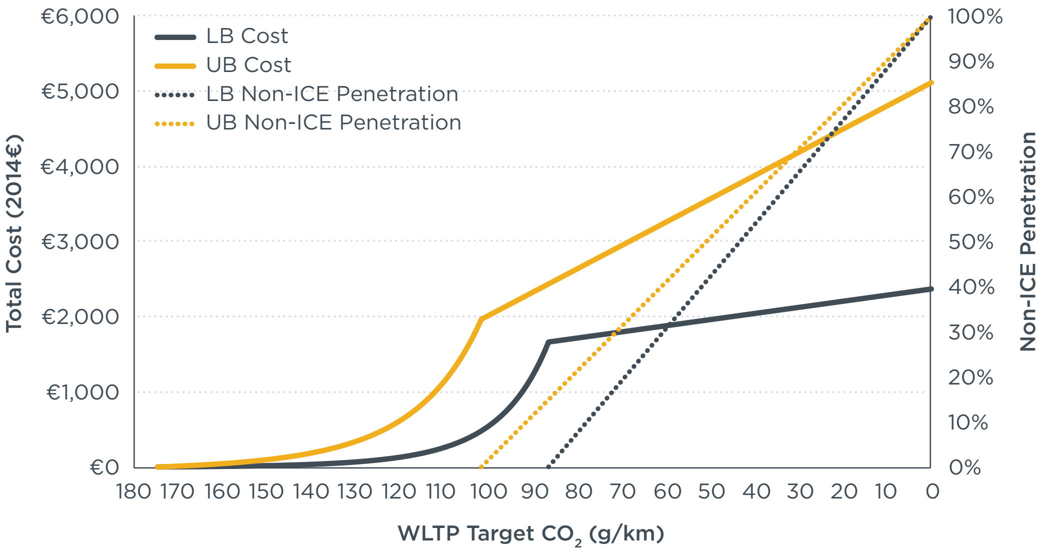


Figure A5-8. 2025 CO_2 Costs for Class D Gasoline Passenger Vehicles over the WLTP

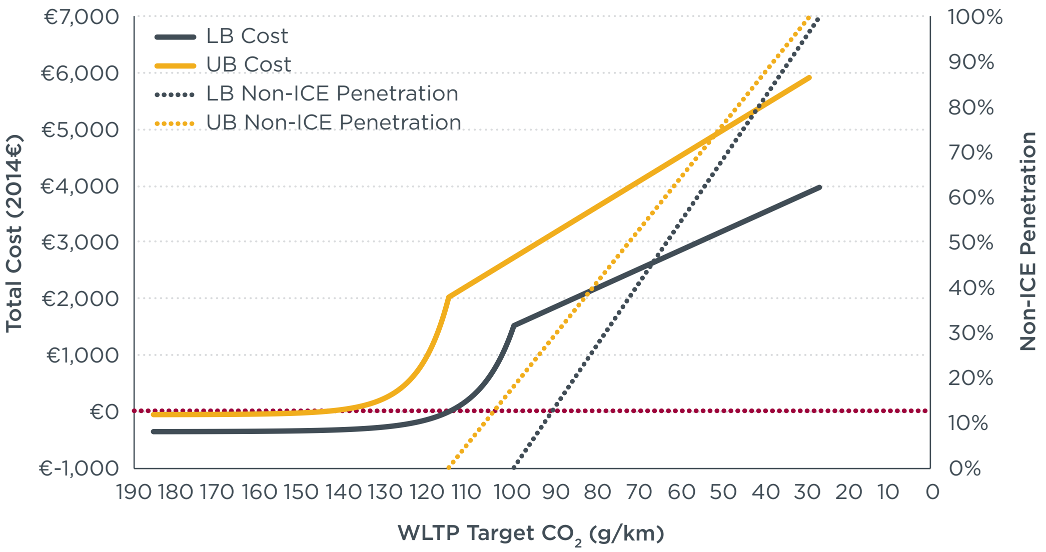
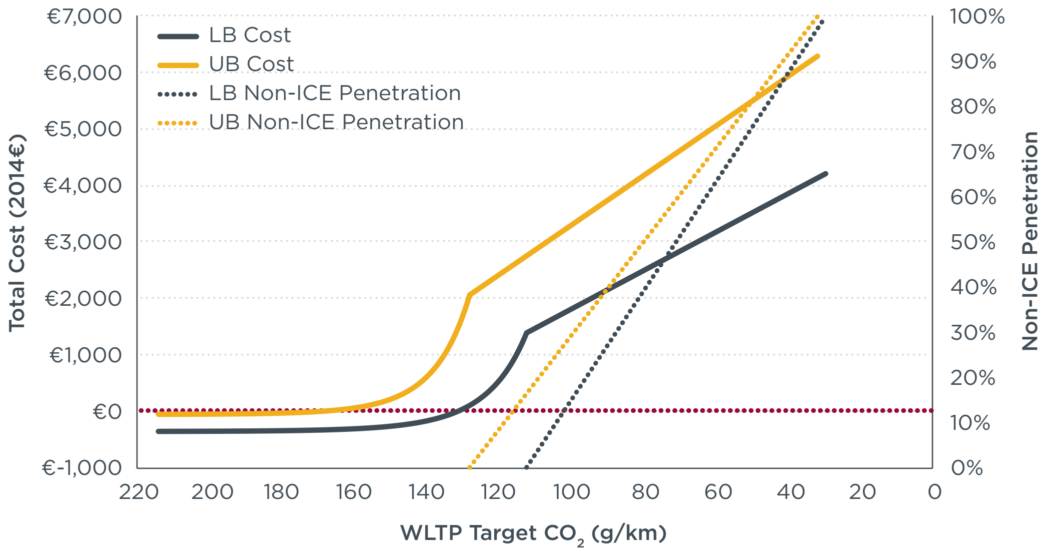


Figure A5-9. 2025 CO_2 Costs for Class E Gasoline Passenger Vehicles over the WLTP



APPENDIX 6

Passenger Vehicle Class-Specific CO_2 Compliance Costs over the WLTP in 2020

All presented cost curves are for an ICE technology exhaustion strategy. Corresponding curves for a least-cost non-ICE transition strategy can be derived as the tangent line from the ICE technology cost curve that passes through the 100% non-ICE market penetration data point.

Figure A6-1. 2020 CO_2 Costs for Class B Diesel Passenger Vehicles over the WLTP

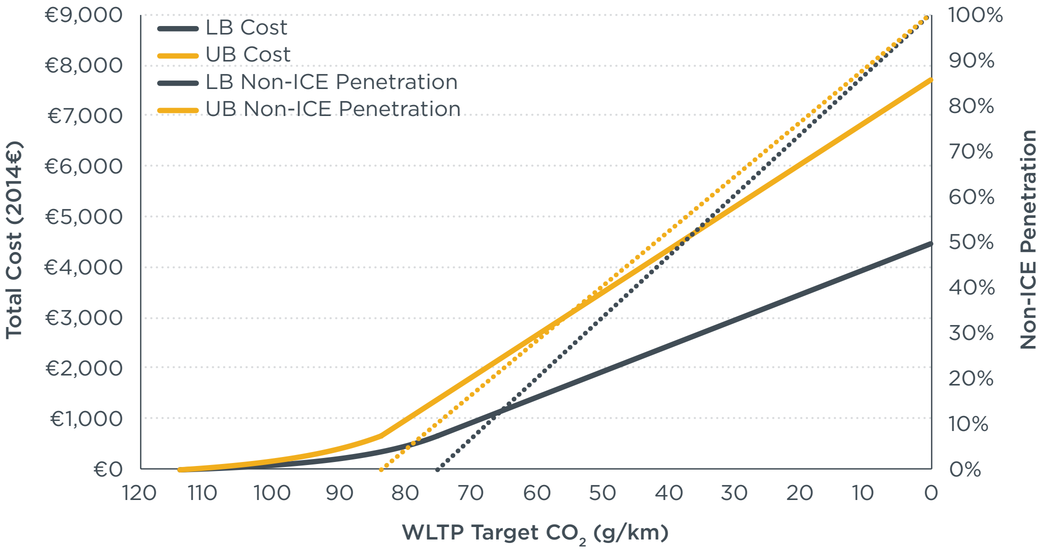


Figure A6-2. 2020 CO_2 Costs for Class C Diesel Passenger Vehicles over the WLTP

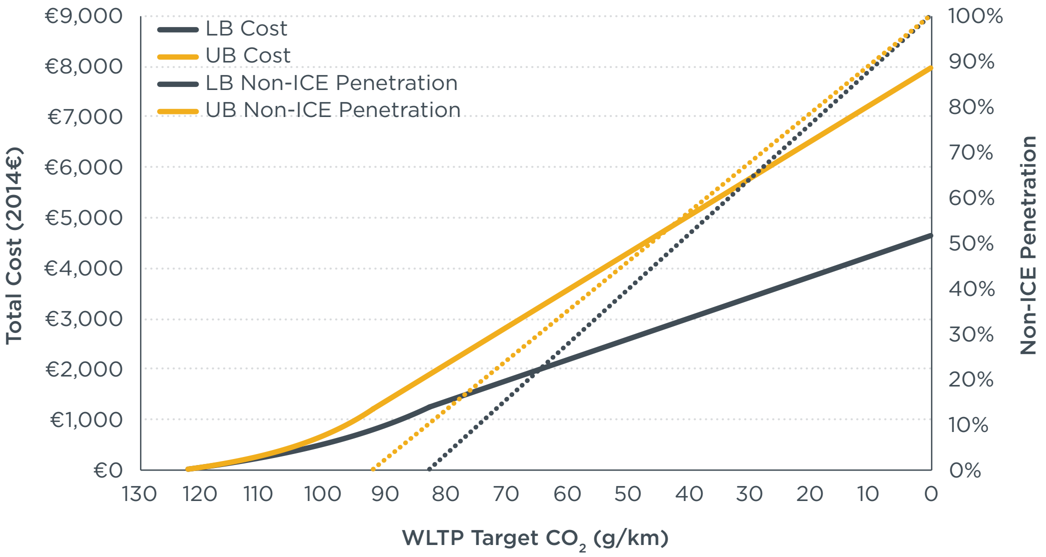


Figure A6-3. 2020 CO_2 Costs for Class D Diesel Passenger Vehicles over the WLTP

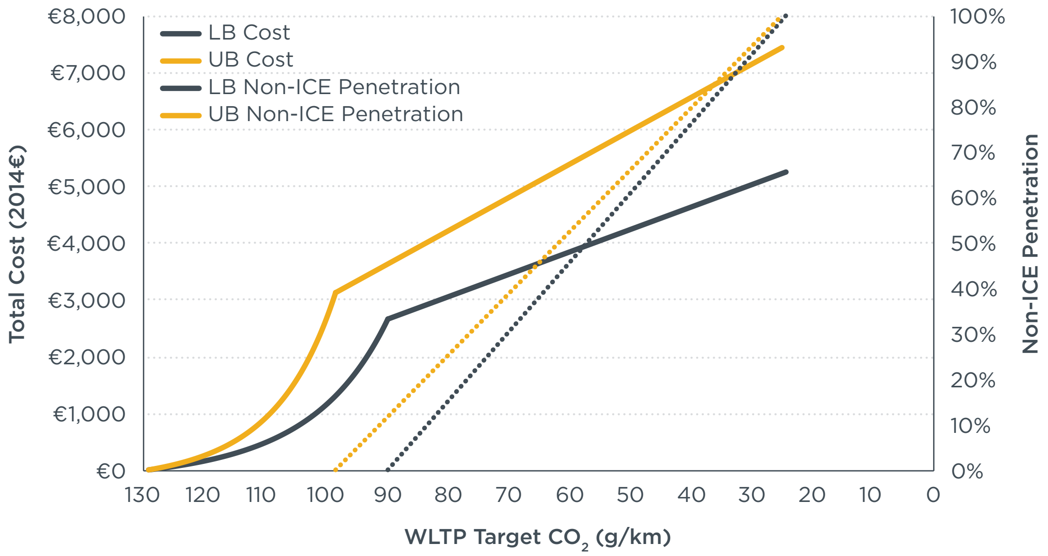


Figure A6-4. 2020 CO_2 Costs for Class E Diesel Passenger Vehicles over the WLTP

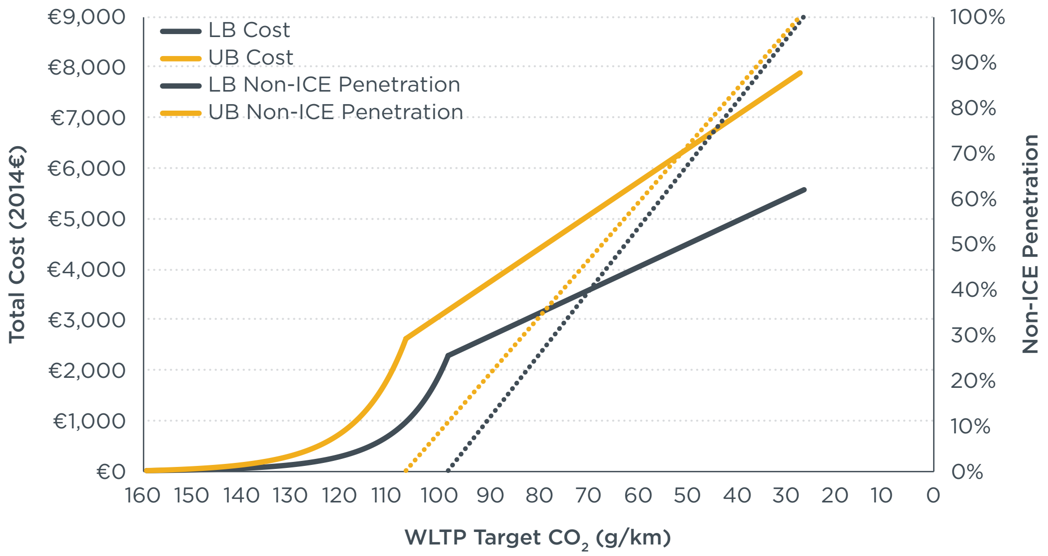


Figure A6-5. 2020 CO_2 Costs for Diesel SUV Passenger Vehicles over the WLTP

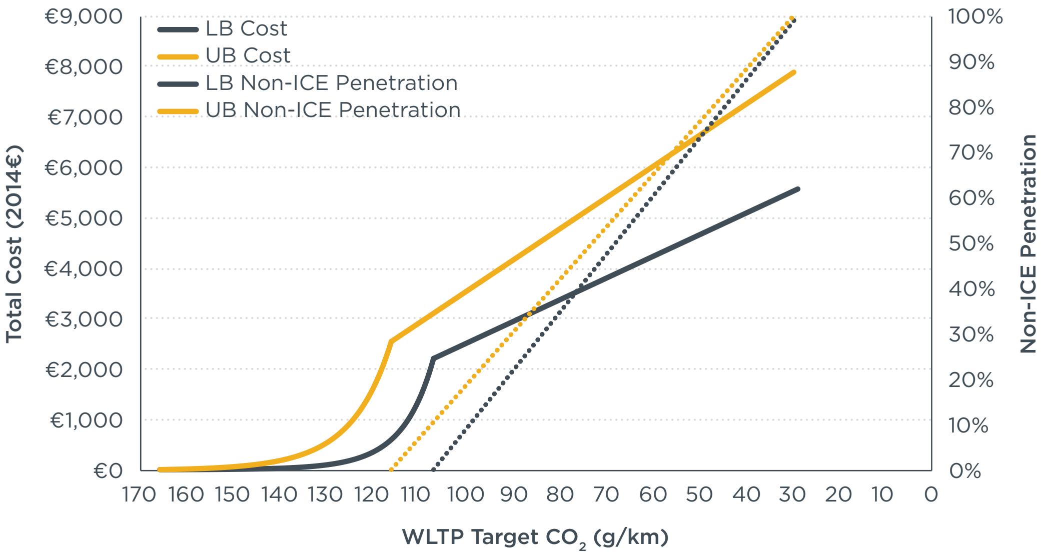


Figure A6-6. 2020 CO_2 Costs for Class B Gasoline Passenger Vehicles over the WLTP

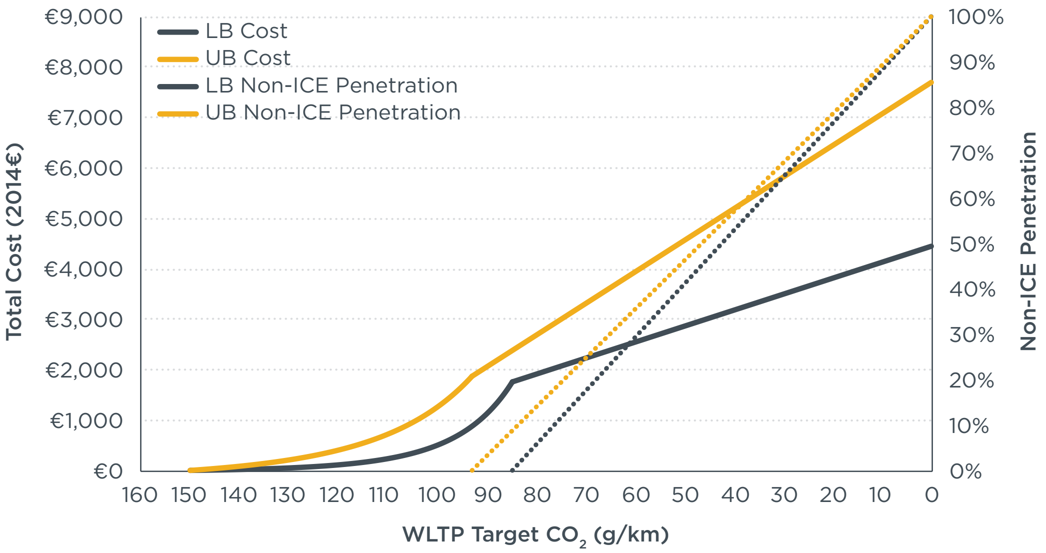


Figure A6-7. 2020 CO_2 Costs for Class C Gasoline Passenger Vehicles over the WLTP

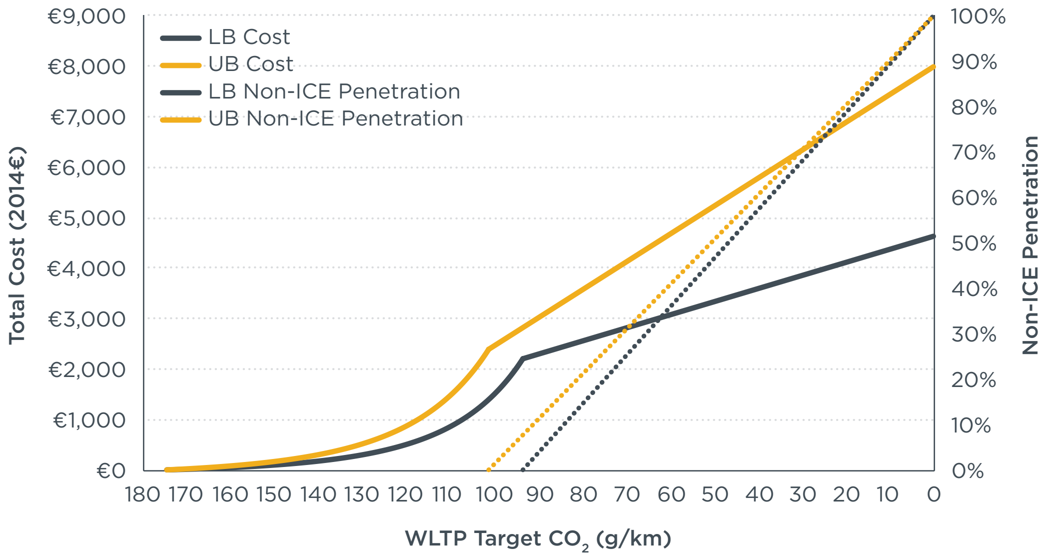


Figure A6-8. 2020 CO_2 Costs for Class D Gasoline Passenger Vehicles over the WLTP

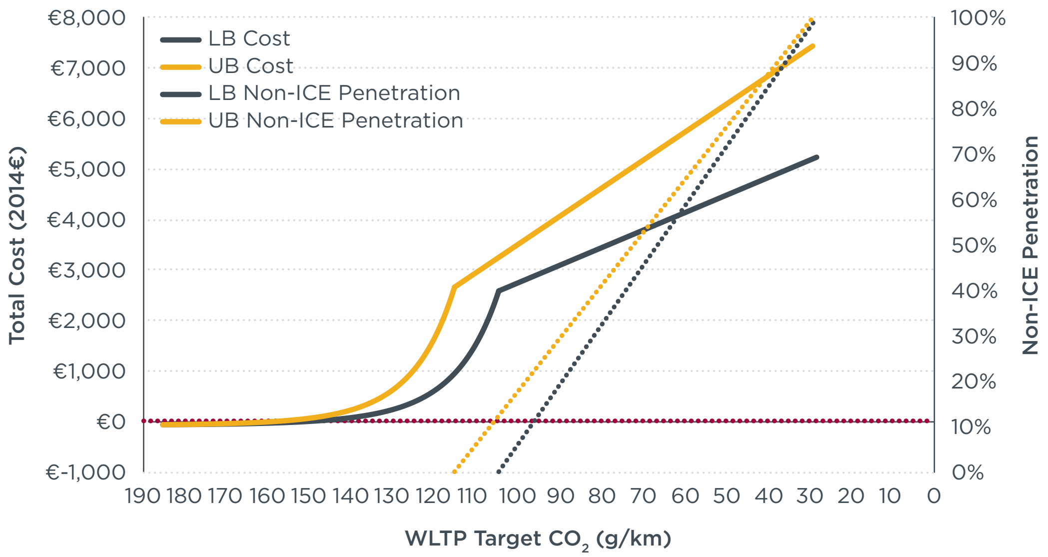


Figure A6-9. 2020 CO_2 Costs for Class E Gasoline Passenger Vehicles over the WLTP