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SERIES: CO_2 REDUCTION TECHNOLOGIES FOR THE EUROPEAN CAR AND VAN FLEET, A 2020-2025 ASSESSMENT

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Summary of the EU cost curve development methodology

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1. Introduction

The goal of this paper is to explain the methodology used to develop technology benefit and cost curves applicable for EU light-duty vehicles in the 2020-2025 timeframe. With appropriate modification of assumptions, the methodology described in this report can be used to develop cost curves in other regions of the world. As described in ICCT Working Paper 2012-4, the CO_2 data used in the development of the EU cost curves are derived from simulation modeling performed for the ICCT by Ricardo Inc.[1,2] These data, which for convenience are generally referred to as the *Ricardo ICCT CO_2 data* in this paper, are combined with technology cost data to generate CO_2 cost curves for five EU vehicle classes (namely, the B, C, D, small N1, and large N1 classes). Technology cost data developed for the ICCT by FEV, Inc. specifically for this exercise, serve as the primary source of cost data.[3,4] These cost data, developed on the basis of vehicle teardown studies, are considered to be superior to other available data due to the fact that they represent current high volume production costs developed specifically for the EU market, and are generally consistent with the technology assumptions employed by Ricardo for the CO_2 impact analysis. For convenience, these cost data are referred to as the *FEV ICCT cost data* in this paper.

In some cases, technologies are assumed in the Ricardo work for which corresponding FEV cost estimates are not available. As a result, secondary technology cost data are employed to fill such gaps. The majority of secondary cost data are derived from cost estimates developed by the U.S. Environmental Protection Agency (EPA), as summarized in that agency's technical support document for the 2017-2025 U.S. greenhouse gas standards proposal.[5] These secondary cost data are referred to as the *EPA cost data* in this paper.[6] In very limited circumstances, other

1 ICCT, "CO_2 reduction technologies for the European car and van fleet, a 2020-2025 assessment: Initial processing of Ricardo vehicle simulation modeling CO_2 data," Working paper 2012-4.

2 Ricardo Inc., "Project Report, Analysis of Greenhouse Gas Emission Reduction Potential of Light Duty Vehicle Technologies in the European Union for 2020-2025," Project C000908, Archive RD.12/96201.2, April 13, 2012.

3 FEV, Inc., "Light-Duty Vehicle Technology Cost Analysis – European Vehicle Market (Phase 1)," Project 10-449-001, March 29, 2012.

4 FEV, Inc., "Light-Duty Vehicle Technology Cost Analysis – European Vehicle Market, Additional Case Studies (Phase 2)," Project 10-449-001, June 19, 2012.

5 U.S. EPA and U.S. National Highway Traffic Safety Administration, "Draft Joint Technical Support Document: Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards," EPA-420-D-11-901, November 2011.

6 While the EPA cost data also represent high volume production costs, both temporal and geographic adjustments are required to render the EPA data consistent with the FEV ICCT cost data. Whereas the EPA data apply to the 2009 U.S. market, the FEV ICCT cost data apply to the EU market in the 2010/2011 timeframe. To convert U.S. cost data to their EU equivalent, 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. The specific technology conversion consisted of a baseline 2.4 liter, I4, 16 valve DOHC naturally aspirated petrol engine with discrete variable valve timing converted to a 1.6 liter, I4, 16 valve DOHC turbocharged petrol direct injection with discrete variable valve timing. The U.S. data are documented in: EPA, "Light-Duty Technology Cost Analysis Pilot Study, EPA-420-R-09-020, December 2009 (as prepared by FEV, Inc.). The EU data are from the previously cited FEV ICCT cost data report.

While the EPA cost data are expressed as 2009 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 2009 dollars when they developed their technical support document for the 2017-2025 U.S. greenhouse gas standards proposal). To convert the detailed system component costs to the same 2009 basis, all costs were adjusted in accordance with the relationship between the 2008 and 2009 U.S. Consumer Price Index (CPI). The derived CPI adjustment is less than 0.4 percent; specifically 0.996442223 = 2009 CPI (214.537) / 2008 CPI (215.303). The ratio of the FEV ICCT (EU) cost data to the 2009-adjusted U.S. cost data for the referenced (identical) technology package reflect both an inherent adjustment of 2009 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 0.823, and is used to adjust all utilized EPA cost data to its EU equivalent.

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ABOUT THIS SERIES. The ICCT has compiled detailed data on the CO_2 reduction potential and associated costs of vehicle technologies for the European light-duty vehicle market (passenger cars and light-commercial vehicles). The analysis incorporates extensive vehicle simulation modeling as well as a detailed tear-down cost assessment. Papers in this series summarize the underlying methodology, input data, the results of the project.

cost data sources have also been utilized. Specifically, costs for petrol particulate filter, diesel particulate filter, and selective catalytic reduction technology are taken from a 2012 ICCT emission control technology cost study.[7,8] For convenience, these aftertreatment cost estimates are generally referred to as the *ICCT cost data* in this paper.

Table 1 provides an overview of the baseline vehicle characteristics associated with the Ricardo simulation modeling. Since, in some cases, these characteristics are not entirely consistent with average vehicle characteristics for a given vehicle class in the EU, the cost curve development process, as described in detail below, includes steps to both adjust baseline data for any CO_2 and cost impacts of such inconsistent assumptions as well as estimate the cost impacts of advanced (i.e., 2020 and later) alternative vehicle technology. In all cases, CO_2 reduction technology is evaluated on a constant performance basis (relative to associated baseline vehicle performance, as measured by simulated zero to 96.6 kilometers per hour (60 miles per hour) acceleration time).

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

Additionally, as stated above the presented cost curves are primarily based on costs developed through teardown studies of current technology. This adds an important element of validation with regard to cost estimates, but it also inherently discounts (to zero) the cost value of future advances in technology design. To the extent that design advances occur, the presented cost curves overstate CO_2 emission reduction costs in the years following such advances. Thus, while teardown cost estimates serve an important role in grounding future cost estimates, they 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 describes adjustments to the baseline Ricardo ICCT CO_2 data. Section 3 describes the basic approach to cost curve construction, including the methodologies employed to adapt the various cost data sources to the Ricardo ICCT CO_2 data. Section 4 describes the steps taken to estimate the CO_2 emissions performance of diesel electric hybrid technology, which is not explicitly included in the Ricardo ICCT CO_2 data. Section 5 summarizes 2020 and 2025 cost curve construction given available CO_2 and cost data, and presents the methodology used to extend the 2020 curve to a representative cost curve for 2015. Section 6 describes a set of final adjustments implemented to better adapt the cost curve data to average EU vehicles, while Section 7 presents the developed cost curves. Section 8 presents a discussion of how the presented cost curves might be interpreted, along with a discussion of associated limitations. Lastly, Section 9 presents definitions for the various abbreviations and acronyms that appear in the paper.

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7 ICCT, Posada Sanchez, F., Bandivadekar, A., and German J., "Estimated Cost of Emission Reduction Technologies for Light-Duty Vehicles," March 2012.

8 Like the FEV ICCT cost and EPA cost data, the ICCT study estimates cost on the basis of direct "current year" cost to the vehicle manufacturer. However, while the FEV ICCT cost and EPA cost data both also include learning factors to adjust current cost estimates to future year costs, no such factors are included with the ICCT study data. Learning factors for the ICCT study data are taken as being identical to the corresponding factors from the FEV ICCT cost data study for positive incremental cost technologies considered to be commercially viable in large volume production the 2010/2011 timeframe. Positive incremental cost technologies are those that require a net additional investment by auto manufacturers. Technologies such as dual clutch (automated manual) transmissions, which can result in cost savings relative to alternative automatic transmission technology, are excluded from consideration in developing learning factors for the ICCT cost data.

Table 1. Ricardo Simulation Modeling Baseline Vehicle Characteristics

Vehicle Class	B Class	C Class	D Class	Small N1	Large N1
Exemplar Vehicle	**Toyota Yaris**	**Ford Focus**	**Toyota Camry**	**Transit Connect**	**Ford Transit**
PETROL VEHICLE CHARACTERISTICS					
Displacement (liters)	1.5	1.6	2.4	2.0	3.8
Engine Configuration	I4	I4	I4	I4	V6
Injection System	PFI	PFI	PFI	PFI	PFI
Turbocharged	No	No	No	No	No
Valve Configuration	DOHC	DOHC	DOHC	DOHC	OHV
Valve Technology	VVT	Fixed	VVT	VVT	Fixed
Transmission	A6	M6	A6	A6	A6
Final Drive Ratio	4.00	3.80	3.23	3.10	3.17
Test Weight (pounds)	2,625	2,906	3,625	3,625	4,500
Test Weight (kg)	1,191	1,318	1,644	1,644	2,041
Enhanced Alternator	Yes	Yes	Yes	Yes	Yes
Idle-Off Technology	Yes	Yes	Yes	Yes	Yes
C_d	0.32	0.29	0.30	0.37	0.34
C_dA (m^2)	0.74	0.65	0.69	1.04	0.95
Rolling Resistance Coefficient	0.0094	0.0079	0.0082	0.0083	0.0072
DIESEL VEHICLE CHARACTERISTICS					
Displacement (liters)	1.2	1.6	2	1.8	2.2
Engine Configuration	I4	I4	I4	I4	I4
Injection System	DI	DI	DI	DI	DI
Turbocharged	Yes	Yes	Yes	Yes	Yes
Valve Configuration	DOHC	DOHC	DOHC	DOHC	DOHC
Valve Technology	Fixed	Fixed	Fixed	Fixed	Fixed
Transmission	A6	M6	A6	A6	A6
Final Drive Ratio	3.45	3.81	3.3	3.55	3.65
Test Weight (pounds)	2,625	2,906	3,625	3,625	4,500
Test Weight (kg)	1,191	1,318	1,644	1,644	2,041
Enhanced Alternator	Yes	Yes	Yes	Yes	Yes
Idle-Off Technology	Yes	Yes	Yes	Yes	Yes
C_d	0.32	0.29	0.30	0.37	0.34
C_dA (m^2)	0.74	0.65	0.69	1.04	0.95
Rolling Resistance Coefficient	0.0094	0.0079	0.0082	0.0083	0.0072

2. Base Vehicle CO_2 Adjustments

Since (as shown in Table 1 above) the baseline CO_2 estimates included in the Ricardo ICCT CO_2 data assume the presence of both an improved alternator capable of some braking energy recovery and 12 volt idle-off technology, and since both technologies were not widely deployed in European vehicles in 2010, adjustments to remove the CO_2 reduction effects of these two technologies are required to establish a zero-cost CO_2 baseline for the year 2010. Similarly, the Ricardo baseline CO_2 estimates for most vehicle classes also assume automatic transmission technology and, in the case of the large N1 class, overhead valve technology for petrol vehicles. The CO_2 effects of both assumptions are also estimated and the Ricardo baseline CO_2 estimates appropriately adjusted to establish an EU-consistent zero-cost CO_2 baseline. These adjustments are applied to all affected vehicle classes for which cost curves are developed. Table 2 presents a summary of the adjustment factors, each of which was developing using the methodologies discussed in the remainder of this section.

To implement the required adjustments, detailed vehicle-specific energy loss analysis was performed for six U.S. vehicles using finely resolved energy distribution data from associated Ricardo simulation modeling (equivalent to the simulation modeling performed to generate the Ricardo ICCT CO_2 data).[9] To eliminate the effect of the advanced alternator on fuel consumption, energy used to power accessories for the six vehicles over the U.S. CAFE cycle was adjusted to reflect both a reduction of alternator efficiency from 70 to 55 percent and the elimination of all accessory-based regenerative braking energy.[10] This calculated change in fuel consumption was regressed against the baseline (before adjustment) fuel consumption to derive a generalized impact algorithm, which was then applied to the baseline Ricardo ICCT CO_2 data (for the EU vehicles evaluated over the U.S. CAFE cycle) to estimate U.S. CAFE cycle CO_2 emissions in the absence of the Ricardo-assumed advanced alternator.[11] These data are then converted to NEDC equivalent CO_2 estimates using the ratio of the Ricardo ICCT CO_2 data for the EU vehicles evaluated over the NEDC to the Ricardo ICCT CO_2 data for those same vehicles evaluated over the U.S. CAFE cycle.

The idle-off adjustment is conceptually similar. Idle emission rates for the six U.S. vehicles are estimated from the detailed energy loss distribution data. These idle emission rates are then regressed against engine displacement to derive a generalized idle emission rate algorithm, which is then applied to the displacements associated with each of the EU baseline engines in the Ricardo ICCT CO_2 data to estimate associated idle emission rates. Combining the estimated idle emission rates with the idle time associated with the NEDC produces an estimate of the additional fuel that would be consumed over the NEDC in the absence of idle-off technology. The ratio of fuel consumption without idle-off technology to fuel consumption with idle-off technology is identical to the corresponding ratio of CO_2 emissions, thereby allowing for the direct calculation of CO_2 emissions over the NEDC in the absence of the Ricardo-assumed idle-off technology.

As indicated above, the baseline CO_2 estimates included in the Ricardo ICCT CO_2 data, with the singular exception of the C class vehicle, also assume the presence of six speed automatic transmission technology. Such an assumption is quite inconsistent with the EU vehicle market, so additional baseline CO_2 adjustments are implemented to reflect five speed manual transmission technology for the B class baseline vehicle and six speed manual transmission technology for the baseline vehicles in all other classes for which cost curves were developed. The transmission CO_2 adjustment is based on supplementary simulation modeling performed by Ricardo (as documented in the Ricardo ICCT CO_2 data reference cited above), wherein a C class Ford Focus was modeled (separately) with a six speed automatic and a six speed manual transmission (over the NEDC). The associated fuel consumption ratio is applied to all six speed automatic transmission baseline vehicle CO_2 estimates to derive corresponding CO_2 estimates for six speed manual transmission baseline vehicles. For the five speed manual transmission adjustment required for the B class vehicle, the six speed manual transmission adjustment is augmented to reflect the fuel consumption ratio of five and six speed manual transmissions as estimated in the fuel consumption data that is

9 The six vehicles cover a wide range of size and performance, consisting of a Toyota Yaris, a Toyota Camry, a Chrysler 300, a Saturn Vue, a Dodge Grand Caravan, and a Ford F150 pickup truck. Although conceptually and fundamentally equivalent to the Ricardo ICCT CO_2 data modeling, the data underlying the adjustment analysis were generated by Ricardo for the U.S. EPA in support of that agency's efforts to establish 2017-2025 greenhouse gas standards for U.S. vehicles. In addition to driving cycle aggregate CO_2 data, Ricardo provided the EPA with finely resolved (i.e., subsecond-by-subsecond) data at the technology system level of detail. These data can be analyzed to develop detailed fuel consumption impacts at the technology system level, which can then be modified as appropriate to estimate the effects of individual technology system changes. For example, accessory consumption can be increased or decreased to reflect changes in alternator efficiency, or input energy can be adjusted to reflect a change in regenerative energy, etc. Such data provide the basis for the adjustments described here. While there is no technical reason that this same system level analysis could not be performed for the Ricardo ICCT CO_2 data directly, the level of effort involved in assembling and performing the basic technology systems analysis is not trivial and thus was not replicated using the EU data specifically. This, however, should not be interpreted as a design weakness since all adjustments are explicitly tailored to the NEDC and applied only on a relative basis to explicit NEDC data.

10 All of the braking energy recovered under the advanced alternator energy capture is used to reduce accessory load.

11 *For a given fuel*, changes in CO_2 are directly proportional to changes in fuel consumption.

included in the cited EPA cost data report. Since this ratio is essentially an efficiency ratio for the U.S. CAFE cycle, and U.S. CAFE cycle and NEDC CO_2 data are similar (once the effects of idle time differences are eliminated, as with idle-off technology), it is expected that U.S. CAFE cycle-based transmission efficiency ratio will provide a reasonably accurate estimate of the effect of moving from five to six speed manual transmission technology in the EU.

Finally, Ricardo modeled the petrol large N1 class Ford Transit baseline vehicle with an overhead valve (OHV) configuration, whereas the baseline configuration for the few EU petrol vehicles in this class include dual overhead cam (DOHC) technology. To adjust the Transit-based large N1 class petrol vehicle to a DOHC baseline, the fuel consumption ratio of a DOHC V6 engine to an OHV V6 engine was derived from data included in the U.S. National Energy Modeling System (NEMS).[12] This ratio, discounted to eliminate the effects of engine downsizing that are assumed in the basic relationship between NEMS DOHC and OHV technology, is applied to the OHV-based CO_2 baseline data for the Ford Transit to derive an associated CO_2 estimate for an equivalent DOHC baseline vehicle. Simulation modeling for all other petrol and all diesel baseline vehicles is based on DOHC technology, so no similar adjustments are required.

Table 2. Baseline Vehicle CO_2 Adjustments

Vehicle Class	B Class	C Class	D Class	Small N1	Large N1
Exemplar Vehicle	**Toyota Yaris**	**Ford Focus**	**Toyota Camry**	**Transit Connect**	**Ford Transit**
PETROL VEHICLE ADJUSTMENT FACTORS					
Eliminate Improved Alternator	1.035	1.035	1.029	1.027	1.021
Eliminate Idle-Off Technology	1.110	1.105	1.110	1.091	1.108
Eliminate A6 Transmission (1)	0.963	1.000	0.941	0.941	0.941
Adjust OHV to DOHC (2)	1.000	1.000	1.000	1.000	0.967
Net CO_2 Adjustment	1.106	1.143	1.075	1.054	1.030
DIESEL VEHICLE ADJUSTMENT FACTORS					
Eliminate Improved Alternator	1.040	1.038	1.035	1.031	1.028
Eliminate Idle-Off Technology	1.130	1.133	1.138	1.118	1.116
Eliminate A6 Transmission (1)	0.963	1.000	0.941	0.941	0.941
Adjust OHV to DOHC (2)	1.000	1.000	1.000	1.000	1.000
Net CO_2 Adjustment	1.131	1.175	1.108	1.085	1.080

Notes: (1) The B class adjustment reflects "movement" from A6 to M5 technology. The C class technology is M6 in the Ricardo modeling, so no adjustment is required. All other classes reflect "movement" from A6 to M6 technology.
(2) All classes except large N1 petrol assume DOHC technology and thus only the large N1 petrol data are adjusted.

12 U.S. Department of Energy, Energy Information Administration, "Transportation Sector Module of the National Energy Modeling System: Model Documentation 2011," DOE/EIA-M070(2011), April 2012.

3. 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.[13,14] However, assemblage of the associated data includes nuances that must be addressed. This section is intended to explain, to the maximum extent practical, both the basic data assemblage process and the nuances associated therewith. It should be recognized, however, that while every effort has been made to provide a thorough description of the cost curve development approach and calculations, readability limitations place a practical limit on the depth of the presented discussion.

Cost curve data has been developed for five EU vehicle classes: B class, C class, D class, small N1 class, and large N1 class vehicles. While Ricardo modeled two baseline C class vehicles with differing CO_2 characteristics, data for the Ford Focus-based modeling is used for C class cost curve development since the underlying vehicle characteristics associated with the Focus-based modeling is more consistent with an average EU C class vehicle. Separate petrol and diesel cost curves were developed for each of the five vehicle classes.

For *petrol vehicles*, the Ricardo ICCT CO_2 data (over the NEDC) is available for a number of basic technology packages: (1) baseline 2010 technology, (2) stoichiometric turbocharged direct injection technology, (3) lean burn turbocharged direct injection technology, (4) stoichiometric turbocharged direct injection technology with dual circuit cooled exhaust gas recirculation, (5) P2 electric hybrid technology coupled with the three direct injection technology packages designated as items 2 through 4 in this list as well as with two Atkinson cycle naturally aspirated engine packages, one with cam profile switching and one with digital valve actuation technology, and (6) powersplit electric hybrid technology coupled the same five internal combustion engine technology packages.

To avoid conflating the issues of future unknown CO_2 standards with future unknown criteria pollutant standards (for NO_x specifically), data related to lean burn turbocharged direct injection technology has been excluded from cost curve development. The need for, and degree of, aftertreatment technology required on lean burn engines depends on the stringency of future NO_x standards. Since it is not clear what level of NO_x standards would be imposed on future lean burn petrol engines, it was decided to exclude lean burn petrol technology from the cost curve development exercise.

Additionally, only one electric hybrid technology package was formally considered in the development of the cost curves – that being the P2 electric hybrid package based on an Atkinson cycle naturally aspirated internal combustion engine with cam profile switching. All of the remaining P2 and all of the powersplit electric hybrid technology packages were excluded on the basis of obviously poorer cost effectiveness. The CO_2 emissions reductions of the P2 technology packages are always greater than those of corresponding powersplit technology packages, and these greater reductions are achieved at lower cost. This is entirely consistent with current trends in the EU, where most manufacturers are moving forward with P2 hybrid technology. Only Toyota and Ford are using powersplit technology.

Within the P2 family, the Atkinson cycle naturally aspirated engine-based packages provide CO_2 reductions that are either nearly equal to or greater than those of the much more expensive turbocharged direct injection packages, with the cheaper cam profile switching-based package providing CO_2 reductions that are relatively closer to those of the digital valve actuation package than the difference in their respective costs would dictate if the latter were the more cost effective approach. Thus, the P2 package based on an Atkinson cycle naturally aspirated engine with cam profile switching reflects the most cost effective hybridized technology approach, and is therefore the only hybrid package subjected to detailed component costing.

For *diesel vehicles*, the Ricardo ICCT CO_2 data (over the NEDC) is available for only two basic technology packages: (1) baseline 2010 technology and (2) 2020 advanced diesel technology. The data provide for no other diesel evaluation options. A third diesel technology option, P2 electric hybrid technology, has been constructed by extrapolating the CO_2 impacts of petrol electric hybrid vehicles to non-hybrid CO_2 data for advanced diesel vehicles. Section 4 below provides additional discussion on both the basis for and methodology employed to implement this extrapolation.

The number of future technology raw data points for both petrol and diesel vehicles is tripled by analyzing each technology package under three road load scenarios. Road load energy is determined over the NEDC

13 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.

14 As indicated previously, the primary source for CO_2 emissions estimates is the Ricardo ICCT CO_2 data and the primary source for associated technology costs is the FEV ICCT cost data. In some cases where primary source data are not available, secondary data sources are utilized as described in the discussion that follows.

through three parameters — mass, rolling resistance, and aerodynamic drag. Technology exists to alter all three road load characteristics. Under the first road load scenario, each of the technology combinations is evaluated at baseline road load conditions (i.e., with the values of the three road load parameters set as they exist for each modeled vehicle today). The second road load scenario assumes 15, 10, and 10 percent reductions in vehicle mass, rolling resistance, and aerodynamic drag respectively, while the third road load scenario assumes respective 30, 20, and 20 percent reductions.[15] In all cases, engine displacement is reduced as necessary to maintain constant (or better) zero to 96.6 kilometers per hour (60 miles per hour) performance.[16] Additional detail on the CO_2 data for these three road load scenarios is available in Working Paper 2012-4.

Finally, although the Ricardo ICCT CO_2 data provides estimates for future non-hybrid technology packages with either an automatic transmission or a dual clutch automated manual transmission, only the dual clutch automated manual transmission data are used to construct the cost curves. Given the limited penetration of automatic transmissions in the EU market, mass conversion to automatic transmission technology is not considered likely, especially given the automated shift capability of the automated manual transmission and its generally lower incremental cost. The sole exception to this approach is for the B class vehicle, where six speed "conventional" manual transmission technology is assumed for all future non-hybrid technology scenarios.[17,18]

To develop aggregate cost estimates for each CO_2 technology package, individual component technologies are costed and then summed to derive an overall cost estimate. Tables 3 through 17 present the component technology list, direct manufacturer cost estimates for 2020, and the associated cost data sources for the various technology packages included in the cost curve development process.[19] Is important to recognize that the actual costing process is performed on a class-by-class basis, so assembling technologies into a "master list" as required for the development of Tables 3 through 17 is somewhat challenging in that some listed technologies may apply to one or more, but not all classes. Vehicle classes to which specific technologies do not apply will report associated technology costs as zero. Differences across classes are primarily limited to the type and gear count of base and future transmissions, with all vehicle classes other than the B class utilizing six speed manual transmission technology in the baseline vehicle and eight speed automatic and eight speed dual clutch automated manual transmissions in the future technology packages. All dual clutch transmission packages utilize a dry clutch system except for the large N1 class, which is assumed to require a wet clutch system.

Additionally, it should be recognized that the costing of technology packages, as summarized in Tables 3 through 17, includes the costing of automatic transmission technology, even though such packages are not utilized in the actual construction of vehicle cost curves. This is primarily an artifact of the manner in which the data analysis exercise

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15 These two alternative road load scenarios are designed to reflect what can best be characterized as "moderate" and "more aggressive" reduction strategies achievable in the 2020 timeframe. Neither level of reduction would require breakthrough technology as demonstrated by a wide range of studies that indicate that reductions in vehicle mass of up to 40 percent and reductions in aerodynamic drag and rolling resistance characteristics of as much as 20 percent are feasible in the study timeframe. While it is not the purpose of this paper to provide a complete bibliography of such supporting studies, interested readers can consult the following for more information (and additional references):

Hucho, W.-H., Grenzwert-Strategie: Halbierung des cW-Wertes scheint möglich. ATZ 111(01/2009): 16-23, 2009.

Goede, M., Volkswagen AG, "SuperLIGHT-Car project – An integrated research approach for lightweight car body innovations," included in the papers compiled for the International Conference on Innovative Developments for Lightweight Vehicle Structures, Wolfsburg, Germany, May 26-27, 2009.

Lotus Engineering Inc., "An Assessment of Mass Reduction Opportunities for a 2017 – 2020 Model Year Vehicle Program," Rev 006A, March 2010.

Schedel, R., Viel Entwicklungspotenzial in der Aerodynamik. Automobiltechnische Zeitschrift (ATZ) 109(01/2007): 40-45, 2007.

U.S. Department of Energy, "2011 Annual Progress Report, Lightweighting Materials," DOE/EE-0674, February 2012.

U.S. EPA and U.S. National Highway Traffic Safety Administration, "Draft Joint Technical Support Document: Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards," EPA-420-D-11-901, November 2011.

U.S. EPA, U.S. National Highway Traffic Safety Administration, and California Air Resources Board, "Interim Joint Technical Assessment Report: Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2017-2025," September 2010.

U.S. National Highway Traffic Safety Administration, "Final Regulatory Impact Analysis, Corporate Average Fuel Economy for MY 2012-MY 2016 Passenger Cars and Light Trucks," March 2010.

16 The Ricardo ICCT CO_2 data assumes a minimum per cylinder displacement of 0.225 liters and a minimum cylinder count of three, effectively limiting the minimum engine displacement to 0.675 liters. Therefore, engine displacement is reduced to either to the point of equal performance or the effective minimum displacement, whichever is greater. This criterion also serves to limit the CO_2 emission reduction potential of technology packages that could provide equal performance at an engine displacement below 0.675 liters.

17 Automated transmission technology is assumed to be required to achieve the CO_2 emission levels estimated for electric hybrid vehicles. In effect, transmission control is an inherent portion of the hybrid control strategy and while manual transmission technology is technologically feasible for electric hybrids, the ability to maximize CO_2 emission reductions requires a fully automated control loop.

18 To derive CO_2 emission estimates for future six speed manual transmissions, the CO_2 estimates for the six speed automatic transmission equipped B class technology packages are adjusted by the fuel consumption ratio of the two transmission technologies, calculated as described above in Section 2.

19 Corresponding cost data for 2025 are also developed, but are not presented here in the interest of brevity.

was initially constructed – wherein costing proceeded in a stepwise manner from those technologies included in Ricardo's baseline CO_2 packages to Ricardo's advanced automatic transmission technology packages to Ricardo's advanced dual clutch automated manual transmission technology packages – adding (or removing) individual component technologies as appropriate as one progressed through this technology hierarchy.[20] Since the costing of the advanced dual clutch automated manual transmission technology packages is dependent on the preceding costing of the advanced automatic transmission technology packages, the costs of the latter are presented, even though the packages themselves are not used in the final cost curve construction process.

To fully understand the various cost items included in the cost tables, it is important to recognize that an integral component of the costing exercise for each vehicle class and technology configuration is the proper sizing and associated cost of the added componentry. Thus the costed technology items are designed to reflect not only specific componentry that has been added (or removed), but also the effect of changes in componentry sizing due to engine downsizing. For example, a smaller engine might require a smaller (and cheaper) turbocharger, a smaller injection system, a smaller aftertreatment device, etc. Sizing considerations vary for each individual technology.

20 Note that the terminology hierarchy does not signify dependence, in that a "lower" hierarchy package is not dependent on the "higher" hierarchy package. The terminology simply signifies that the costs of a "lower" hierarchy package inherently includes the costs (and technologies) already estimated for the "higher" hierarchy package. Rather than rebuild a complete technology list for every package, each succeeding package simply adds technologies to, or removes technologies from, the cumulative technology list associated with the preceding technology package. The hierarchical process is one of convenience, not dependence.

Table 3. 2020 Cost of Petrol STDI Technology at Baseline Road Load (Euros)

Vehicle Class	B Class	C Class	D Class	Small N1	Large N1	Cost Data Source
Exemplar Vehicle	**Toyota Yaris**	**Ford Focus**	**Toyota Camry**	**Transit Connect**	**Ford Transit**	
COST OF TECHS INCLUDED IN RICARDO BASELINE (BUT WHICH ARE NOT IN AVERAGE EU BASELINE)						
M5	0	0	0	0	0	FEV ICCT
M6 to A6	0	388	395	391	403	FEV ICCT
Fixed Valves	0	0	0	0	0	EPA
VVT	28	0	28	28	0	EPA
Improved Alternator	54	54	54	54	54	EPA
Start-Stop (12V BAS)	275	279	313	296	372	FEV ICCT
Total Ricardo Baseline Cost over EU Baseline	**357**	**722**	**790**	**770**	**830**	**Sum**
ADVANCED TECHNOLOGY — AUTOMATIC (OR MANUAL) TRANSMISSION CONFIGURATION						
VVT (if not in Ricardo Baseline)	0	28	0	0	28	EPA
CPS (DVVL)	88	88	88	88	88	EPA
Spray-Guided DI (10.5:1 CR, 25-30 bar)	106	106	108	107	115	FEV ICCT
Turbo (Two stage series sequential)	450	452	479	462	505	FEV ICCT
Downsizing	-147	-150	-168	-160	-401	FEV ICCT
Friction Reduction (3.5% FC Reduction)	94	94	94	94	123	EPA
A6 to A8 (if AT)	0	35	35	35	35	FEV ICCT
Internal Transmission Improvements	151	151	151	151	151	EPA
M5 to M6 (if MT)	156	0	0	0	0	EPA
Shift Optimization & Early TC Lockup (if AT)	0	39	39	39	39	EPA
Advanced Alternator with Electric Coolant Pump	33	33	33	33	33	EPA
EPS	67	67	67	67	67	EPA
Particulate Filter	49	50	59	53	66	ICCT
Weight Change	0	0	0	0	0	EPA
Rolling Resistance Change	0	0	0	0	0	EPA
Aerodynamic Drag Change	0	0	0	0	0	EPA
Start-Stop System Size Change	-31	-35	-56	-47	-105	FEV ICCT
Total Incremental Cost over Ricardo Baseline	**1,016**	**957**	**927**	**920**	**743**	**Sum**
Total Incremental Cost over EU Baseline	**1,373**	**1,679**	**1,717**	**1,690**	**1,573**	**Sum**
ADVANCED TECHNOLOGY — DUAL CLUTCH AUTOMATED MANUAL (OR MANUAL) TRANSMISSION CONFIGURATION						
Delete A8 (if AT)	0	-35	-35	-35	-35	FEV ICCT
A6 to 8DDCT (if moving from AT)	0	-16	-16	-16	-16	EPA
8DDCT to 8WDCT (if wet clutch)	0	0	0	0	47	EPA
Weight Change	0	0	0	0	0	EPA
Rolling Resistance Change	0	0	0	0	0	EPA
Aerodynamic Drag Change	0	0	0	0	0	EPA
Particulate Filter Size Change	-2	0	0	0	2	ICCT
Engine Size Change	-2	0	0	0	2	FEV ICCT
Start-Stop System Size Change	-2	0	0	0	2	FEV ICCT
GDI System Size Change	0	0	0	0	0	FEV ICCT
Turbocharger System Size Change	-2	0	0	0	2	FEV ICCT
Total Incremental Cost over Ricardo Baseline	**1,007**	**907**	**878**	**871**	**746**	**Sum**
Total Incremental Cost over EU Baseline	**1,364**	**1,629**	**1,668**	**1,641**	**1,576**	**Sum**

A list of abbreviations and acronyms appears below as Section 9.

Table 4. 2020 Cost of Petrol STDI Technology at 15/10/10 Road Load (Euros)

Vehicle Class	B Class	C Class	D Class	Small N1	Large N1	Cost Data Source
Exemplar Vehicle	Toyota Yaris	Ford Focus	Toyota Camry	Transit Connect	Ford Transit	
ADVANCED TECHNOLOGY — AUTOMATIC (OR MANUAL) TRANSMISSION CONFIGURATION						
Baseline Road Load System Cost	1,373	1,679	1,717	1,690	1,573	RL0
Weight Change	178	203	276	269	337	EPA
Rolling Resistance Change	4	5	4	4	4	EPA
Aerodynamic Drag Change	30	30	30	30	30	EPA
Particulate Filter Size Change	-2	-3	-4	-3	-5	ICCT
Engine Size Change	-3	-3	-5	-4	-6	FEV ICCT
Start-Stop System Size Change	-3	-4	-6	-5	-7	FEV ICCT
GDI System Size Change	-1	-1	-1	-1	-1	FEV ICCT
Turbocharger System Size Change	-3	-3	-5	-4	-6	FEV ICCT
Total Incremental Cost over EU Baseline	**1,573**	**1,901**	**2,005**	**1,975**	**1,917**	**Sum**
ADVANCED TECHNOLOGY — DUAL CLUTCH AUTOMATED MANUAL (OR MANUAL) TRANSMISSION CONFIGURATION						
Baseline Road Load System Cost	1,364	1,629	1,668	1,641	1,576	RL0
Weight Change	178	203	276	269	337	EPA
Rolling Resistance Change	4	5	4	4	4	EPA
Aerodynamic Drag Change	30	30	30	30	30	EPA
Particulate Filter Size Change	-1	-3	-4	-3	-5	ICCT
Engine Size Change	-1	-4	-5	-4	-7	FEV ICCT
Start-Stop System Size Change	-1	-4	-6	-4	-8	FEV ICCT
GDI System Size Change	0	-1	-1	-1	-1	FEV ICCT
Turbocharger System Size Change	-1	-3	-5	-4	-7	FEV ICCT
Total Incremental Cost over EU Baseline	**1,573**	**1,851**	**1,955**	**1,927**	**1,919**	**Sum**

A list of abbreviations and acronyms appears below as Section 9.

Table 5. 2020 Cost of Petrol STDI Technology at 30/20/20 Road Load (Euros)

Vehicle Class	B Class	C Class	D Class	Small N1	Large N1	Cost Data Source
Exemplar Vehicle	**Toyota Yaris**	**Ford Focus**	**Toyota Camry**	**Transit Connect**	**Ford Transit**	
ADVANCED TECHNOLOGY — AUTOMATIC (OR MANUAL) TRANSMISSION CONFIGURATION						
Baseline Road Load System Cost	1,373	1,679	1,717	1,690	1,573	RLO
Weight Change	769	810	1,101	1,074	1,342	EPA
Rolling Resistance Change	42	42	40	43	40	EPA
Aerodynamic Drag Change	118	119	119	119	118	EPA
Particulate Filter Size Change	-2	-3	-8	-6	-10	ICCT
Engine Size Change	-3	-4	-11	-8	-12	FEV ICCT
Start-Stop System Size Change	-3	-4	-12	-9	-14	FEV ICCT
GDI System Size Change	-1	-1	-2	-1	-2	FEV ICCT
Turbocharger System Size Change	-3	-4	-10	-8	-12	FEV ICCT
Total Incremental Cost over EU Baseline	**2,290**	**2,635**	**2,934**	**2,894**	**3,022**	**Sum**
ADVANCED TECHNOLOGY — DUAL CLUTCH AUTOMATED MANUAL (OR MANUAL) TRANSMISSION CONFIGURATION						
Baseline Road Load System Cost	1,364	1,629	1,668	1,641	1,576	RLO
Weight Change	769	810	1,101	1,074	1,342	EPA
Rolling Resistance Change	42	42	40	43	40	EPA
Aerodynamic Drag Change	118	119	119	119	118	EPA
Particulate Filter Size Change	-1	-3	-8	-7	-11	ICCT
Engine Size Change	-1	-4	-11	-8	-13	FEV ICCT
Start-Stop System Size Change	-1	-4	-12	-9	-15	FEV ICCT
GDI System Size Change	0	-1	-2	-2	-2	FEV ICCT
Turbocharger System Size Change	-1	-4	-10	-8	-13	FEV ICCT
Total Incremental Cost over EU Baseline	**2,290**	**2,584**	**2,884**	**2,843**	**3,022**	**Sum**

A list of abbreviations and acronyms appears below as Section 9.

Table 6. 2020 Cost of Petrol STDI with Cooled EGR at Baseline Road Load (Euros)

Vehicle Class	B Class	C Class	D Class	Small N1	Large N1	Cost Data Source
Exemplar Vehicle	Toyota Yaris	Ford Focus	Toyota Camry	Transit Connect	Ford Transit	
ADVANCED TECHNOLOGY — AUTOMATIC (OR MANUAL) TRANSMISSION CONFIGURATION						
SGTDI Cost at Baseline Road Load	1,016	957	927	920	743	SGTDI
EGR System	29	29	34	31	37	FEV ICCT
Weight Change	0	0	0	0	0	EPA
Rolling Resistance Change	0	0	0	0	0	EPA
Aerodynamic Drag Change	0	0	0	0	0	EPA
Particulate Filter Size Change	0	0	0	0	0	ICCT
Engine Size Change	0	0	0	0	0	FEV ICCT
Start-Stop System Size Change	0	0	0	0	0	FEV ICCT
GDI System Size Change	0	0	0	0	0	FEV ICCT
Turbocharger System Size Change	0	0	0	0	0	FEV ICCT
Total Incremental Cost over Ricardo Baseline	**1,045**	**986**	**961**	**951**	**780**	**Sum**
Total Incremental Cost over EU Baseline	**1,403**	**1,708**	**1,751**	**1,721**	**1,610**	**Sum**
ADVANCED TECHNOLOGY — DUAL CLUTCH AUTOMATED MANUAL (OR MANUAL) TRANSMISSION CONFIGURATION						
SGTDI Cost at Baseline Road Load	1,007	907	878	871	746	SGTDI
EGR System	28	29	34	31	38	FEV ICCT
Weight Change	0	0	0	0	0	EPA
Rolling Resistance Change	0	0	0	0	0	EPA
Aerodynamic Drag Change	0	0	0	0	0	EPA
Particulate Filter Size Change	0	0	0	0	0	ICCT
Engine Size Change	0	0	0	0	0	FEV ICCT
Start-Stop System Size Change	0	0	0	0	0	FEV ICCT
GDI System Size Change	0	0	0	0	0	FEV ICCT
Turbocharger System Size Change	0	0	0	0	0	FEV ICCT
Total Incremental Cost over Ricardo Baseline	**1,035**	**936**	**912**	**902**	**784**	**Sum**
Total Incremental Cost over EU Baseline	**1,393**	**1,658**	**1,702**	**1,672**	**1,614**	**Sum**

A list of abbreviations and acronyms appears below as Section 9.

Technology costs based on FEV ICCT cost data are scaled in a number of ways, depending on the technology parameters of interest.[21] With the exception of transmission technology, FEV generally estimated costs for each technology package for up to nine engine configurations; ranging from small I3 to large V8 engines. For technologies such as turbocharged direct injection, which generally also include engine downsizing to maintain constant performance, there are changes in baseline and "with technology" engine size as well as possible configuration changes (e.g., 2.4 liter I4 baseline to 1.6 liter I4 "with technology," or 3.0 liter V6 baseline to 2.0 liter I4 "with technology").

21 It is important to recognize that "scaling" cost data is not meant to imply that all of the costs associated with a scalable technology are variable, or that the scaling is necessarily linear. Scaling algorithms for some technologies are linear, while those for other are nonlinear – however, *all* scaling algorithms include a fixed cost component so that an X percent change in an independent cost influence (such as engine displacement) will *not* translate into an X percent change in technology cost. For example, a hypothetical scaling algorithm might be of the form: cost equals 10 times liters of displacement plus 100 euros, wherein 100 euros would be the fixed cost associated with an engine of any displacement. Thus, a two liter engine would incur costs of 120 euros, while a one liter engine would incur costs of 110 euros – so that a 50 percent reduction in displacement induces only an 8 percent reduction in cost.

Table 7. 2020 Cost of Petrol STDI with Cooled EGR at 15/10/10 Road Load (Euros)

Vehicle Class	B Class	C Class	D Class	Small N1	Large N1	Cost Data Source
Exemplar Vehicle	Toyota Yaris	Ford Focus	Toyota Camry	Transit Connect	Ford Transit	
ADVANCED TECHNOLOGY — AUTOMATIC (OR MANUAL) TRANSMISSION CONFIGURATION						
Baseline Road Load System Cost	1,403	1,708	1,751	1,721	1,610	RL0
EGR System Size Change	-1	-1	-2	-2	-2	FEV ICCT
Weight Change	178	203	276	269	337	EPA
Rolling Resistance Change	4	5	4	4	4	EPA
Aerodynamic Drag Change	30	30	30	30	30	EPA
Particulate Filter Size Change	-2	-3	-4	-3	-5	ICCT
Engine Size Change	-3	-3	-5	-4	-6	FEV ICCT
Start-Stop System Size Change	-3	-4	-6	-5	-7	FEV ICCT
GDI System Size Change	-1	-1	-1	-1	-1	FEV ICCT
Turbocharger System Size Change	-3	-3	-5	-4	-6	FEV ICCT
Total Incremental Cost over EU Baseline	**1,601**	**1,929**	**2,036**	**2,004**	**1,952**	**Sum**
ADVANCED TECHNOLOGY — DUAL CLUTCH AUTOMATED MANUAL (OR MANUAL) TRANSMISSION CONFIGURATION						
Baseline Road Load System Cost	1,393	1,658	1,702	1,672	1,614	RL0
EGR System Size Change	0	-1	-2	-2	-3	FEV ICCT
Weight Change	178	203	276	269	337	EPA
Rolling Resistance Change	4	5	4	4	4	EPA
Aerodynamic Drag Change	30	30	30	30	30	EPA
Particulate Filter Size Change	-1	-3	-4	-3	-5	ICCT
Engine Size Change	-1	-4	-5	-4	-7	FEV ICCT
Start-Stop System Size Change	-1	-4	-6	-4	-8	FEV ICCT
GDI System Size Change	0	-1	-1	-1	-1	FEV ICCT
Turbocharger System Size Change	-1	-3	-5	-4	-7	FEV ICCT
Total Incremental Cost over EU Baseline	**1,601**	**1,879**	**1,987**	**1,956**	**1,954**	**Sum**

A list of abbreviations and acronyms appears below as Section 9.

Scaling costs for such technology is more complex, as costs can vary both as a function of engine configuration (which can affect "parts count") and displacement (which can affect technology system size). Generally a "first cut" cost is established on the basis of the FEV configuration that most closely matches the engine configuration change associated with the Ricardo ICCT CO_2 data. For example the FEV-estimated cost for an I4 to smaller I4 engine is matched with a Ricardo ICCT technology package that reflects a similar degree of downsizing. In this manner, the "parts count" associated with the Ricardo ICCT technology package is properly matched to the FEV ICCT cost data.

However, since the actual displacements associated with the pre and post technology packages may differ across the Ricardo and FEV technology assumptions, the FEV ICCT cost data is also analyzed to isolate the unit-change (i.e., per liter) displacement cost and this "non-cylinder drop" cost of displacement change is used to precisely estimate the cost of the displacement change associated with the Ricardo ICCT CO_2 data. In this fashion, the cost of engine configuration and displacement changes (both petrol and diesel), petrol direct injection, and turbocharger (both petrol and diesel) technology are "fine tuned" on the basis of both "cylinder drop" (if applicable) and per-unit displacement cost change adjustments. In all cases, these adjustments are calculated directly from the FEV ICCT cost data.

Table 8. 2020 Cost of Petrol STDI with Cooled EGR 30/20/20 Road Load (Euros)

Vehicle Class	B Class	C Class	D Class	Small N1	Large N1	Cost Data Source
Exemplar Vehicle	**Toyota Yaris**	**Ford Focus**	**Toyota Camry**	**Transit Connect**	**Ford Transit**	
ADVANCED TECHNOLOGY — AUTOMATIC (OR MANUAL) TRANSMISSION CONFIGURATION						
Baseline Road Load System Cost	1,403	1,708	1,751	1,721	1,610	RL0
EGR System Size Change	-1	-1	-4	-3	-5	FEV ICCT
Weight Change	769	810	1,101	1,074	1,342	EPA
Rolling Resistance Change	42	42	40	43	40	EPA
Aerodynamic Drag Change	118	119	119	119	118	EPA
Particulate Filter Size Change	-2	-3	-8	-6	-10	ICCT
Engine Size Change	-3	-4	-11	-8	-12	FEV ICCT
Start-Stop System Size Change	-3	-4	-12	-9	-14	FEV ICCT
GDI System Size Change	-1	-1	-2	-1	-2	FEV ICCT
Turbocharger System Size Change	-3	-4	-10	-8	-12	FEV ICCT
Total Incremental Cost over EU Baseline	**2,318**	**2,663**	**2,963**	**2,922**	**3,055**	**Sum**
ADVANCED TECHNOLOGY — DUAL CLUTCH AUTOMATED MANUAL (OR MANUAL) TRANSMISSION CONFIGURATION						
Baseline Road Load System Cost	1,393	1,658	1,702	1,672	1,614	RL0
EGR System Size Change	0	-1	-4	-3	-5	FEV ICCT
Weight Change	769	810	1,101	1,074	1,342	EPA
Rolling Resistance Change	42	42	40	43	40	EPA
Aerodynamic Drag Change	118	119	119	119	118	EPA
Particulate Filter Size Change	-1	-3	-8	-7	-11	ICCT
Engine Size Change	-1	-4	-11	-8	-13	FEV ICCT
Start-Stop System Size Change	-1	-4	-12	-9	-15	FEV ICCT
GDI System Size Change	0	-1	-2	-2	-2	FEV ICCT
Turbocharger System Size Change	-1	-4	-10	-8	-13	FEV ICCT
Total Incremental Cost over EU Baseline	**2,318**	**2,612**	**2,914**	**2,871**	**3,054**	**Sum**

A list of abbreviations and acronyms appears below as Section 9.

A number of FEV ICCT costs other than engine downsizing also generally scale with displacement (independent of engine configuration). It is important to note, however, that the FEV ICCT cost data as published are not characterized in terms of cost per unit change in displacement, but are always precisely estimated for a given pre and post technology engine configuration. All per displacement change algorithms are developed through regression analysis as part of the cost curve construction exercise. Technology costs estimated through such analysis include belt alternator starter idle-off systems, petrol cooled EGR, and M6 to 6DDCT transmission technology. ICCT cost data for particulate filter and selective catalytic reduction technology are also subjected to regression analysis and scaled with engine displacement.

Similarly, a number of FEV ICCT costs generally scale with the number of engine cylinders. Such costs include diesel high pressure injection technology, diesel variable valve timing and lift technology, and diesel dual loop EGR technology. As with displacement scaling, the FEV ICCT cost data as published are not characterized in terms of cost per unit change in cylinder count, but are always precisely estimated for a given pre and post technology engine configuration. All per cylinder count cost change algorithms are developed through regression analysis as part of the cost curve construction exercise.

Table 9. 2020 Cost of P2 Petrol HEV Technology at Baseline Road Load (Euros)

Vehicle Class	B Class	C Class	D Class	Small N1	Large N1	Cost Data Source
Exemplar Vehicle	Toyota Yaris	Ford Focus	Toyota Camry	Transit Connect	Ford Transit	
ADVANCED TECHNOLOGY — DUAL CLUTCH AUTOMATED MANUAL TRANSMISSION CONFIGURATION						
Displacement Adjustment (FEV to Ricardo)	72	74	74	65	48	FEV ICCT
P2 System	1,797	1,994	2,120	2,065	2,147	FEV ICCT
Climate Control System Credit	-118	-118	-124	-124	-124	FEV ICCT
Start-Stop Baseline System Credit	-275	-279	-313	-296	-372	FEV ICCT
Improved Baseline Alternator Credit	-54	-54	-54	-54	-54	EPA
7DDCT-to-A6	80	80	80	80	80	EPA
A6 to 6DDCT	-177	0	0	0	0	EPA
A6 to 8DDCT	0	-16	-16	-16	-16	EPA
8DDCT to 8WDCT (if wet clutch)	0	0	0	0	47	EPA
M5 to A6 (if AT not in ICE Baseline)	542	0	0	0	0	FEV ICCT
VVT (if not in Ricardo Baseline)	0	28	0	0	28	EPA
CPS	88	88	88	88	88	EPA
Friction Reduction (3.5% FC Reduction)	94	94	94	94	123	EPA
Internal Transmission Improvements	151	151	151	151	151	EPA
Shift Optimization	21	21	21	21	21	EPA
Total Incremental Cost over Ricardo Baseline	**2,220**	**2,061**	**2,120**	**2,072**	**2,165**	**Sum**
Total Incremental Cost over EU Baseline	**2,578**	**2,783**	**2,910**	**2,842**	**2,995**	**Sum**

A list of abbreviations and acronyms appears below as Section 9.

Table 10. 2020 Cost of P2 Petrol HEV Technology at 15/10/10 Road Load (Euros)

Vehicle Class	B Class	C Class	D Class	Small N1	Large N1	Cost Data Source
Exemplar Vehicle	Toyota Yaris	Ford Focus	Toyota Camry	Transit Connect	Ford Transit	
ADVANCED TECHNOLOGY — DUAL CLUTCH AUTOMATED MANUAL TRANSMISSION CONFIGURATION						
Baseline Road Load System Cost	2,578	2,783	2,910	2,842	2,995	RLO
Weight Change	196	225	298	292	366	EPA
Weight Change Impact on Motor/Battery Size	-62	-78	-89	-85	-91	FEV ICCT
Rolling Resistance Change	4	5	4	4	4	EPA
Aerodynamic Drag Change	30	30	30	30	30	EPA
Engine Size Change	-11	-12	-20	-15	-22	FEV ICCT
Total Incremental Cost over EU Baseline	**2,735**	**2,952**	**3,133**	**3,067**	**3,281**	**Sum**

A list of abbreviations and acronyms appears below as Section 9.

Table 11. 2020 Cost of P2 Petrol HEV Technology at 30/20/20 Road Load (Euros)

Vehicle Class	B Class	C Class	D Class	Small N1	Large N1	Cost Data Source
Exemplar Vehicle	Toyota Yaris	Ford Focus	Toyota Camry	Transit Connect	Ford Transit	
ADVANCED TECHNOLOGY — DUAL CLUTCH AUTOMATED MANUAL TRANSMISSION CONFIGURATION						
Baseline Road Load System Cost	2,578	2,783	2,910	2,842	2,995	RLO
Weight Change	733	899	1,117	1,172	1,463	EPA
Weight Change Impact on Motor/Battery Size	-123	-163	-179	-177	-190	FEV ICCT
Rolling Resistance Change	42	42	40	43	40	EPA
Aerodynamic Drag Change	118	119	119	119	118	EPA
Engine Size Change	-140	-145	-156	-149	-45	FEV ICCT
Total Incremental Cost over EU Baseline	**3,207**	**3,534**	**3,850**	**3,850**	**4,381**	**Sum**

A list of abbreviations and acronyms appears below as Section 9.

Table 12. 2020 Cost of Advanced Diesel Technology at Baseline Road Load (Euros)

Vehicle Class	B Class	C Class	D Class	Small N1	Large N1	Cost Data Source
Exemplar Vehicle	Toyota Yaris	Ford Focus	Toyota Camry	Transit Connect	Ford Transit	
COST OF TECHS INCLUDED IN RICARDO BASELINE (BUT WHICH ARE NOT IN AVERAGE EU BASELINE)						
M5	0	0	0	0	0	FEV ICCT
M6 to A6	0	388	395	391	403	FEV ICCT
Fixed Valves	0	0	0	0	0	EPA
Improved Alternator	54	54	54	54	54	EPA
Start-Stop (12V BAS)	262	279	296	288	305	FEV ICCT
Total Ricardo Baseline Cost over EU Baseline	**317**	**722**	**745**	**734**	**762**	**Sum**
ADVANCED TECHNOLOGY — AUTOMATIC (OR MANUAL) TRANSMISSION CONFIGURATION						
VVT (Costs Included in CPS Costs)	0	0	0	0	0	FEV ICCT
CPS (aka DVVL)	80	80	80	80	86	FEV ICCT
Charge Air Cooling (Air-to-Air, included in turbo costs)	0	0	0	0	0	FEV ICCT
Turbo (Two stage series sequential)	478	490	532	499	561	FEV ICCT
Credit for baseline single stage turbo	-191	-196	-213	-200	-224	FEV ICCT
Enhanced EGR	72	72	72	72	72	FEV ICCT
Increased Injection Pressure	7	7	7	7	9	FEV ICCT
Engine Size Change	-229	-278	-266	-291	-26	FEV ICCT
Friction Reduction (3.5% FC Reduction)	94	94	94	94	123	EPA
A6 to A8 (if AT)	0	35	35	35	35	FEV ICCT
M5 to M6 (if MT)	156	0	0	0	0	EPA
Internal Transmission Improvements	151	151	151	151	151	EPA
Shift Optimization & Early TC Lockup (if AT)	0	39	39	39	39	EPA
Advanced Alternator with Electric Coolant Pump	33	33	33	33	33	EPA
EPS	67	67	67	67	67	EPA
Weight Change	0	0	0	0	0	EPA
Rolling Resistance Change	0	0	0	0	0	EPA
Aerodynamic Drag Change	0	0	0	0	0	EPA
Start-Stop System Size Change	-2	-14	-11	-18	-7	FEV ICCT
DPF Size Change	-7	-36	-30	-47	-18	ICCT
SCR Size Change	-3	-20	-16	-25	-9	ICCT
Total Incremental Cost over Ricardo Baseline	**705**	**523**	**573**	**496**	**891**	**Sum**
Total Incremental Cost over EU Baseline	**1,022**	**1,244**	**1,318**	**1,229**	**1,654**	**Sum**
ADVANCED TECHNOLOGY — DUAL CLUTCH AUTOMATED MANUAL (OR MANUAL) TRANSMISSION CONFIGURATION						
Delete A8 (if AT)	0	-35	-35	-35	-35	FEV ICCT
A6 to 8DDCT (if moving from AT)	0	-16	-16	-16	-16	EPA
8DDCT to 8WDCT (if wet clutch)	0	0	0	0	47	EPA
Engine Size Change	-2	-2	3	0	7	FEV ICCT
Weight Change	0	0	0	0	0	EPA
Rolling Resistance Change	0	0	0	0	0	EPA
Aerodynamic Drag Change	0	0	0	0	0	EPA
High Pressure Injection System Size Change	0	0	0	0	0	FEV ICCT
VVTL System Size Change	0	0	0	0	0	FEV ICCT
Dual Loop EGR System Size Change	0	0	0	0	0	FEV ICCT
Start-Stop System Size Change	0	-1	1	0	2	FEV ICCT
Turbocharger System Size Change	-1	-1	1	0	2	FEV ICCT
DPF Size Change	-1	-1	2	0	5	ICCT
SCR Size Change	-1	-1	1	0	2	ICCT
Total Incremental Cost over Ricardo Baseline	**701**	**466**	**529**	**445**	**904**	**Sum**
Total Incremental Cost over EU Baseline	**1,017**	**1,188**	**1,275**	**1,178**	**1,666**	**Sum**

A list of abbreviations and acronyms appears below as Section 9.

Table 13. 2020 Cost of Advanced Diesel Technology at 15/10/10 Road Load (Euros)

Vehicle Class	B Class	C Class	D Class	Small N1	Large N1	Cost Data Source
Exemplar Vehicle	**Toyota Yaris**	**Ford Focus**	**Toyota Camry**	**Transit Connect**	**Ford Transit**	
ADVANCED TECHNOLOGY — AUTOMATIC (OR MANUAL) TRANSMISSION CONFIGURATION						
Baseline Road Load System Cost	1,022	1,244	1,318	1,229	1,654	RLO
Weight Change	178	203	276	269	337	EPA
Rolling Resistance Change	4	5	4	4	4	EPA
Aerodynamic Drag Change	30	30	30	30	30	EPA
DPF Size Change	-15	-18	-25	-12	-29	ICCT
SCR Size Change	-8	-10	-13	-7	-16	ICCT
Engine Size Change	-22	-27	-36	-18	-43	FEV ICCT
High Pressure Injection System Size Change	0	0	0	0	0	FEV ICCT
VVTL System Size Change	0	0	0	0	0	FEV ICCT
Dual Loop EGR System Size Change	0	0	0	0	0	FEV ICCT
Start-Stop System Size Change	-6	-7	-10	-5	-11	FEV ICCT
Turbocharger System Size Change	-7	-9	-12	-6	-15	FEV ICCT
Total Incremental Cost over EU Baseline	**1,176**	**1,411**	**1,531**	**1,485**	**1,911**	**Sum**
ADVANCED TECHNOLOGY — DUAL CLUTCH AUTOMATED MANUAL (OR MANUAL) TRANSMISSION CONFIGURATION						
Baseline Road Load System Cost	1,017	1,188	1,275	1,178	1,666	RLO
Weight Change	178	203	276	269	337	EPA
Rolling Resistance Change	4	5	4	4	4	EPA
Aerodynamic Drag Change	30	30	30	30	30	EPA
DPF Size Change	-15	-17	-25	-13	-29	ICCT
SCR Size Change	-8	-9	-13	-7	-16	ICCT
Engine Size Change	-22	-25	-36	-20	-43	FEV ICCT
High Pressure Injection System Size Change	0	0	0	0	0	FEV ICCT
VVTL System Size Change	0	0	0	0	0	FEV ICCT
Dual Loop EGR System Size Change	0	0	0	0	0	FEV ICCT
Start-Stop System Size Change	-6	-6	-10	-5	-11	FEV ICCT
Turbocharger System Size Change	-8	-8	-12	-7	-15	FEV ICCT
Total Incremental Cost over EU Baseline	**1,171**	**1,359**	**1,488**	**1,429**	**1,924**	**Sum**

A list of abbreviations and acronyms appears below as Section 9.

In a fashion analogous to that for non-hybrid technology, FEV estimated P2 hybrid technology costs for six engine configurations; ranging from small I3 to large V8 engines. "First cut" costs for the P2 systems associated with the Ricardo ICCT CO_2 data are estimated using the cost data for the FEV P2 system that is closest in size to the Ricardo-assumed system. These first cut costs are then "fine tuned" on the basis of the motor and battery sizes assumed in the Ricardo ICCT cost data. To develop the algorithms associated with this "fine tuning" exercise, the FEV ICCT cost data for motor size/cost and battery size/cost across the six P2 systems that were costed were regressed to develop cost versus size relationships. These relationships are then used to estimate the final P2 package costs for the specific motor and battery sizes assumed in the Ricardo ICCT cost data. While FEV ICCT cost data are unadjusted for all system components other than the motor and battery subsystems, it should be recognized that such unadjusted components only account for about 20 percent of total P2 system costs.[22]

22 It should be recognized that the motor and battery subsystems used as the basis for P2 cost scaling include more than simply the motor/generator and battery. System costs also include associated clutches, lubrication system components, pumps, power electronics, control units, sensors, switches, relays, wiring, cooling systems, casing, connectors, etc.

Table 14. 2020 Cost of Advanced Diesel Technology at 30/20/20 Road Load (Euros)

Vehicle Class	B Class	C Class	D Class	Small N1	Large N1	Cost Data Source
Exemplar Vehicle	**Toyota Yaris**	**Ford Focus**	**Toyota Camry**	**Transit Connect**	**Ford Transit**	
ADVANCED TECHNOLOGY — AUTOMATIC (OR MANUAL) TRANSMISSION CONFIGURATION						
Baseline Road Load System Cost	1,022	1,244	1,318	1,229	1,654	RLO
Weight Change	769	810	1,101	1,074	1,342	EPA
Rolling Resistance Change	42	42	40	43	40	EPA
Aerodynamic Drag Change	118	119	119	119	118	EPA
DPF Size Change	-31	-35	-50	-34	-58	ICCT
SCR Size Change	-17	-19	-27	-18	-31	ICCT
Engine Size Change	-45	-51	-73	-50	-85	FEV ICCT
High Pressure Injection System Size Change	0	0	0	0	0	FEV ICCT
VVTL System Size Change	0	0	0	0	0	FEV ICCT
Dual Loop EGR System Size Change	0	0	0	0	0	FEV ICCT
Start-Stop System Size Change	-12	-13	-19	-13	-22	FEV ICCT
Turbocharger System Size Change	-16	-18	-25	-17	-29	FEV ICCT
Total Incremental Cost over EU Baseline	**1,831**	**2,079**	**2,385**	**2,333**	**2,926**	**Sum**
ADVANCED TECHNOLOGY — DUAL CLUTCH AUTOMATED MANUAL (OR MANUAL) TRANSMISSION CONFIGURATION						
Baseline Road Load System Cost	1,017	1,188	1,275	1,178	1,666	RLO
Weight Change	769	810	1,101	1,074	1,342	EPA
Rolling Resistance Change	42	42	40	43	40	EPA
Aerodynamic Drag Change	118	119	119	119	118	EPA
DPF Size Change	-31	-34	-51	-34	-61	ICCT
SCR Size Change	-17	-18	-28	-18	-33	ICCT
Engine Size Change	-46	-49	-75	-50	-89	FEV ICCT
High Pressure Injection System Size Change	0	0	0	0	0	FEV ICCT
VVTL System Size Change	0	0	0	0	0	FEV ICCT
Dual Loop EGR System Size Change	0	0	0	0	0	FEV ICCT
Start-Stop System Size Change	-12	-13	-20	-13	-23	FEV ICCT
Turbocharger System Size Change	-16	-17	-26	-17	-30	FEV ICCT
Total Incremental Cost over EU Baseline	**1,825**	**2,028**	**2,334**	**2,282**	**2,930**	**Sum**

A list of abbreviations and acronyms appears below as Section 9.

Nevertheless, the “fine tuned” costs are considered to be quite accurate given that the size versus cost correlations of the six P2 systems available in the FEV ICCT cost data exceed 99 percent.

For P2 technology under the alternative road load scenarios, motor size is assumed to scale with vehicle test weight change. Battery size is estimated from a regression analysis of the motor and battery sizes across the six P2 systems included in the FEV ICCT cost data. Total P2 system costs are then calculated in the same fashion as described for the baseline road load scenario.

For technologies that are costed on the basis of EPA cost data, the appropriate technology “size” is selected from the available EPA data. Generally, the EPA cost data are resolved to the level of cylinder count and engine configuration, making it relatively straightforward to select the appropriate technology cost estimate. It is important to recognize that it is the future engine configuration, as opposed to the baseline engine configuration, that is the appropriate basis for selecting costs. For example, the cam phasing system for a downsized four cylinder future engine will be cheaper than the same system that would have been required on an associated six cylinder baseline engine.

Table 15. 2020 Cost of P2 Diesel HEV Technology at Baseline Road Load (Euros)

Vehicle Class	B Class	C Class	D Class	Small N1	Large N1	Cost Data Source
Exemplar Vehicle	**Toyota Yaris**	**Ford Focus**	**Toyota Camry**	**Transit Connect**	**Ford Transit**	
ADVANCED TECHNOLOGY — DUAL CLUTCH AUTOMATED MANUAL TRANSMISSION CONFIGURATION						
Net Petrol P2 HEV System Costs at Baseline Road Load	2,578	2,783	2,910	2,842	2,995	Petrol P2
Advanced Diesel Costs at Baseline Road Load	1,017	1,188	1,275	1,178	1,666	AdvDie
Undo Gasoline Engine Size Change Cost	-72	-74	-74	-65	-48	FEV ICCT
Implement Diesel Engine Size Change Cost	56	34	28	19	26	FEV ICCT
High Pressure Injection System Size Change	0	0	0	0	0	FEV ICCT
VVTL System Size Change	0	0	0	0	0	FEV ICCT
Dual Loop EGR System Size Change	0	0	0	0	0	FEV ICCT
Start-Stop Baseline System Credit	-260	-265	-286	-270	-300	FEV ICCT
Turbocharger System Size Change	-2	-9	-11	-14	-12	FEV ICCT
Improved Baseline Alternator Credit	-54	-54	-54	-54	-54	EPA
M5 to M6 Credit	-156	0	0	0	0	EPA
M6 to A6 Credit	0	-388	-395	-391	-403	FEV ICCT
VVT Credit	0	-28	0	0	-28	EPA
CPS (aka DVVT) Credit	-88	-88	-88	-88	-88	EPA
Friction Reduction Credit	-94	-94	-94	-94	-123	EPA
A6 to 6DDCT Credit	0	0	0	0	0	EPA
A8 to 8DDCT Credit	0	16	16	16	16	EPA
8DDCT to 8WDCT Credit (if wet clutch)	0	0	0	0	-47	EPA
Internal Transmission Improvement Credit	-151	-151	-151	-151	-151	EPA
Shift Optimization Credit	0	-39	-39	-39	-39	EPA
Advanced Alternator Credit	-33	-33	-33	-33	-33	EPA
EPS Credit	-67	-67	-67	-67	-67	EPA
DPF Size Change	-4	-19	-23	-29	-24	ICCT
SCR Size Change	-2	-10	-12	-15	-13	ICCT
Total Incremental Cost over EU Baseline	**2,669**	**2,703**	**2,903**	**2,747**	**3,274**	**Sum**

Credits for non-sized based changes correct for the inclusion of the indicated technologies in both P2 and non-P2 system costs.
A list of abbreviations and acronyms appears below as Section 9.

Road load technology (i.e., mass, rolling resistance, and aerodynamic drag) generally scale with the degree of change implemented, on both a total and per-unit cost basis. For example, the per-kilogram cost of mass reduction is higher for a 20 percent reduction than a 10 percent reduction. In other words, scaling algorithms are inherently nonlinear, with the rate of change in per-unit costs increasing with increasing changes in road load technology. For these parameters, cost scaling is inherently algorithmic and thus costs can be adapted to a particular technology package simply on the basis of the magnitude of change in each road load parameter (if any).[23]

23 It should be noted that there is ongoing work related to the cost of changes in vehicle mass – work that is not yet available for use in this study. The influence of mass reduction technology on the developed cost curves will be revisited once these data are available.

Table 16. 2020 Cost of P2 Diesel HEV Technology at 15/10/10 Road Load (Euros)

Vehicle Class	B Class	C Class	D Class	Small N1	Large N1	Cost Data Source
Exemplar Vehicle	**Toyota Yaris**	**Ford Focus**	**Toyota Camry**	**Transit Connect**	**Ford Transit**	
ADVANCED TECHNOLOGY -- DUAL CLUTCH AUTOMATED MANUAL TRANSMISSION CONFIGURATION						
Baseline Road Load System Cost	2,669	2,703	2,903	2,747	3,274	RLO
Weight Change	196	225	298	292	366	EPA
Weight Change Impact in Motor/Battery Size	-62	-78	-89	-85	-91	FEV ICCT
Rolling Resistance Change	4	5	4	4	4	EPA
Aerodynamic Drag Change	30	30	30	30	30	EPA
DPF Size Change	-16	-16	-23	-7	-29	ICCT
SCR Size Change	-9	-9	-12	-4	-15	ICCT
Engine Size Change	-6	-5	-8	-2	-10	FEV ICCT
High Pressure Injection System Size Change	0	0	0	0	0	FEV ICCT
VVTL System Size Change	0	0	0	0	0	FEV ICCT
Dual Loop EGR System Size Change	0	0	0	0	0	FEV ICCT
Turbocharger System Size Change	-8	-8	-11	-3	-14	FEV ICCT
Total Incremental Cost over EU Baseline	**2,799**	**2,845**	**3,093**	**2,971**	**3,514**	**Sum**

A list of abbreviations and acronyms appears below as Section 9.

Table 17. 2020 Cost of P2 Diesel HEV Technology at 30/20/20 Road Load (Euros)

Vehicle Class	B Class	C Class	D Class	Small N1	Large N1	Cost Data Source
Exemplar Vehicle	**Toyota Yaris**	**Ford Focus**	**Toyota Camry**	**Transit Connect**	**Ford Transit**	
ADVANCED TECHNOLOGY — DUAL CLUTCH AUTOMATED MANUAL TRANSMISSION CONFIGURATION						
Baseline Road Load System Cost	2,669	2,703	2,903	2,747	3,274	RLO
Weight Change	733	899	1,117	1,172	1,463	EPA
Weight Change Impact in Motor/Battery Size	-123	-163	-179	-177	-190	FEV ICCT
Rolling Resistance Change	42	42	40	43	40	EPA
Aerodynamic Drag Change	118	119	119	119	118	EPA
DPF Size Change	-30	-31	-44	-25	-56	ICCT
SCR Size Change	-16	-17	-23	-13	-30	ICCT
Engine Size Change	-10	-11	-15	-8	-19	FEV ICCT
High Pressure Injection System Size Change	0	0	0	0	0	FEV ICCT
VVTL System Size Change	0	0	0	0	0	FEV ICCT
Dual Loop EGR System Size Change	0	0	0	0	0	FEV ICCT
Turbocharger System Size Change	-15	-16	-22	-12	-28	FEV ICCT
Total Incremental Cost over EU Baseline	**3,367**	**3,525**	**3,896**	**3,844**	**4,573**	**Sum**

A list of abbreviations and acronyms appears below as Section 9.

Finally, although not explicitly included in the Ricardo ICCT CO_2 data, CO_2 estimates have been developed for P2 diesel electric hybrid vehicles. Section 4 provides a description of the methodology used to develop such CO_2 estimates. The cost estimation process for P2 diesel electric hybrid vehicles is consistent with the cost estimation approach for P2 petrol electric hybrid vehicles. Since petrol and diesel vehicles, as represented in the Ricardo ICCT CO_2 data, have identical weight and road load configurations, incremental P2 system costs should also be the same (since the electric hybrid componentry required to achieve the same level of performance will be identical in both scope and size). The degree of diesel engine downsizing allowed by electric hybridization is estimated from the engine displacement change observed in the Ricardo ICCT CO_2 data for a non-hybrid advanced petrol engine versus a hybridized version of the same engine. Specifically, the STDI with cooled EGR technology package is used for this calculation as it reflects a petrol liter-equivalent fuel consumption rate over the NEDC that is similar to the advanced diesel technology package.[24] Various credits, as delineated in Table 15, are implemented to account for technologies that are included in both the P2 and non-hybridized system costs.

4. P2 Diesel Electric Hybrid CO_2 Estimates

While the Ricardo ICCT CO_2 data include explicit estimates for petrol electric hybrid technology, no counterpart is provided for diesel vehicles. To include diesel electric hybrid technology in the developed cost curves, CO_2 estimates for such technology were developed from surrogate data included in the Ricardo ICCT CO_2 data. Initially, a rather detailed study of P2 hybridization impacts with regard to the distribution of petrol CO_2 benefits between braking energy recovery and "load leveling" effects was investigated as the most appropriate mechanism for integrating advanced diesel and P2 electric hybrid technology.[25] However, during this investigative work, it became clear that: (1) braking energy recovery is responsible for the bulk (70-80 percent depending on vehicle size) of hybridization benefits for high efficiency advanced technology engines, and (2) the petrol liter-equivalent fuel consumption of advanced diesel and non-hybridized petrol technology is quite similar.

Since braking energy over the NEDC is defined by the cycle and is essentially invariant across vehicles of the same road load characteristics (as is the case for the petrol and diesel vehicles in each vehicle class), the energy recovery benefits of hybridization will be the same for petrol and diesel vehicles of equivalent road load. Thus, 70-80 percent of petrol hybridization benefits should transfer directly to diesel vehicles. Moreover, since petrol liter-equivalent fuel consumption of petrol and diesel vehicles is similar for a given class, the potential "load leveling" benefits of advanced diesel hybridization over a given driving cycle (specifically, the NEDC) should also be substantially similar to those of an advanced petrol vehicle. This does not imply that the specific energy loss mechanisms of petrol and diesel are identical, but rather that the opportunity to offset the inherent losses of each is similar when both are evaluated over the NEDC (or any other driving cycle). In short, the relative benefits of hybridization for advanced petrol and diesel vehicles (as represented in the Ricardo ICCT CO_2 data) should be similar.

On this basis, the fuel consumption (and thus CO_2) ratio of a P2 hybridized advanced diesel engine to its non-hybridized counterpart should be equivalent to the corresponding ratio for an advanced petrol vehicle. For cost curve development, this ratio is calculated by comparing the CO_2 emissions for a hybridized STDI petrol vehicle with cooled EGR to the CO_2 emissions for a non-hybridized STDI petrol vehicle with cooled EGR (with both CO_2 estimates taken from the Ricardo ICCT CO_2 data). This ratio is then applied to the advanced diesel CO_2 estimate from the Ricardo ICCT CO_2 data to derive an equivalent CO_2 estimate for a P2 hybridized advanced diesel vehicle. This exercise is performed individually for each vehicle class.

It is important to note that while CO_2 and cost estimates were developed for P2 hybridized advanced diesel engines, the resulting cost curve data points were substantially less cost effective than the road load technology packages applied to the non-hybridized advanced diesel vehicles. As a result, none of the P2 hybridized advanced diesel technology packages were included in the regression analysis used to construct the presented cost curves (as described in Section 5 below). Thus, while the development of the hybridized advanced diesel technology packages was informative, the estimates were ultimately of no influence on the derived cost curves.

5. Cost Curve Data Points for 2020, 2025, and 2015

Using the methodology described above, cost curve data points were developed for 2020 and 2025, as explicit cost data are included for both years in the various data sources utilized. As indicated in Section 1 above, the basic cost data represent *current* high volume production costs developed specifically for the EU market. The cost data studies also estimate the year is which high volume production is achievable and apply technology-specific learning factors to adjust current cost estimates to future year costs (in this case 2020 and 2025).[26] While the cited cost references should be consulted for a detailed description of the learning data assumed for each technology, the following learning factors (that specifically apply to petrol direct injection and turbocharging technology)

24 The observed differences range from -4.9 percent (petrol "petrol liter-equivalent" fuel consumption is lower than diesel) to +2.8 percent (diesel "petrol liter-equivalent" fuel consumption is lower than petrol). Specific differences across vehicle classes are: -4.9, -2.2, -0.7, +0.5, + 1.8, and +2.8 percent, such that available data are balanced equally on either side of zero (i.e., no "petrol liter energy equivalent" fuel consumption difference).

25 This study utilized the same detailed energy loss data cited above in footnote 9.

26 The ICCT cost data are an exception, in that only current cost estimates are included. See footnote 8 for an explanation of how future year costs were estimated for these data.

illustrate how such factors influence 2020 and 2025 direct manufacturer cost estimates:

Example 2012 Learning Factor: 1.00

Example 2020 Learning Factor: 0.82

Example 2025 Learning Factor: 0.74

In this example, high volume production is estimated to feasible in 2012, and direct costs to the manufacturer in 2020 and 2025 are estimated to be 82 and 74 percent of current high volume production costs respectively. Although learning is applied to cost estimates, CO_2 data are applied without change to both 2020 and 2025 (i.e., the CO_2 reduction effectiveness of the underlying technologies is assumed to be unchanged over the five year timeframe).

The resulting data points for 2020 and 2025 are plotted and those data points that define the most cost effective CO_2 reductions (i.e., those data points on the "efficient frontier") are subjected to CO_2 independent/cost dependent regression analysis to define a best fit exponential curve. These curves, developed independently for petrol and diesel vehicles, constitute the cost curves for 2020 and 2025. The preceding sections of this paper describe the approach used to generate the fundamental data points that underlie these cost curves. Section 6 below describes one final adjustment that is implemented prior to the finalization of these curves for use in the EU.

For illustrative purposes, it was also desirable to generate equivalent cost curves for 2015. Conceptually, this is a more complex undertaking since there are both cost effects related to learning (and production volume) *and* technology effects related to maturity and marketability. However, since detailed analysis had already been conducted by the U.S. EPA that considered both cost and technology effects, an evaluation of the U.S. data allowed for a simplified approach to isolating the relationship between the 2015 and 2020 technology supply and cost curves.[27] The U.S. data were subjected to CO_2 independent/cost dependent regression analysis to define cost curves for both 2015 and 2020. The ratio between the resulting curves was subsequently regressed (CO_2 independent/ratio dependent) to define the relationship between 2015 and 2020 costs. This relationship was then applied to the 2020 EU cost curves to derive equivalent 2015 cost curves. The specific derived relationship is:

$$\text{2015/2020 cost ratio} = [-0.3 \times (\text{Percent } CO_2 \text{ Reduction})^{0.5}] + 1.61$$

So, a 10 percent CO_2 reduction is estimated to cost 52 percent more in 2015 than in 2020, while a 50 percent CO_2 reduction is estimated to cost 40 percent more in 2015 than 2020.

6. Adjustments to the Cost Curve Data to Better Represent the Baseline EU Fleet

Since the Ricardo ICCT CO_2 data reflect estimates for only a single representative vehicle within each class, there are often differences between the characteristics of the subject vehicle and EU fleet average characteristics for the class. Tables 18 through 22 provide a comparison of such characteristics. To better reflect the characteristics of the EU fleet, the cost curve data points developed according to the methods described in the previous sections are normalized to the current EU class average CO_2 levels, which results in an inherent correction for differences in Ricardo and EU-average vehicle characteristics such as vehicle mass, engine power output, etc. In effect, the CO_2 data are treated in percent reduction terms, with a zero percent reduction corresponding to the current class average CO_2 value. Each CO_2 data point in the Ricardo ICCT CO_2 dataset is expressed in terms of percent reduction relative to the Ricardo ICCT CO_2 baseline and this percent reduction is then applied to the current EU class average CO_2 value to determine the corresponding EU class average CO_2 reduction data point. Cost estimates are carried through this normalization process without change.

27 The U.S. data are summarized in a November 10, 2011 U.S. EPA memorandum from Todd Sherwood to Air Docket EPA-HQ-OAR-2010-0799 with the subject line "OMEGA Master-sets and Ranked-sets of Packages." The "target" docket is the depository for materials related to the U.S. 2017-2025 light duty vehicle CO_2 rulemaking, and the cost and impact data are directly related to the EPA/NHTSA Technical Report cited above as a cost estimate reference for the EU cost curve work. The docket and the referenced memorandum (which has a "posted date" of December 1, 2011) can be accessed at www.regulations.gov/#!docketDetail;D=EPA-HQ-OAR-2010-0799.

It should be noted that the EPA data are for model years 2016, 2021, and 2025. The 2016 and 2021 data are utilized for the EU analysis to develop a five year cost curve impact, which is then applied to the 2020 EU cost curve to derive a 2015 equivalent. Although both intervals reflect a five year period, there is a one year shift in the explicit applicability of the relationship. The shift is viewed as insignificant since the curve data are used only in a relative sense for an identical five year interval and since, while 2016 costs can be expected to be modestly lower than 2015 costs, so too can 2021 costs as compared to 2020 – so that the relative five year relationship should generally be immune from significant change in the absence of an expected "step change" effect between either 2015 and 2016 or 2020 and 2021 (and no such "step change" is evident in either the U.S. or EU data).

Table 18. B Class Vehicle Characteristics (1)

Parameter	Petrol		Diesel	
	Ricardo	EU-27 (in 2010)	Ricardo	EU-27 (in 2010)
VEHICLE MAKE/MODEL	TOYOTA YARIS	N/A	TOYOTA YARIS	N/A
Engine Size	1.5 liter I4	1.3 liter I4	1.2 liter I4	1.5 liter I4
Engine Power (kW)	82	63	59	61
Engine Type	PFI	PFI (2)	n/a	n/a
Test Weight (kg, 3)	1,191	1,090	1,191	1,160
Transmission Type	A6	MT (4)	A6	MT (4)
0-100 km/hr (seconds)	9.9	13.2	12.2	13.3
NEDC CO_2 (g/km)	128	136	108	113
Other Considerations	Includes Idle-Off, Euro 5 Emissions	No Idle-Off, Euro 4 Emissions (5)	Includes Idle-Off, Euro 5 Emissions	No Idle-Off, Euro 4 Emissions (5)

Notes: (1) B class market share is approximately 29 percent, 38 percent of which is diesel powered.
(2) Direct injection market share is approximately 2 percent.
(3) Vehicle weight in running order (weight of empty vehicle plus 75 kg).
(4) Manual transmission market share is approximately 94 percent (86 percent M5, 8 percent M6).
(5) Euro 4 market share is approximately 60 percent.

Table 19. C Class Vehicle Characteristics (1)

Parameter	Petrol		Diesel	
	Ricardo	EU-27 (in 2010)	Ricardo	EU-27 (in 2010)
VEHICLE MAKE/MODEL	FORD FOCUS	N/A	FORD FOCUS	N/A
Engine Size	1.6 liter I4	1.6 liter I4	1.6 liter I4	1.7 liter I4
Engine Power (kW)	88	86	97	83
Engine Type	PFI	PFI (2)	n/a	n/a
Test Weight (kg, 3)	1,318	1,270	1,318	1,360
Transmission Type	M6	MT (4)	M6	MT (4)
0-100 km/hr (seconds)	9.1	11.3		11.6
NEDC CO_2 (g/km)	139	156	122	131
Other Considerations	Includes Idle-Off, Euro 5 Emissions	No Idle-Off, Euro 4 Emissions (5)	Includes Idle-Off, Euro 5 Emissions	No Idle-Off, Euro 4 Emissions (5)

Notes: (1) C class market share is approximately 32 percent, 38 percent of which is diesel powered.
(2) Direct injection market share is approximately 19 percent.
(3) Vehicle weight in running order (weight of empty vehicle plus 75 kg).
(4) Manual transmission market share is approximately 91 percent (49 percent M5, 42 percent M6).
(5) Euro 4 market share is approximately 60 percent.

Table 20. D Class Vehicle Characteristics (1)

Parameter	Petrol		Diesel	
	Ricardo	EU-27 (in 2010)	Ricardo	EU-27 (in 2010)
VEHICLE MAKE/MODEL	CAMRY/AVENSIS	N/A	CAMRY/AVENSIS	N/A
Engine Size	2.4 liter I4	2.0 liter I4	2.0 liter I4	2.0 liter I4
Engine Power (kW)	118	127	122	109
Engine Type	PFI	PFI (2)	n/a	n/a
Test Weight (kg, 3)	1,644	1,440	1,644	1,500
Transmission Type	A6	MT (4)	A6	MT (4)
0-100 km/hr (seconds)	8.3	9.3	7.6	9.9
NEDC CO_2 (g/km)	166	177	133	148
Other Considerations	Includes Idle-Off, Euro 5 Emissions	No Idle-Off, Euro 4 Emissions (5)	Includes Idle-Off, Euro 5 Emissions	No Idle-Off, Euro 4 Emissions (5)

Notes: (1) D class market share is approximately 11 percent, 80 percent of which is diesel powered.
(2) Direct injection market share is approximately 37 percent.
(3) Vehicle weight in running order (weight of empty vehicle plus 75 kg).
(4) Manual transmission market share is approximately 81 percent (13 percent M5, 68 percent M6).
(5) Euro 4 market share is approximately 95 percent.

Table 21. Small N1 Class Vehicle Characteristics (1)

Parameter	Petrol		Diesel	
	Ricardo	EU-27 (in 2010)	Ricardo	EU-27 (in 2010)
VEHICLE MAKE/MODEL	TRANSIT CONNECT	N/A	TRANSIT CONNECT	N/A
Engine Size	2.0 liter I4	1.4 liter I4	1.8 liter I4	1.5 liter I4
Engine Power (kW)	101	59	66	62
Engine Type	PFI	PFI	n/a	n/a
Test Weight (kg, 2)	1,644	1,210	1,644	1,380
Transmission Type	A6	MT	A6	MT
0-100 km/hr (seconds)	10.2	---	13.7	---
NEDC CO_2 (g/km)	182	161	146	143
Other Considerations	Includes Idle-Off, Euro 5 Emissions	No Idle-Off, Euro 4 Emissions (3)	Includes Idle-Off, Euro 5 Emissions	No Idle-Off, Euro 4 Emissions (3)

Notes: (1) The small N1 class is assumed to consist of N1-I and N1-II category vehicles, 94 percent of which are diesel powered.
(2) Vehicle weight in running order (weight of empty vehicle plus 75 kg).
(3) Euro 4 market share is greater than 90 percent.

Table 22. Large N1 Class Vehicle Characteristics (1)

Parameter	Petrol		Diesel	
	Ricardo	EU-27 (in 2010)	Ricardo	EU-27 (in 2010)
VEHICLE MAKE/MODEL	**FORD TRANSIT**	**N/A**	**FORD TRANSIT**	**N/A**
Engine Size	3.8 liter V6	n/a	2.2 liter I4	2.2 liter I4
Engine Power (kW)	154	n/a	103	93
Engine Type	PFI	n/a	n/a	n/a
Test Weight (kg, 2)	2,041	n/a	2,041	2,030
Transmission Type	A6	n/a	A6	MT
0-100 km/hr (seconds)	8.6	n/a	10.3	---
NEDC CO_2 (g/km)	230	n/a	166	227
Other Considerations	Includes Idle-Off, Euro 5 Emissions	n/a	Includes Idle-Off, Euro 5 Emissions	No Idle-Off, Euro 4 Emissions (3)

Notes: (1) The large N1 class is assumed to consist of N1-III category vehicles, 99 percent of which are diesel powered.
(2) Vehicle weight in running order (weight of empty vehicle plus 75 kg).
(3) Euro 4 market share is greater than 90 percent.

7. Derived Cost Curves

Based on the approach described in the preceding sections, EU-specific cost curves were developed for petrol and diesel vehicles in the B, C, D, small N1, and large N1 vehicle classes. Figures 1 through 10 depict the developed class-specific cost curves for 2015, 2020, and 2025. The reader is referred to the discussion in the preceding sections for a detailed explanation of how these curves were developed, but in summary, a series of cost curve data points were developed on the basis of CO_2 simulation modeling and associated cost estimates. Data for technology packages utilizing automatic transmission technology were excluded as unrealistic for the EU market. Lean burn petrol technology was also excluded due to uncertainty with regard to potential future NO_x control requirements (and, more precisely, the associated uncertainty on technology cost). Finally, only the most cost effective hybrid electric vehicle technology was carried forward through the cost curve development process.[28]

The resulting data points were plotted and those data points that define the most cost effective CO_2 reductions (i.e., those data points that define the lowest cost for a given CO_2 reduction) are subjected to CO_2 independent/cost dependent regression analysis to define a best fit exponential curve. These curves constitute the depicted cost curves in the figures that follow.

Each depicted cost curve is inherently associated with a given year because both the cost and CO_2 reduction potential of a given technology can vary over time. Costs are generally a function of production volume, learning, and evolution of scientific knowledge and these influences vary over time. Time also plays a role in determining when a particular technology is market ready. For example, the cost curve for 2015 may exclude some technologies that underlie the cost curve for 2020 due to the fact that the 2020 technology is not considered to be market ready in 2015.

Figures 1 through 10 include cost curves for 2015, 2020, and 2025 – but the depicted data points apply specifically to 2020. Data points for the other years are purposefully omitted to enhance readability (but the depicted curves are, of course, based on the specific data points – depicted or otherwise – corresponding to the designated year).

Figures 11 through 14 summarize the class-specific cost curves for 2020 and 2025, as well as depict fleet-weighted average cost curves for those same years. The fleet-weighted average curves are based on current fuel-specific (i.e., petrol and diesel) and class-specific (i.e., B class, C class, etc.) market shares, so that the derived fleet average curves are not optimized to reflect the potential cost reduction impacts of either class or fuel shifting approaches to compliance. A subsequent paper in this series will evaluate the potential effects of shifts in market shares.

28 Neither plug-in hybrid (PHEV) nor electric-only (EV) technology is considered in this analysis, as neither technology is required to achieve the level of evaluated CO_2 reduction. That is not to say that vehicle manufacturers will not introduce such technology over the evaluated time period, simply that such introduction is not required to meet the CO_2 levels expected in that period. Manufacturers will almost certainly continue to introduce and refine both PHEV and EV technologies over the near term to spur continued technology development and garner valuable marketing experience should such technology ultimately be required for compliance with future, as yet unforeseen, emission standards. Moreover, both the U.S. and the EU offer regulatory incentives (in the form of CO_2 reduction credits that exceed to actual CO_2 performance) that will reward manufacturers for the introduction of PHEV and EV technology.

Figures 11 and 12 respectively depict the 2020 and 2025 cost curves for passenger vehicles. These curves are constructed relative to a 130 g/km CO_2 baseline, representative of the 2015 EU CO_2 target for passenger vehicles. Figures 13 and 14 depict corresponding cost curves for N1 vehicles, based on a 175 g/km CO_2 baseline representative of the 2017 EU CO_2 target for light commercial vehicles.

Figures 15 through 18 present the fleet average cost curves in isolation. Figure 15 depicts the 2020 and 2025 passenger vehicle curves relative to a 2010 CO_2 baseline, while Figure 16 depicts the corresponding curves relative to the 2015 EU CO_2 target for passenger vehicles. Figure 17 depicts the 2020 and 2025 N1 fleet average cost curves relative to a 2010 CO_2 baseline, while Figure 18 depicts the corresponding curves relative to the 2017 EU CO_2 target for light commercial vehicles.

Finally, Figures 19 through 24 show the relationship between the generated cost curves and some of the current vehicles being marketed in the EU. In reviewing these figures, it should be recognized that due to the difficulty of isolating the price impacts of CO_2 changes from other vehicle pricing influences, as well as isolating the manufacturer-specific component of any such price changes, only the CO_2 differentials of current EU market vehicles are presented.

As shown in Figure 19, the 2012 Ford Focus EcoBoost emits approximately 31 percent less CO_2 emissions than its 2010 predecessor. The key technology changes contributing to this reduction include gasoline direct injection in combination with turbocharging and downsizing. Engine displacement is reduced from 1.6 to 1.0 liters, allowing for a drop in cylinder count (from 4 cylinders to 3), while peak engine power is unchanged. The 2012 model also uses start-stop technology. As depicted, the observed transition from the 2010 Ford Focus to the 2012 EcoBoost model corresponds closely with the downsized gasoline direct injection technology package on the C class petrol cost curve given that the cost curve package reduces engine displacement more aggressively (to 0.8 liters) and also makes use of a more efficient transmission (8DCT), which increase CO_2 reductions to about 40 percent.

Figure 20 shows the CO_2 reductions observed for the Audi A3 between 2010 and 2012. Similar to the Ford Focus, both start-stop and gasoline direct injection with turbocharging and downsizing technology has been implemented. The degree of A3 downsizing is reduced as compared to the Focus – with the A3 displacement declining from 1.6 to 1.2 liters, while the Focus declined from 1.6 to 1.0 liters. However, the 2012 Audi A3 makes use of a 7-speed DCT and thereby achieves a CO_2 reduction (29 percent) similar to that of the Focus (31 percent).

Figure 21 depicts the CO_2 emissions for the 2012 Toyota Prius hybrid technology vehicle relative to the C class petrol cost curve. As indicated, the vehicle reaches 89 g/km CO_2 (on the NEDC) despite its significant weight. However, since there is no non-hybrid version of the Prius to serve as a baseline, the depicted CO_2 reduction is calculated from the fleet average C class baseline. According to the Ricardo vehicle simulations, Prius-type technology would be expected to generate CO_2 reductions on the order of 50 percent relative to a 2010 baseline vehicle. This is supported by available B class data, where the 2012 Toyota Yaris hybrid emits 79 g/km CO_2, a 52 percent reduction relative to the 2010 non-hybrid Yaris.

On the diesel side, making use of start-stop technology as in the 2012 Audi A3 allows for a 14 percent reduction compared to the 2010 A3 without start-stop (as depicted in Figure 22). This corresponds very well with the corresponding technology package on the diesel C class cost curve. Reducing road load to a limited extent, as with the 2012 Ford Fiesta Econetic, allows for additional CO_2 reduction (on the order of 19 percent), as depicted in Figure 23.

The Peugeot 3008 is one of the few diesel hybrid examples available on the market today. Compared to the 2010 non-hybrid 3008, hybridization leads to a 43 percent reduction in CO_2, despite the greater weight of the hybrid vehicle (as depicted in 24). This reduction corresponds closely to the base diesel hybrid technology package used in the development of the C class diesel cost curve.

These comparisons serve to illustrate two important points. First, there are some vehicles marketed today that already meet the standards envisioned for 2020. Second, the emission reductions observed for various technologies match those estimated for, and used in, the development of the presented cost curves quite closely. This serves as important real world validation of the cost curve development process.

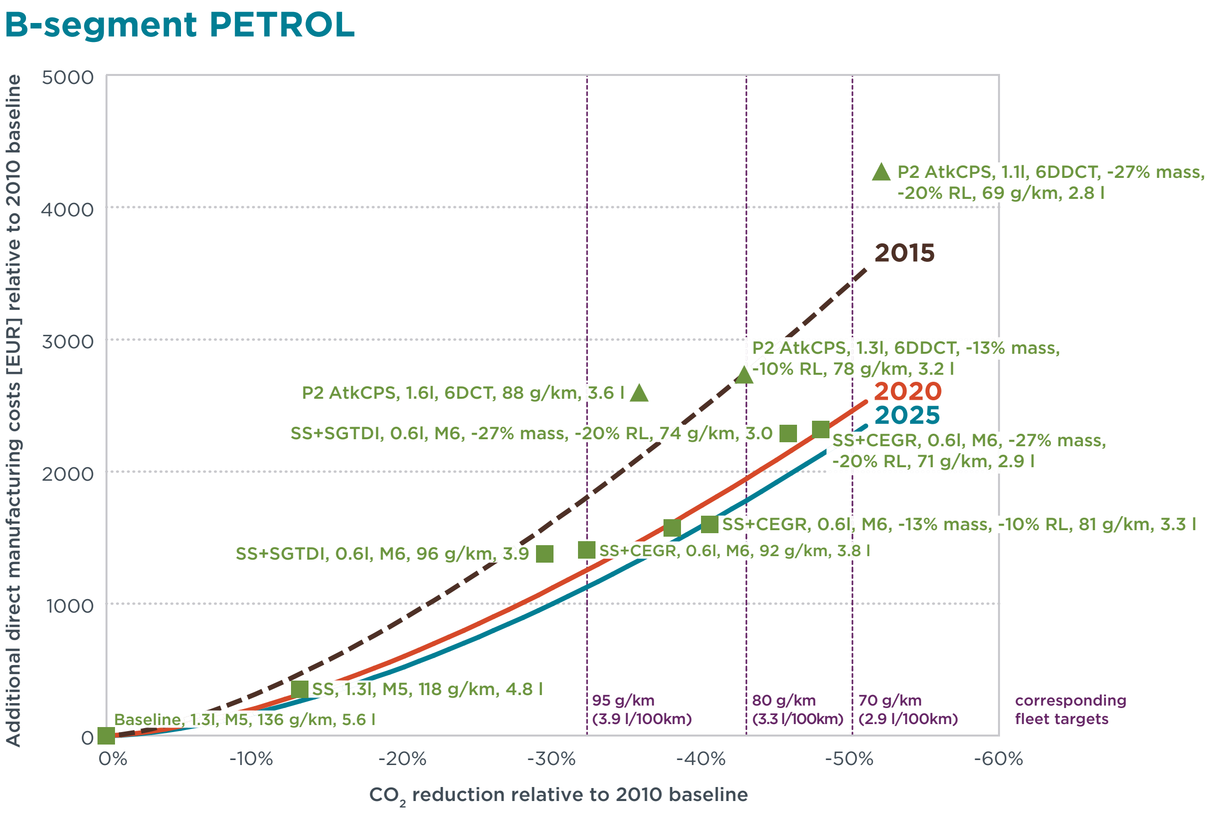


Figure 1. B Class Cost Curve for Petrol Vehicles

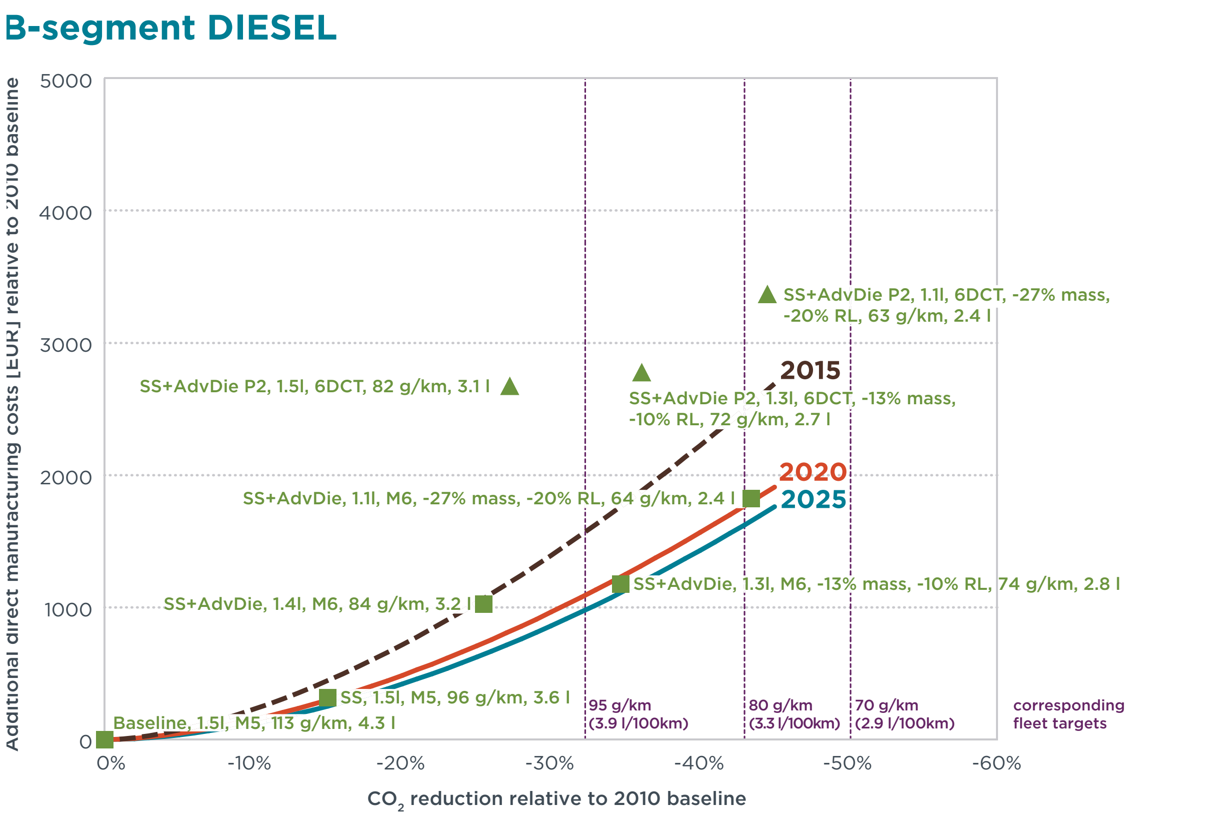


Figure 2. B Class Cost Curve for Diesel Vehicles

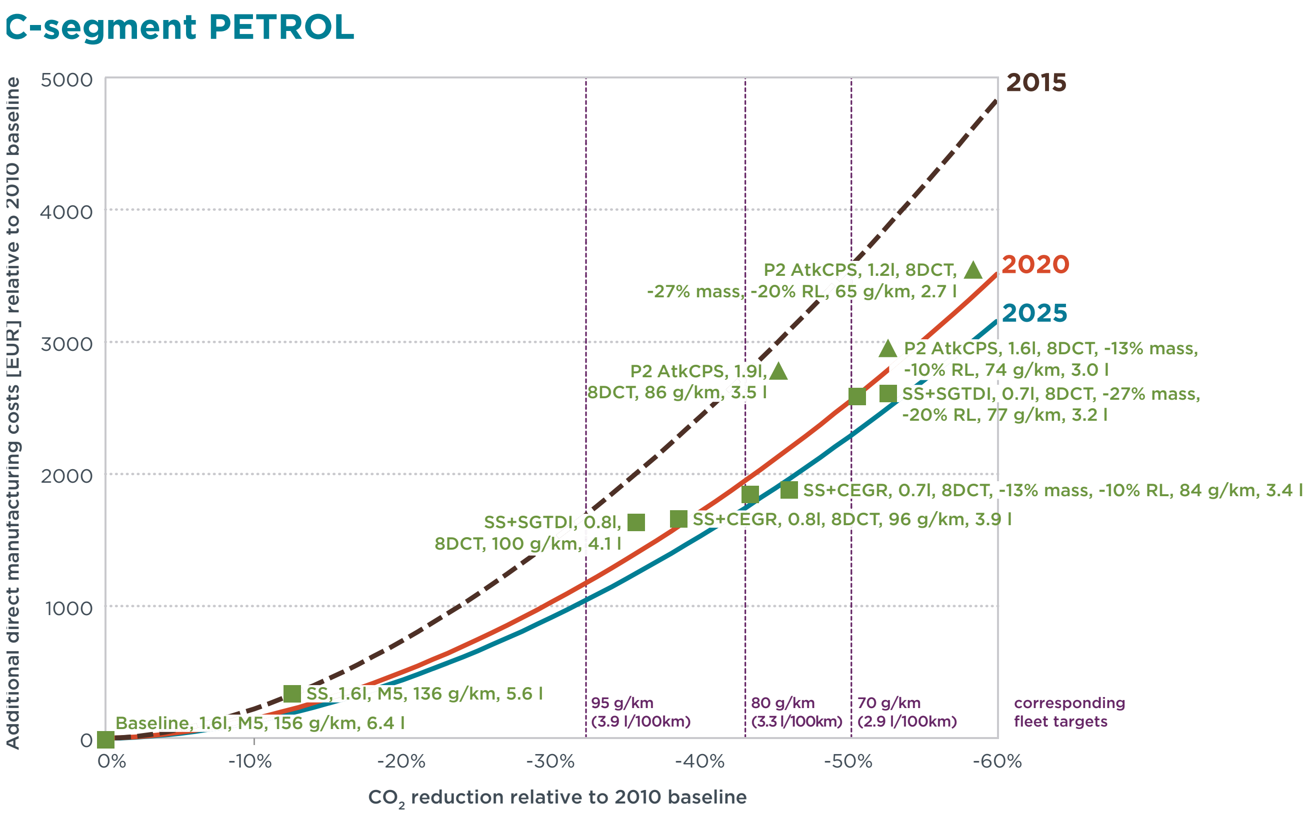


Figure 3. C Class Cost Curve for Petrol Vehicles

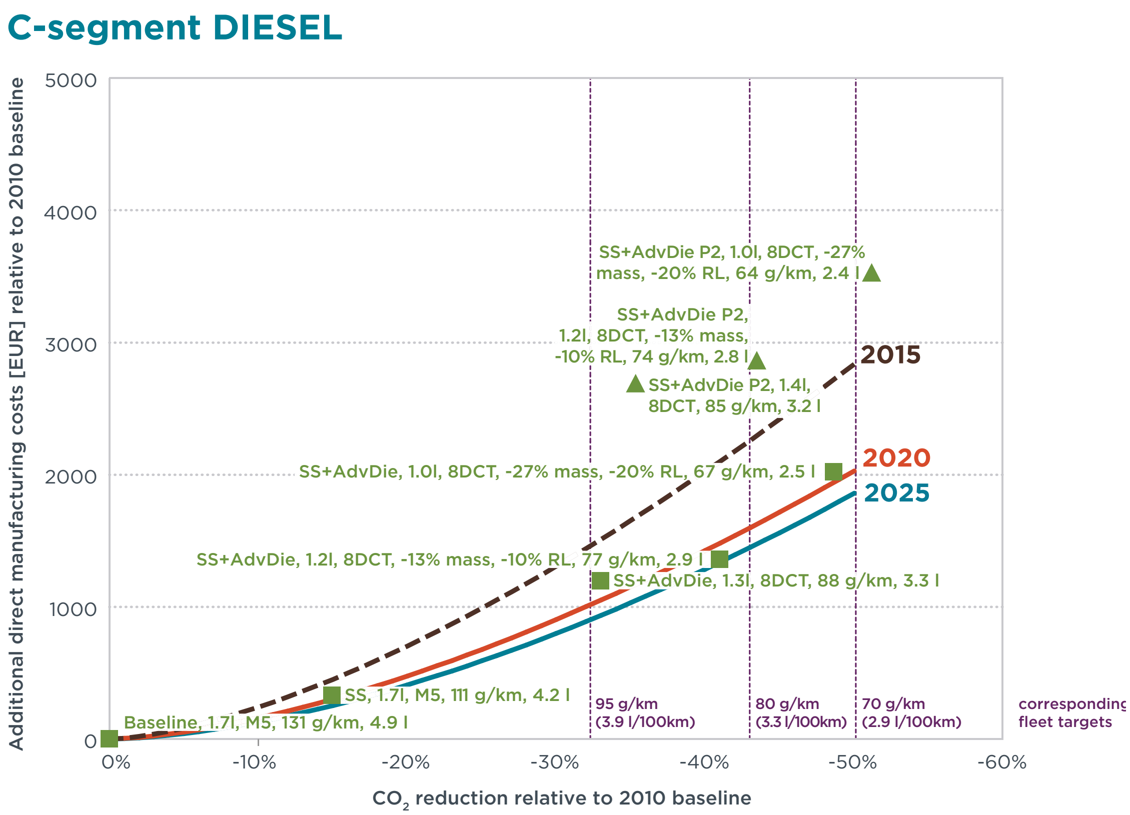


Figure 4. C Class Cost Curve for Diesel Vehicles

D-segment PETROL

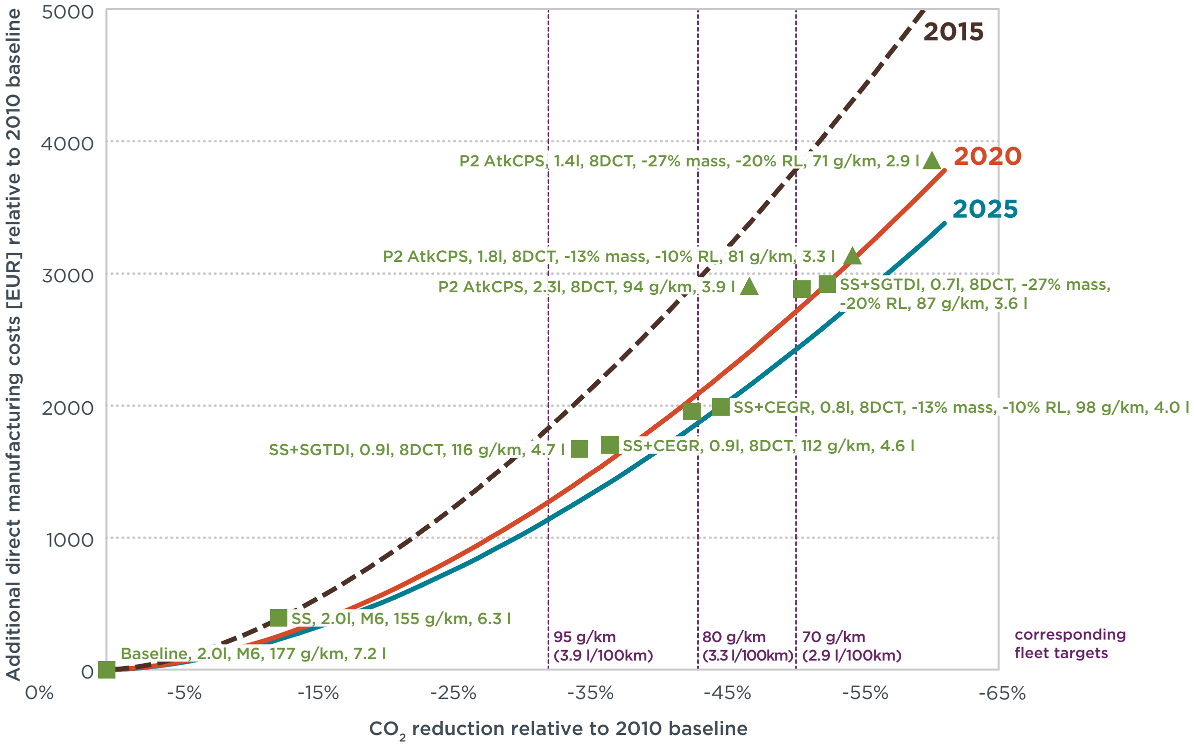


Figure 5. D Class Cost Curve for Petrol Vehicles

D-segment DIESEL

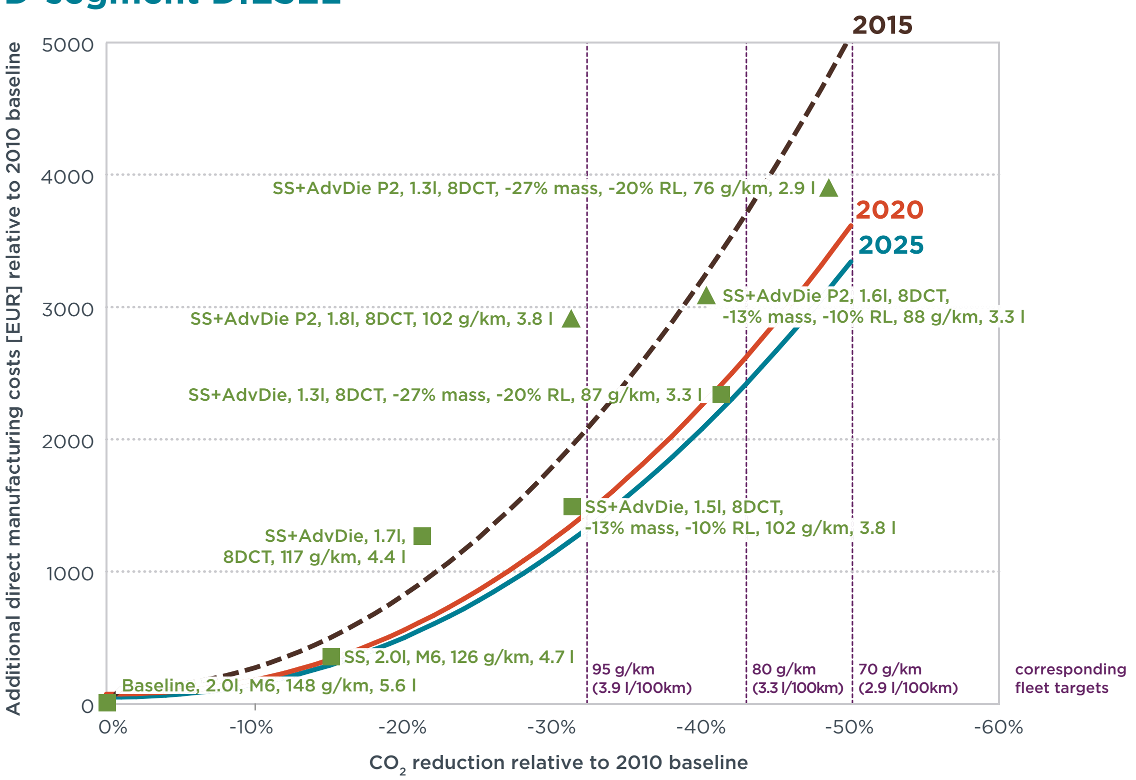


Figure 6. D Class Cost Curve for Diesel Vehicles

Small N1-segment Petrol

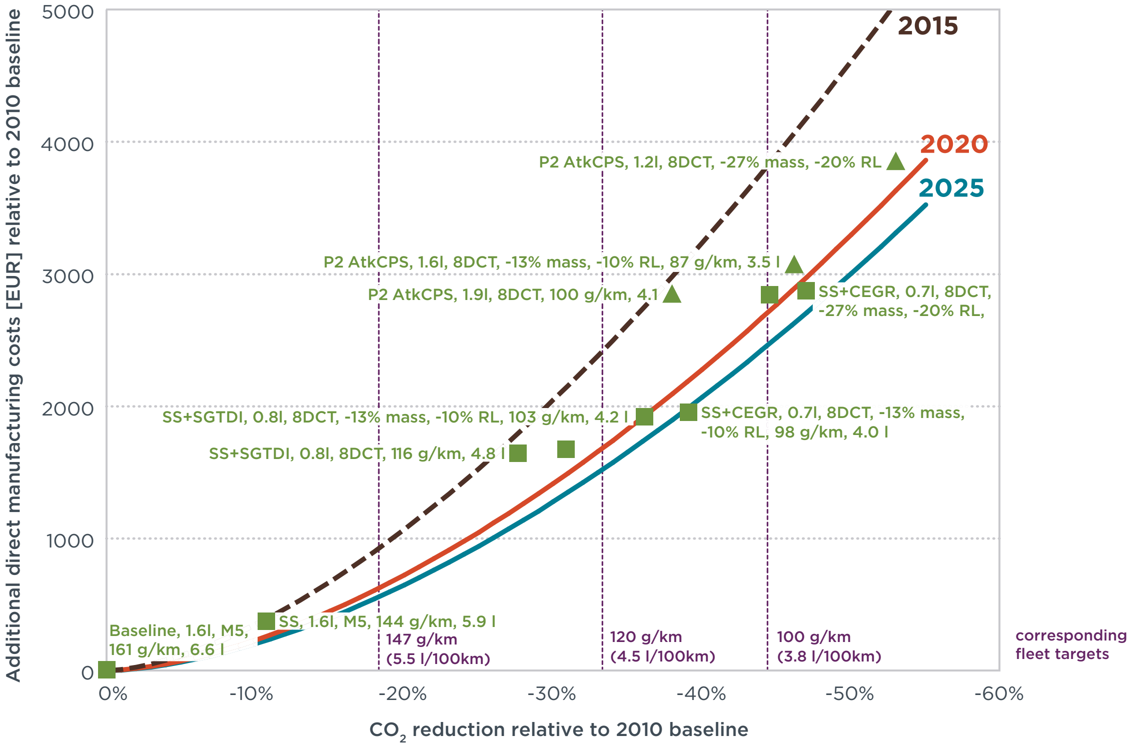


Figure 7. Small N1 Class Cost Curve for Petrol Vehicles

Small N1-segment DIESEL

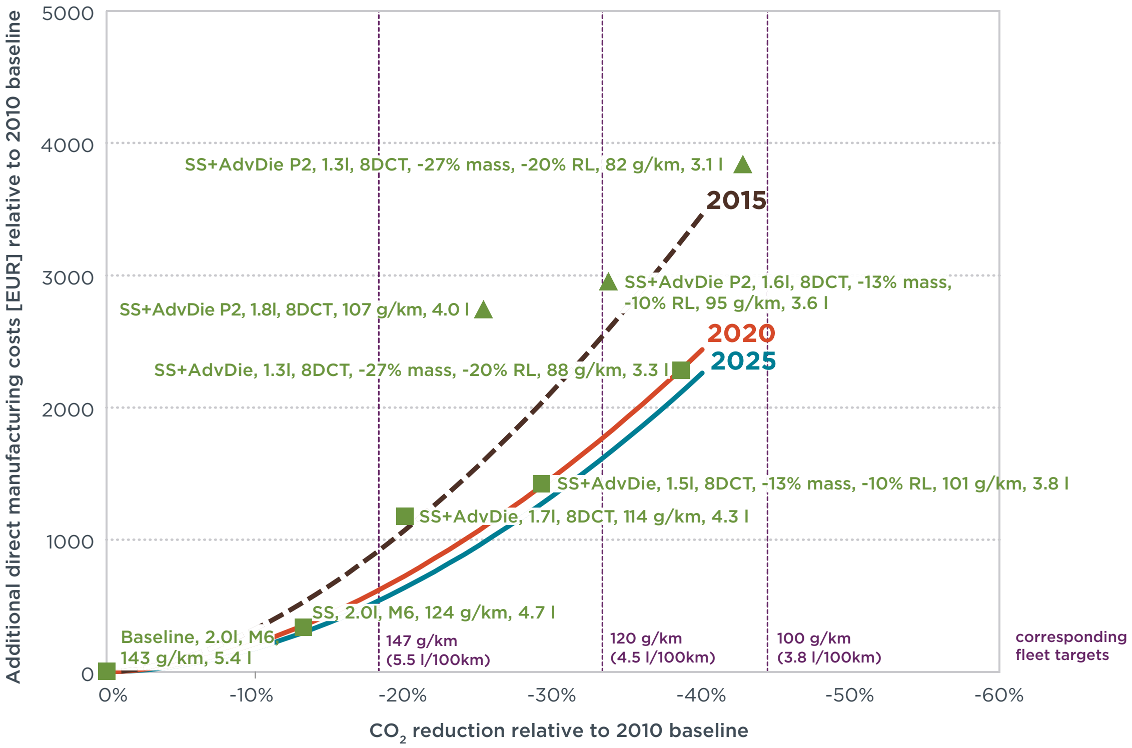


Figure 8. Small N1 Class Cost Curve for Diesel Vehicles

Large N1-segment PETROL

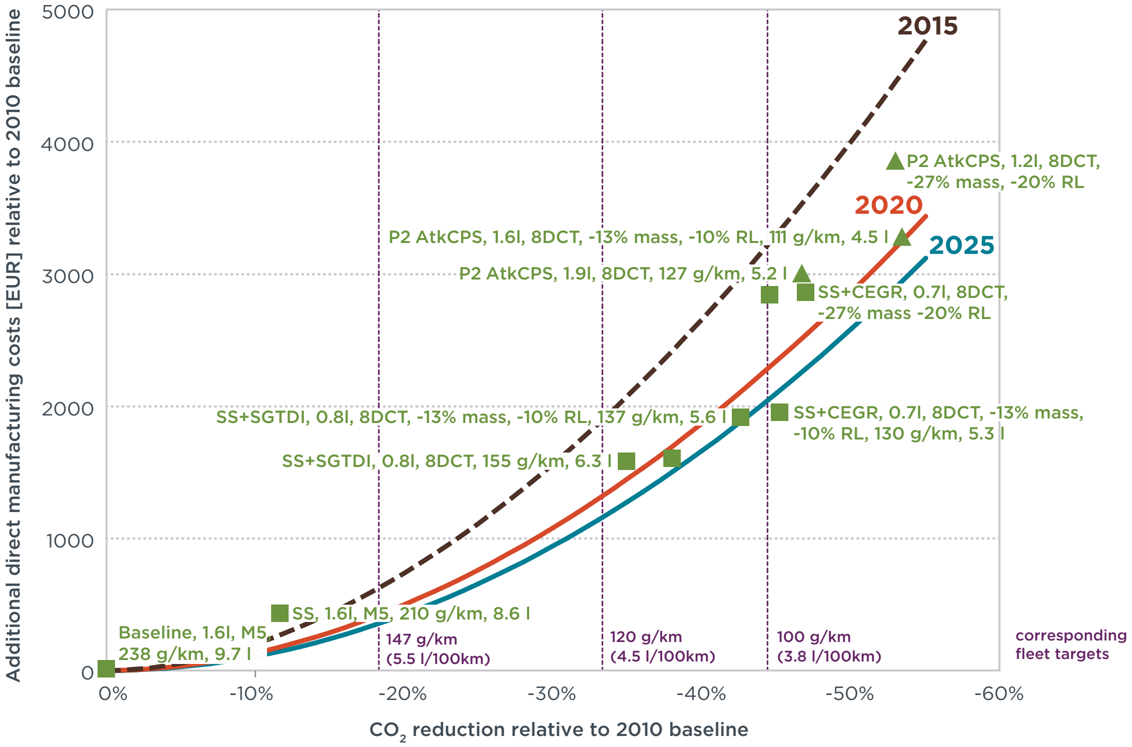


Figure 9. Large N1 Class Cost Curve for Petrol Vehicles

Large N1-segment DIESEL

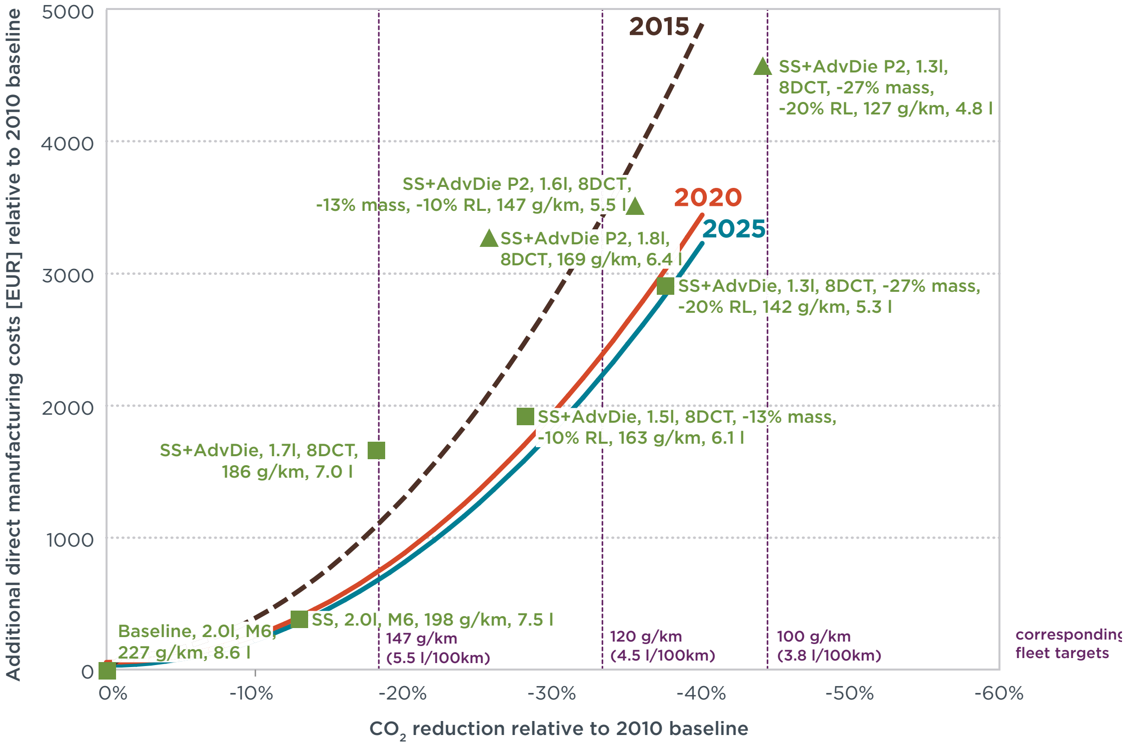


Figure 10. Large N1 Class Cost Curve for Diesel Vehicles

All passenger vehicle segments

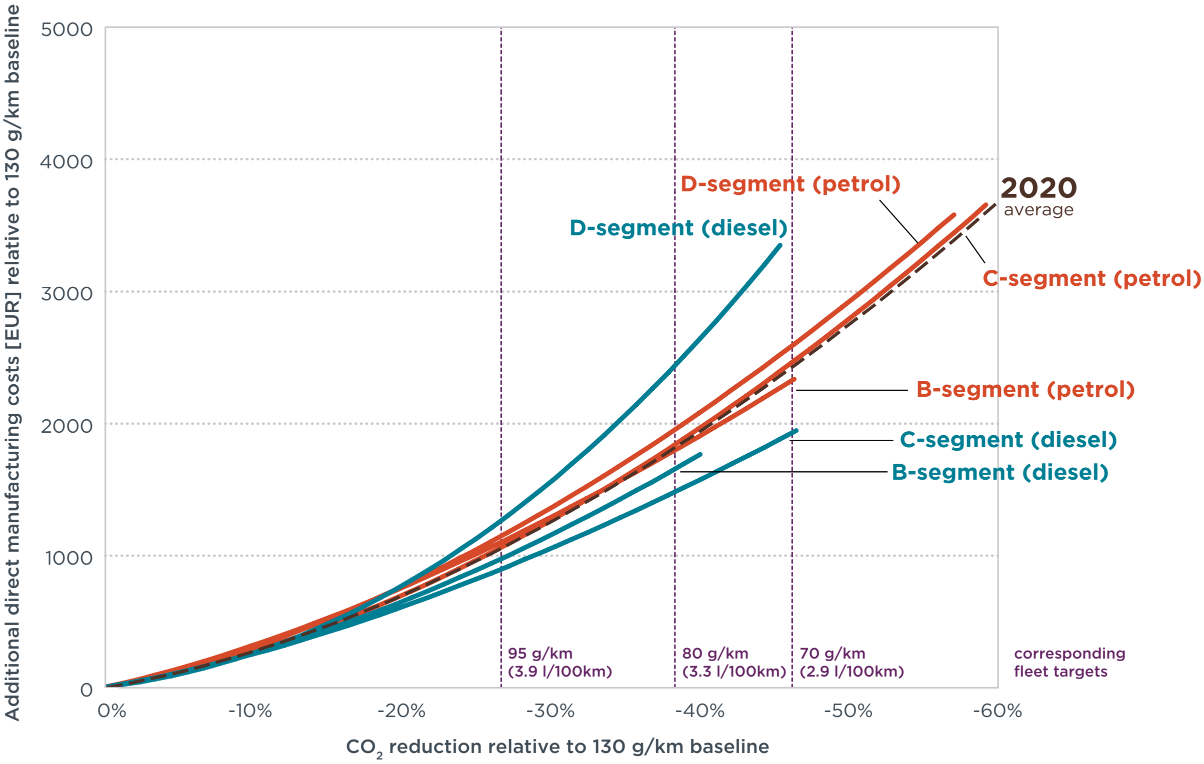


Figure 11. 2020 Passenger Vehicle Cost Curves Relative to 2015 EU Target

All passenger vehicle segments

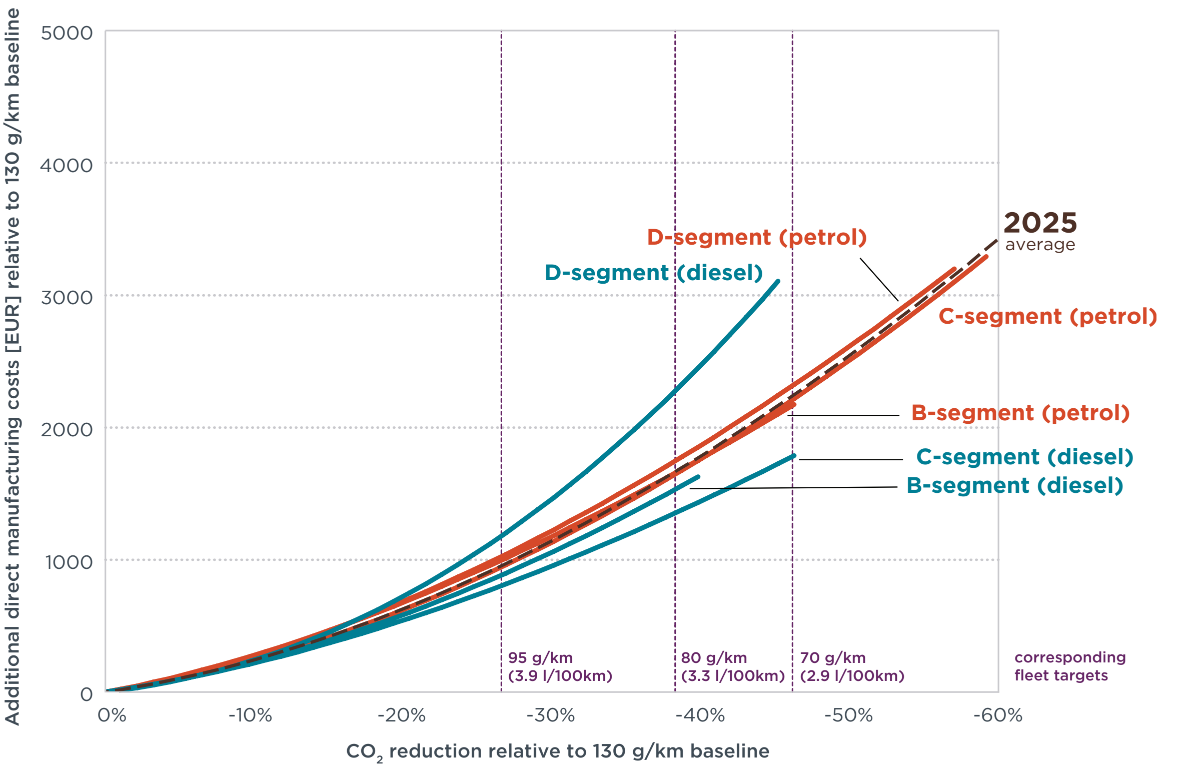


Figure 12. 2025 Passenger Vehicle Cost Curves Relative to 2015 EU Target

All light-commercial vehicles

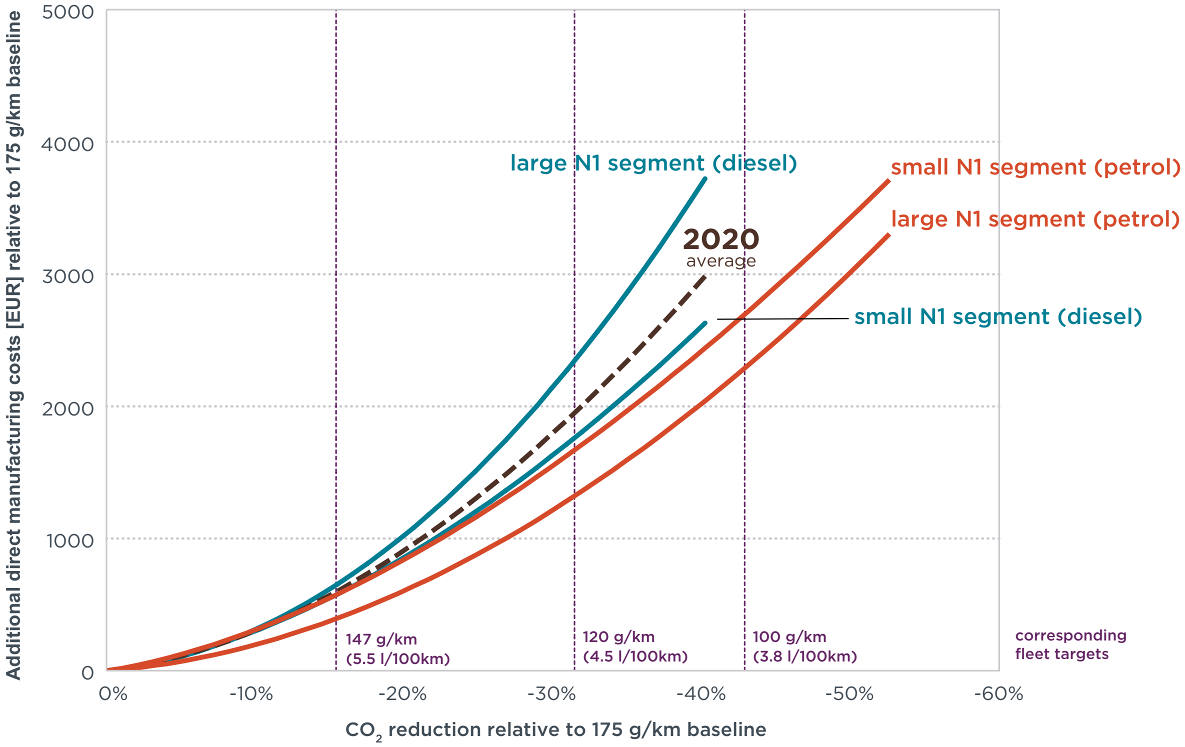


Figure 13. 2020 N1 Class Cost Curves Relative to 2017 EU Target

All light-commercial vehicles

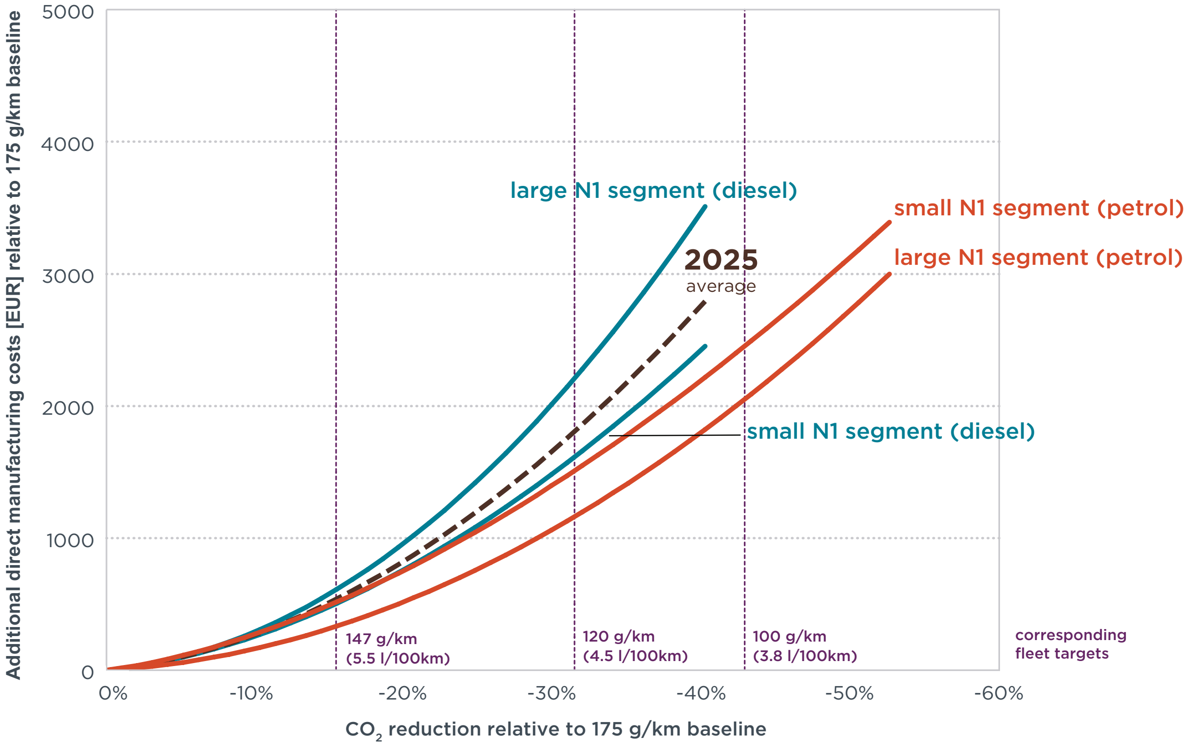


Figure 14. 2025 N1 Class Cost Curves Relative to 2017 EU Target

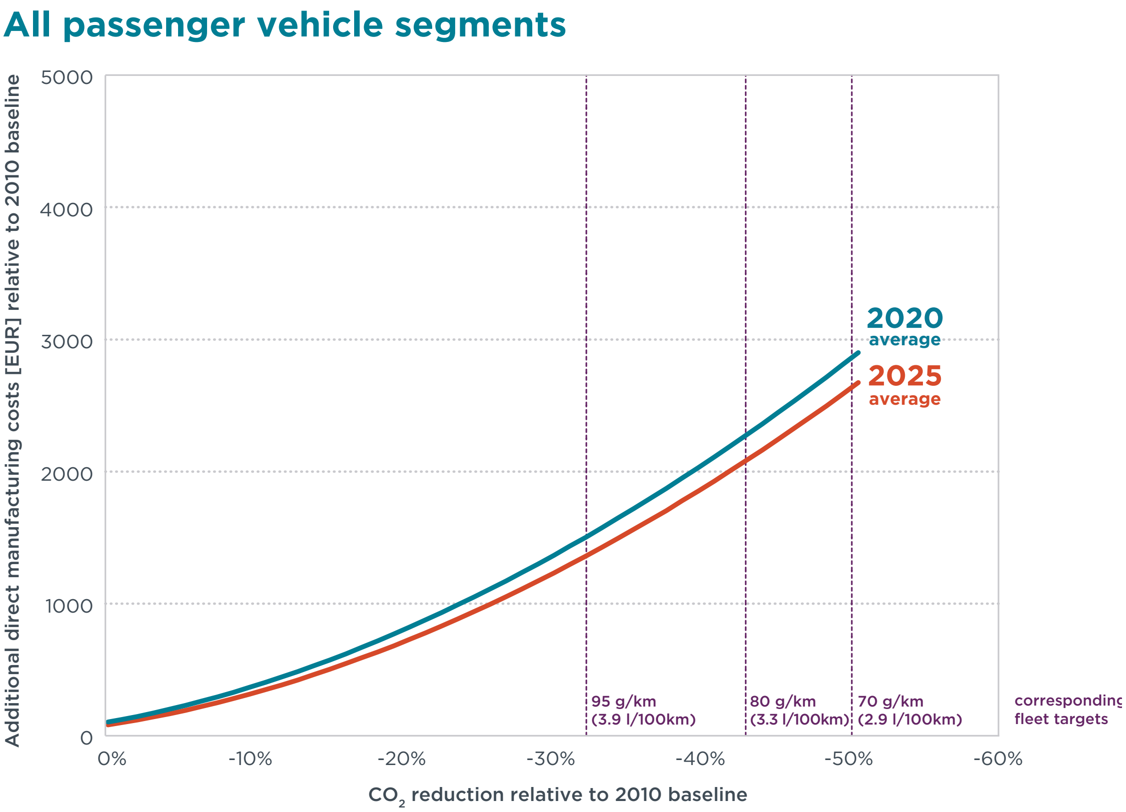


Figure 15. Passenger Vehicle Cost Curves Relative to 2010 EU Baseline

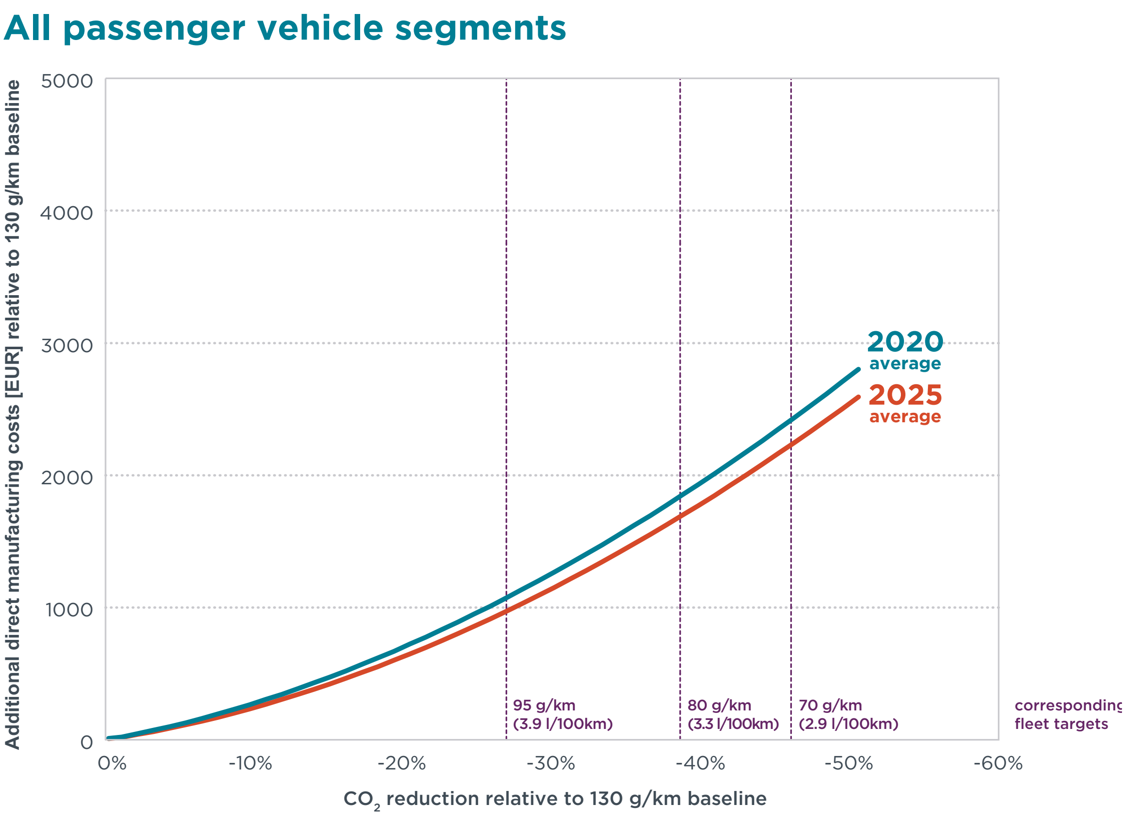


Figure 16. Passenger Vehicle Cost Curves Relative to 2015 EU Target

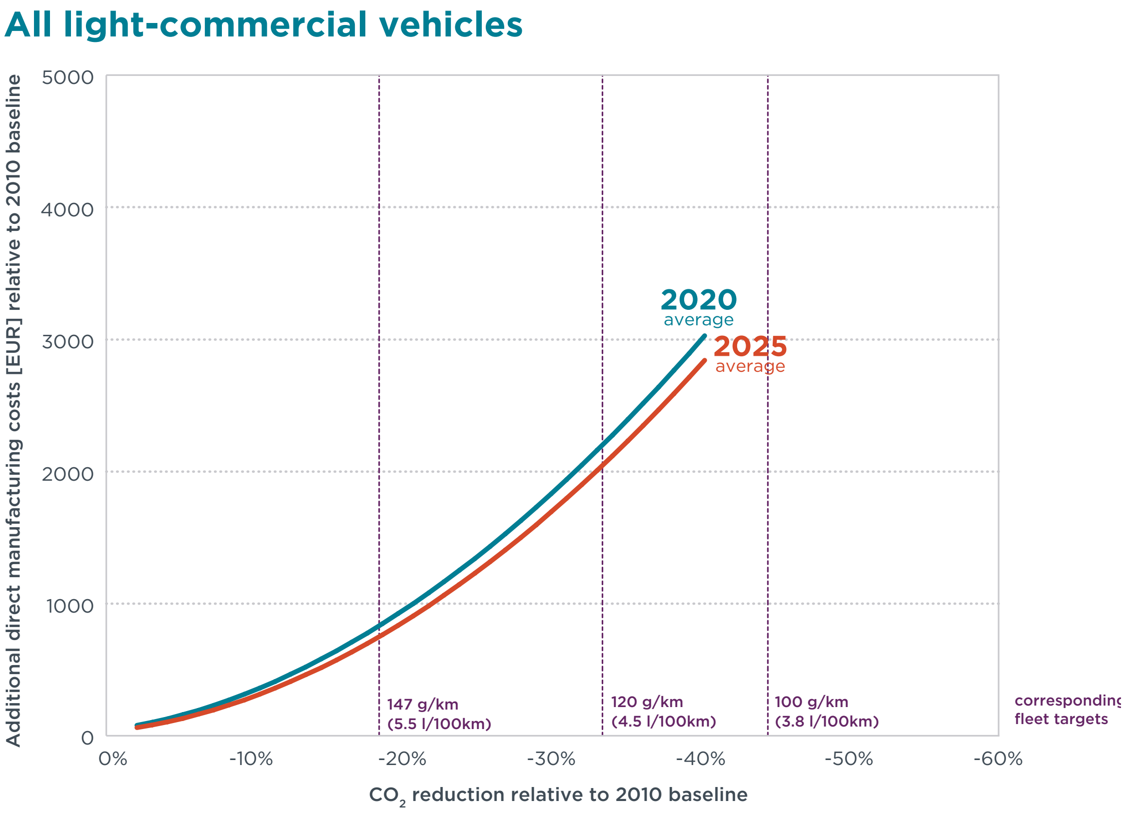


Figure 17. N1 Class Cost Curves Relative to 2010 EU Baseline

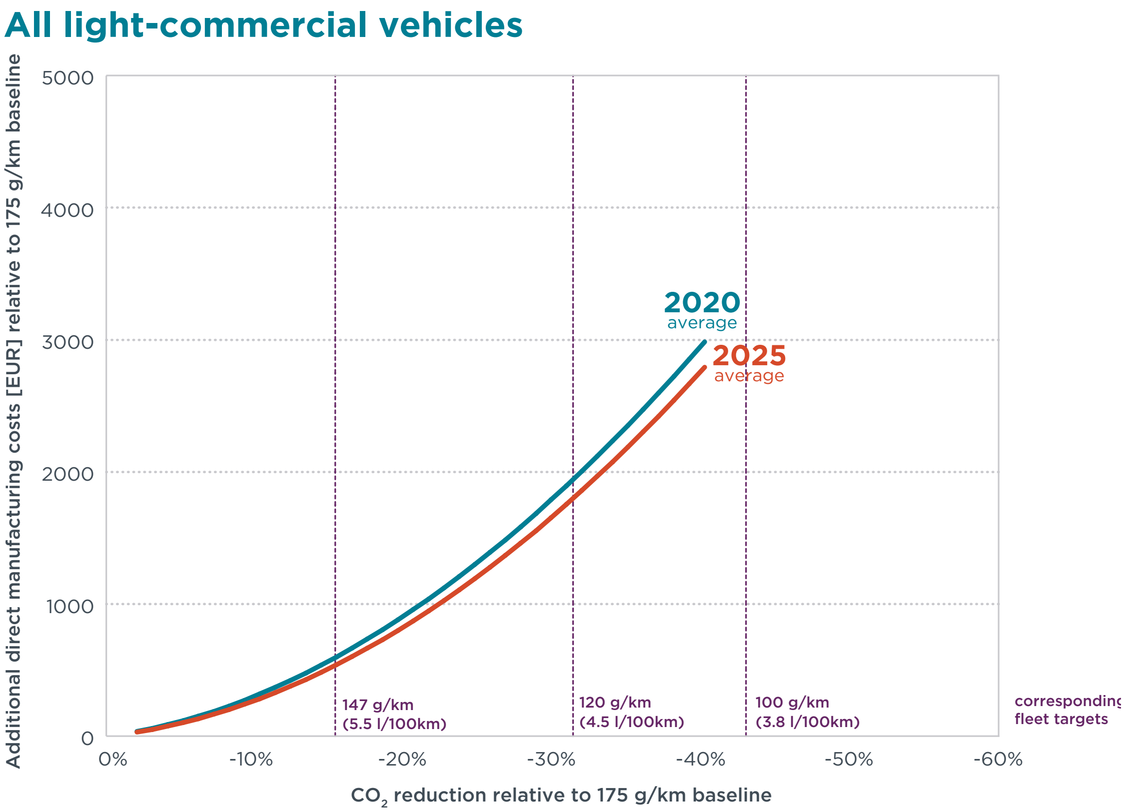
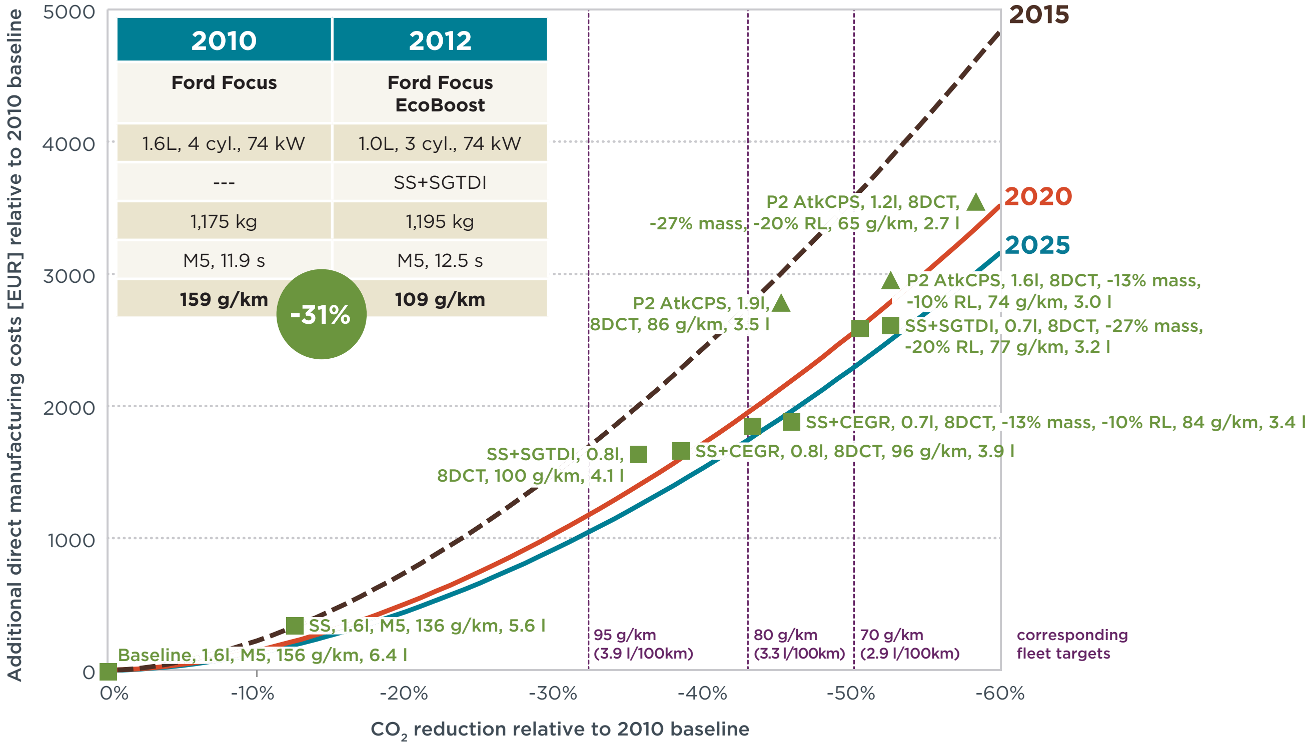


Figure 18. N1 Class Cost Curves Relative to 2017 EU Target

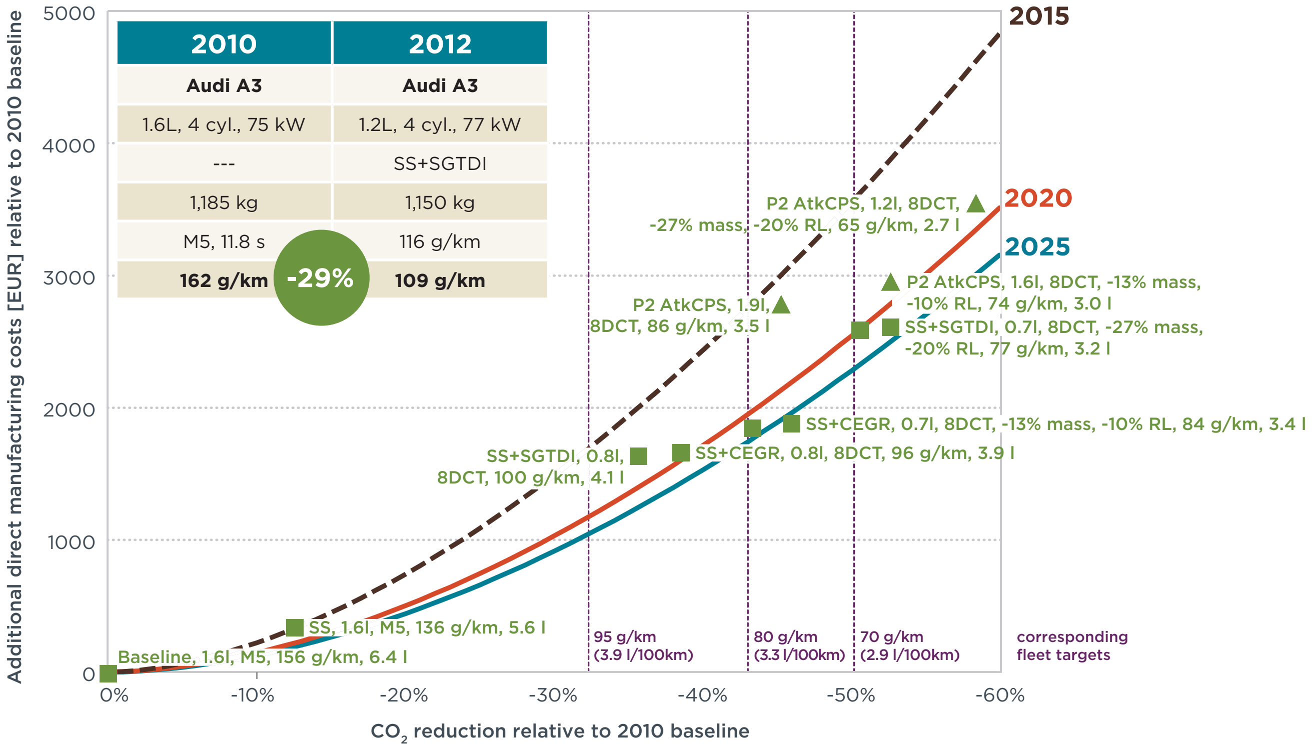
C-segment PETROL



2010	2012
Ford Focus	Ford Focus EcoBoost
1.6L, 4 cyl., 74 kW	1.0L, 3 cyl., 74 kW
---	SS+SGTDI
1,175 kg	1,195 kg
M5, 11.9 s	M5, 12.5 s
159 g/km	**109 g/km**

Figure 19. 2012 Ford Focus Compared to C Class Petrol Cost Curve

C-segment PETROL



2010	2012
Audi A3	Audi A3
1.6L, 4 cyl., 75 kW	1.2L, 4 cyl., 77 kW
---	SS+SGTDI
1,185 kg	1,150 kg
M5, 11.8 s	116 g/km
162 g/km	**109 g/km**

Figure 20. 2012 Audi A3 Compared to C Class Petrol Cost Curve

C-segment PETROL

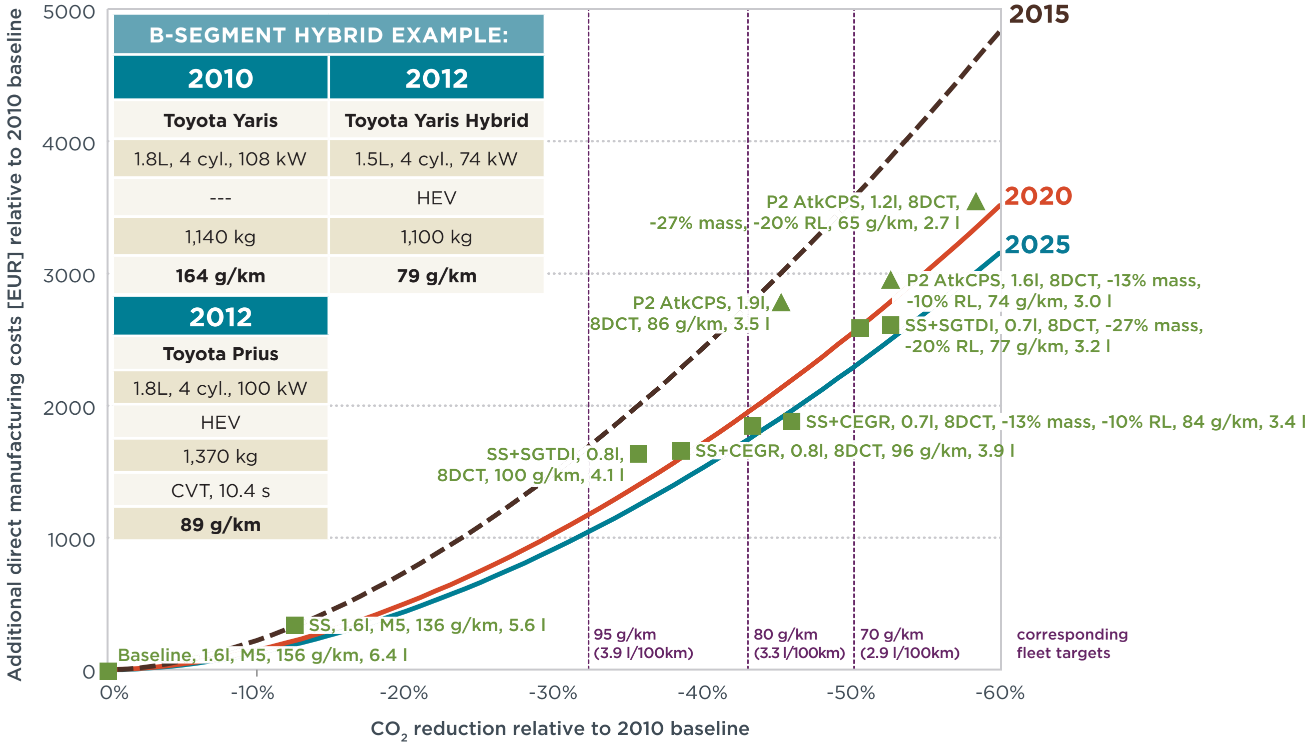


Figure 21. 2012 Toyota Prius Compared to C Class Petrol Cost Curve

C-segment DIESEL

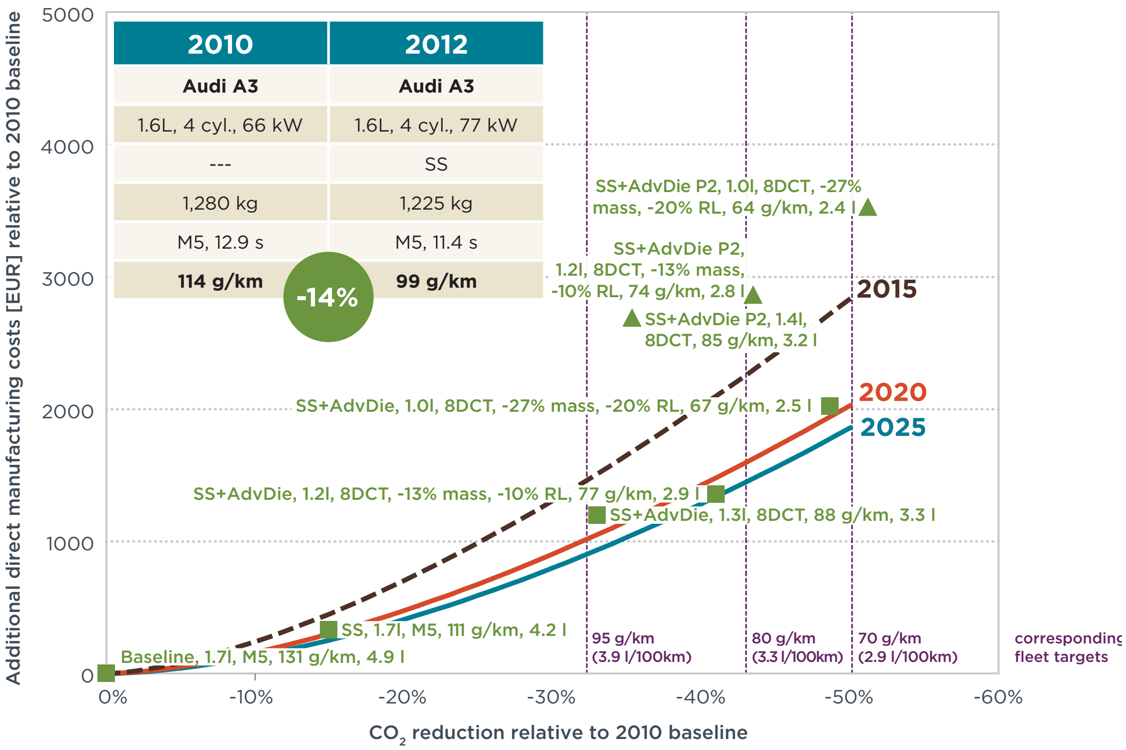


Figure 22. 2012 Audi A3 Compared to C Class Diesel Cost Curve

C-segment DIESEL

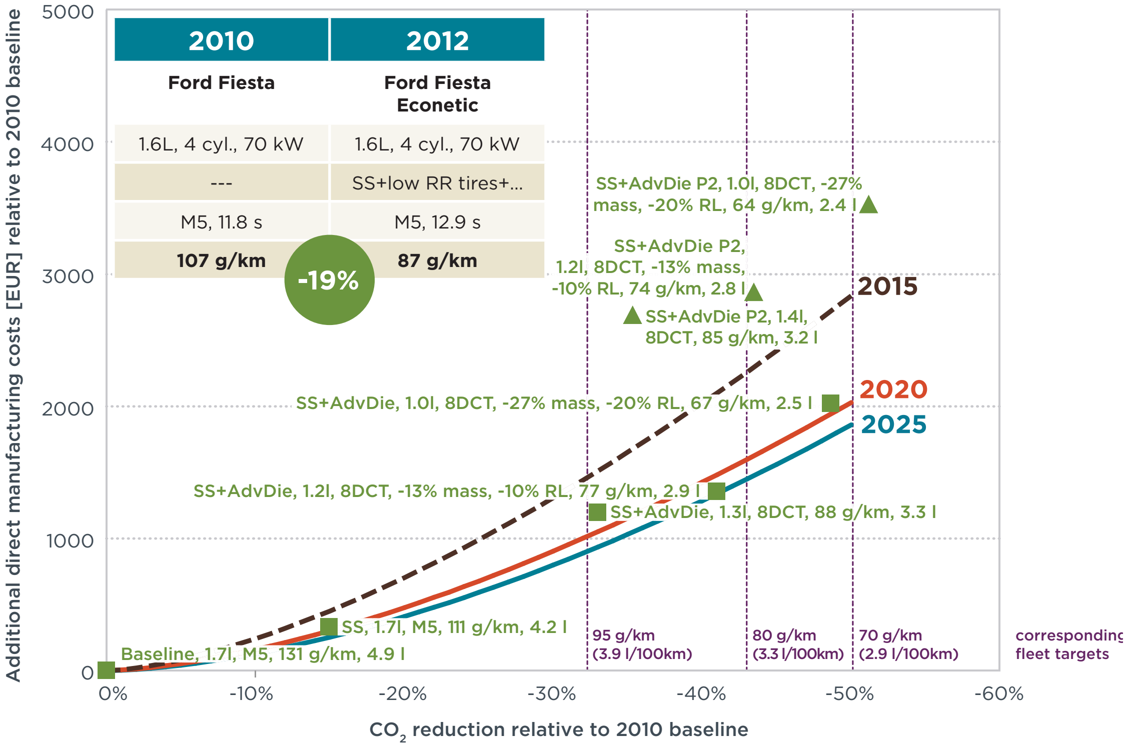


Figure 23. 2012 Ford Fiesta Compared to C Class Diesel Cost Curve

C-segment DIESEL

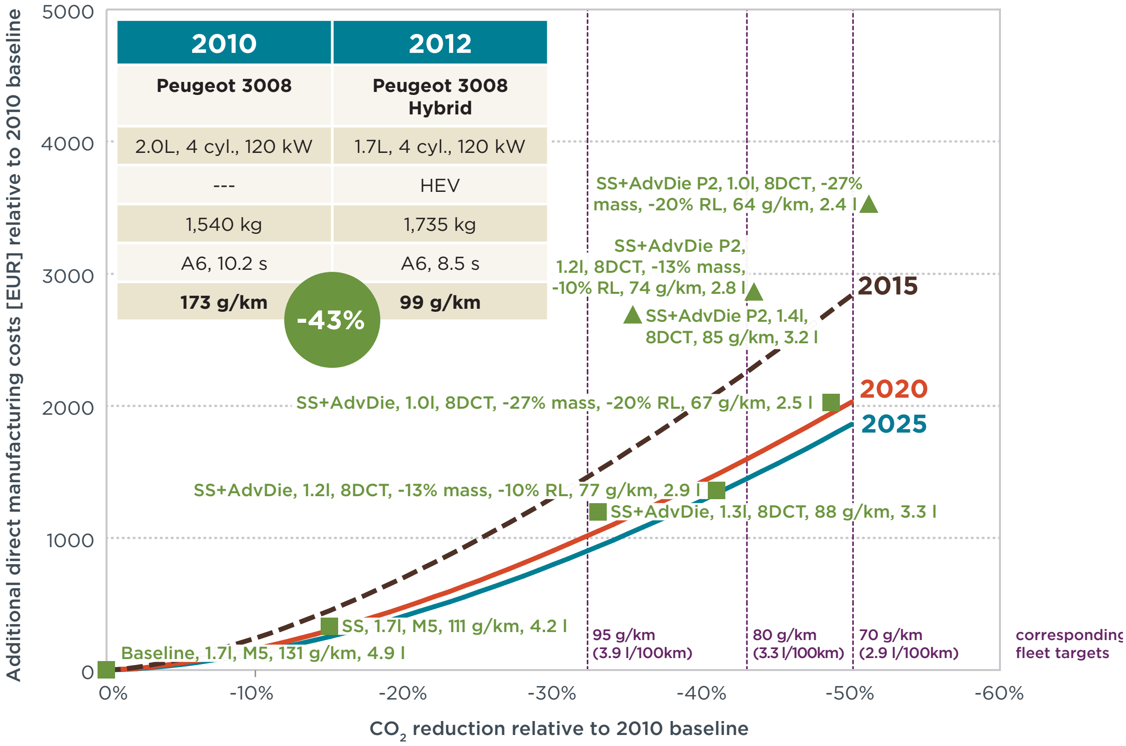


Figure 24. 2012 Peugeot 3008 Compared to C Class Diesel Cost Curve

8. Final Remarks and Outlook

This paper presents a set of preliminary cost curves for the EU light-duty vehicle fleet and describes the methodology employed in their development. Based on the derived curves, the following conclusions can be drawn for the average EU market.

- The estimated additional cost for attaining a CO_2 target of 95 g/km for passenger vehicles by 2020 is approximately €1000 per vehicle (see Figure 15-16).
- The estimated additional cost for attaining a CO_2 target of 147 g/km for light-commercial vehicles by 2020 is approximately €500 per vehicle (see Figures 17 and 18).
- The 2020 targets can be attained by improvements to internal combustion engines and moderate lightweighting. The introduction of neither electric or hybrid vehicle technology is required to meet either fleet average CO_2 target.
- The costs for attaining target CO_2 levels below 95 g/km (passenger cars) and 147 g/km (light-commercial vehicles) depend on the specific target and on the lead time allowed for compliance. For example, it is estimated that a 2025 target of 80 g/km (passenger cars) can be attained at an additional cost of approximately €1750 per vehicle compared to a baseline of 130 g/km (see Figure 16). Other estimates can be derived from the cost curves presented in this paper. Generally, 2025 costs are about 10 percent lower than the 2020 costs.

It is important to understand that the cost curves 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.

The presented cost curves are based on extensive vehicle simulation modeling and detailed teardown cost assessments, mirroring the industry approach of assessing the emission reduction potential and cost of future technologies. The analysis is expected to be a best practice example for the development of vehicle technology cost curves, and the results an accurate representation of current cost estimates for future CO_2 emission targets in the EU.

Limitations to the approach and the presented cost curves include:

- An underlying assumption of the cost assessment is that all technologies are manufactured entirely in Western Europe — more precisely in Germany. In reality, a significant portion of the manufacturing processes will take place in Eastern Europe, or even outside of Europe in countries with lower labor costs than in Germany. It is expected that in such a scenario, with manufacturing taking place in Eastern Europe, the associated cost curves would be approximately 15-20 percent lower than those presented herein. A more detailed analysis of this effect will be presented in a subsequent working paper in this series.
- 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 to 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.
- Agencies developing 2017-2025 greenhouse gas standards for light-duty vehicles in the U.S. are in the process of carrying out an extensive analysis of vehicle lightweighting costs. The results of this analysis will be transferred to the EU vehicle market and integrated into the cost curve analysis presented in this paper. While the analysis is not yet complete, it is expected that it will show that modest mass reductions are substantially cheaper than is assumed in the analysis underlying this paper – which should effectively reduce technology costs relative to those implied by the currently derived 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 petrol 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 petrol vehicle compliance costs are generally lower than those for diesel vehicles. A detailed assessment of this effect will be presented in a subsequent working paper in this series.

- All CO_2 emission reduction technology is evaluated on a constant performance basis. It is assumed that the zero to 96.6 kilometers per hour (60 miles per hour) acceleration time for reduced CO_2 vehicles is unchanged from that 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 upper range costs, and that the real costs for meeting 95 g/km and other potential CO_2 emission targets is likely to be lower than indicated above. A detailed analysis of alternative cost curve scenarios will be presented in subsequent working papers in this series.

9. Abbreviations and Acronyms

AdvDie	Advanced Diesel
AT	Automatic Transmission
AtkCPS	Atkinson Cycle Engine with Cam Phase Switching
A6	Six Speed Automatic Transmission
A8	Eight Speed Automatic Transmission
BAS	Belt Alternator Starter
BMEP	Brake Mean Effective Pressure
CAFE	U.S. Corporate Average Fuel Economy
C_d	Coefficient of Drag
C_dA	Coefficient of Drag times Vehicle Frontal Area
CO_2	Carbon Dioxide
CEGR	Cooled Exhaust Gas Recirculation
CPI	U.S. Consumer Price Index
CPS	Cam Phase Switching
CR	Compression Ratio
DCT	Dual Clutch (Automated Manual) Transmission
DI	Direct Injection
DOHC	Dual Overhead Cam Configuration
DPF	Diesel Particulate Filter
DVVL	Discrete Variable Valve Lift
EPA	U.S. Environmental Protection Agency
EGR	Exhaust Gas Recirculation
EPS	Electronic Power Steering
EU	European Union
FC	Fuel Consumption
g	Gram(s)
GDI	Gasoline (Petrol) Direct Injection
HEV	Hybrid Electric Vehicle
hr	hour
ICCT	International Council on Clean Transportation
ICE	Internal Combustion Engine
I3	Three Cylinder Inline Configuration Engine
I4	Four Cylinder Inline Configuration Engine
kg	Kilogram(s)
km	Kilometer(s)
kW	Kilowatt(s)
l	Liter(s)
MT	Manual Transmission
m^2	square meters
M5	Five Speed Manual Transmission
M6	Six Speed Manual Transmission
NEDC	New European Driving Cycle
NO_x	Oxides of Nitrogen
n/a	Not Applicable
OHV	Overhead Valve Configuration
PFI	Port Fuel Injection
RL	Road Load
RL0	Baseline Road Load Scenario
RL1	Alternative 15/10/10 Road Load Scenario
RL2	Alternative 30/20/20 Road Load Scenario
RR	Rolling Resistance
SCR	Selective Catalytic Reduction
SGTDI	Stoichiometric Gasoline (Petrol) Turbocharged Direct Injection
SOHC	Single Overhead Cam Configuration
SS	Start-Stop (Idle-Off) Technology
STDI	Stoichiometric Turbocharged Direct Injection
TC	Torque Converter
U.S.	United States
V	Volt(s)
VVT	Variable Valve Timing
VVTL	Variable Valve Timing and Lift
V6	Six Cylinder V-Configuration Engine
V8	Eight Cylinder V-Configuration Engine
15/10/10	Percent Mass/Drag/Rolling Resistance Road Load Reduction
30/20/20	Percent Mass/Drag/Rolling Resistance Road Load Reduction
6DCT	Six Speed Dual Clutch (Automated Manual) Transmission
6DDCT	Six Speed Dry Dual Clutch (Automated Manual) Transmission
7DDCT	Seven Speed Dry Dual Clutch (Automated Manual) Transmission
8DCT	Eight Speed Dual Clutch (Automated Manual) Transmission
8DDCT	Eight Speed Dry Dual Clutch (Automated Manual) Transmission
8WDCT	Eight Speed Wet Dual Clutch (Automated Manual) Transmission