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

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

Summary of mass reduction impacts on EU cost curves

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DATE: January 2013
KEYWORDS: Vehicle technologies, passenger cars, light-commercial vehicles, CO_2 reduction

1. Introduction

This paper discusses the impacts of new vehicle mass reduction data on CO_2 benefit and cost curves for EU light-duty vehicles in the 2020-2025 timeframe. This paper is the third in a series, with the previous two papers describing the methodology and data used to generate CO_2 cost curves for EU vehicles. Those papers have been published as ICCT Working Papers 2012-4 and 2012-5.[1],[2] Subsequent to the release of Working Papers 2012-4 and 2012-5, a new analysis on the cost of vehicle mass reduction has been completed by FEV, Inc.[3] The associated cost data have the potential to alter the previously developed cost curves, and the analysis documented in this paper is designed to quantify such effect. This paper also investigates the effect that CO_2 regulatory structures that do not fully reward (or penalize) vehicle manufacturers for the CO_2 influences of changes in vehicle mass might have on the overall compliance costs of CO_2 standards.

As with the previous studies in this series, data are evaluated in terms of effects on five vehicle classes. CO_2 impacts for these classes, namely B, C, D, Small N1, and Large N1 class vehicles, are based on simulation modeling performed for the Toyota Yaris, Ford Focus, Toyota Camry, Ford Transit Connect, and Ford Transit respectively. All baseline modeling is for 2010-era vehicle design and technology.

To integrate the recently released mass reduction cost data into the EU vehicle cost curves, the mass reduction cost data were expressed in the form of a generalized function so that the specific costs for a range of potential mass reductions could be evaluated. The first half of this paper is dedicated to describing the methodology employed and the resulting mass reduction cost curves developed. The second half of the paper presents the effects that accrue to the overall EU vehicle CO_2 compliance cost curves when these newly developed mass reduction cost curves are integrated with the CO_2 impacts and compliance costs of other (i.e., non-mass reduction) technologies.

As with previous work in this series, the primary cost curves that are developed are strictly technology-based. The relative effectiveness of potential regulatory structures that might be imposed to drive CO_2 emission reductions – specifically with regard to associated influences on technology neutrality – are not considered in the primary cost curve analyses. This paper does, however, also include a secondary set of cost curves designed to evaluate the potential impacts of 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 – on the cost of CO_2 standard compliance. This secondary evaluation is conducted through an analysis of compliance costs both with and without mass reduction technology. The scenario with mass reduction technology reflects the potential compliance

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, July 9, 2012.

2 ICCT, "CO_2 reduction technologies for the European car and van fleet, a 2020-2025 assessment: Summary of the EU cost curve development methodology," Working paper 2012-5, November, 2, 2012.

3 FEV, Inc., "Light-Duty Vehicle Mass Reduction and Cost Analysis -European Market," FEV 11-683-001, January 18, 2013.

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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, and the results of the project.

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costs of a regulatory structure that is fully technology neutral (e.g., a single standard or vehicle size-based regulatory structure), while the latter scenario reflects the potential compliance costs of a structure that *fully* discounts mass reduction as a compliance option (i.e., a regulatory structure that adjusts CO_2 standards to fully offset any CO_2 impacts associated with mass reduction). This is a bounding analysis, in that compliance costs for regulatory structures that *partially* discount the CO_2 effects of mass reduction will be between the two bounds evaluated in this paper.

As with previously presented cost curves, underlying cost data are primarily based on teardown studies of current technology. The teardown approach adds an important element of validation with regard to cost estimates, but it also inherently discounts (to zero) cost reductions due to any 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 capability, design, and manufacturing. Accordingly, the presented curves should be viewed as relatively conservative, in that aggregate future costs could be significantly lower than estimated.

The remaining sections of this paper detail the specific steps undertaken to integrate the newly released mass reduction cost data into EU light-duty vehicle cost curves. Section 2 describes the newly released mass reduction cost data and specific adjustments implemented for the analysis documented in this paper. Section 3 describes the methods used to develop mass reduction cost curves from the newly released data. Section 4 discusses the methodology employed to integrate the mass reduction cost curves into the larger EU cost curve analysis (that includes other CO_2 reduction technologies). Section 5 presents the resulting cost curves, while Section 6 discusses the potential cost impacts of the current regulatory structure in the EU. Section 7 provides a series of closing remarks. Section 8 discusses data limitations and future work. Finally, Section 9 presents definitions for the various abbreviations and acronyms that appear in the paper.

2. Mass Reduction Cost Data

Mass reduction cost data used to develop the EU CO_2 cost curves presented in the preceding paper in this series (Working Paper 2012-5) were based on data developed by the U.S. Environmental Protection Agency (EPA) in support of that agency's (then current) 2017-2025 U.S. light-duty vehicle greenhouse gas standards proposal.[4] Shortly before the release of Working Paper 2012-5 (but after the underlying analysis), the EPA finalized its 2017-2025 U.S. light-duty vehicle greenhouse gas standards, but the underlying mass reduction cost data are substantially unchanged from the data used in the earlier proposal. The basic EPA mass reduction cost estimation approach involves aggregating data from "various available studies in the literature as well as confidential information provided by several auto firms ... for purposes of estimating the cost of mass-reduction in the 2017-2025 timeframe."[5] In its final rulemaking, the EPA also discusses several recently completed or ongoing studies that would be important for a refinement of mass reduction cost estimates – including a study that served as a precursor to the work that is the basis for the mass reduction costs used in this paper – but ultimately elected to exclude quantitative consideration of these new study data due to an unaccommodating regulatory time schedule.[6] The EPA did update its base year for expressing costs from 2009 to 2010, but its mass reduction cost curve, as shown in Figure 1, is otherwise unchanged from that used in the development of the EU cost curves presented in Working Paper 2012-5.[7]

In contrast, the new cost curves presented in this paper are based on recent mass reduction costs estimated by FEV on the basis of detailed teardown studies for a 2010 Toyota Venza, as described in detail in the previously referenced 2013 FEV report. The Venza was selected for the FEV study because it was a new model introduced in 2010 with a state-of-the-art safety design. It is based on the Toyota Camry and is more carlike than Toyota's other crossover sport-utilities, such as the RAV4 and the Highlander.

4 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.

5 U.S. EPA and U.S. National Highway Traffic Safety Administration, "Joint Technical Support Document: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards," EPA-420-R-12-901, August 2012.

6 The precursor study is: FEV, Inc. "Light-Duty Vehicle Mass Reduction and Cost Analysis — Midsize Crossover Utility Vehicle," EPA Contract Number EP-C-12-014, Work Assignment Number 0-3, EPA-420-R-12-026, August 2012.

7 The adjustment factor employed by the EPA to convert 2009 U.S. dollars to 2010 U.S. dollars was 1.01185, so the basic slope of 4.31 $US2009/pound that underlies Figure 1 is expressed as 4.36 $US2010/pound in the EPA's final rulemaking. Either value leads to the data presented in Figure 1 when converted to euros per kilogram.

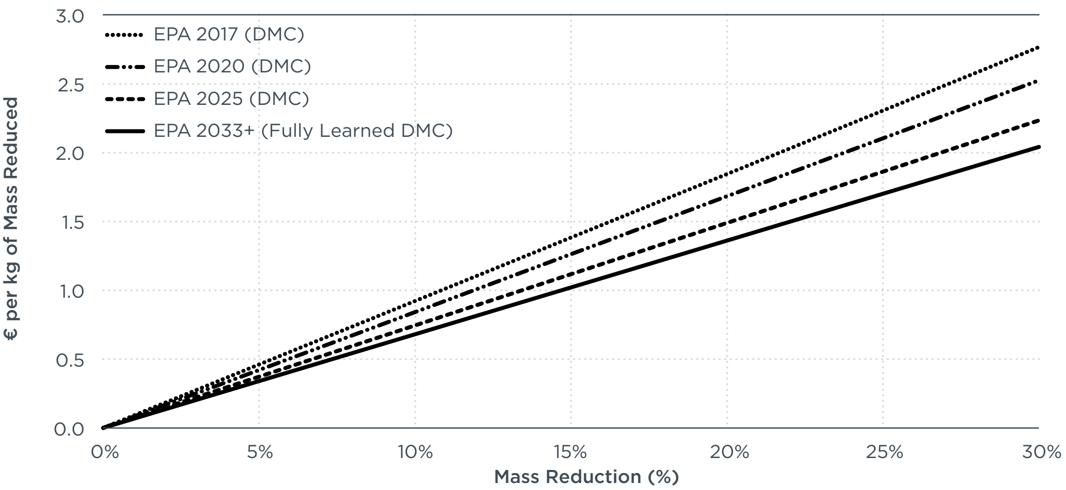

Figure 1. U.S. EPA Mass Reduction Cost Curve
Costs are direct costs to the vehicle manufacturer (DMC).

The primary impact estimation metric for the FEV work is incremental direct manufacturing costs, developed by comparing differences between alternative and baseline componentry. Component costs were estimated using comprehensive costing databases covering raw materials cost, labor rates, manufacturing overhead, and mark-up costs. For the source study underlying this paper, all costing databases were tailored for the European market. In the initial study for the US EPA, FEV was specifically tasked with identifying the cost of a 20 percent mass reduction package without compromising vehicle function, performance, or safety.[8] No powertrain, or any other vehicle system architecture changes, were implemented by FEV.

FEV's work did not distinguish mass reduction potential or cost by vehicle class or size. However, the mass reduction cost curve derived from the FEV work is expressed in relative terms (i.e., cost per percent reduction), so that the absolute mass reduction associated with any given vehicle scales in accordance with its base mass. Lighter vehicles will have a smaller mass reduction at a given percentage change than heavier vehicles, so that costs expressed in terms of relative changes in mass inherently scale for changes in vehicle base mass. While the FEV study did not explicitly evaluate mass reduction potential across vehicle classes, another mass reduction study recently released by Lotus Engineering did investigate this issue.[9] In this second study, Lotus finds mass reduction potential to be between 28-37 percent for 16 light-duty vehicle classes, ranging from micro cars to large pickup trucks – basically indicating an approximate ±15 percent variation around a central mass reduction potential of 32.6 percent. Based on these data, this paper assumes that mass reduction potential does not change across vehicle classes and that mass reduction costs across classes are constant in *percentage* reduction space.[10]

FEV evaluated nearly 250 vehicle components for mass reduction potential.[11] The total base mass of the evaluated components was 1641.70 kg, of which 312.48 kg (or 19 percent) were targeted for reduction. With fluids and other minor components, the total base vehicle weight was 1711 kg, so the precise "implemented" mass reduction was 18.3 percent. Table 1 presents a summary of the 312.48 kg of mass reduction, with associated costs, sorted in order of increasing cost per kg of mass reduced.[12] This allows for the ready identification of both relatively cheap and relatively expensive mass reduction options. It is important to note that the presented mass reduction and cost data include secondary (or compounded) benefits.

8 The implications of a 20 percent mass reduction target are important in distinguishing FEV's work from a "maximum possible" mass reduction study. The FEV work makes no attempt to define the maximum mass reduction level feasible, either in a given timeframe or through the use of the most aggressive mass reduction options.

9 Lotus Engineering Inc., "Evaluating the Structure and Crashworthiness of a 2020 Model-Year, Mass-Reduced Crossover Vehicle Using FEA Modeling," prepared for the California Air Resources Board (ARB) under Contract Number 09-621, August 31, 2012.

10 The ICCT has commissioned FEV to evaluate the specific mass reduction potential of EU vehicles relative to that of the Venza used as the basis for the analysis conducted for this paper. Should this evaluation reveal significant differences, the ICCT will conduct a follow-up sensitivity analysis.

11 A summary of the evaluated components, along with their associated subsystems, systems, base mass, and reduced mass is included as Appendix A.

12 Unless otherwise indicated, all cost data in this paper are direct nominal costs to the vehicle manufacturer. Nominal indicates that learning factors derived by FEV for calendar years 2012-2025 are not applied to the direct costs, nor are indirect cost multipliers intended to reflect additional costs incurred during the distribution and sales of vehicles. Such factors are included, as appropriate, in the EU cost curve development process, but are excluded during comparative cost discussions to facilitate a consistent comparison metric.

Such benefits accrue due to the fact that mass reduction is synergistic. Since less energy is required to move a reduced mass, the vehicle engine can be downsized. Similarly, components such as the vehicle suspension, brakes, and body can be made smaller or lighter since they need not support the same mass or dissipate the same energy. FEV assumed secondary mass reduction for the engine, brake, suspension, fueling, and body-in-white systems. Of the 312.48 kg of mass reduction, 42.78 kg are associated with secondary mass reduction (so that secondary mass reduction represents 13.7 percent of total reductions, or 15.9 percent of primary mass reductions).[13] As indicated in Table 1, FEV achieves an 18.3 percent reduction in vehicle mass at a cost *savings* of 0.45 euros per kg reduced.

13 Such levels of secondary mass reduction are quite conservative based on estimates produced in other studies. For example, in a study conducted as part of the United States Automotive Materials Partnership (USAMP) Cooperative Research Program, Shaw (United States Steel Corporation) and Polewarczyk (General Motors Corporation) found secondary mass reductions ranging from 60-150 percent of primary mass reductions, equivalent to 38-60 percent of total mass reductions; with the range defined by whether or not the powertrain can be targeted for secondary mass reduction (see U.S. Department of Energy, “Lightweighting Material, 2010 Annual Progress Report,” DOE/EE-0577, Objective ASP241, January 2011). In its 2011 study of fuel economy technology, the U.S. National Academy of Sciences (see “Assessment of Fuel Economy Technologies for Light-Duty Vehicles,” The National Academies Press, Washington, D.C., 2011) cites two mass reduction studies. Both of these studies (one by Ibis Associates and one by Ricardo, Inc.) estimate potential secondary mass reductions equal to 30 percent of primary reductions, or 23 percent of total mass reductions. In the previously cited support document for its 2017-2025 light-duty vehicle greenhouse gas rulemaking, the U.S. EPA states that secondary mass reductions “in the two most recent mass reduction projects by EPA and NHTSA” equal 70 percent of primary mass reductions, or 41 percent of total mass reductions. Clearly, the secondary mass reduction estimates of the FEV study, at 16 percent of primary and 14 percent of total, are significantly more conservative than other estimates in the subject literature.

Table 1. Mass Reductions (kg) and Costs (€) as Reported by FEV (in increasing €/kg)

Vehicle Component(s)	kg	€	€/kg
Cylinder Head Covers	0.052	-5.15	-99.67
Planetary Gears	0.263	-19.65	-74.59
Oil/Air Separator	0.219	-4.51	-20.57
Headliner Assembly	0.010	-0.18	-17.84
Brake Lines and Hoses	1.541	-25.91	-16.81
Exterior Mirrors	0.218	-3.58	-16.43
Fuel Rails	0.115	-1.88	-16.34
Parking Brake Cables and Attaching Components	2.117	-29.00	-13.70
Fender Seals	0.018	-0.22	-12.34
Infotainment Antennas and Cables	0.049	-0.51	-10.33
Electronic Climate Control Unit	0.009	-0.09	-10.06
Connect Rods (Connecting Rod & Cap)	0.596	-5.24	-8.79
Rear Side Door Dynamic Weatherstrip	0.356	-2.83	-7.94
Throttle Housing Assembly; including Supplies	0.245	-1.93	-7.90
Rear Spoiler Assembly	0.190	-1.50	-7.87
Seat Harness	0.009	-0.07	-7.51
Front Side Door Dynamic Weatherstrip	0.427	-3.17	-7.43
Rear Closure Finishers	0.145	-1.07	-7.41
Inlet Valves	0.015	-0.11	-7.41
Outlet Valves	0.015	-0.11	-7.41
Radiator Grill	0.155	-1.12	-7.23
Hood Dynamic Weatherstrip	0.030	-0.22	-7.12
Steering Column Assembly	1.148	-8.13	-7.08
Torque Converter Assembly	4.904	-34.13	-6.96
Parking Brake Shoes and Hardware	5.031	-32.75	-6.51
Rear Strut / Damper Assembly	4.785	-26.08	-5.45
Load Compartment Side Trim	3.842	-20.48	-5.33
Driver Information Center	0.027	-0.15	-5.32
Rear 60% Seat	13.551	-63.85	-4.71
Parking Brake Controls	2.487	-11.46	-4.61
Steering Wheel Trim	0.011	-0.05	-4.52
Static Sealing	1.198	-5.40	-4.51
Battery Cables	0.220	-0.91	-4.13
Front Window/Windshield Defrosting	0.393	-1.62	-4.12
Covers	1.276	-4.81	-3.77
Rear Closure Interior Trim Panel	0.027	-0.10	-3.65
Module - Front Bumper and Fascia	0.491	-1.69	-3.45
Module - Rear Bumper and Fascia	0.514	-1.76	-3.43
Carpet Support	0.021	-0.07	-3.29
Miscellaneous: Wipers and Washers Subsystem	0.100	-0.32	-3.21
Sun Visors	0.067	-0.21	-3.16
Air Distribution Duct Components	1.454	-4.35	-2.99
Main Floor Trim	0.075	-0.22	-2.95
Center Stack	0.728	-2.13	-2.92
Piston Cooling	0.124	-0.36	-2.92
Engine Down Size	10.365	-28.97	-2.80
Rear Caliper, Anchor and Attaching Components	5.025	-13.79	-2.74
Cargo Retention	0.161	-0.43	-2.67
Upper Exterior and Roof Finish	0.090	-0.24	-2.67
Front Drivers Seat	4.715	-11.53	-2.44
Cylinder Head	0.900	-2.11	-2.35
Front Strut / Damper Assembly	9.326	-19.77	-2.12
IP Cluster	0.049	-0.10	-2.08
HVAC Main Unit: Air Box/Core & Evaporator	0.478	-1.00	-2.08
Cowl Vent Grill Assembly	0.104	-0.21	-2.02
Actuator Assemblies	1.443	-2.90	-2.01
Road Wheels and Tire Assembly	30.833	-59.20	-1.92
Floor Mats – OEM	0.809	-1.54	-1.91
Rear LH & RH Door Trim Panel	0.689	-1.28	-1.87
Front Caliper, Anchor and Attaching Components	7.500	-13.69	-1.83
Pillar Trim Upper	0.275	-0.49	-1.79
Rear Suspension Links/Arms Upper and Lower	0.995	-1.74	-1.75
Pistons (Including Ring Packs, Pins, Circlips)	0.092	-0.15	-1.68
Miscellaneous: Air Intake Subsystem	0.122	-0.20	-1.64
Tensioners	0.125	-0.20	-1.61
Front Left & Right Door Trim Panel	0.726	-1.15	-1.59
Water Pumps	1.601	-2.54	-1.59
Load Compartment Floor Trim	1.077	-1.61	-1.49
Pillar Trim Lower	0.289	-0.43	-1.48
Lower Exterior Finishers	0.463	-0.69	-1.48
Fuel Vapor Canister Assembly	0.497	-0.70	-1.41
Air Filter Box	0.144	-0.20	-1.40
Heat Exchangers	0.990	-1.38	-1.39
Rear Wheel Arch Liners	0.122	-0.16	-1.31

Vehicle Component(s)	kg	€	€/kg
Crankcase Adaptor	1.924	-2.41	-1.25
Front Drive Unit	0.733	-0.91	-1.23
Vacuum Booster System Assembly	1.242	-1.48	-1.19
Guides	0.054	-0.06	-1.13
Front End and Engine Compartment Wiring	0.283	-0.29	-1.01
Load Compartment Transverse Trim	0.858	-0.87	-1.01
Engine Compartment Trim	0.268	-0.26	-0.98
Steering Gear	0.123	-0.11	-0.93
Fuel Filler	0.548	-0.47	-0.86
Under Eng. Closures/Air Dams	0.231	-0.20	-0.85
Transaxle Case	2.947	-2.46	-0.83
Engine Management & Electronic Systems	0.388	-0.32	-0.82
Enclosures	1.024	-0.84	-0.82
Covers	1.092	-0.87	-0.79
Steering Wheel	0.326	-0.25	-0.77
Fuel Tank Assembly	11.659	-8.76	-0.75
Transaxle Housing	3.706	-2.36	-0.64
Oil Pans (Oil Sump)	0.167	-0.08	-0.51
Roof	7.200	-3.47	-0.48
Engine and Transmission Wiring	0.143	-0.04	-0.27
Front Passenger Seat	3.638	-0.95	-0.26
Front Strut Frame	13.800	-3.16	-0.23
Front Rotor and Shield	5.023	-1.08	-0.22
Emission Control Components	4.729	-0.83	-0.17
Spare Wheel and Tire Assembly	2.000	-0.20	-0.10
Rear Stabilizer (Anti-Roll) Bar Assembly	1.560	-0.09	-0.06
Power Steering Electronic Controls	0.210	-0.01	-0.03
Other Parts for Cylinder Head	0.095	0.00	0.00
Miscellaneous: Rear View Mirror Subsystem	0.000	0.00	0.00
Miscellaneous: Front Brake Subsystem	0.124	0.00	0.00
Acoustic Control Components	2.789	0.10	0.03
Rear Suspension Knuckle Assembly	5.765	0.51	0.09
Ladder	12.100	1.59	0.13
Instrument Panel Harness	0.110	0.02	0.17
Rear 40% Seat	1.488	0.48	0.32
Oil Pump Assembly	1.034	0.39	0.38
Body and Rear End Wiring	0.123	0.05	0.38
Underbody	8.100	4.40	0.54
Front Stabilizer (Anti-Roll) Bar Assembly	2.879	1.85	0.64
Front Suspension Knuckle Assembly	6.759	4.41	0.65
Windshield and Front Quarter Window (Fixed)	1.559	1.21	0.77
Inflatable Knee Bolster or Active Leg Protection	0.377	0.34	0.90
Cross-Car Beam (IP)	3.975	3.69	0.93
Front Structure	5.700	5.38	0.94
Passenger Airbag / Cover Unit	0.483	0.50	1.04
Headlamp Cluster Assembly	0.531	0.55	1.04
Instrument Panel Main Molding	1.627	1.75	1.07
Rear Strut Frame	2.538	3.89	1.53
Engine Mountings	1.114	1.72	1.54
First Row Door Window Lift Assembly	0.939	1.60	1.70
Second Row Door, Quarter & Rear Window Lift	0.939	1.60	1.70
Front Half Shaft	0.770	1.31	1.70
Rear Rotor and Shield	1.216	2.13	1.75
Air Conditioning Compressors	0.709	1.42	2.01
Camshaft Phaser and/or Cam Sprockets	1.391	3.01	2.16
Front Suspension Links/Arms Upper and Lower	1.934	4.86	2.51
Back Window Assembly	1.218	3.19	2.62
Rear Side Door Glass	1.176	3.08	2.62
Back and Rear Quarter Windows (Fixed)	0.230	0.60	2.62
Rear Hatch	7.200	22.59	3.14
Cylinder Block	5.058	16.24	3.21
Hood	7.700	29.49	3.83
Bodyside	17.570	76.20	4.34
Miscellaneous: Lubrication Subsystem	0.067	0.30	4.54
Body Air Outlets	0.103	0.49	4.74
Valve Springs	0.154	0.80	5.22
Steering Wheel Airbag	0.200	1.45	7.26
Camshafts	2.133	16.51	7.74
Front Fenders	2.000	16.48	8.24
Shift Module Assembly	1.726	22.24	12.88
Front Bumper	0.400	8.08	20.19
Carrier Gears	3.227	110.64	34.29
Bolt on BIP Components	0.000	11.12	---
Vehicle Totals	**312.48**	**-142.0**	**-0.45**

Negative costs indicate cost savings.

As described above, FEV was tasked with defining a 20 percent mass reduction package. Since the basic package achieved somewhat less than the 20 percent target, FEV performed a supplemental assessment wherein they identified up to 63.25 kg of additional mass reduction potential and associated costs. If fully implemented, these additional mass reduction options would result in a total mass reduction potential of 375.73 kg, or 22 percent of base vehicle mass. The additional measures consisted of:

- Applying aluminum wire to all wiring harnesses,
- Eliminating the spare tire and using run flat tires,
- The configuration effects of engine downsizing (e.g., reduced cylinder count),
- Downsizing the transmission and gear train, and
- Utilizing aluminum doors.

Based on discussions with FEV, the ICCT opted to include only the engine and transmission downsizing and the aluminum doors as reasonable and feasible in the 2020 timeframe. Table 2 depicts the mass reduction benefits and costs of the included measures. Relative to the full slate of additional options identified by FEV, included options (as presented in Table 2) reflect the exclusion of aluminum wire on all harnesses as infeasible in the target timeframe, the elimination of run flat tire technology due to uncertainties about consumer acceptance and baseline market penetration, and the elimination of the downsized gear train as too expensive. As indicated, the options retained result in an additional 47.54 kg of mass reduction at a cost of 97.09 euros (2.04 euros per kg).

As shown in Table 3, FEV's mass reduction package (presented in Table 1 above) includes twelve mass reduction options with primary mass reduction costs in excess of four euros per kg. Three of these options are related to the body-in-white (BIW) and are therefore integral to the structural integrity and safety of the reduced mass package. However, nine of the options are independent of the BIW and can be implemented (or not) based solely on their cost effectiveness. Given their unreasonably high cost, these nine options were removed from the FEV mass reduction package prior to the development of the mass reduction cost curves generated in this analysis. One of the nine dropped options (the front bumper) carries a secondary mass reduction benefit that was retained while the associated primary mass reduction was dropped.[14] In total (as shown in Table 3), 9.8 kg of mass were added back to the reduced mass package at an aggregate cost savings of 18.2 euros per kg. It should be recognized, however, that adding 9.8 kg of mass back into the reduced mass vehicle also had the effect of reducing the secondary mass benefits associated with the original FEV reduced mass package, resulting in a net mass increase of 11.4 kg.

Table 2. Additional FEV Mass Reduction Options Used in This Paper

Mass Reduction Option	Mass Change (kg)	Cost (€)	€/kg
Engine Downsizing (Configuration)	14.43	0.00	0.00
Transmission Downsizing	4.63	-6.29	-1.36
Aluminum Doors	28.48	103.38	3.63
Net Impact of Additional Options	47.54	97.09	2.04

Note that engine downsizing costs are not zero. Since they are accounted for as an independent CO_2 reduction technology in the EU costs curves, they are treated as zero with regard to mass reduction technology to avoid cost double-counting. The downsizing cost estimated by FEV in their mass reduction study for the Venza was 188.55 euros (13.07 euros per kg). The mass reduction benefits of the downsizing are not accounted for elsewhere.

14 Secondary reductions are facilitated by the cumulative primary mass reductions of all components that contribute to vehicle level mass reduction, not just the primary mass reductions of the component or system exhibiting the reduction. Thus, while secondary mass reductions should be (and are) adjusted for changes in cumulative primary mass reduction, they continue to apply across all components subject to secondary mass reduction whether or not those components themselves have a primary mass reduction.

Table 3. High Cost FEV Mass Reduction Options

Mass Reduction Option	Total Mass Reduction (kg)	Primary Mass Reduction (kg)	Secondary Mass Reduction (kg)	Primary Mass Reduction Cost (€/kg)	Total Mass Reduction Cost (€/kg)	Keep or Drop
Misc: Lubrication Subsystem	0.067	0.067	0.000	4.5	4.5	Drop
Body Air Outlets	0.103	0.103	0.000	4.7	4.7	Drop
Front Structure	5.700	2.850	2.850	4.8	0.9	Keep (a)
Valve Springs	0.154	0.154	0.000	5.2	5.2	Drop
Steering Wheel Airbag	0.200	0.200	0.000	7.3	7.3	Drop
Camshafts	2.133	2.133	0.000	7.7	7.7	Drop
Front Fenders	2.000	2.000	0.000	8.2	8.2	Drop
Bodyside	17.570	8.785	8.785	11.2	4.3	Keep (a)
Shift Module Assembly	1.726	1.726	0.000	12.9	12.9	Drop
Carrier Gears	3.227	3.227	0.000	34.3	34.3	Drop
Front Bumper	0.400	0.200	0.200	44.4	20.2	Drop (b)
Bolt on BIP Components	0.000	0.000	0.000	——	——	Keep (a)
Net Impacts	33.280	21.445	11.835	14.0	8.1	
Drops-Only Net	9.810	9.810	0.000	18.1	18.1	
Keeps-Only Net	23.470	11.635	11.835	10.5	3.9	

Notes: (a) Retained as a critical structural and safety component of the FEV body-in-white.
(b) Primary reductions dropped, secondary reductions retained.

As shown in Table 1 above, the original FEV reduced mass package delivered 312.48 kg of mass reduction (18.3 percent vehicle mass reduction) at a net savings of 0.45 euros per kg. The reduced mass package with high cost options removed delivers 301.11 kg of mass reduction (17.6 percent vehicle mass reduction) at a net savings of 1.05 euros per kg. When the additional FEV mass reduction options shown in Table 2 – combined with an incremental secondary mass reduction impact of 7.5 kg – are implemented on top of the reduced mass package with high cost options removed, the net package delivers 356.19 kg of mass reduction (20.8 percent vehicle mass reduction) at a net savings of 0.67 euros per kg. Table 4 presents a summary of these data.

Table 4. Summary of FEV Mass Reduction Benefits and Costs

Mass Reduction Package	Total Mass Reduction (kg)	Total Mass Reduction (percent)	Total Mass Reduction Cost (€/kg)
A. Mass Reduction Package as Described in FEV's Report	312.48	18.3	-0.45
B. Package A with Nine High Cost Mass Reduction Options Removed	301.11	17.6	-1.05
C. Package B with Three Additional Mass Reduction Options Added	356.19	20.8	-0.67

As described above, FEV was tasked with defining mass reduction options capable of generating a 20 percent vehicle mass reduction. A similar study, but targeting a 30 percent vehicle mass reduction, was performed at approximately the same time by Lotus Engineering.[15] Both studies were based on the same baseline vehicle and both built off of and improved upon the analysis approach and data developed for an earlier study conducted by Lotus Engineering.[16] Thus, the analysis methods and baseline vehicle components evaluated by FEV and Lotus Engineering are consistent, so that the additional Lotus work targeting a 30 percent mass reduction package can be utilized to augment the work performed by FEV. Since the latest Lotus work is primarily limited to the detailed analysis of a BIW structure capable of promoting a 30 percent vehicle level mass reduction, the Lotus work is not a vehicle level substitute for the FEV data. It is possible, however, to replace the detailed FEV BIW with the similarly detailed Lotus BIW, while retaining the FEV non-BIW data. For the most part, this is a one-to-one replacement exercise, the only exception being that the added mass reductions associated with the more aggressive Lotus Engineering BIW also generate modestly larger secondary mass reduction benefits (2.8 kg) in the non-BIW components. Table 5 presents a comparison of the FEV and Lotus

15 Lotus Engineering Inc., "Evaluating the Structure and Crashworthiness of a 2020 Model-Year, Mass-Reduced Crossover Vehicle Using FEA Modeling," prepared for the California Air Resources Board (ARB) under Contract Number 09-621, August 31, 2012.

16 Lotus Engineering Inc., "An Assessment of Mass Reduction Opportunities for a 2017 – 2020 Model Year Vehicle Program," Revision 006A, prepared for the International Council on Clean Transportation (ICCT), March 2010.

Engineering BIW estimates, while Table 6 presents a summary of the various mass reduction package estimates. Finally, Figure 2 shows these package benefits and costs relative to the EPA's mass reduction cost curve.[17] As indicated, all of the evaluated mass reduction options are substantially less expensive than assumed in the EPA cost curve used in the development of the EU cost curves presented in the previous paper in this series (Working Paper 2012-5).

3. Mass Reduction Cost Curves

The mass reduction package estimates summarized in Table 6 and Figure 2 were developed into generalized cost curves through a detailed examination of the component mass reduction options. Two distinct curves were developed, one based on the adjusted mass reduction target data developed by FEV (package C in Table 6 and Figure 2) and one based on these same data but with the Lotus reduced mass BIW substituted for the FEV reduced mass BIW (package D in Table 6 and Figure 2). The former curve was taken as representative of mass reduction potential in 2020, while the latter was assumed to represent achievable reductions in the 2025 timeframe.

Table 5. Comparison of FEV and Lotus BIW Impact Estimates

Mass Reduction Package	Mass Reduction (kg)	Cost (€)	Cost (€/kg)
1. BIW as Described in FEV's Report	50.79	95.07	1.87
2. FEV BIW after High Cost Options Removed and Additional Options Added	54.35	86.50	1.59
3. Lotus BIW	140.70	229.24	1.63
4. Differential Between Lotus BIW and FEV BIW (3 minus 2)	86.35	142.74	1.65

Note: The FEV BIW mass reductions change as adjustments are made to the base mass reduction package in accordance with the secondary mass impacts of those adjustments. The primary mass reductions associated with the FEV BIW are constant.

Table 6. Summary of Mass Reduction Package Benefits and Costs

Mass Reduction Package	Total Mass Reduction (kg)	Total Mass Reduction (percent)	Total Mass Reduction Cost (€/kg)
A. Mass Reduction Package as Described in FEV's Report	312.48	18.3	-0.45
B. Package A with Nine High Cost Mass Reduction Options Removed	301.11	17.6	-1.05
C. Package B with Three Additional Mass Reduction Options Added	356.19	20.8	-0.67
D. Package C with FEV BIW Replaced with Lotus Engineering BIW	445.33	26.0	-0.23

As discussed above, and summarized in Tables 1, 2, and 3, FEV developed component-level impact estimates for approximately 150 mass reduction options. Some of these options generated mass reductions at significant cost savings, while others resulted in additional incurred costs. While it is possible to rank order these component-level options and plot cumulative mass reductions and costs to define a "curve" that terminates at the associated full package mass reduction data point presented in Figure 2, a modified approach was employed for this paper. The reason for this modification is that simple rank ordering does not capture the potential for systemic relationships between component-level mass reduction options. Treating component effects as independent of the systems of which they are a part has the potential to both overstate the cost of a component modification that enables modifications in one or more other components and understate the cost of the enabled component reduction(s). To surmount this potential problem, this paper relies on cost curves developed at the system (or subsystem) level, produced by aggregating all associated component-level mass reduction impacts and costs. Table 7 lists the aggregate system definitions used for this paper, as well as summarizes the mass reduction impacts for each system for the two evaluated mass reduction packages.[18]

In addition to a system level approach, it is also necessary – for proper cost curve development proposes – to reallocate secondary mass reductions from those components and

17 Note that fully learned EPA costs are referenced in this comparison as these are the costs that are comparable to the nominal mass reduction costs underlying the other depicted data points in Figure 2.

18 The tabulated system definitions are as defined by FEV. Each of the FEV component-level mass reduction options is associated with a specific vehicle system (or subsystem) and these associations are fully defined in the FEV mass reduction work. No modifications to these definitions have been implemented for this paper. The paper does, however, for narrative convenience, imprecisely apply the term "system" to both FEV-defined systems and subsystems.

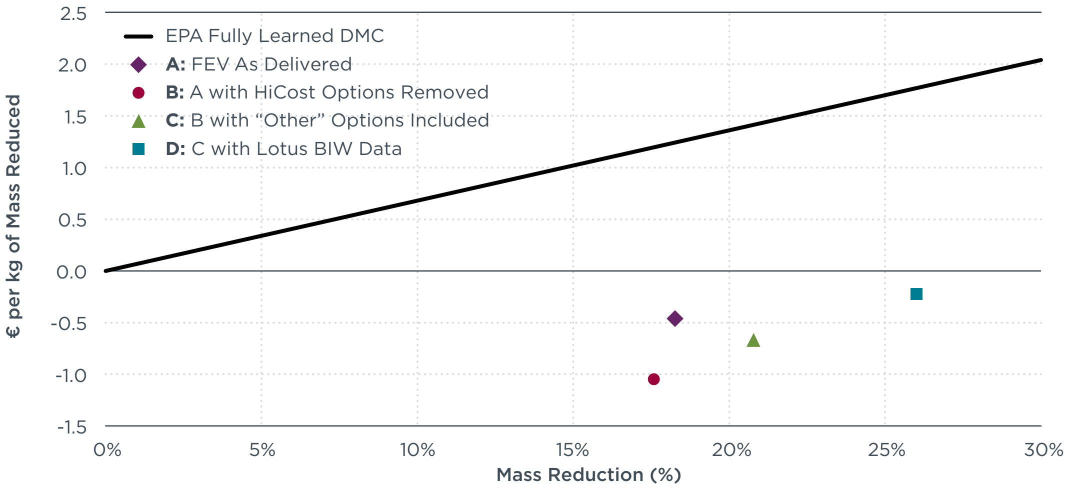

Figure 2. Mass Reduction Package Nominal Costs Versus EPA Cost Curve
Costs are direct costs to the vehicle manufacturer (DMC).

systems that receive the secondary benefits to those components and systems that create them. Although this does not alter total mass reductions or costs in any way, it is absolutely necessary to properly account for the total mass impacts of both components and systems. As shown in Table 8, secondary mass benefits accrue in only seven of the 32 systems (and subsystems) exhibiting mass reductions, with three systems accounting for 95 percent of total secondary reductions.[19] However, these secondary reductions are facilitated by the cumulative primary mass reductions of *all* components that contribute to vehicle-level mass reduction. The benefits and costs of the secondary mass reductions are due to the cumulative effects of the contributing components, not the component or system exhibiting the reduction. To account for this, secondary benefits and costs must be distributed across component mass reduction options in accordance with the share that each contributes to the total primary vehicle-level mass reduction. Otherwise, the systems accruing secondary benefits will appear to be inaccurately inexpensive, while those facilitating those same benefits will appear to be inaccurately expensive. Properly reallocating the benefits and costs eliminates these accounting anomalies, without affecting either the total vehicle-level mass reduction or cost estimates developed by FEV and Lotus.[20]

19 Eighteen individual components contribute secondary mass reductions to the seven systems.

20 While FEV did not develop mass reduction cost curves at the level of detail required for this paper, they do properly include a similar secondary mass reduction reallocation algorithm in their cost curve development work.

Table 7. Summary of System-Level Mass Reduction Benefits

Vehicle System (Subsystem)	FEV-BIW Mass Reduction (kg)	Lotus-BIW Mass Reduction (kg)	Mass Reduction Difference (kg)
Engine System	43.774	45.434	1.659
Transmission System	18.576	18.576	0.000
Body Structure Subsystem	54.345	140.700	86.355
Body Closure Subsystem	43.628	43.646	0.019
Bumpers Subsystem	0.228	0.260	0.032
Interior Trim and Ornamentation Subsystem	8.924	8.924	0.000
Sound and Heat Control Subsystem (Body)	0.268	0.268	0.000
Sealing Subsystem	2.029	2.029	0.000
Seating Subsystem	23.392	23.392	0.000
Instrument Panel and Console Subsystem	6.330	6.330	0.000
Occupant Restraining Device Subsystem	0.860	0.860	0.000
Exterior Trim and Ornamentation Subsystem	1.147	1.147	0.000
Rear View Mirrors Subsystem	0.218	0.218	0.000
Front End Modules	0.491	0.491	0.000
Rear End Modules	0.514	0.514	0.000
Glass (Glazing), Frame and Mechanism Subsystem	6.062	6.062	0.000
Handles, Locks, Latches and Mechanisms Subsystem	0.000	0.000	0.000
Rear Hatch Lift assembly	0.000	0.000	0.000
Wipers and Washers Subsystem	0.100	0.100	0.000
Suspension System	67.490	68.239	0.749
Driveline System	1.503	1.503	0.000
Brake System	32.837	32.937	0.100
Frame and Mounting System	16.338	16.338	0.000
Exhaust System	7.518	7.518	0.000
Fuel System	12.900	13.124	0.224
Steering System	1.817	1.817	0.000
Climate Control System	2.333	2.333	0.000
Information, Gage and Warning Device System	0.076	0.076	0.000
Electrical Power Supply System	0.000	0.000	0.000
In-Vehicle Entertainment System	1.073	1.073	0.000
Lighting System	0.531	0.531	0.000
Electrical Distribution and Electronic Control System	0.889	0.889	0.000
Net Vehicle-Level Package	356.191	445.329	89.138

Table 8. Summary of System-Level Secondary Mass Reduction Benefits

Vehicle System (Subsystem)	FEV-BIW Mass Reduction (kg)	Lotus-BIW Mass Reduction (kg)	Mass Reduction Difference (kg)
Engine System	11.815	13.474	1.659
Body Structure Subsystem	28.949	72.126	43.177
Body Closure Subsystem	0.132	0.150	0.019
Bumpers Subsystem	0.228	0.260	0.032
Suspension System	5.335	6.085	0.749
Brake System	0.711	0.811	0.100
Fuel System	1.595	1.819	0.224
Net Vehicle-Level Package	48.765	94.726	45.960

Once secondary mass reduction impacts and costs are properly reallocated to contributing components, rank-ordering system level impacts in terms of cost per kilogram of mass reduced and plotting the resulting cumulative impacts produces a series of data points ranging from near-zero mass reduction to the vehicle-level mass reduction package impacts summarized above in Table 6 and Figure 2. Figure 3 depicts the data points for mass reductions of two percent and greater.[21] The depicted curves represent exponential regressions forced through the vehicle-level mass reduction package data point (the upper rightmost data point of each set of data points). The specific equations for each of the depicted curves are of the form:

$$€/kg\ cost = [a \times (percent\ mass\ reduction)^{z}] + b$$

and the evaluated parameters are:

	a	z	b	r^2
FEV BIW Curve (2020 Nominal)	42.57953	1.6276	-3.97684	0.99
Lotus BIW Curve (2025 Nominal)	40.35639	1.7487	-4.06337	0.99

Two characteristics of the depicted cost curves should be noted. First, the presented curves are cumulative cost curves as opposed to marginal cost curves. The independent parameter is the net (or cumulative) cost of any given mass reduction, incremental costs can be determined via the differential between the net costs of two given mass reductions. Expressing the curves in this manner denote no special consideration, it is simply more convenient for the calculations associated with this work. Second, Figure 3 includes an extrapolation of the both cost curves through mass reductions of 30 percent. The 2025 curve is actually used to estimate the cost of a 30 percent mass reduction in this paper, but the utility of the 2020 curve is limited to a 20 percent mass reduction (and thus the extrapolation is shown in gray and is intended solely to facilitate a visual comparison of the two curves over the depicted range of the x axis).[22]

All of the data depicted to this point have been expressed in terms of nominal costs. These data effectively represent the long term direct manufacturing cost differentials for competing technologies (generally alternative “new” technology versus baseline “old” technology) under an identical set of boundary conditions (including, for example, high production volumes, equivalent market maturity, and unchanged manufacturing cost structures). Learning factors, also developed by FEV as an integral component of their study, are applied to convert nominal cost data to data applicable to any given year. In the case of mass reduction, these learning factors can generally be thought of as “reverse” or “un” learning factors, since they increase cost differentials (relative to nominal cost estimates) in the period through at least 2025 – i.e., that period evaluated in this paper.

21 Two percent is representative of an inflection point in the cost curve. There are four data points between zero and two percent that exhibit costs ranging from -15 to -5 euros per kilogram of mass reduced. These data points have been ignored in the cost curves generated for this paper. They contribute no useful information since the smallest non-zero mass reductions evaluated are five percent. By ignoring these data, the cost curves produced for this paper will *overestimate* the cost of mass reductions between zero and two percent. This does not affect the data presented in this paper in any way, but caution is advised in using the presented cost curves for other applications.

22 The extrapolation of the 2025 curve is relatively modest, extending from 26 to 30 percent.

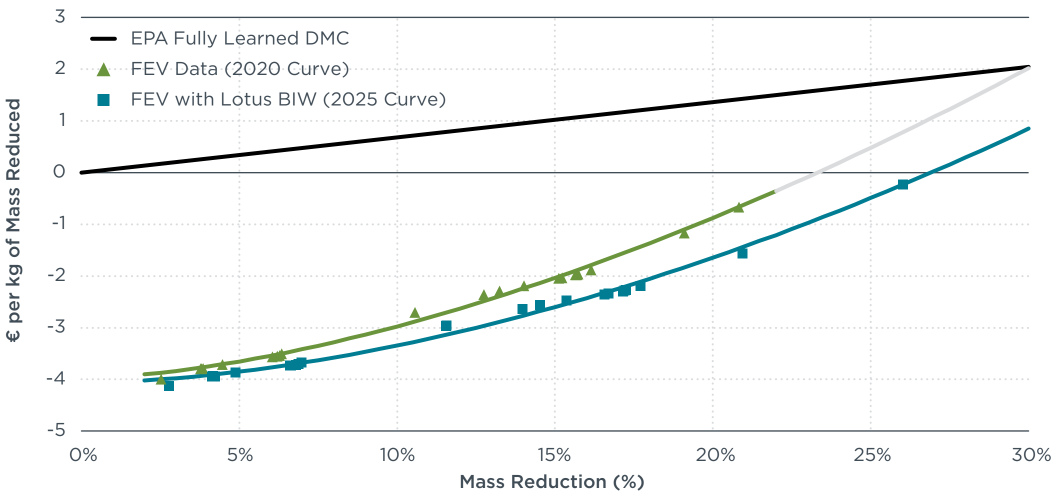

Figure 3. Nominal Mass Reduction Cost Curves Versus EPA Cost Curve
Costs are direct costs to the vehicle manufacturer (DMC).

Figure 4 presents the 2020 and 2025 mass reduction cost curves including the application of the learning factors for 2020 and 2025 respectively. These are the actual cost curves used for the direct manufacturing cost (DMC) evaluations presented in this paper (the dotted curves are the nominal cost curves presented previously in Figure 3). Note that the EPA curves, included in Figure 4 for comparative purposes, also include the application of 2020 and 2025-specific learning factors as assumed by that agency in its associated 2017-2025 U.S. light-duty vehicle greenhouse gas rulemaking.

It is also perhaps helpful to explicitly note that there are two mass parameters in the depicted cost curves. The first is the percentage mass reduction depicted as movement along the x axis. The second results from the fact that y axis costs are presented per unit reduction in mass. As the magnitude of mass reduction increases, the cost per unit mass reduction also increases as expected. However, because the cost per unit mass is negative for a wide range of mass reductions, it may not be inherently obvious that net *savings* can increase as mass reductions increase even though the cost per unit mass reduction is increasing at the same time. In effect, higher mass reductions are offsetting the reduced per unit savings of those reductions. While it is not possible to generalize this relationship since it is dependent on the base mass of the affected vehicle, it is possible to depict the relationship for any given vehicle base mass. For example, Figure 5 shows the absolute cost of mass reduction for the curves depicted in Figure 4 for two base vehicle masses, 1200 and 2000 kilograms – base masses that roughly approximate the lightest and heaviest vehicles evaluated in this paper. As depicted, although cost savings per unit mass reduction decrease continuously with increasing mass reduction, net cost savings increase through about 11.5 percent mass reduction for the 2020 cost curve and through about 14 percent mass reduction for the 2025 cost curve – after which net cost savings decrease. Recognizing this relationship can be helpful in understanding the effects of integrating the mass reduction cost curves into the more general cost curve analysis that follows.

Finally, FEV also developed indirect cost multipliers (ICMs) to convert direct manufacturing cost impacts to total cost (TC) impacts (reflecting the additional post-manufacturing cost impacts of vehicle distribution and sales). Figure 6 depicts the cost curves that result from the application of the FEV indirect cost multipliers. The methodology used to develop the curves is identical to that already described for the direct manufacturing cost curves. The reader is referred to the cited FEV report for additional discussion of ICM derivation and application.

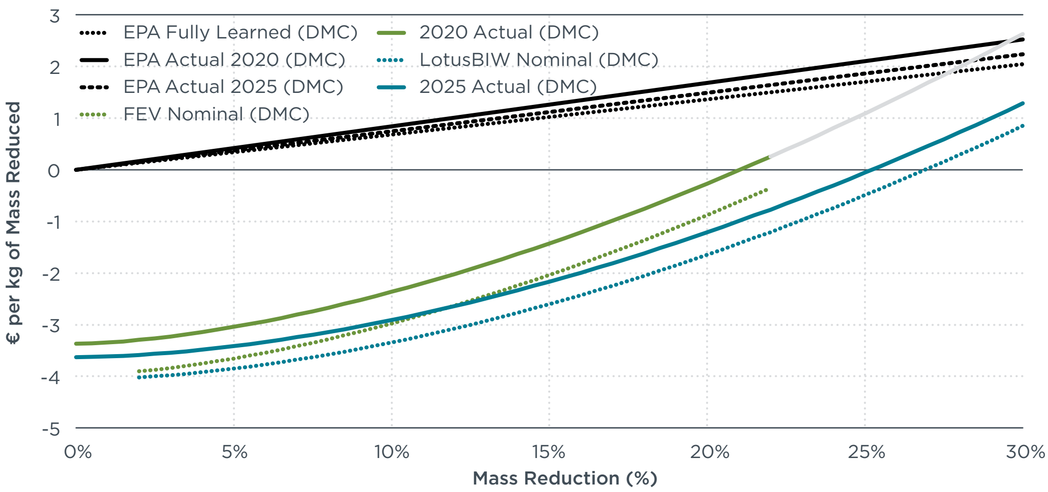

Figure 4. Actual Mass Reduction with Learning Versus Nominal Cost Curves

Note: DMC means Direct Manufacturing Cost.

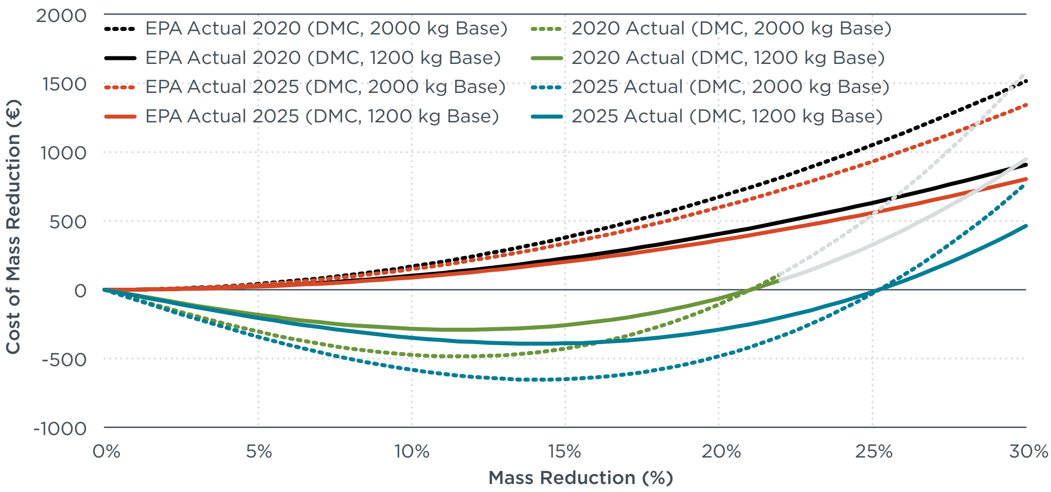

Figure 5. Mass Reduction Cost Curves in Net Cost Space

Note: DMC means Direct Manufacturing Cost.

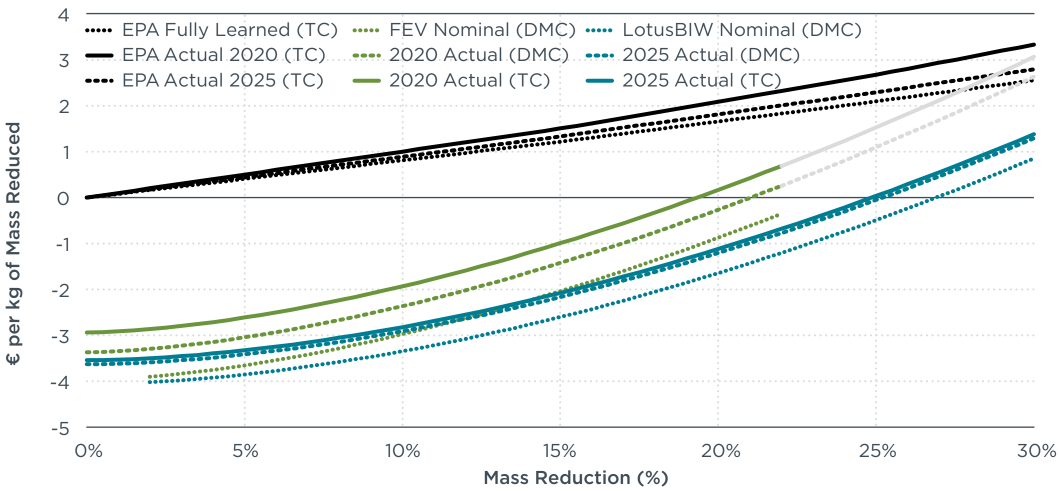

Figure 6. Mass Reduction Total Cost Curves

Note: DMC means Direct Manufacturing Cost, TC means Total Cost (TC = DMC × Indirect Cost Multiplier).

4. Integration of the Mass Reduction Cost Curves Into the EU Cost Curve Analysis

As discussed in ICCT Working Paper 2012-5, the basic methodology used to develop CO_2 cost curves for EU light-duty vehicles consists of combining CO_2 data resulting from vehicle simulation modeling performed by Ricardo Inc. with technology cost data developed through vehicle teardown studies by FEV, Inc. In cases where FEV cost data were not available, secondary cost data were utilized – which were most often derived from work performed in support of the U.S. EPA's 2017-2025 light-duty vehicle greenhouse gas standards rulemaking. The cost of vehicle mass reduction was one of the technology costs derived from this EPA work. The primary purpose of this paper is to investigate the impact of replacing the previously utilized EPA-derived mass reduction cost data with the newly developed mass reduction cost curves presented herein. So, on a fundamental level, the EU cost curves that follow are based on the simple substitution of one mass reduction cost curve (as documented herein) for another (as derived from the EPA and used in ICCT Working Paper 2012-5). The preceding sections include comparative depictions of the mass reduction curves.

There are, however, five additional updates to the previous work that were implemented for this paper. First, the final EPA 2017-2025 light-duty vehicle greenhouse gas standards rulemaking included a revised set of support documents. As part of the analysis performed for this paper, the technology cost data from these revised documents were reviewed and any previous corresponding costs used for the EU cost curve work were updated. In all cases, the impacts of such revisions were either nil or negligible.

Table 9. Change in Simulation Model Baseline CO_2 Data

Fuel	Vehicle Class	New g/km	Old g/km	New-Old g/km
Petrol	B Class	131.3	128.3	3.0
	C Class	133.5	138.7	-5.2
	D Class	170.4	165.9	4.5
	Large N1	236.8	230.6	6.2
	Small N1	180.5	181.4	-0.9
Diesel	B Class	113.1	108.3	4.8
	C Class	118.5	121.6	-3.1
	D Class	133.2	132.5	0.7
	Large N1	166.6	166.1	0.5
	Small N1	148.0	146.0	2.0

Second, some reporting errors were found in the Ricardo baseline vehicle CO_2 data used to develop the EU costs curves. Table 9 presents a summary of the previously used (old) and corrected (new) data. As indicated, errors as large as 6 g/km were discovered and corrected. The curves reported in this paper are based on the corrected baseline data.

Third, the previously developed cost curves were based on modeling data for two alternative road load scenarios – one of which assumed a 15 percent reduction in vehicle mass in tandem with 10 percent reductions in vehicle rolling resistance and aerodynamic drag, and one of which assumed a 30 percent reduction in vehicle mass in tandem with 20 percent reductions in vehicle rolling resistance and aerodynamic drag. These scenarios were applied, with appropriately estimated costs, to generate cost curves for both 2020 and 2025. Subsequent to the release of the cost curves, the ICCT has elected to cap 2020 mass reduction potential at 20 percent. In some cases, this decision affects both the shape and range of the 2020 cost curves presented in this paper relative to those presented in earlier work.

Fourth, to facilitate the removal of the 30 percent mass reduction road load scenario from 2020 cost curve work, two new road load scenarios were added to the cost curve analysis. Road load scenario three assumes a 10 percent reduction in vehicle mass in tandem with 5 percent reductions in vehicle rolling resistance and aerodynamic drag, while road load scenario four assumes a 20 percent reduction in vehicle mass in tandem with 15 percent reductions in vehicle rolling resistance and aerodynamic drag. The CO_2 reduction benefits and costs of these scenarios were developed in exactly the same manner as those for the previous two road load scenarios, as documented in detail in the previous papers in this series.

Fifth, four secondary road load scenarios analogous to those just described, but without any change in vehicle mass, were evaluated to isolate the potential effects of regulatory structures that *fully* discount the CO_2 reduction potential of vehicle mass reductions. The associated CO_2 reduction benefits and costs of these secondary scenarios were developed in exactly the same manner as those for primary road load scenarios, as documented in detail in the previous papers in this series. Table 10 presents a summary of the assumptions associated with the four primary and secondary road load scenarios.

Table 10. Road Load Scenario Definitions

Road Load Scenario	Primary Road Load Scenario Changes			Secondary Road Load Scenario Changes		
	MASS REDUCTION	ROLLING RESISTANCE REDUCTION	AERODYNAMIC DRAG REDUCTION	MASS REDUCTION	ROLLING RESISTANCE REDUCTION	AERODYNAMIC DRAG REDUCTION
1	15%	10%	10%	0%	10%	10%
2	30%	20%	20%	0%	20%	20%
3	10%	5%	5%	0%	5%	5%
4	20%	15%	15%	0%	15%	15%

5. Resulting EU Cost Curves

Figures 7 and 8 depict an example of the resulting cost curves. Specifically, the figures depict the cost curves for EU C class petrol and diesel vehicles respectively. Both figures present cost curves for 2020 and 2025, with and without mass reduction technology.[23] As indicated, the cost of CO_2 standard compliance is lower assuming that mass reduction technology is creditable.

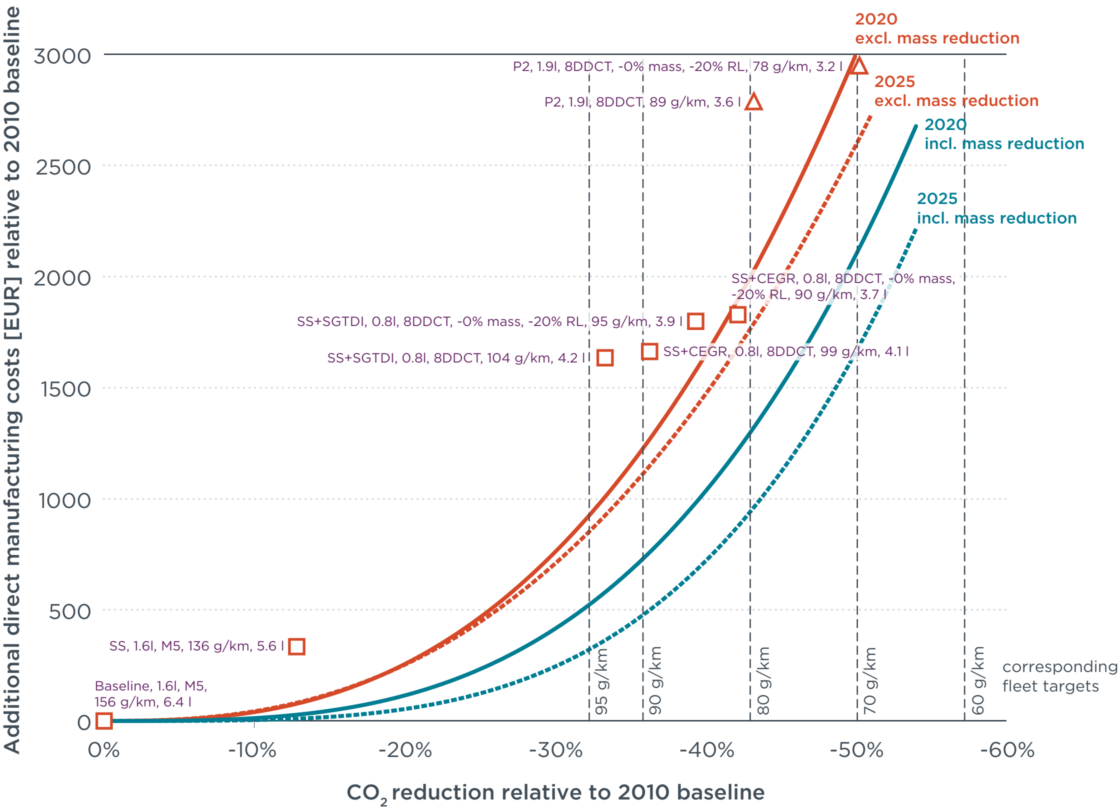

Figure 7. Cost Curves for Class C Petrol Vehicles

23 The vehicle technology packages included in the figures provide examples of the types of technology packages included in the underlying analysis. To facilitate readability, not all evaluated technology packages are included.

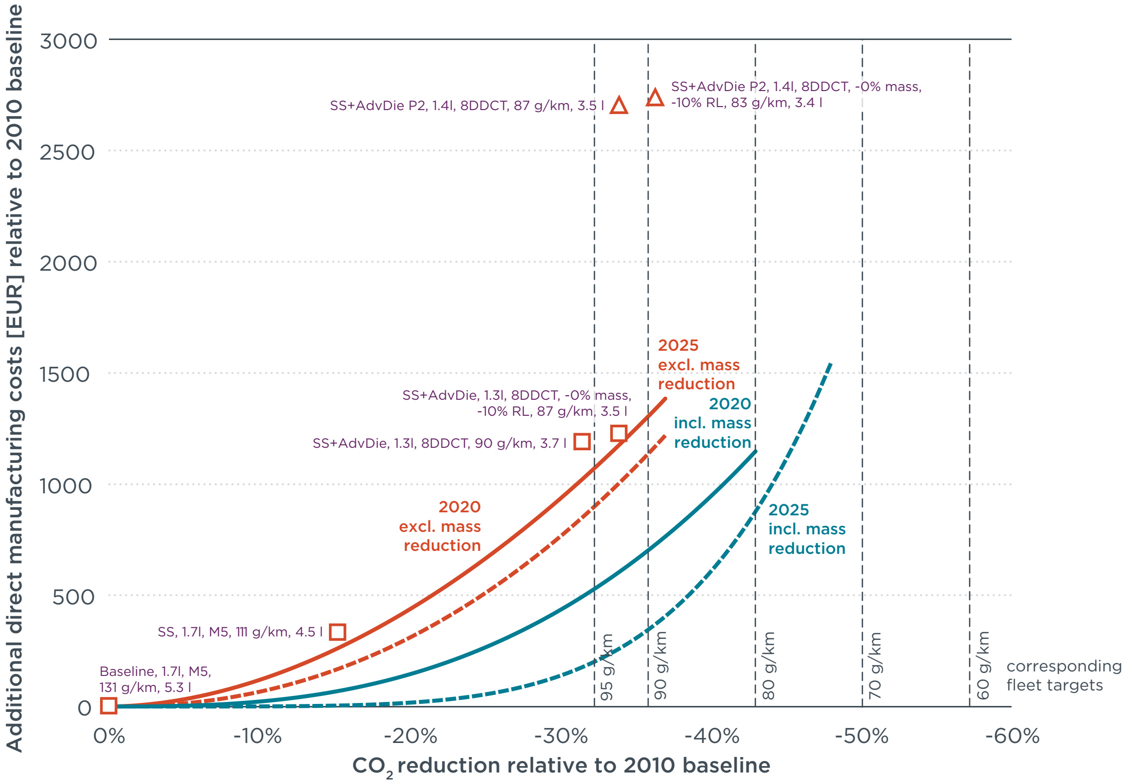

Figure 8. Cost Curves for Class C Diesel Vehicles

When the CO_2 emission reduction benefit of mass reduction technology is *fully discounted*, the cost of compliance with a 95 g/km CO_2 standard in 2020 increases by about 500 euros for petrol vehicles and about 600 euros for diesel vehicles compared to a situation in which mass reduction technology is *fully creditable*.[24] Differences are even greater in 2025 as mass reduction options are assumed to expand beyond the 20 percent mass reduction cap assumed for 2020.[25]

Figures 9 and 10 depict corresponding curves for passenger car classes evaluated for this paper. As indicated, the trends are similar to those of the C class vehicles, although there is variation between classes. The endpoints of the cost curves depend on the technologies included in the cost curve. For example, for C class petrol vehicles, P2 hybrid technology was found to be a cost effective measure and was therefore included for the cost curve construction. The resulting maximum CO_2 reduction potential for C class petrol vehicles in 2020 is approximately 50 percent if mass reduction benefits are excluded, or 54 percent if mass reduction benefits are included (see Figure 7). For C class diesel vehicles, P2 hybrid technology was found to result only in marginally higher CO_2 reductions than advanced non-hybrid diesel technology, while carrying much higher costs. P2 technology is, therefore, not included in the C class diesel cost curve construction. Hence, the maximum CO_2 reduction potential – and the endpoint of the diesel cost curve – is approximately 36 percent if mass reduction benefits are excluded, or 43 percent if mass reduction benefits are included (see Figure 8).

To better depict a generalized relationship, Figures 11 and 12 depict characteristic cost curves for 2020 and 2025 constructed by weighting the individual cost curves for each of the vehicle segments by their respective market shares. For this it is assumed that market distributions across vehicle classes and fuel shares within vehicle classes do not change over time (i.e., the market share of petrol and diesel vehicles within each vehicle class and the market shares of B, C, and D class vehicles remain constant between 2010 and 2020/25.

The darker shaded areas in Figures 11 and 12 indicate the CO_2 reduction range where cost curve data for *all* vehicle segments are available (i.e., the area is constrained by the endpoint of the least ambitious cost curve, which is that of the B class diesel vehicle). The lower bound of the area is defined by a scenario in which mass reduction technology is *fully* creditable, while the upper bound is

24 Note that the CO_2 target values indicated in the figures assume that all vehicle segments reduce CO_2 by an identical percentage. The C Class target itself is not 95 g/km per se, but the level of CO_2 that would result in a fleet average CO_2 level of 95 g/km.

25 Note that costs in 2020 and 2025 without mass reduction technology are not identical due to learning that is assumed to occur in the intervening five year period.

defined by a scenario where mass reduction technology is *fully discounted*. For example, the additional direct manufacturing costs to achieve a CO_2 standard of 95 g/km in 2020 are between 600 and 1200 euros relative to the 2010 baseline. The 600 euro estimate assumes a technology neutral CO_2 regulatory structure wherein mass reduction technology is *fully* creditable (e.g., a structure based on vehicle footprint), whereas the 1200 euro estimate is for a regulatory structure wherein mass reduction technology is *fully* discounted. The current EU vehicle weight-based structure *strongly*, but not *fully*, discounts mass reduction technology. The compliance costs under such a system are, therefore, assumed to be closer to – but less than – 1200 euros. Based on the methodology employed to develop the EU regulatory structure, it can be estimated that the cost for meeting a 95 g/km CO_2 standard in 2020 will be approximately 960 euros relative to the 2010 baseline.[26]

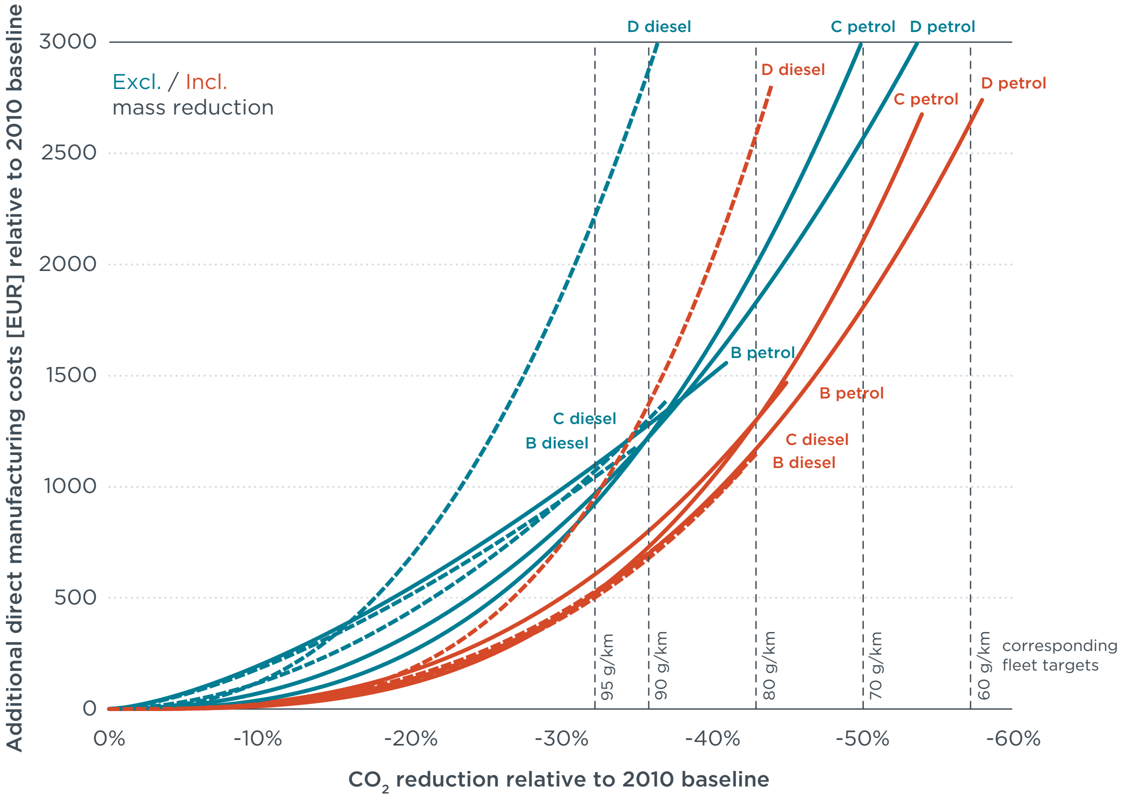

Figure 9. 2020 Class-Specific Cost Curves for Passenger Vehicles

26 This estimate is based on the fact that in developing their CO_2 standard algorithm, the EU initially calculated the algorithm on the basis of fully discounting mass reduction technology and then adjusted the algorithm by a factor of 60 percent to provide some disincentive to upweight and some credit for lightweighting. Assuming the EU calculations properly capture the relationship between weight and CO_2, it can be expected that the current program will function as if it retains 40 percent of the benefits of mass reduction. Since the full benefit of mass reduction equates to a cost reduction of 600 euros (1200 minus 600), 40 percent of that benefit is 240 euros, resulting in a net cost of 960 euros (1200 minus 240).

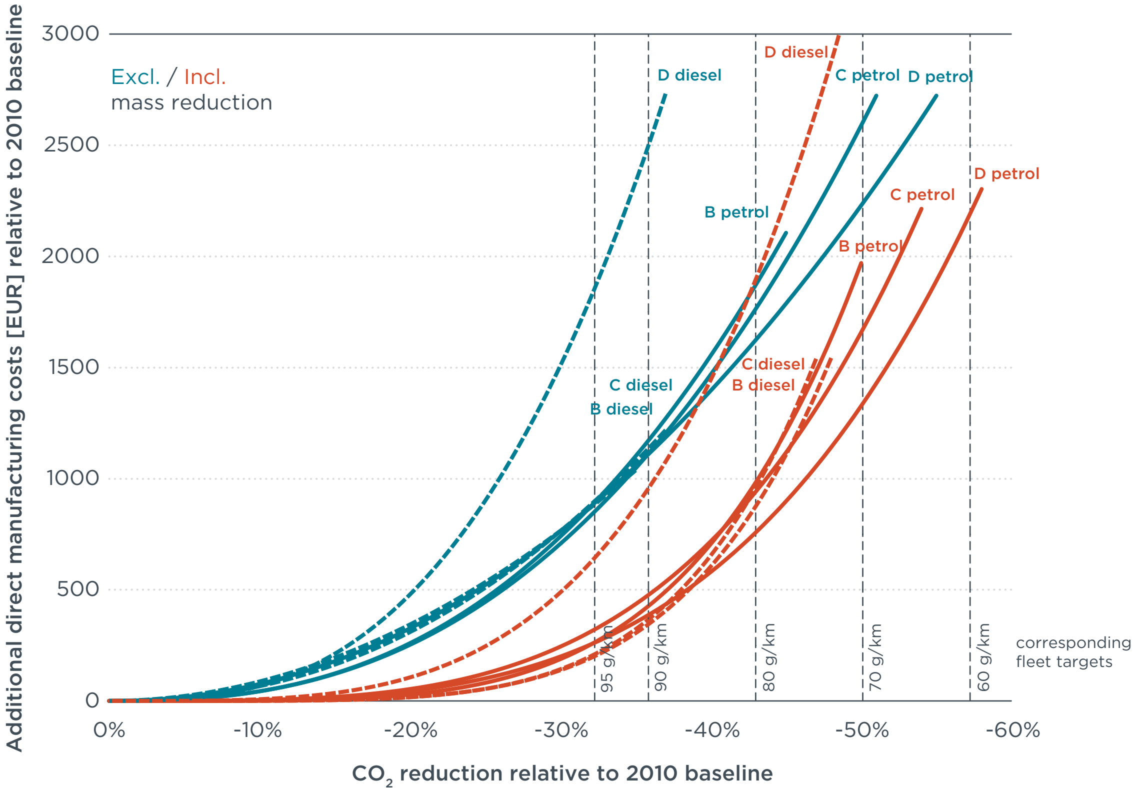

Figure 10. 2025 Class-Specific Cost Curves for Passenger Vehicles

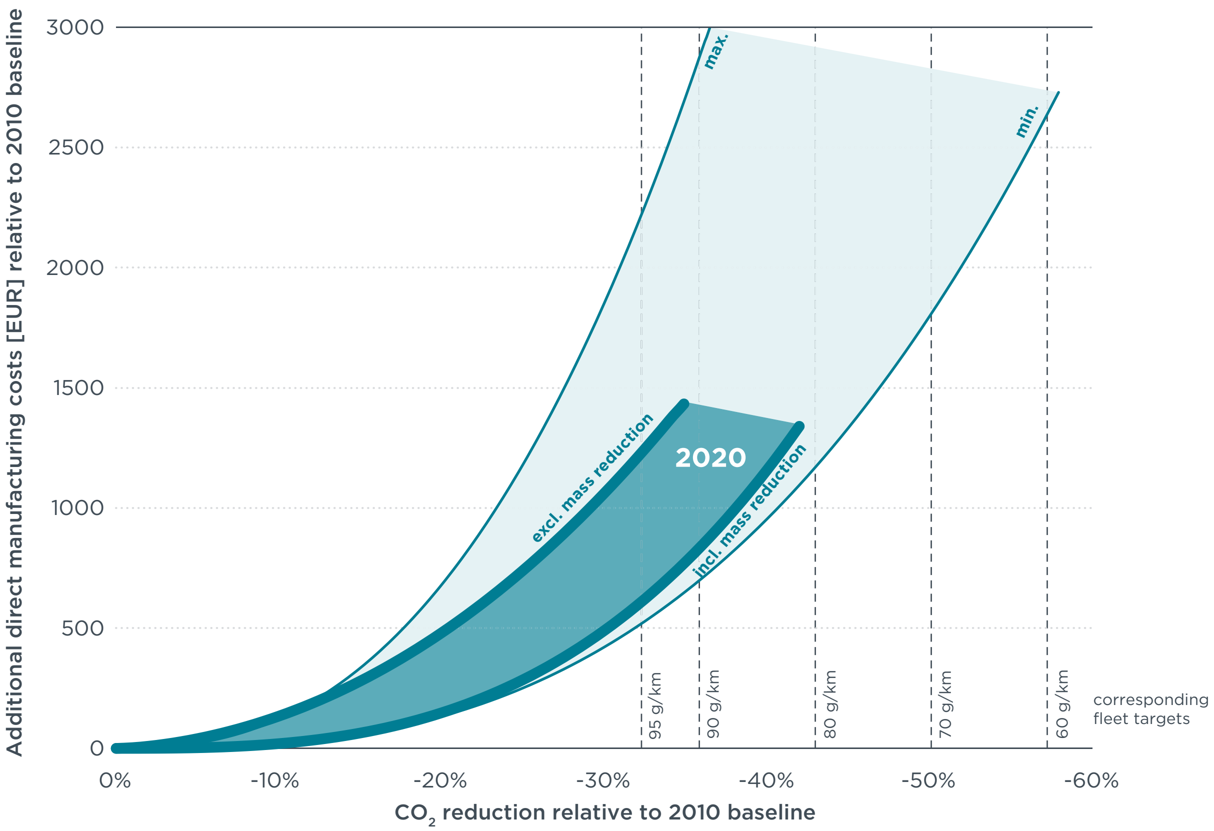

Figure 11. 2020 Passenger Vehicle Cost Curves Relative to 2010 Base

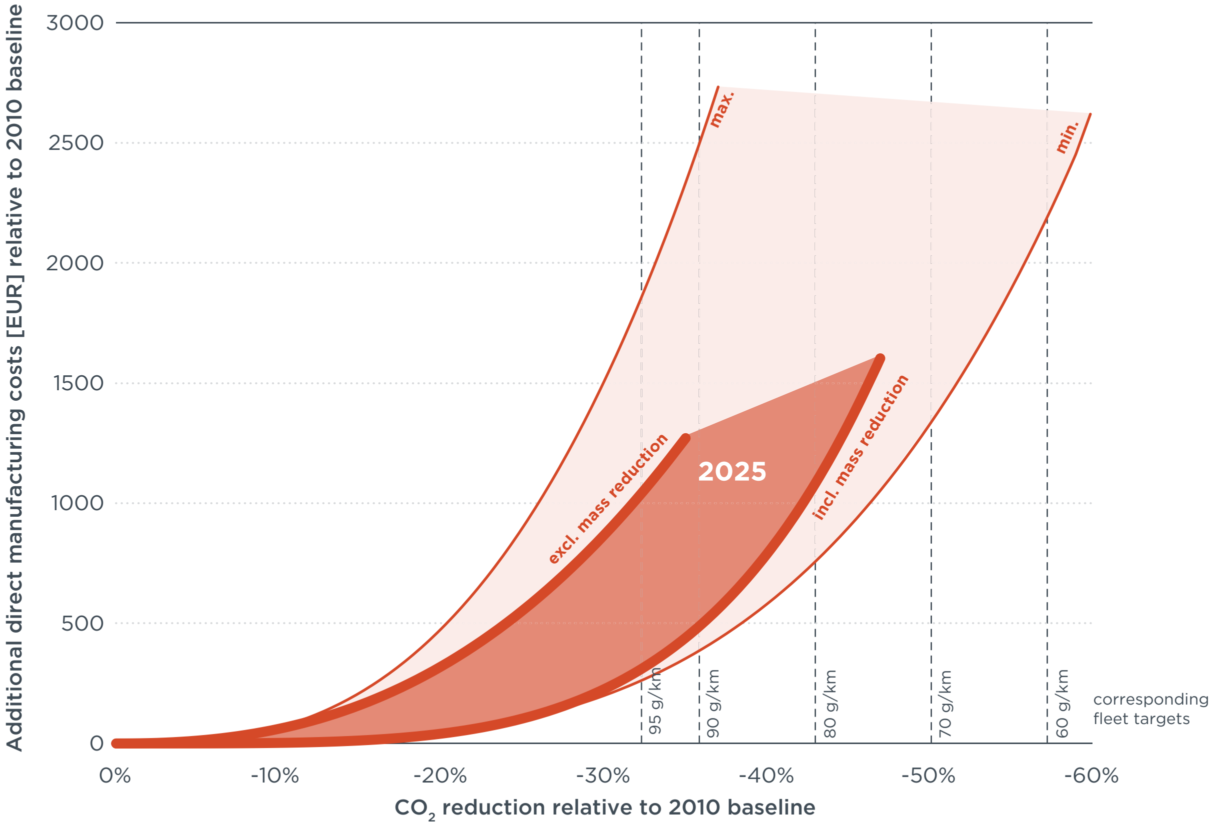

Figure 12. 2025 Passenger Vehicle Cost Curves Relative to 2010 Base

The lighter shaded areas in Figures 11 and 12 indicate the CO_2 reductions that are feasible in the most and least costly vehicle segments. The "maximum" curve indicates the most expensive cost curve (which reflects the D class diesel vehicle without mass reduction benefits), while the "minimum" curve indicates the least expensive cost curve (which reflects the D class petrol vehicle with mass reduction benefits). Meeting a CO_2 standard that is outside the darker shaded areas but within the lighter shaded areas requires either advances in technology beyond that considered in this analysis and/or shifts in vehicle class-specific of fuel-specific market shares.

Figures 13 and 14 depict similar characteristic curves, but expressed relative to the 2015 CO_2 standard of 130 g/km for passenger cars. Since the 130 g/km value is not far from the 2010 market average (140 g/km), the resulting cost curves are almost identical, and the compliance cost for a 95 g/km CO_2 standard in 2020 remain in the neighborhood of 500-1000 euros relative to the 2015 baseline.

Figures 15 through 18 depict corresponding cost curves for N1 (light-commercial) vehicles. The costs for meeting the current 147 g/km CO_2 standard in 2020 are in the range of 200 to 500 euros per vehicle relative to the 2010 baseline.[27]

27 It should be noted that for N1 vehicles, the least expensive cost curves are for small and large N1 petrol vehicles. Since these vehicles currently account for only about 6 percent of the market, the respective cost curves were not used to determine the lighter shaded areas in Figures 17 and 18. Instead, only the small and large N1 diesel vehicle cost curves were used.

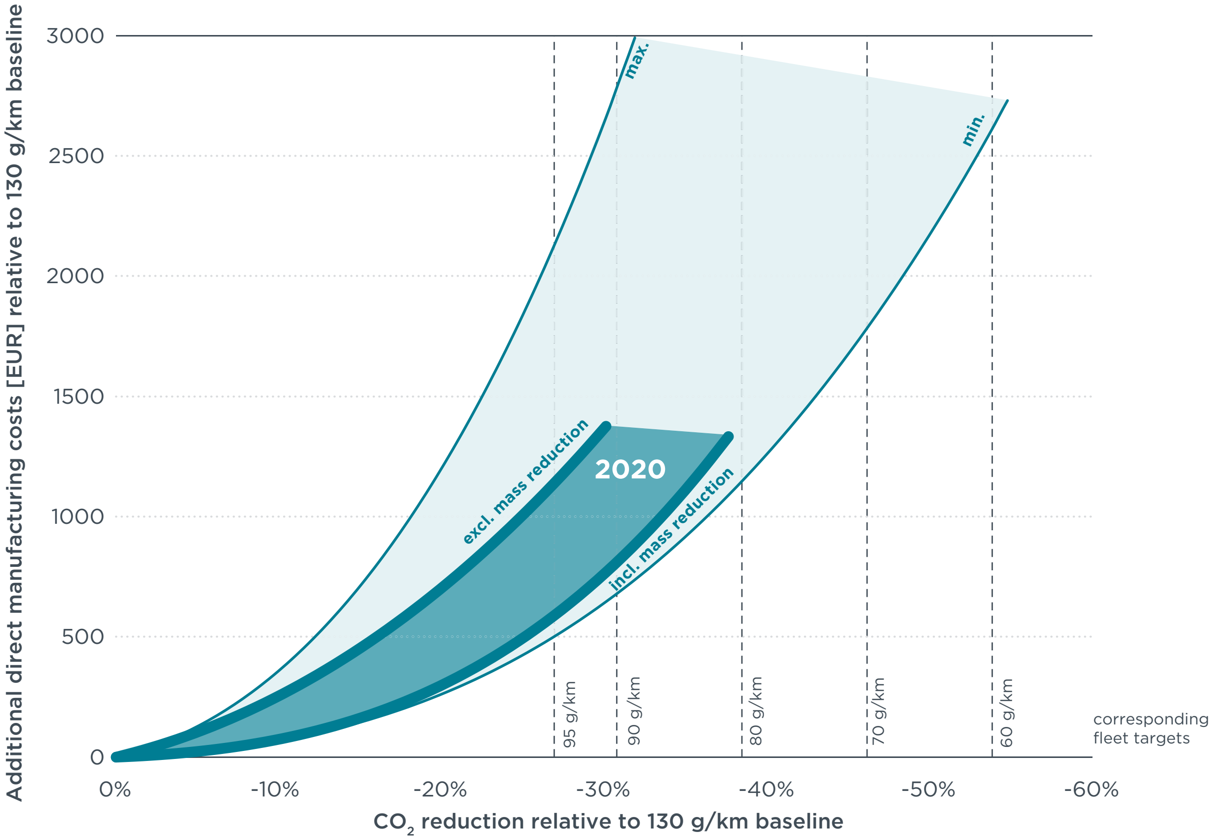

Figure 13. 2020 Passenger Vehicle Cost Curves Relative to 2015 Target

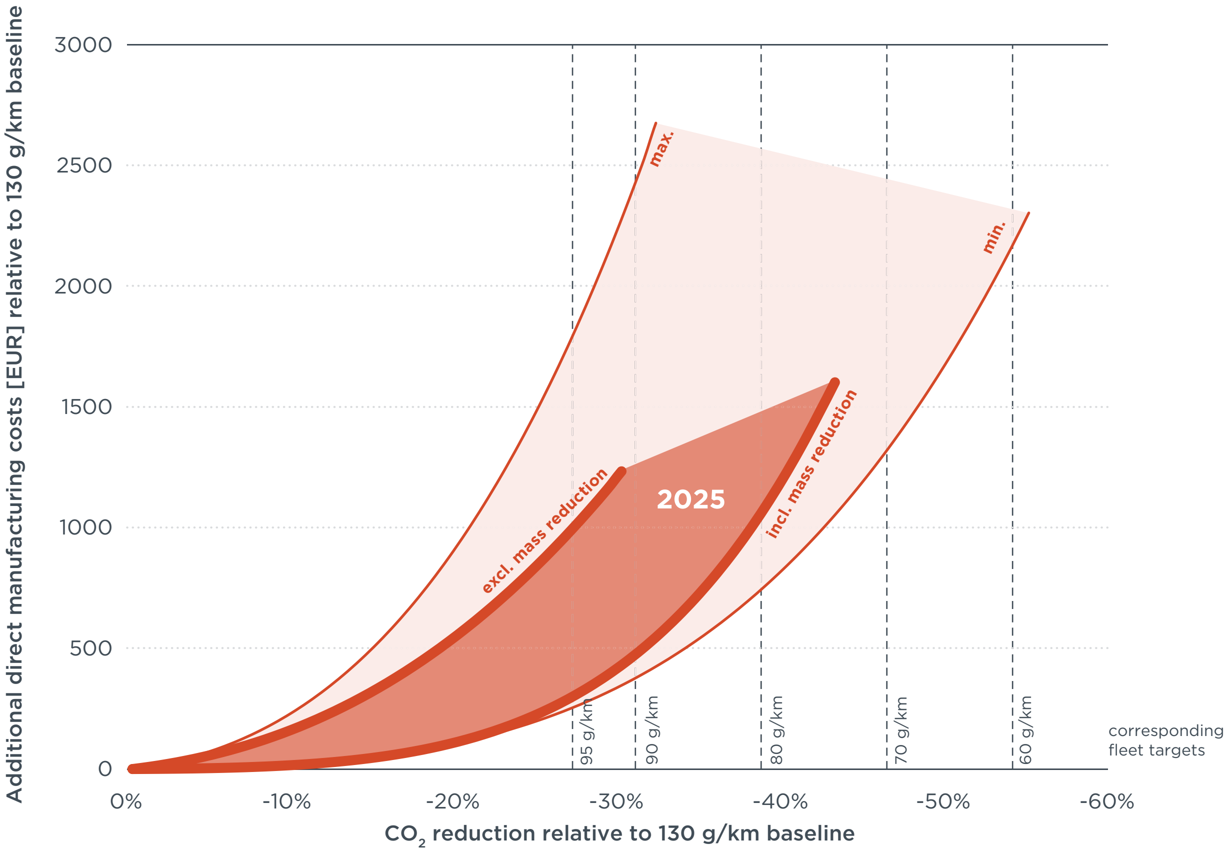

Figure 14. 2025 Passenger Vehicle Cost Curves Relative to 2015 Target

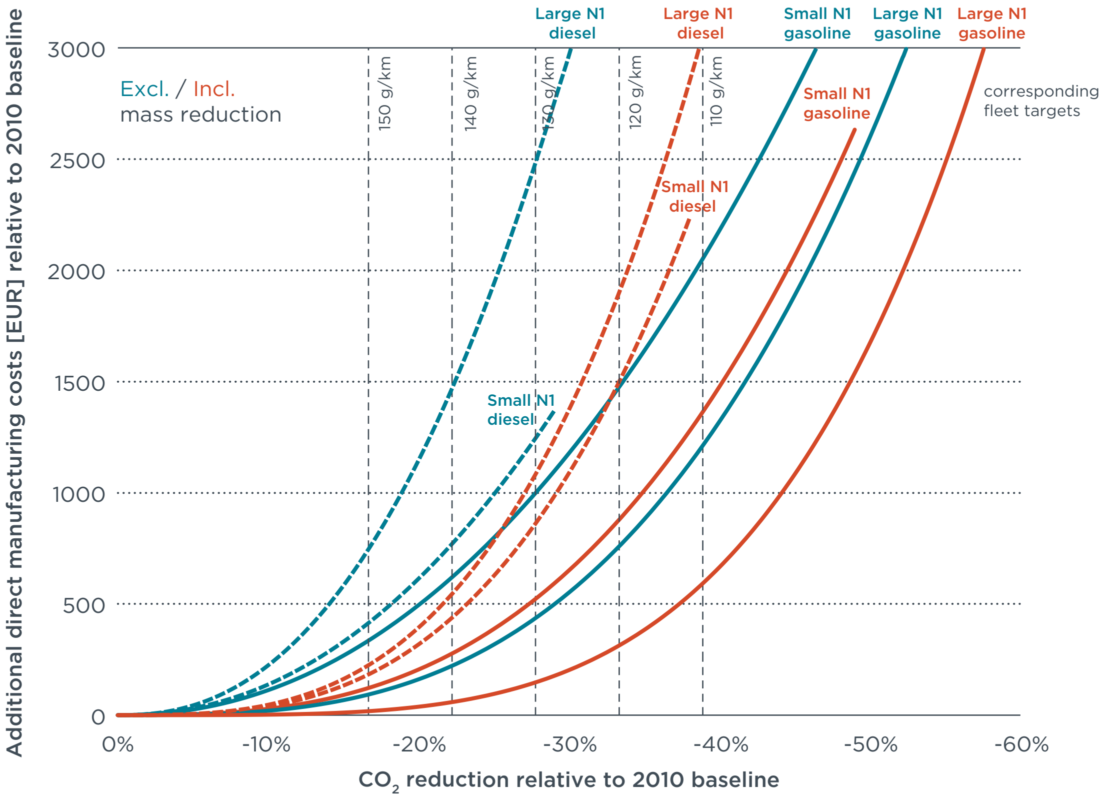

Figure 15. 2020 Cost Curves for N1 Class Vehicles

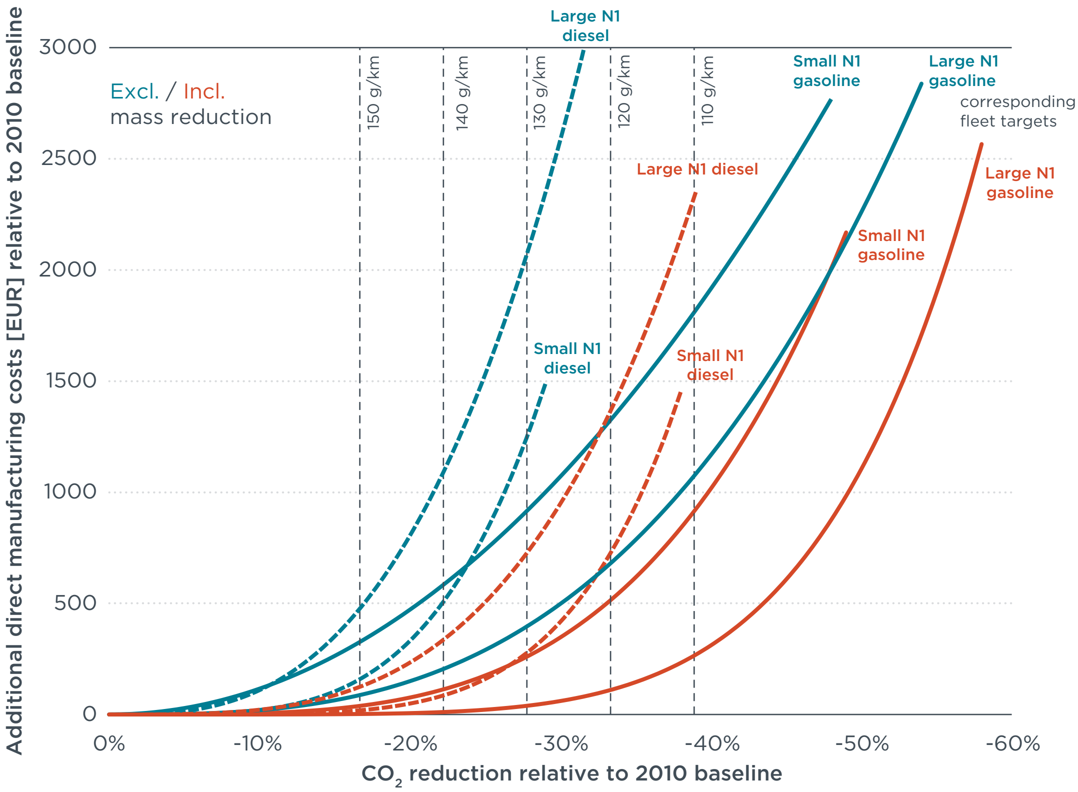

Figure 16. 2025 Cost Curves for N1 Class Vehicles

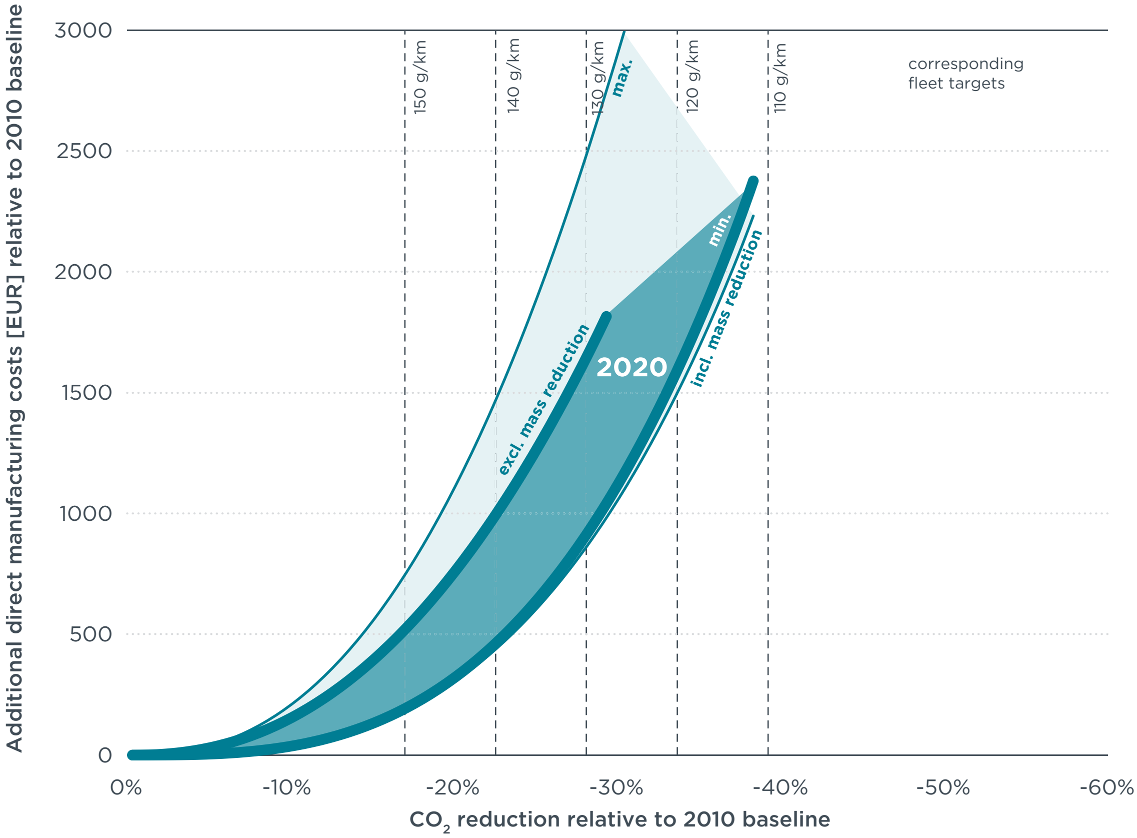

Figure 17. Characteristic 2020 N1 Cost Curves Relative to 2010 Base

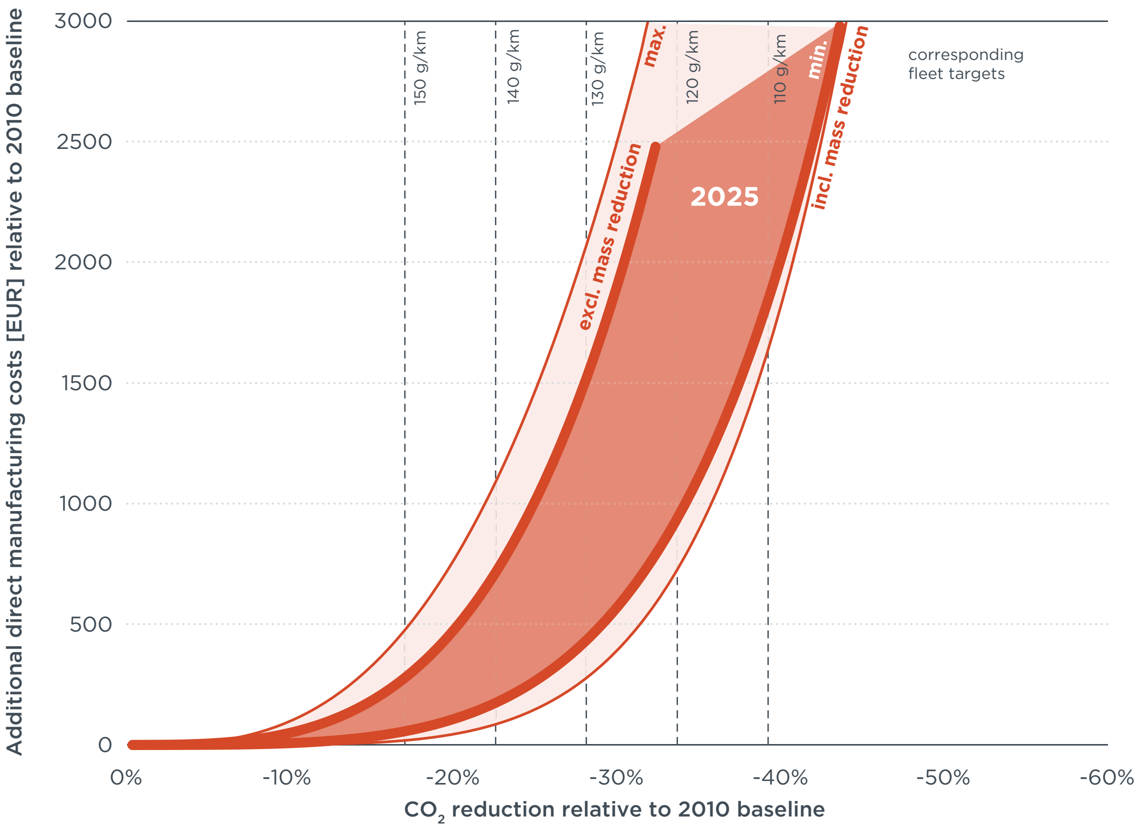

Figure 18. Characteristic 2025 N1 Cost Curves Relative to 2010 Base

6. Regulatory Structure Impacts

Figures 19 through 23 demonstrate the potential effect of the CO_2 regulatory structure on average and manufacturer-specific compliance costs. [28] Figure 19 shows the current status of various manufacturers, taking into account their 2011 fleet average weight and CO_2, as well as the respective CO_2 target lines for 2015 and 2020 under the EU weight-based structure.[29] The depicted bubble sizes represent the compliance costs associated with reducing CO_2 from 2011 levels to 2020 target levels, assuming that mass reduction is *fully* discounted. On average, the compliance cost is found to be 1,220 euros. Figure 20 provides corresponding data for a 2020 size-based regulatory structure under which mass reduction is fully creditable. The compliance costs are lower for all manufacturers, averaging 607 euros (as compared to 1,220 euros for the weight-based regulatory structure).

There were significant differences in the compliance status of manufacturers in 2011 with respect to their 2015 CO_2 standards. Some manufacturers were already quite close to their 2015 CO_2 targets, while others were still facing substantial CO_2 reduction requirements. It is possible to eliminate the effects of this differential compliance status by examining required reductions in the 2015-2020 timeframe assuming that all manufacturers are in compliance with their respective 2015 CO_2 targets. Figure 21 shows the required (percentage change) CO_2 reduction from a 2015 baseline. On average, a 27 percent reduction is required to meet a 95 g/km CO_2 standard, regardless of regulatory structure. At the individual vehicle manufacturer level, there are small differences in required reductions. For most manufacturers, the specific regulatory structure does not result in any difference in CO_2 reduction requirements. In cases where differences are observed, differences are generally less than 2-3 percent.

Figures 22 and 23 depict manufacturer-specific compliance costs measured from a 2015 baseline. As indicated, even though required CO_2 reductions are very similar under the mass-based and footprint-based regulatory structures, compliance costs are much lower when mass reduction benefits are fully creditable. Under such a structure, the average cost to meet a 95 g/km CO_2 standard in 2020 is about 550 euros relative to a 2015 130 g/km CO_2 baseline. For a regulatory structure wherein mass reduction benefits are *fully* discounted, the compliance costs *to achieve the same CO_2 standard* would be about 1150 euros, more than twice as much as under a structure that fully credits mass reduction benefits. Similar results can be found at the individual manufacturer level, with the fully creditable structure being 43-63 percent less expensive than a fully discounted structure. As previously discussed, the current EU weight-based structure *strongly*, but not *fully*, discounts mass reduction technology so that the actual difference between the EU and a fully creditable regulatory structure will be somewhat smaller. Using the same approach previously described, compliance costs in the EU would be about 910 euros as compared to 550 euros under a structure where mass reduction benefits are fully creditable. It is clear that a technology-neutral CO_2 regulatory structure that fully credits the benefits of vehicle mass reduction is much more cost effective than a structure that discounts mass reduction benefits, and leads to lower compliance costs for society as a whole.

28 For this analysis, we define two regulatory structures; the European Commission weight-based CO_2 regulatory structure with a slope of 0.0333 ($CO_2 = 95 + 0.0333 \times (m-m_0)$, where m_0 = 1389 kilograms) and a footprint-based regulatory structure with a slope of 17.0 ($CO_2 = 95 + 17 \times (f-f_0)$, where f_0 = 3.99 square meters). The slope of the footprint-based structure is identical to that analyzed in the latest European Commission Impact Assessment (see European Commission, "Commission Staff Working Document, Impact Assessment, Accompanying the documents, *Proposal for a regulation of the European Parliament and of the Council amending Regulation (EC) No 443/2009 to define the modalities for reaching the 2020 target to reduce CO2 emissions from new passenger cars* and *Proposal for a regulation of the European Parliament and of the Council amending Regulation (EU) No 510/2011 to define the modalities for reaching the 2020 target to reduce CO2 emissions from new light commercial vehicles*, SWD(2012) 213 final, Parts I and II, Brussels, 11.7.2012). As a first approximation, the same market average cost curve was applied to all manufacturers (i.e., it is implicitly assumed that the baseline technology level is the same for all manufacturers). In practice, baseline technology differs across manufacturers, so that individual manufacturers may have different compliance costs than estimated in this paper. Nevertheless, it is expected that average cost estimates are accurate, as are the relative differences between manufacturer-specific costs under the two alternative regulatory structures.

29 The 2015 target line is as adopted, while the 2020 target line is from the current European Commission proposal.

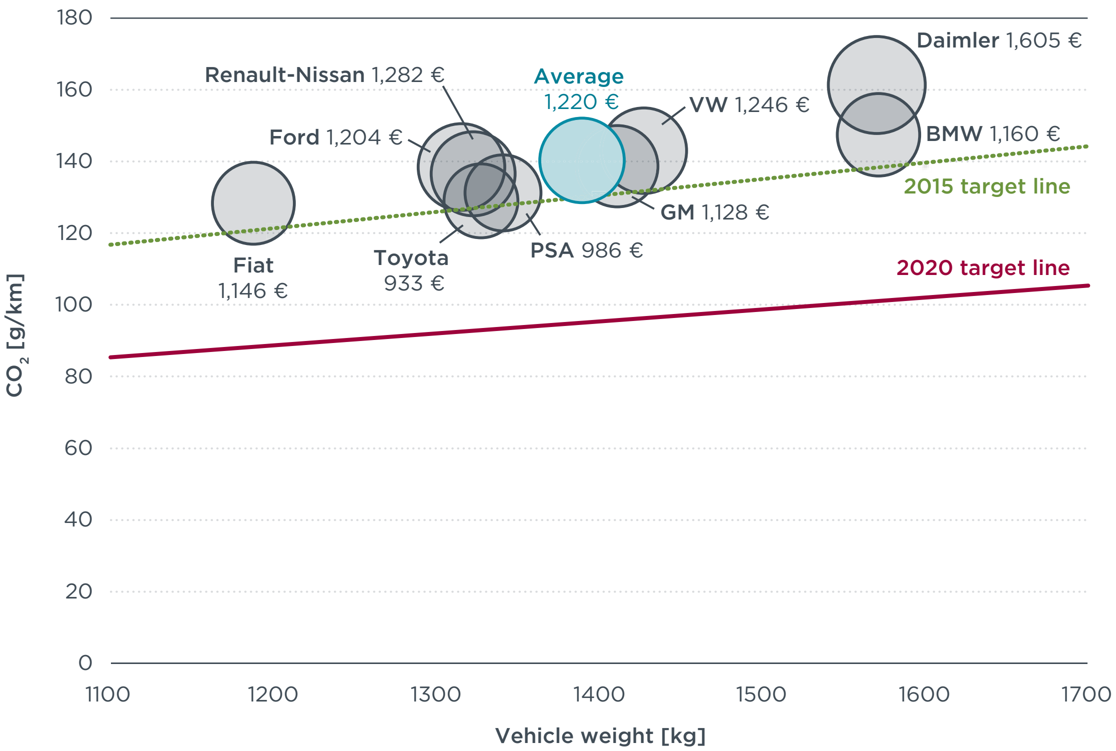

Figure 19. 2011 CO_2 and 2011-2020 Compliance Costs by Manufacturer for a Weight-Based System Fully Discounting Mass Reduction

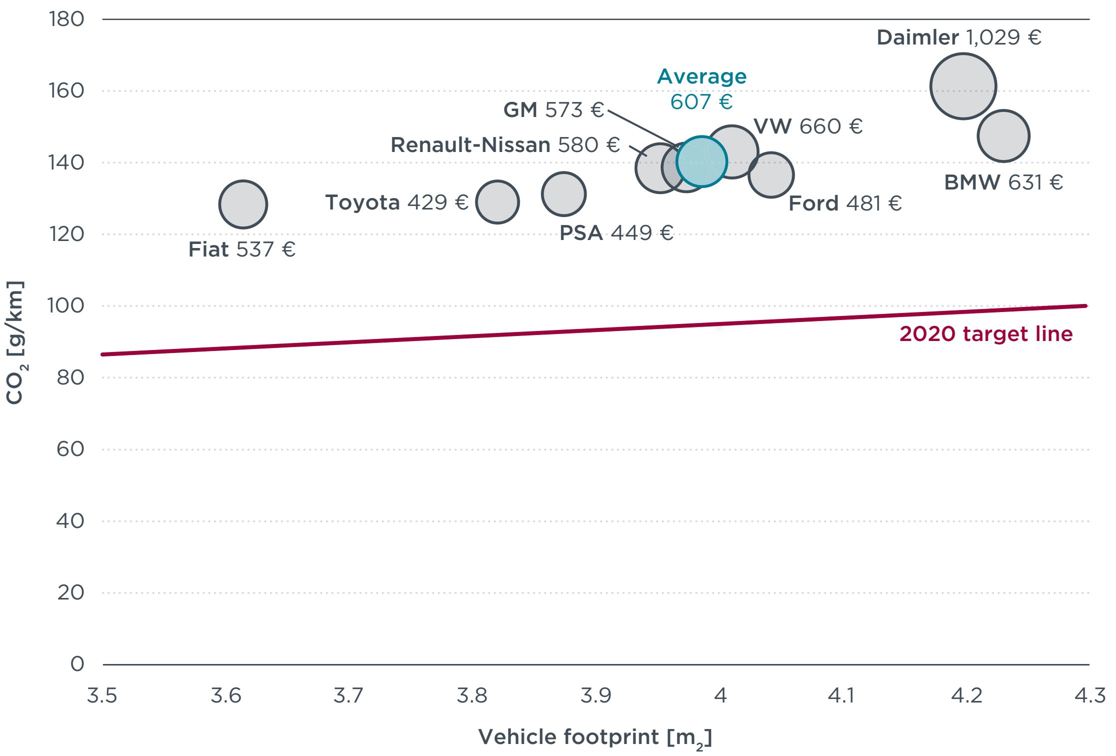

Figure 20. 2011 CO_2 and 2011-2020 Compliance Costs by Manufacturer for a Size-Based System Fully Crediting Mass Reduction

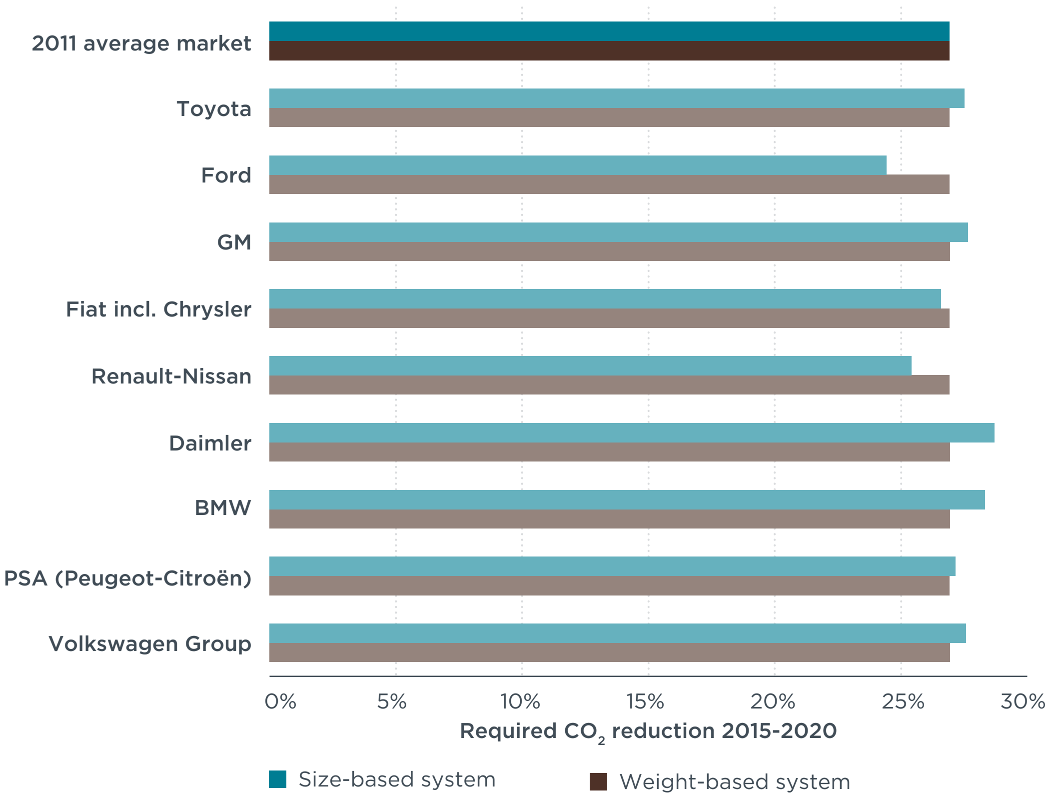

Figure 21. 2015-2020 CO_2 Reduction Requirements by Manufacturer

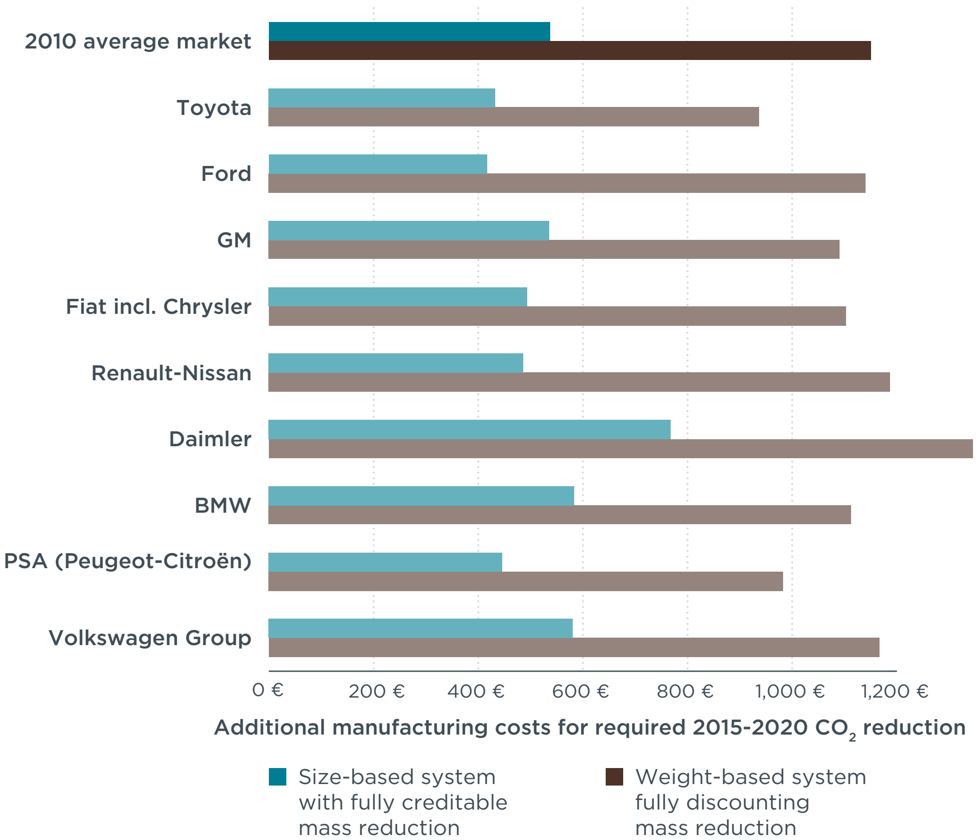

Figure 22. 2015-2020 Additional Manufacturing Costs by Manufacturer

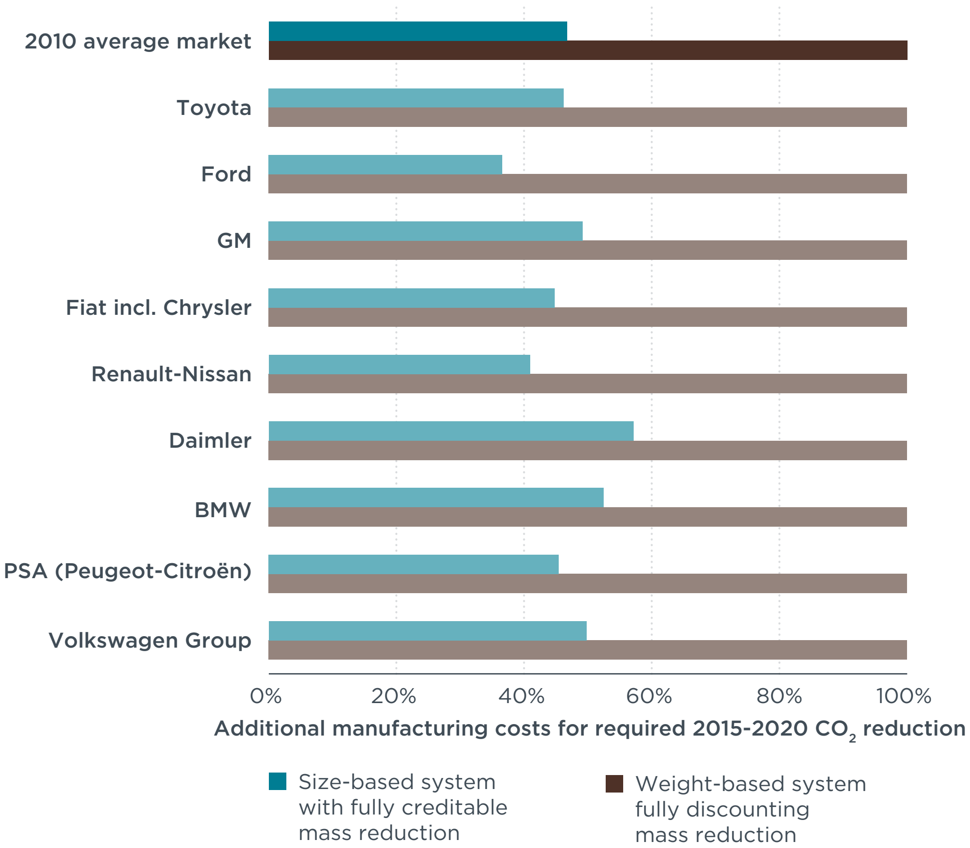

Figure 23. 2015-2020 Relative Additional Costs by Manufacturer

7. Summary Remarks

This paper presents a set of revised cost curves for the EU light-duty vehicle fleet that investigate: (1) the effects of newly released mass reduction cost data, and (2) the potential compliance cost effects of regulatory structures that discount the CO_2 benefits of mass reduction technology. Based on the revised curves, the following conclusions can be drawn for the average EU market.

- The estimated additional cost to attain a CO_2 standard of 95 g/km for passenger vehicles by 2020 is lower than 1000 euros per vehicle relative to 2010 baseline, and as low as 600 euros per vehicle under a CO_2 regulatory structure that fully credits vehicle mass reduction.
- The estimated additional cost to attain a CO_2 standard of 147 g/km for light-commercial vehicles by 2020 is approximately 500 euros per vehicle relative to a 2010 baseline, and as low as 200 euros per vehicle under a CO_2 regulatory structure that fully credits vehicle mass reduction.
- The 2020 targets can be attained by improvements to internal combustion engines and moderate mass reduction, with some degree of hybridization. It is expected that most manufacturers will be able to achieve compliance without introducing hybrids, but some manufacturers will likely need hybrid technology to offset atypical high-CO_2 fleet characteristics. Electric vehicles (either pure battery electric or plug-in hybrid electric) are not required to meet either fleet average CO_2 target. Note that manufacturers may still elect to introduce such vehicles for research, experience gathering, and other purposes.
- The cost to attain CO_2 standards below 95 g/km (passenger cars) and 147 g/km (light-commercial vehicles) depends on the specific standard and on the lead time allowed for compliance. Assuming that future market shares of fuels and vehicle classes remain constant, estimates can be derived from the cost curves presented in Figures 13-14 and 17-18.
- Compliance costs are much lower under a regulatory structure that fully credits the CO_2 emission reduction benefits of vehicle mass reduction than under a structure where mass reduction technologies are not fully creditable. In the extreme case of a regulatory structure that fully discounts vehicle mass reduction, compliance costs are twice as high. A technology neutral (e.g., size-based) CO_2 regulatory structure is, therefore, expected to result in significantly greater benefits for society than the current EU weight-based structure.

As with previous work in this series, 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. Nevertheless, 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.

8. Data Limitations and Future Work

Limitations to the approach and the presented cost curves include:

- An underlying cost assessment assumption 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 10-20 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 cost assessment assumption is that costs are based on high volume mass production, 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 fully discounts 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.
- 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, should diesel and gasoline fuel taxes be harmonized. Such a shift could have an impact on fleet average compliance costs. A detailed assessment of this effect will be presented in a subsequent 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. Subsequent working papers in this series will continue to investigate alternative cost curve scenarios.

9. Abbreviations and Acronyms

AdvDie	Advanced Diesel
ARB	California Air Resources Board
BIP	Body-in-Primer (Paint)
BIW	Body-in-White
CEGR	Cooled Exhaust Gas Recirculation
CO_2	Carbon Dioxide
DCT	Dual Clutch (Automated Manual) Transmission
DMC	Direct Manufacturing Costs
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
EU	European Union
excl.	Excluding
g	Gram(s)
g/km	Grams per kilometer
HEV	Hybrid Electric Vehicle
ICCT	International Council on Clean Transportation
ICM	Indirect Cost Multiplier
incl.	Including
kg	Kilogram(s)
km	Kilometer(s)
l	Liter(s)
max.	Maximum
min.	Minimum
Misc.	Miscellaneous
M5	Five Speed Manual Transmission
M6	Six Speed Manual Transmission
NHTSA	U.S. National Highway Traffic Safety Administration
P2	P2 Design HEV
RL	Road Load
SGTDI	Stoichiometric Gasoline (Petrol) Turbocharged Direct Injection
SS	Start-Stop (Idle-Off) Technology
TC	Total Cost (DMC × ICM)
U.S.	United States
USAMP	U.S. Automotive Materials Partnership
6DDCT	Six Speed Dry Dual Clutch (Automated Manual) Transmission
8DDCT	Eight Speed Dry Dual Clutch (Automated Manual) Transmission
8WDCT	Eight Speed Wet Dual Clutch (Automated Manual) Transmission
€	Euro
$US2009	2009 U.S. Dollars
$US2010	2010 U.S. Dollars

Appendix A. Vehicle Systems and Components Evaluated by FEV

Vehicle System/Subsystem/Component(s)	Base Mass (kg)	Mass Change (kg)
Engine System	**172.60**	**30.25**
Engine System Roll-up (Engine Down Size)	172.60	10.37
Engine Frames, Mounting, and Brackets Subsystem	15.27	1.11
Engine Mountings	12.39	1.11
Miscellaneous	2.89	0.00
Crank Drive Subsystem	24.73	0.69
Crankshaft	18.19	0.00
Flywheel	2.18	0.00
Connect Rods (Assemblies: Connecting Rod, Connecting Rod Cap)	2.68	0.60
Pistons (Assemblies, Including Pistons, Ring Packs, Piston Pins, Circlips)	1.69	0.09
Counter Balance Subsystem	7.22	0.00
Dynamic Parts	2.58	0.00
Static Parts	2.49	0.00
Miscellaneous	2.14	0.00
Cylinder Block Subsystem	30.13	7.11
Cylinder Block	19.96	5.06
Crankshaft Bearing Caps	3.64	0.00
Piston Cooling	0.14	0.12
Crankcase Adaptor	6.17	1.92
Water Jacket	0.19	0.00
Miscellaneous	0.04	0.00
Cylinder Head Subsystem	21.12	1.05
Cylinder Head	13.66	0.90
Guides for Valvetrain	0.28	0.00
Camshaft Bearing Housing	1.29	0.00
Camshaft Carrier	3.08	0.00
Other Parts for Cylinder Head	0.46	0.10
Cylinder Head Covers	2.35	0.05
Valvetrain Subsystem	9.78	3.71
Inlet Valves	0.39	0.01
Outlet Valves	0.35	0.01
Valve Springs	0.54	0.15
Spring Retainers, Cotters, Spring Seats	0.16	0.00
Actuation Elements: Rockers, Finger Followers, Hydraulic Lash Adjusters, etc.	1.01	0.00
Camshafts	4.90	2.13
Camshaft Phaser and/or Cam Sprockets	2.43	1.39
Timing Drive Subsystem	4.31	1.45
Timing Wheels (Sprockets)	0.18	0.00
Tensioners	0.25	0.12
Guides	0.54	0.05
Belts, Chains	0.52	0.00
Covers	2.82	1.28
Accessory Drive Subsystem	0.55	0.00
Tensioners	0.44	0.00

continued

Appendix A Continuation. Vehicle Systems and Components Evaluated by FEV

Vehicle System/Subsystem/Component(s)	Base Mass (kg)	Mass Change (kg)
Belts	0.11	0.00
Air Intake Subsystem	13.99	0.51
Intake Manifold	7.12	0.00
Air Filter Box	1.52	0.14
Air Filters	0.18	0.00
Throttle Housing Assembly; including Supplies	3.09	0.24
Miscellaneous	2.09	0.12
Fuel Induction Subsystem	0.54	0.11
Fuel Rails	0.39	0.11
Fuel Injectors	0.15	0.00
Exhaust Subsystem	7.39	0.00
Exhaust Manifold	7.21	0.00
Oxygen Sensors	0.18	0.00
Lubrication Subsystem	3.34	0.23
Oil Pans (Oil Sump)	1.75	0.17
Oil Pumps	1.04	0.00
Pressure Regulators	0.10	0.00
Oil Filter	0.31	0.00
Miscellaneous	0.15	0.07
Cooling Subsystem	14.10	2.59
Water Pumps	2.87	1.60
Thermostat Housings	0.21	0.00
Heat Exchangers	9.54	0.99
Pressure Regulators	0.03	0.00
Expansion Tanks	0.28	0.00
Miscellaneous	1.17	0.00
Breather Subsystem	0.90	0.22
Oil/Air Separator	0.85	0.22
Valves	0.05	0.00
Engine Management, Engine Electronic, Electrical Subsystem	2.65	0.39
Spark Plugs, Glow Plugs	0.20	0.00
Engine Management Systems, Engine Electronic Systems	1.30	0.39
Engine Electrical Systems (including Wiring Harnesses, Earth Straps, Ignition Harness, Coils, Sockets)	1.07	0.00
Miscellaneous	0.09	0.00
Accessory Subsystems (Start Motor, Generator, etc.)	16.56	0.71
Starter Motors	2.91	0.00
Alternators	6.03	0.00
Air Conditioning Compressors	7.23	0.71
Miscellaneous	0.40	0.00
Transmission System	**92.76**	**18.90**
External Components	0.02	0.00
Venting Caps (Transmission Breather)	0.02	0.00
Case Subsystem	24.57	7.75
Transaxle Case	8.30	2.95

continued

Appendix A Continuation. Vehicle Systems and Components Evaluated by FEV

Vehicle System/Subsystem/Component(s)	Base Mass (kg)	Mass Change (kg)
Transaxle Housing	11.48	3.71
Covers	4.79	1.09
Gear Train Subsystem	41.44	3.49
Planetary Gears	32.41	0.26
Carrier Gears	9.03	3.23
Launch Clutch Subsystem	9.75	4.90
Torque Converter Assembly	9.75	4.90
Oil Pump and Filter Subsystem	6.53	1.03
Oil Pump Assembly	4.65	1.03
Covers	1.67	0.00
Filters	0.21	0.00
Mechanical Controls Subsystem	6.30	0.00
Valve Body Assembly	6.30	0.00
Electrical Controls Subsystem	0.78	0.00
Controller	0.41	0.00
Switch	0.37	0.00
Parking Mechanism Subsystem	0.90	0.00
Pawls	0.90	0.00
Driver Operated External Controls Subsystem	2.48	1.73
Shift Module Assembly	2.48	1.73
Body System (Group -A-)	**528.88**	**68.32**
Body Structure Subsystem	383.95	50.79
Underbody	40.20	8.10
Front Structure	42.00	5.70
Roof	31.30	7.20
Bodyside	161.90	17.57
Rear Wheel Arch Liners	1.22	0.12
Ladder	99.13	12.10
Bolt on BIP Components	8.20	0.00
Body Closure Subsystem	137.48	17.13
Hood	17.80	7.70
Front Door	53.20	0.00
Rear Door	42.40	0.00
Rear Hatch	15.00	7.20
Under Eng. Closures/Air Dams	2.28	0.23
Front Fenders	6.80	2.00
Bumpers Subsystem	7.45	0.40
Front Bumper	5.05	0.40
Rear Bumper	2.40	0.00
Body System (Group -B-)	**220.61**	**42.00**
Interior Trim and Ornamentation Subsystem	65.20	8.92
Main Floor Trim	5.90	0.08
NVH Pads	5.49	0.00
Headliner Assembly	5.51	0.01
Sun Visors	1.02	0.07

continued

Appendix A Continuation. Vehicle Systems and Components Evaluated by FEV

Vehicle System/Subsystem/Component(s)	Base Mass (kg)	Mass Change (kg)
Front LH & RH Door Trim Panel	6.78	0.73
Rear LH & RH Door Trim Panel	6.69	0.69
Pillar Trim Lower	1.45	0.29
Load Compartment Side Trim	11.08	3.84
Rear Closure Interior Trim Panel	0.28	0.03
Cargo Retention	1.61	0.16
Floor Mats - OEM	6.77	0.81
Load Compartment Floor Trim	5.39	1.08
Pillar Trim Upper	1.76	0.28
Load Compartment Transverse Trim	5.11	0.86
Carpet Support	0.39	0.02
Sound and Heat Control Subsystem (Body)	4.50	0.27
Heat Insulation Shields - Engine Bay	2.55	0.00
Noise Insulation, Engine Bay	0.42	0.00
Engine Compartment Trim	1.53	0.27
Sealing Subsystem	8.23	2.03
Front Side Door Dynamic Weatherstrip	1.71	0.43
Static Sealing	4.79	1.20
Rear Side Door Dynamic Weatherstrip	1.43	0.36
Hood Dynamic Weatherstrip	0.12	0.03
Fender Seals	0.17	0.02
Seating Subsystem	92.55	23.39
Front Drivers Seat	26.91	4.72
Front Passenger Seat	22.75	3.64
Rear 60% Seat	26.48	13.55
Rear 40% Seat	16.41	1.49
Instrument Panel and Console Subsystem	32.69	6.33
Cross-Car Beam (IP)	10.37	3.98
Instrument Panel Main Molding	11.84	1.63
Applied Parts - (IP)	0.01	0.00
Center Stack	10.48	0.73
Occupant Restraining Device Subsystem	17.44	1.06
Seat Belt Assembly Front Row	4.25	0.00
Passenger Airbag / Cover Unit	2.43	0.48
Restraint Electronics	0.23	0.00
Seat Belts - Second Row	3.35	0.00
Front Side Airbag	0.86	0.00
Deployable Roll Bar Systems	3.19	0.00
Inflatable Knee Bolster or Active Leg Protection	2.02	0.38
Tether Anchorages - Non Integrated	0.01	0.00
Steering Wheel Airbag	1.10	0.20
Body System (Group -C-)	**26.56**	**2.37**
Exterior Trim and Ornamentation Subsystem	13.38	1.15
Radiator Grill	1.46	0.16
Lower Exterior Finishers	4.35	0.46

continued

Appendix A Continuation. Vehicle Systems and Components Evaluated by FEV

Vehicle System/Subsystem/Component(s)	Base Mass (kg)	Mass Change (kg)
Upper Exterior and Roof Finish	0.87	0.09
Rear Closure Finishers	1.38	0.15
Badging	0.05	0.00
Rear Spoiler Assembly	1.84	0.19
Cowl Vent Grill Assembly	2.72	0.10
Miscellaneous	0.71	0.00
Rear View Mirrors Subsystem	2.75	0.22
Interior Mirror	0.53	0.00
Exterior Mirrors	2.22	0.22
Miscellaneous	0.01	0.00
Front End Modules	5.03	0.49
Module - Front Bumper and Fascia	5.03	0.49
Rear End Modules	5.39	0.51
Module - Rear Bumper and Fascia	5.39	0.51
Body System (Group -D-) Glazing & Body Mechatronics	**63.46**	**6.16**
Glass (Glazing), Frame and Mechanism Subsystem	48.01	6.06
Windshield and Front Quarter Window (Fixed)	15.73	1.56
First Row Door Window Lift Assembly	3.13	0.94
Back and Rear Quarter Windows (Fixed)	2.13	0.23
Second Row Door, Quarter & Rear Closure Window Lift Assembly	3.13	0.94
Back Window Assembly	7.04	1.22
Front Side Door Glass	8.85	0.00
Rear Side Door Glass	6.59	1.18
Switch Pack - Front Door	0.37	0.00
Switch Pack - Rear Door	0.24	0.00
Front Side Doors Glass Runs & Belts	0.46	0.00
Rear Side Doors Glass Runs & Belts	0.33	0.00
Handles, Locks, Latches and Mechanisms Subsystem	4.93	0.00
Side Door Latches	2.22	0.00
Rear Closure Latches	1.06	0.00
Outer Handles and Actuation	1.25	0.00
Hood Support and Struts	0.35	0.00
Miscellaneous	0.07	0.00
Rear Hatch Lift assembly	4.56	0.00
Rear Hatch Lift Mechanism - Power or Manual	3.27	0.00
Rear Hatch Switches	0.03	0.00
Rear Hatch Sensors	0.09	0.00
Rear Hatch Finishers	0.85	0.00
Miscellaneous	0.32	0.00
Wipers and Washers Subsystem	5.96	0.10
Wiper Assembly Front	4.06	0.00
Wiper Assembly Rear	1.06	0.00
Miscellaneous	0.84	0.10
Suspension System	**241.49**	**66.83**
Front & Rear Suspension Subsystem - EDAG Adjustment	0.00	0.00

continued

Appendix A Continuation. Vehicle Systems and Components Evaluated by FEV

Vehicle System/Subsystem/Component(s)	Base Mass (kg)	Mass Change (kg)
Front Suspension Subsystem	32.89	11.57
Front Road Spring	0.00	0.00
Front Suspension Links/Arms Upper and Lower	11.61	1.93
Front Suspension Knuckle Assembly	12.49	6.76
Front Stabilizer (Anti-Roll) Bar Assembly	8.79	2.88
Rear Suspension Subsystem	23.58	8.32
Rear Suspension Links/Arms Upper and Lower	8.48	1.00
Rear Suspension Knuckle Assembly	11.34	5.76
Rear Stabilizer (Anti-Roll) Bar Assembly	3.77	1.56
Shock Absorber Subsystem	42.94	14.11
Front Strut / Damper Assembly	22.53	9.33
Rear Strut / Damper Assembly	20.41	4.78
Wheels And Tires Subsystem	142.07	32.83
Road Wheels and Tire Assembly	122.84	30.83
Spare Wheel and Tire Assembly	19.23	2.00
Driveline System	33.66	1.50
Rear Drive Housed Axle Subsystem	8.63	0.00
Front Drive Housed Axle Subsystem	6.35	0.73
Front Drive Unit	6.35	0.73
Front Drive Half-Shafts Subsystem	18.67	0.77
Front Half Shaft	18.67	0.77
Brake System	**86.71**	**32.75**
Front Rotor/Drum and Shield Subsystem	32.97	12.65
Front Rotor and Shield	18.92	5.02
Front Caliper, Anchor and Attaching Components	13.93	7.50
Miscellaneous	0.12	0.12
Rear Rotor/Drum and Shield Subsystem	23.44	6.24
Rear Rotor and Shield	14.89	1.22
Rear Caliper, Anchor and Attaching Components	8.55	5.03
Parking Brake and Actuation Subsystem	13.40	9.63
Parking Brake Controls	3.69	2.49
Parking Brake Cables and Attaching Components	2.12	2.12
Parking Brake Shoes and Hardware	7.60	5.03
Brake Actuation Subsystem	5.54	2.98
Master Cylinder and Reservoir	0.82	0.00
Actuator Assemblies	2.38	1.44
Brake Lines and Hoses	2.34	1.54
Power Brake Subsystem (for Hydraulic)	2.83	1.24
Vacuum Booster System Assembly	2.83	1.24
Brake Controls Subsystem	8.53	0.00
Brake Controls	8.53	0.00
Frame and Mounting System	**43.73**	**16.34**
Frame Sub System	43.73	16.34
Special Protective Structures	0.06	0.00
Body Isolators	0.77	0.00

continued

Appendix A Continuation. Vehicle Systems and Components Evaluated by FEV

Vehicle System/Subsystem/Component(s)	Base Mass (kg)	Mass Change (kg)
Front Strut Frame	32.55	13.80
Rear Strut Frame	10.35	2.54
Exhaust System	**26.62**	**7.52**
Acoustical Control Components Subsystem	11.74	2.79
Acoustic Control Components	11.74	2.79
Exhaust Gas Treatment Components Subsystem	14.87	4.73
Emission Control Components	14.87	4.73
Fuel System	**24.28**	**12.70**
Fuel Tank And Lines Subsystem	21.02	12.21
Fuel Tank Assembly	18.78	11.66
Fuel Distribution	0.52	0.00
Fuel Filler	1.72	0.55
Fuel Vapor Management Subsystem	3.26	0.50
Fuel Vapor Canister Assembly	3.26	0.50
Steering System	**24.23**	**1.82**
Steering Gear Subsystem	8.82	0.12
Steering Gear	8.82	0.12
Power Steering Subsystem	7.48	0.21
Power Steering Electronic Controls	7.48	0.21
Steering Column Subsystem	5.08	1.15
Steering Column Assembly	5.08	1.15
Steering Column Switches Subsystem	0.55	0.00
Steering Column and Shroud Mounted - Switches and Clockspring	0.55	0.00
Steering Wheel Subsystem	2.29	0.34
Steering Wheel	2.00	0.33
Steering Wheel Mounted Switches	0.18	0.00
Steering Wheel Trim	0.11	0.01
Climate Control System	**15.66**	**2.44**
Air Handling/Body Ventilation Subsystem	12.81	2.03
Air Distribution Duct Components	1.86	1.45
Body Air Outlets	0.91	0.10
HVAC Main Unit: Air Distribution Box/ Heater Core & Evaporator	10.05	0.48
Heating/Defrosting Subsystem	1.03	0.39
Front Window/Windshield Defrosting	0.51	0.39
Supplementary Heat Source	0.52	0.00
Refrigeration/Air Conditioning Subsystem	1.33	0.00
AC Lines, Receiver Drier and Accumulator	1.26	0.00
Miscellaneous	0.07	0.00
Controls Subsystem	0.48	0.01
Mechanical Control Head	0.33	0.00
Electronic Climate Control Unit	0.16	0.01
Information, Gage and Warning Device System	**1.90**	**0.08**
Instrument Cluster Subsystem	1.40	0.08
Driver Information Center	0.45	0.03
IP Cluster	0.95	0.05

continued

Appendix A Continuation. Vehicle Systems and Components Evaluated by FEV

Vehicle System/Subsystem/Component(s)	Base Mass (kg)	Mass Change (kg)
Horn Subsystem	0.50	0.00
Electrical Power Supply System	**0.00**	**0.00**
Service Battery Subsystem	0.00	0.00
In-Vehicle Entertainment System	**4.59**	**1.07**
Receiver and Audio Media Subsystem	3.15	1.02
Enclosures	1.21	1.02
Electronic Boards	1.04	0.00
Plastic Enclosure	0.65	0.00
Multimedia Interface (USB)	0.26	0.00
Antenna Subsystem	0.16	0.05
Infotainment Antennas and Cables	0.16	0.05
Speaker Subsystem	1.28	0.00
Speakers	1.28	0.00
Lighting System	**10.04**	**0.53**
Front Lighting Subsystem	6.09	0.53
Headlamp Cluster Assembly	5.56	0.53
Supplemental Front Lamps	0.53	0.00
Interior Lighting Subsystem	0.00	0.00
Rear Lighting Subsystem	3.83	0.00
Rear Combination Lamp	2.61	0.00
Supplemental Rear Lamps	1.07	0.00
License Plate Lamp	0.03	0.00
CHMSL (Center High Mount Stop Light)	0.12	0.00
Lighting - Special Mechanisms Subsystem	0.00	0.00
Lighting Switches Subsystem	0.13	0.00
Miscellaneous	0.13	0.00
Electrical Distribution and Electronic Control System	**23.94**	**0.89**
Electrical Wiring and Circuit Protection Subsystem	23.94	0.89
Front End and Engine Compartment Wiring	7.53	0.28
Instrument Panel Harness	6.13	0.11
Body and Rear End Wiring	6.60	0.12
Battery Cables	0.68	0.22
Engine and Transmission Wiring	2.67	0.14
Seat Harness	0.33	0.01
Vehicle Totals	**1641.70**	**312.48**