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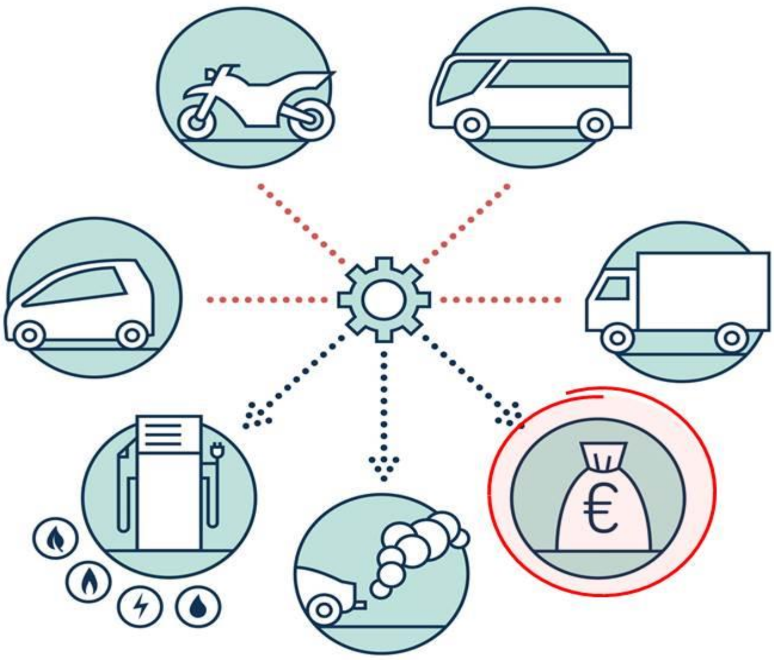

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Light Duty Vehicle CO_2 Emission Reduction Cost Curves and Cost Assessment - the DIONE Model

The present report presents a set of computational modules for assessing the costs and savings of different CO_2 emission targets for new light duty vehicles. In particular, these models allow constructing cost curves, identifying cost-optimal CO_2 emission reduction distributions over the different powertrains and segments composing a vehicle fleet, and calculating additional manufacturing costs, fuel and energy savings, and total costs or savings resulting from different scenarios.

The modules have been developed and employed in support of the impact assessment for the Commission's proposal for post-2020 CO_2 targets for light duty vehicles.

Contents

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Executive summary

The European Union (EU) is committed to reducing its greenhouse gas emissions and energy consumption. As part of a European Strategy for Low-Emission Mobility, the European Commission has been preparing a revision of the CO_2 emission performance standards for new cars and vans, with the aim of setting new targets for the period after 2020. The economic impacts of different policy options for this Regulation had to be assessed, which requires analysing the costs for the vehicle manufacturers, and the costs and savings for consumers.

With its DIONE family of software applications, the EC JRC offers a set of analytical tools that can be used to support the analysis. Different computational modules have been developed specifically to support the assessment of policy options for light duty vehicle CO_2 emissions reduction, in particular:

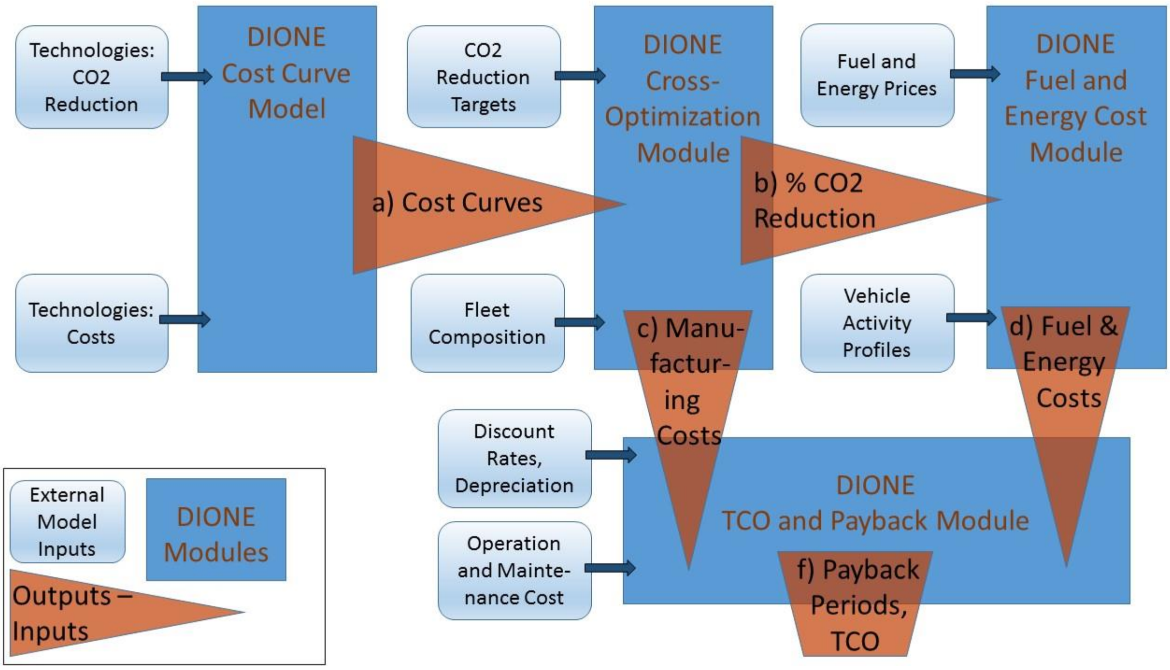
— DIONE Cost Curve Model: Develops cost curves, applying an optimisation technique, which provide cost estimates associated with reaching a given CO_2 reduction for a given vehicle segment and powertrain.

— DIONE Cross-Optimization Module: Identifies cost-optimal strategies to reach given emission targets and respective vehicle manufacturing costs, building on the cost curves. Cross-optimization outcomes can be used to assess the impact of different policy options on manufacturing costs for different manufacturer categories, contributing to the economic assessment.

— DIONE Fuel and Energy Cost Module: Calculates the lifetime fuel and energy costs for the optimized vehicles for each manufacturer category.

— DIONE TCO and Payback Module: Computes payback periods for additional vehicle manufacturing costs as well as total costs of ownership, summarizing the results from the previous steps. This allows assessing the societal costs associated with a policy option, the cost for the end-consumer, e.g., total costs of ownership over vehicle lifetime, as well as costs for consumers (new vehicle buyers and second-hand vehicle buyers).

Figure 1: Flowchart of DIONE Modules



The interaction between the modules, as well as inputs needed and outputs produced, are sketched in Figure 1. As can be seen, main outputs of the model are a) the CO_2 reduction cost curves (per vehicle segment, powertrain and year of analysis). These are passed on to the cross-optimization module, which identifies b) cost-optimal CO_2 reductions and c) associated manufacturing costs. The CO_2 reductions are then handed over to the fuel and energy cost module which outputs d) annual and lifetime fuel and energy costs. These, together with the manufacturing costs, are inputs to the calculation of e) payback and total costs of ownership. The analysis is run on the level of vehicle segments and powertrains separately in the first three modules, and then summarized into weighted averages for the new fleet of a given year for calculating average total costs.

Parameters needed as external scenario inputs are listed below. For the present calculations, most of these have been based on dedicated PRIMES-TREMOVE model runs for the respective policy scenarios. Each scenario is defined by:

— A list of technologies available for CO_2 reduction with specified CO_2 reductions and costs per year of analysis (see [3]),

— CO_2 reduction target level and settings for distribution of effort among vehicle manufacturers (including limit value curve slopes and parameters), transformed into manufacturer CO_2 reduction targets,

— fleet composition, resulting from PRIMES-TREMOVE scenario runs, broken down into manufacturer fleets according to different assumptions, and

— fuel and energy cost development pathways and vehicle mileages (based on PRIMES-TREMOVE).

More than 400 cost curves have been developed for the cost assessment carried out at EC JRC, and more than a hundred cross-optimization scenarios have been run to explore sensitivities in a rigorous manner. The methodology of the DIONE modules is described in the present report, and input data used as well as cost curves developed for the analysis are documented.

1 Introduction

The European Union supports the long-term goal to limit global warming to well below 2°C above pre-industrial levels and pursues efforts to limit the temperature increase to 1.5°C, as embraced by the EU with its ratification of the Paris agreement in 2016 [14]. Within this framework, the European Commission reinforced its commitment to transport decarbonisation with the July 2016 Communication on a European low-emission mobility strategy [15], which emphasizes the need to increase efficiency of the transport system, deploy low-emission alternative energy for transport, and move towards low- and zero-emission vehicles. As one instrument to implement this strategy, the Commission is revising the CO_2 emission targets for cars and vans (defined by the European Regulations 443/2009 and 510/2011), with the aim to set new targets for post-2020.

To support the analysis for post-2020 CO_2 emission targets for cars and vans, the JRC has developed and applied several analytical tools (modules), which are described in this report. For an overview of the modules, see the description in the Executive Summary and Figure 1.

These new modules supplement the existing DIONE fleet impact model which can be used for vehicle fleet projections (see [1],[2]), but can also be run independently using fleet composition data from third sources. The new modules have been used for developing more than 400 cost curves and analysing different scenario variants for setting post-2020 light duty vehicle targets under different conditions.

The present report provides a technical documentation of the four modules along with input data used, and presents exemplary outcomes. It is organized in four main sections 2 to 5, one of them dedicated to each of the modules, presenting first the details of the calculation followed by an illustrative presentation of module outcomes. It concludes with a short summary.

2 The DIONE Cost Curve Model

A large number of technologies are available which can contribute to the reduction of CO_2 emissions from new light-duty vehicles within the next decade. This includes technologies for improving the efficiency of conventional combustion engines and transmission systems, as well as the introduction of electrified powertrains. Within an earlier project, commissioned by DG CLIMA, state-of the art and developing technologies were identified, and their CO_2 reduction potentials and costs were quantified (see [3]). Starting from this data, JRC's DIONE cost curve model develops CO_2 reduction cost curves, which describe the mathematical relationship between CO_2 reduction potentials and related costs for different powertrains and vehicle segments.

Cost curves were constructed for

- 2 years: 2025 and 2030
- 7 vehicle segments: small, lower medium, upper medium and large cars and small, medium and large vans
- 8 powertrains: gasoline (SI), diesel (CI), gasoline and diesel plug-in hybrids (SI PHEV, CI PHEV), gasoline and diesel range-extended electrified vehicles (SI REEV, CI REEV), battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV); hybrids without the option of plugging in (HEV) are included in the conventional SI and CI powertrains as one of the optional technologies
- Different cost scenarios: typical, low and high costs, plus a very low cost scenario as a sensitivity for battery costs of advanced electrified (xEV) powertrains, i.e., all PHEV, REEV, BEV and FCEV, based on [16]

In total, this gives rise to a set of 420 cost curves, as described in Annex 1 and Annex 2, which were used as an input to the JRC cost analysis. All curves show the costs of reducing emissions as measured under the Worldwide harmonized Light vehicles Test Procedure (WLTP), relative to a 2013 baseline vehicle of the same segment. Reference powertrains are 2013 conventional gasoline vehicles for SI(+HEV), SI REEV, SI REEV, BEV and FCEV and 2013 diesel conventional vehicles for CI(+HEV), CI REEV, and CI REEV.

To develop a cost curve, in a first step, an optimization is carried out to identify cost-optimal packages of CO_2 reduction technologies. Then, several transformation steps are applied to transform the solutions found. Finally, a cost curve is fit to the set of solutions. These steps are explained below.

2.1 Identifying Optimal Technology Packages

The DIONE cost curve model applies a new optimization approach, combining Ant Colony Optimization and Local Search, to identify optimal technology packages for reducing CO_2 emissions from LDV. Given the set of available CO_2 reduction technologies, the problem consists in finding, among all possible packages (i.e., combinations of these technologies or subsets of them), the set of optimal configurations which have minimal total costs and maximum total CO_2 reduction. Each package found by the algorithm specifies a pareto optimal technology package, i.e., a combination of technologies that can be added to a baseline vehicle to achieve a given emission reduction at lowest possible costs (or achieves the highest emission reduction at a given cost level).

The large numbers of possible optimization problems, as well as the amount of possible combinations of technologies, make the problem computationally difficult (NP-hard). Moreover, available technologies are not always compatible, i.e., not all technologies can be combined with each other'. For example, various levels of engine downsizing technologies are available but there would never be a package containing more than one, which means that a simple combinatorial approach cannot be applied. Moreover, as the present dataset contains a number of 82 technologies, it is technically impossible to apply a brute force approach (2^{82}-1 combinations to evaluate). Therefore, the optimization approach applied here is based on an Ant Colony Optimization (ACO) combined with local search heuristics to solve the problem in an efficient way and make the algorithm adaptable to the changes in input parameters that instantiate this problem. This choice was motivated by the recent successes of Swarm Intelligence approaches to solve complex and dynamic problems with a system of cooperating/interacting agents ([4]).

The two-objective optimization problem considered can be formalized as follow.

Given a set of technologies $T=\{t_1, \ldots, t_N\}$, each characterized by its cost c_i, CO_2 reduction r_i and by a list of incompatible technologies $\{t_{ij}\}$, the problem consists of finding a set of all feasible subsets of T (in terms of compatibility between technologies), called packages P_k, which are pareto-optimal in the sense explained below.

Each package is represented by a point in the two-dimensional space of the objectives, and its coordinates are obtained by computing the total cost C and total CO_2 reduction R of the package P_k:

$$C_k = \sum_{t_i \in P_k} c_i \quad (1)$$

$$R_k = 1 - \prod_{t_i \in P_k} (1 - r_i) \quad (2)$$

Since we are treating a two-objective optimization, the concept of optimality is extended. We will say that a package P_n is *better than* package P_m if the following condition holds:

$$C_n<C_m \text{ and } R_n \geq R_m \text{ or } C_n=C_m \text{ and } R_n>R_m \quad (3)$$

Geometrically this condition consists constructing a coordinate system with emission reduction R at the abscissa and costs C at the ordinate, shifting the origin towards (R_m,C_m) and checking which quadrant (R_n,C_n) is situated in. If it falls in the 4th quadrant (lower right quadrant, including the vertical and horizontal axis) it means it is *better* than the first, while if is in the 2nd quadrant (upper left quadrant, including axes), it means that is worse, and the following condition holds:

$$C_n>C_m \text{ and } R_n<=R_m \text{ or } C_n=C_m \text{ and } R_n<R_m \quad (4)$$

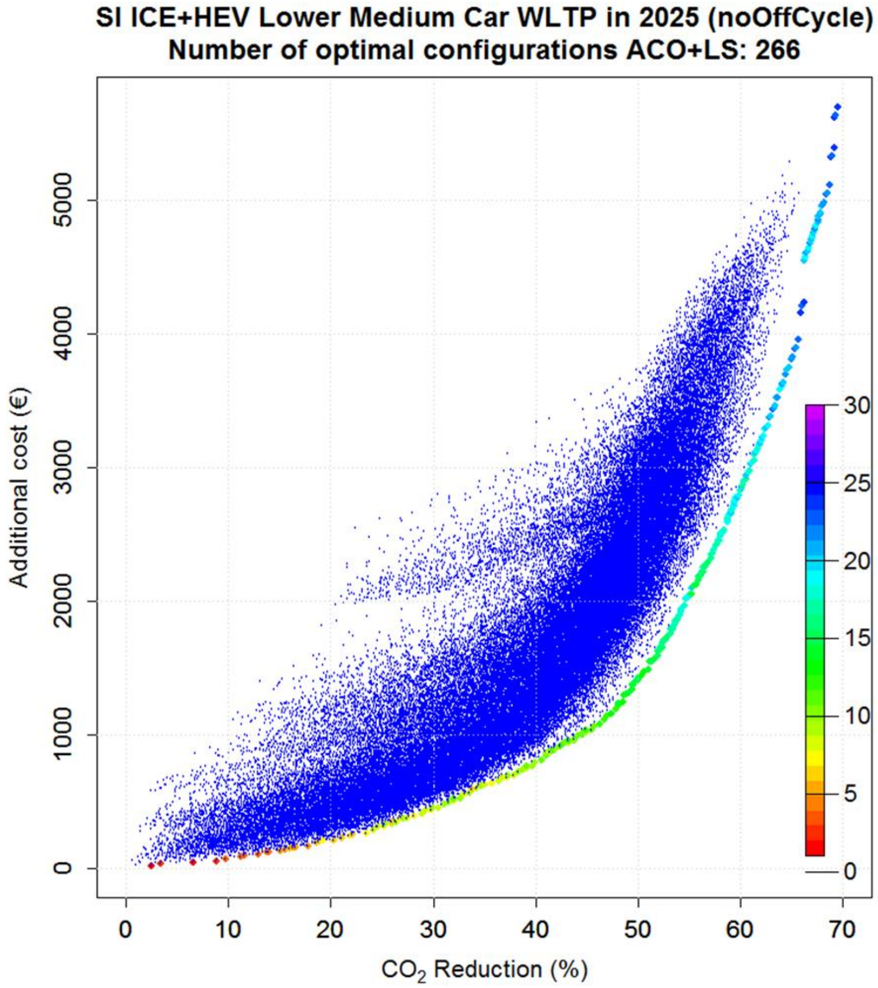
If P_n is a *better* package than P_m in terms of the objective functions, P_m cannot belong to the set of the optimal packages. It is also said that P_m is *dominated* by P_n.

On the other hand, we will say that P_n is *pareto optimal* with P_m if the following condition holds:

$$C_n>C_m \text{ and } R_n>R_m \text{ or } C_n<C_m \text{ and } R_n<R_m \quad (5)$$

Geometrically, this means that (R_n,C_n) can be found in the 1st or 3rd quadrant of the coordinate system originating at (R_m,C_m) (respectively the upper right or lower left quadrant, excluding the vertical and horizontal axes). In this last case, both packages are pareto optimal, therefore they will both be included in the pareto optimal set. The set of all pareto optimal points is the pareto front.

Figure 2: Randomly sampled intermediate packages visited by the ants (blue dots), along with optimal packages found by ACO (coloured). For the optimal packages, the number of technologies they are composed of is indicated by the colour scale.



The Ant Colony Optimization (ACO) approach implies the creation of an underlying graph where nodes are the technologies, and edges are connecting those that are compatible; on this graph, ants can propagate and leave their pheromones, the mechanism by which it is possible to encode locally global information. If a link is present between 2 technologies, the ant can step from a node to the next, "visiting" the technologies not selected yet; in this sense, "visiting" means to add the technology to the partially complete configuration, so this walk translates into a building process, step by step, of a set of packages of increasing cardinality. For each step, the ant has also to check if the possible technology to choose is compatible with the technologies "visited" before. To this aim, the ant has an incompatibility list containing all technologies incompatible with those previously visited. At each ant step, a new package is found and added to the solution, which is then composed by a collection of packages of increasing size. The ant leaves pheromones on every link it uses. The walk ends when the ant has no more nodes to visit, that is, when no further technology can be added to the last package found. At the end of the propagation, the pheromones undergo two main updates: a uniform evaporation on all the links and a deposition on the packages found. This is accomplished by evaluating goodness of each package of the newly constructed solution: each package of the solution is compared to the packages stored in the best solution. If a package is not one of the best, some Local Search might be attempted (generally if its size is between 6 and 12 technologies). At this point, the pheromone deposition can take place: the pheromones are incremented on the links proportionally to the goodness of that package. The goodness consists in a solutions' cost efficiency, i.e., the total CO2 reduction/total cost. Otherwise, if it is one of the best (better or pareto) with respect to those stored in the best solution, pheromones are boosted on the links used again proportionally to the goodness of the package. The packages beaten in the best solution are identified and removed, and the better (or pareto) are added. In this way the best solution keeps improving and stores the best packages found so far by any ant.

An illustration of optimization outcomes is shown in Figure 2. The small blue dots represent the combined CO_2 reduction and costs of technology packages visited by the ant, but refused as they were dominated by better solutions. The colored dots, forming the lower envelope of the cloud, represent the pareto optimal packages, their colour scale indicating the rough number of technologies a package is composed of. They will be retained for fitting the cost curve.

2.2 Parameter Transformation

Once a set of pareto-optimal technology packages has been found for a given year, powertrain, vehicle segment and cost scenario, a number of adjustments are made to each point before fitting the cost curve. These transformations are needed for

- 2013 Baseline adjustment: Accounting for technologies that are already deployed in the 2013 baseline,
- Scaling for batteries: Handling battery cost (or H_2 storage cost) savings for xEV,
- Scaling for overlapping technologies: Avoiding that potentials covered by different technologies are double-counted, and
- Re-baseline xEV: setting xEV energy and CO_2 savings relative to 2013 conventional vehicles, for comparability

For these steps, the same algorithms are used as described in [3]. Input data used can be found in the same source, with two exceptions. Firstly, a new very low battery cost scenario was added, based on [16]. Secondly, updated information has become available with regard to the measurement of CO_2 emissions under the WLTP cycle for PHEV and REEV powertrains ([6], [7], [5]). It has been found that conventional vehicles have higher WLTP than NEDC CO_2 emissions, whereas for PHEV and REEV, the uplift factor is around one. Thus, the emission reduction of PHEV and REEV compared to conventional vehicles is higher under WLTP than under NEDC especially as the size of the battery package increases. As the cost curves sketch the costs of reducing emissions relative to conventional baseline vehicles, PHEV and REEV emission reductions should be higher under WLTP than under NEDC, which was not captured previously.

2.3 Fitting Cost Curves

On the basis of the optimal packages found by the ACO optimization, vehicle CO_2 emission reduction cost curves can be constructed by fitting a curve that best represents them. The cost curve represents the pareto front (the optimal packages) in a continuous analytical form. The derived cost curves are a useful input for applications such as the evaluation of different CO_2 reduction scenarios, e.g. for calculating the costs associated with a certain CO_2 reduction target for vehicles, identifying cost-minimizing distributions of CO_2 reduction efforts across different vehicle types and technologies, and identifying maximum feasible CO_2 reductions.

Several functional forms of fitting functions were tested, with the requirement for the fit to have a non-negative second derivative. The functional forms showing the required behaviour are those represented by a lower-degree polynomial or a constant plus a hyperbolic function, which achieve a much more representative fit with a consistently lower squared-error. As a result, two distinct families of fitting functions were chosen: one for the internal combustion engines powertrains (SI and CI (+HEV)) and one for all xEV powertrains, which in fact can be regarded by the same fitting function, that is a polynomial (either constant or second degree with no constant) plus a simple hyperbole. The fitting procedure was performed by a Levenberg-Marquardt non-linear regression algorithm using the minpack.lm library in R. With this method, all cases could be fit with just some minor adjustments, e.g. requesting passage of the fit through certain points. Details of the fitting process are documented in [3].

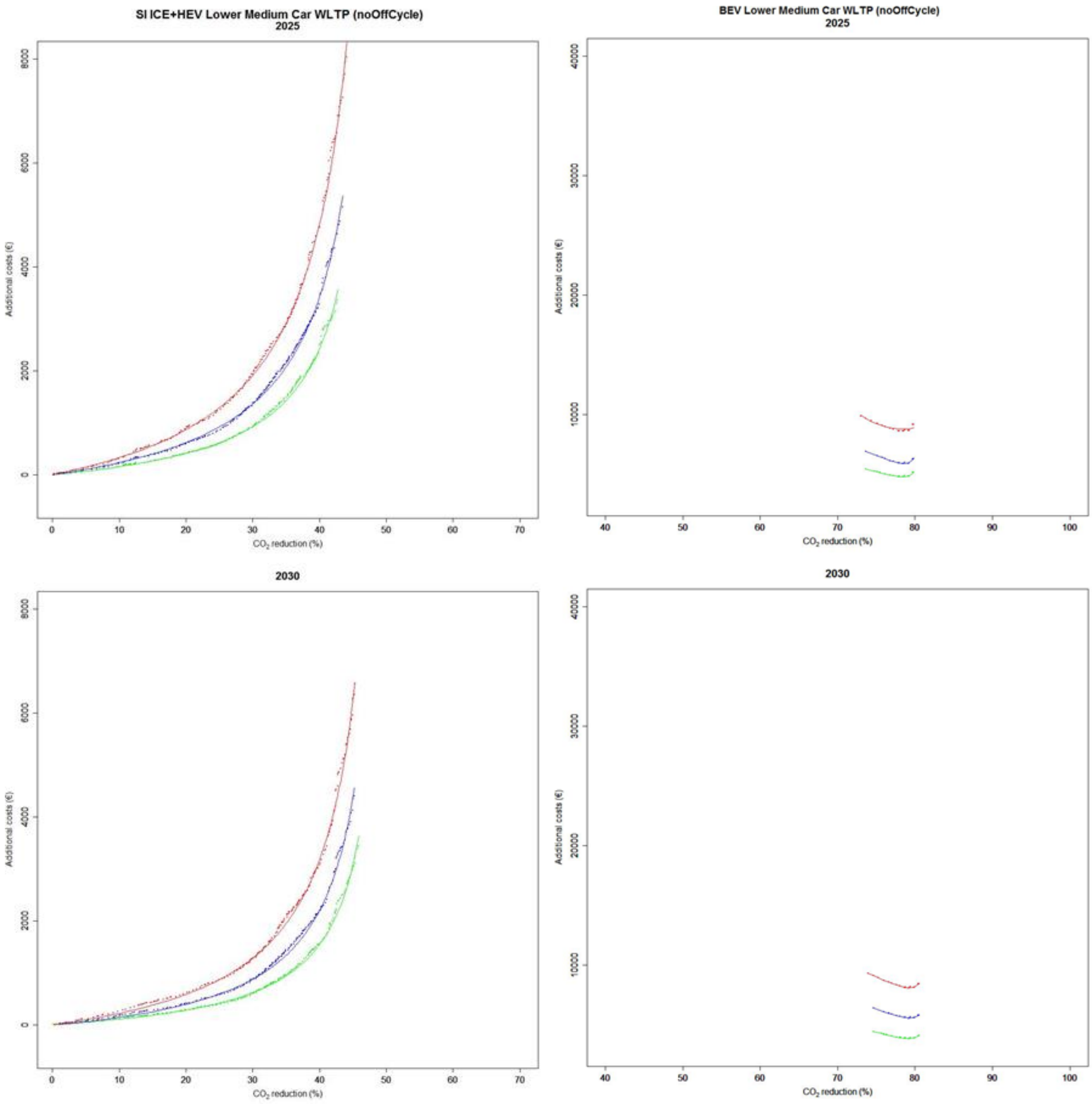
2.4 Resulting Cost Curves

For conventional powertrains, i.e., SI(+HEV) and CI(+HEV) powertrains, the form of the fitting function is

$$y = C + \frac{c}{x - x_0} \tag{6}$$

where C, c, and x_0 are the 3 parameters found by the fit. An example of fitted ICE curves for lower medium segment cars is shown on the left hand side of Figure 3.

Figure 3: Optimal technology packages (dots) and fitted curves for Lower Medium Cars, SI+HEV powertrain (left) and BEV (right) in 2025 (top) and 2030 (bottom).



For xEVs powertrains, i.e., PHEVs, REEVs, BEV and FCEV, the following functional form is used

$$y = a \cdot x^2 + b \cdot x + \frac{c}{x - x_0} \tag{7}$$

where a, b, c, x_0 are the fitting parameters which determine the shape of the fitting curve. An example of fitted BEV curves for lower medium segment cars can be seen on the right hand side of Figure 3.

The parameter values for the set of 420 cost curves used for supporting the assessment of post-2020 LDV CO_2 targets are documented in Annex 1.

3 The DIONE Cross-Optimization Module

The DIONE Cross-Optimization Module was developed to determine the cost minimizing CO_2 and energy consumption reduction for each powertrain and segment, given a CO_2 reduction target and fleet composition scenario as well as the cost curves described above. As the cost curves have positive first and second derivatives, this is a mathematical problem with a unique solution.

While transport and energy system models operate at fleet level, CO_2 targets need to be met by at manufacturer or manufacturer group level. Cross-optimization was thus developed to be feasible for subsets of the total fleet.

Necessary inputs for cross-optimization at manufacturer level are:

- Manufacturer fleet composition: within the study [5], different scenarios were run in the PRIMES-TREMOVE model, for each of which a total road fleet composition trajectory in terms of segments and powertrains results. These were sub-split into manufacturer fleets on the basis of a manufacturer typology and different hypotheses of uptake shares of xEV powertrains. Details are documented in the study.
- Manufacturer CO_2 reduction targets: from the overall targets for each scenario in combination with settings such as potential limit functions, slope etc., specific targets were derived for each manufacturer category, documented in [5].

Based on manufacturer-level cross-optimization outcomes, a detailed analysis of optimal manufacturer strategies under a given policy can be carried out.

3.1 Module Description

The formulation of the cross-optimization problem is the following.

Each manufacturer is characterized by a percentage p_i each associated with a segment s_k with k=1,..,N_s and powertrain pt_h with h=1,...,N_{PT}. In the present study, the combinations of these elements are N_s =7 (small, lower medium, upper medium and large cars and small, medium and large LDVs), and N_{pt} =8 (SI+HEV, CI+HEV, SI PHEV, CI PHEV, SI REEV, CI REEV, BEV, FCEV), therefore there are i=1, ...,56 segment-powertrain combinations with fixed shares p_i thus N=56.

The CO_2 reductions for each segment-powertrain combination, called x_i, are the independent variables of the problem. They are associated with cost functions $c_i(x_i)$.

The problem consists in finding the x^{opt} = (x_1^{opt}..., x_N^{opt}) minimizing the overall costs, which is calculated using the cost curves, each relative to the appropriate segment-powertrain combination i, the value of the x_i, and the p_i and is thus defined as:

$$C = \sum_{i=1}^{N} p_i \cdot c_i\,(x_i) \tag{8}$$

which has to be minimized subject to the constraints that the overall total CO_2 reduction, R cannot be less than a fixed value, MIN_{CO_2}, that is:

$$R = \sum_{i=1}^{N} p_i \cdot x_i \geq MIN_{CO_2} \tag{9}$$

Because of the properties of every cost curve to be monotonically increasing (first derivative greater than zero) and with second derivative greater than zero too, it would be obvious that (8) would be minimized when all costs c_i are at their minimum, therefore for the minimum value of the relative x_i. However condition (9) imposes a minimum overall CO_2 reduction. The inequality in (9) defines a hyperplane through the space of which only the points in one half space are acceptable solutions of (8), which cuts out the trivial solutions. An optimization routine solving this problem was implemented using the *constrOptim* algorithm of the library {stats} in R which solves the linear constrained optimization problem in x_i, finding the set of optimal points x_{opt}.

Outputs from the Cross-Optimization Module are optimal CO_2 reduction (for conventional vehicles and PHEV, REEV) or energy consumption reduction (for BEV, FCEV), x_{opt} per manufacturer, segment and powertrain and the corresponding manufacturing costs (C_{opt}).

Aggregating costs by manufacturer category the relative burden each policy puts on the manufacturer categories can be assessed. Furthermore, the x_{opt} outputs are used for subsequent steps of analysis such as the calculation of CO_2 emissions by vehicle type and segment as well as fuel and energy costs, and C_{opt} results are a direct input for total cost of ownership calculations.

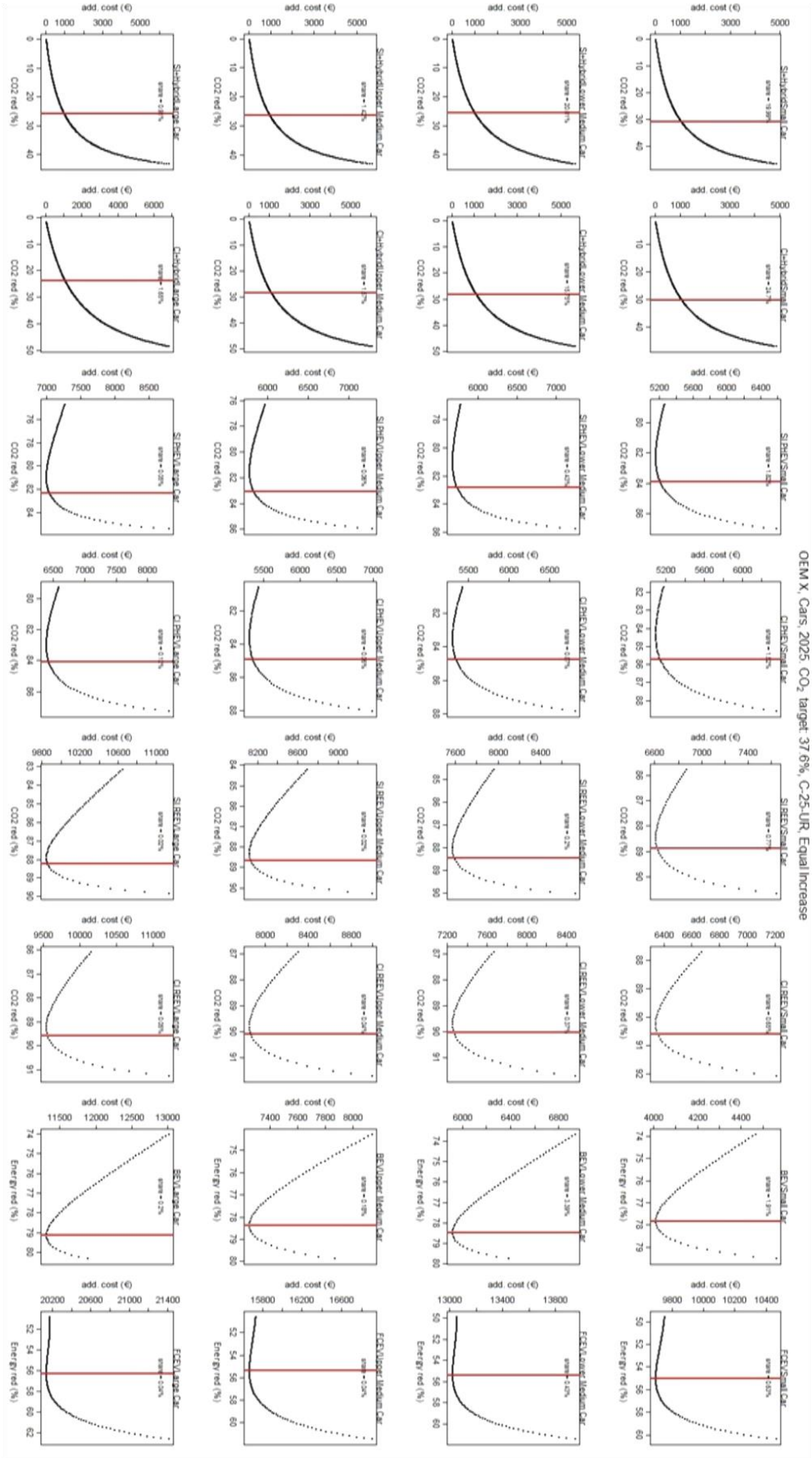
3.2 Cross-Optimization Results

The cross-optimization module yields cost-optimal CO_2 reductions for all segments and powertrains for each given manufacturer, CO_2 reduction target and year. An illustration of results for one manufacturer is given in Figure 4. Each frame shows, in black, the cost curve for reducing CO_2 emissions in a given segment (row-wise) and for a given powertrain (column-wise). The red bars indicate the optimal solutions found by cross-optimization. The shares of the vehicle segment-powertrain categories composing the manufacturer's fleet are given, as well, to help understand the effect of reductions in the different categories, as manufacturers need to meet their targets for their respective fleet on average, over all powertrains and segments. The cost optimal solution for the displayed manufacturer's conventional cars is to reduce small conventional cars' (both SI and CI) emissions by roughly 30% and lower medium cars' emissions by around 25% (SI) and 28% (CI), with similar reductions for the larger segments. Costs of these reductions are in the order of magnitude of 1000 EUR per car. For PHEV and REEV CO_2 emission reductions are in the range of 80 to 90%. For BEV and FCEV, emission reductions on the WLTP cycle are always a full 100%, therefore the graphic does not show their emission reduction but the reduction in energy consumption compared to their respective reference vehicle.

Results, as displayed in Figure 4, are calculated for each manufacturer, policy target scenario, and year and for different assumptions on future xEV distribution over manufacturers. They can be aggregated by calculating weighted averages, e.g. by manufacturer for comparing the effect different targets have on diverse manufacturer categories, or by segment for the analysis of impacts on different vehicles.

Furthermore, average additional technology costs per segment and powertrain over all manufacturers are used as one input for the payback and total cost of ownership computation which will be discussed in Section 5.

Figure 4: Illustration of optimal CO_2 reduction for all segments and powertrains, for an example manufacturer and car CO_2 reduction target, 2025. Black lines are cost curves, red lines indicate the solution.



4 The DIONE Fuel and Energy Cost Module

The implementation of technologies for reducing vehicle CO_2 emissions causes additional manufacturing costs, but also leads to reduced fuel or energy consumption during vehicle operation. Fuel and energy savings can thus compensate for higher upfront costs the vehicle user is facing. The DIONE fuel and energy cost module is used for calculating fuel savings of vehicles under different scenarios, compared to a baseline vehicle. The calculation steps carried out are described below.

4.1 Module Description

Step 1: Determining the cost curve baseline powertrain and corresponding 2013 CO_2 emissions and CO_2-to-energy conversion

The cost curves specify the costs of CO_2 or energy consumption reduction relative to a baseline 2013 conventional powertrain, which is

— 2013 SI for SI (+HEV), SI PHEV, SI REEV, BEV, and FCEV

— 2013 CI for CI (+HEV), CI PHEV, CI REEV.

To each of the 56 powertrain-segment combinations, the following parameters are assigned:

— 2013 base powertrain-segment WLTP CO_2 emissions (gCO_2/km), CO2_2013

— 2025 and 2030 fuel emission factor (gCO_2/MJ) corresponding to the fuel used by the respective baseline powertrain, $EF_{pt,year}$

These inputs were provided by the study [5].

Step 2: Calculation of target year WLTP-based specific energy consumption (MJ/km)

For each manufacturer (the index used is "OEM"), powertrain, segment and target year, WLTP based energy consumption [MJ/km] is calculated as:

$$E\_WLTP_{OEM,pt,s,year} = CO2\_2013_{pt,s} * (1 - x_{opt,\ OEM,pt,s,year}) / EF_{pt,year} \tag{10}$$

where CO2_2013 are the 2013 base powertrain WLTP emissions, $1-x_{opt}$ are remaining emissions or energy consumption in the target year, and $EF_{pt,year}$ is the emission conversion factor for the powertrain. This approach applies to all vehicle types, however for PHEV and REEV it outputs CO_2 emissions from conventional fuel consumption only, whereas for BEV and FCEV, it yields electricity/hydrogen consumption.

Step 3: Converting energy consumption to RW basis

WLTP energy consumption figures are converted to real world by multiplying WLTP based energy consumption obtained in the previous step by real world over WLTP uplift factors, f_RW for each powertrain and segment, 2025 and 2030.

$$E\_RW_{OEM,pt,s,year} = E\_WLTP_{OEM,pt,s,year} * f\_RW_{pt,s,year} \tag{11}$$

Step 4: PHEV and REEV electric energy consumption

Energy consumption determined in the previous steps only includes conventional fuel consumption for PHEV and REEV. Their electrical energy consumption needs to be accounted for separately as follows:

$$EC_{OEM,pt,s,year} = E\_RW_{OEM,pt,s,year} \tag{12}$$

$$EE_{OEM,pt,s,year} = percentElectric_{pt} / (1 - percentElectric_{pt}) * E\_RW_{OEM,pt,s,year} \tag{13}$$

for pt={PHEV, REEV}, where EC and EE are conventional and electric energy consumption, respectively. Electric drive shares $percentElectric_{pt}$ for PHEV and REEV were taken from [5].

Step 5: Calculating fuel costs

Further inputs needed for this step are:

- Overall vehicle mileages per segment and powertrain ($M_{pt,s}$) as well as mileage profiles over vehicle lifetime were based on PRIMES-TREMOVE. MC, ME are the respective mileages run on conventional and electric propulsion by each vehicle type. For conventional cars, BEV and PHEV total mileage is assigned to one propulsion type, whereas for PHEV and REEV, total mileage is subsplit using the electric shares.
- Costs of conventional fuels (Cost_CE), and electricity and hydrogen (Cost_EE) were aligned with the inputs used in the PRIMES-TREMOVE scenarios. They were discounted and weighted by powertrain-segment activity over vehicle age, such that they could be used as multiplicators within the calculation.

Total fuel and energy cost per powertrain and segment is calculated as the sum over specific energy consumption times mileage times costs for each fuel type a vehicle consumes. An index for vehicle 'age' is introduced to trace energy costs over the lifetime of the vehicle, as vehicle activity varies with its age. Moreover, the age index is used to refer to the energy costs in a given year. For example, for a new vehicle of year=2025, age=2 in 2027, thus mileage will be chosen for age 2 and energy costs will be selected to be those of year 2025 plus 2, thus 2027:

$$EnCost_{OEM,pt,s,year,age} = EC_{OEM,pt,s,year} * MC_{pt,s,age} * Cost\_CE_{pt,s,year+age} + EE_{OEM,pt,s,year} * ME_{pt,s,age} * Cost\_EE_{pt,s,year+age} \quad (14)$$

This calculation step yields cumulated, discounted energy costs per segment, powertrain and vehicle age for new 2025 and 2030 vehicles. Average fleet fuel and energy costs can be obtained by weighting the powertrains' and segments' costs by target year fleet composition.

4.2 Fuel and Energy Cost Results

Table 1 shows an illustration of inputs, intermediate results and outputs from the fuel and energy consumption calculation as described in the previous section for one scenario, one manufacturer, one year and one car segment. Outputs vary with the discount rates and tax settings chosen according to the perspective, social or end-user (see Section 5.3), both included in the table.

Tables of the same structure result for all manufacturers, years, and segments for every scenario run.

Table 1: Exemplary fuel and energy cost results

Power-train	Perspec-tive	opt_x	CO2_ 2013	conv. factor	RW-WLTP corr. factor	EC	EE	%Electric	Cost CE	Cost_ EE	Mileage	En Cost
SI+HEV	Social	0.30	168.9	69.20	1.15	1.97	0.00	0.00	0.02	0.00	177068	6636
CI+HEV	Social	0.32	144.9	73.94	1.12	1.49	0.00	0.00	0.02	0.00	221250	6430
SI PHEV	Social	0.83	168.9	69.20	1.68	0.68	0.27	0.28	0.02	0.04	221250	5385
CI PHEV	Social	0.86	144.9	73.94	1.68	0.47	0.21	0.30	0.02	0.04	221250	3930
SI REEV	Social	0.90	168.9	69.20	1.68	0.42	0.33	0.44	0.02	0.04	221250	4858
CI REEV	Social	0.90	144.9	73.94	1.68	0.32	0.28	0.46	0.02	0.04	221250	3953
BEV	Social	0.79	168.9	69.20	1.13	0.00	0.57	1.00	0.00	0.04	177068	4124
FCEV	Social	0.56	168.9	69.20	1.13	0.00	1.22	1.00	0.00	0.03	221250	9065
SI+HEV	Enduser	0.30	168.9	69.20	1.15	1.97	0.00	0.00	0.04	0.00	67315	5537
CI+HEV	Enduser	0.32	144.9	73.94	1.12	1.49	0.00	0.00	0.04	0.00	96993	5291
SI PHEV	Enduser	0.83	168.9	69.20	1.68	0.68	0.27	0.28	0.04	0.06	96993	4252
CI PHEV	Enduser	0.86	144.9	73.94	1.68	0.47	0.21	0.30	0.04	0.06	96993	2813
SI REEV	Enduser	0.90	168.9	69.20	1.68	0.42	0.33	0.44	0.04	0.06	96993	3552
CI REEV	Enduser	0.90	144.9	73.94	1.68	0.32	0.28	0.46	0.04	0.06	96993	2684
BEV	Enduser	0.79	168.9	69.20	1.13	0.00	0.57	1.00	0.00	0.06	67315	2175
FCEV	Enduser	0.56	168.9	69.20	1.13	0.00	1.22	1.00	0.00	0.04	96993	4589

5 The DIONE TCO and Payback Module

The DIONE total cost of ownership (TCO) and Payback module is designed to summarize the different cost types over different time frames, and thus to assess economic impacts of policy options from the perspective of vehicle end-users as well as the society. To this end, manufacturing costs for achieving given CO_2 emission targets, fuel and energy cost savings due to the increased efficiency, and potential changes in operation and maintenance costs are combined for the respective vehicle powertrains and segments and compared to respective costs under a reference scenario.

Total costs of ownership calculations are carried out for each vehicle powertrain, segment and age, under a reference scenario as well as under different policy scenarios. On this basis, total additional costs or savings under the policy scenarios relative to the baseline can be compared for single vehicle types or the total fleet, at different vehicles ages. Setting parameter values for discount and depreciation accordingly, this is done from an end-user as well as a societal perspective. For example, first end-user costs are calculated for the first five life-years of a vehicle, and societal costs over a vehicle lifespan of 15 years.

The following subsection provides information on the operation and maintenance cost estimates used, followed by a technical description of the TCO and payback module. Then, settings used for the different perspectives are described, followed by an illustrative presentation of results in a last subsection.

5.1 Operation and Maintenance Costs

Apart from manufacturing and energy costs, operation and maintenance costs vary for different powertrains, segments, and years of analysis. Operation and maintenance cost estimation was carried out in [5]. They include annual insurance costs, maintenance costs and other ownership costs such as taxes.

5.2 Module description

The DIONE cost module summarizes cost differences for vehicles under policy scenarios relative to a reference. First, the differences for the different cost types are calculated as follows:

Manufacturing costs per manufacturer, powertrain, segment and year for each scenario result from the Cross-Optimization calculations. Additional manufacturing costs for improving the efficiency of a vehicle are calculated by a pairwise comparison of the scenario vehicles to their closest conventional vehicle under the reference scenario. Unless otherwise specified in the subsequent settings section, the closest conventional powertrain cc_pt for each vehicle type is the one used for the cost curves and specified in Section 2, and additional costs result directly from the cost curves. Where a different closest conventional powertrain is set, this is implement via the $\text{RebaseCosts}_{s,pt}$ substracted in the following equation.

$$\text{C\_opt\_diff}_{OEM,s,pt,year,age} = \text{C\_opt\_scen'}_{OEM,s,pt,year,age} - \text{C\_opt\_ref'}_{OEM,s,cc\_pt,year,age} - \text{RebaseCosts}_{s,pt} \quad (15)$$

The previous equation (15) yields additional manufacturing cost by vehicle age, considering the depreciated part of manufacturing costs C_opt_scen’ and C_opt_ref’ at each point in time,:

$$\text{C\_opt\_scen'}_{OEM,s,pt,year,age} = \text{C\_opt\_scen}_{OEM,s,pt,year} *(1-\text{ResV}_{age}) \quad (16)$$

$$\text{C\_opt\_ref'}_{OEM,conv\_s,pt,year,age} = \text{C\_opt\_ref}_{OEM,s,pt,year} *(1-\text{ResV}_{age}) \quad (17)$$

Discounted cumulated **energy costs** for all manufacturers, powertrains, segments, years and vehicle ages have been calculated as described in Section 4.1, using the DIONE Fuel and Energy Cost Module. Again, scenario and reference cost difference is calculated in a pairwise comparison:

$$EnCost\_diff_{OEM,s,pt,year,age} = EnCost\_scen_{OEM,s,pt,year,age} - EnCost\_ref_{OEM,s,cc\_pt,year,age} \quad (18)$$

The same logic applies to **operation and maintenance cost** differences. These are identical for all manufacturer and vehicle ages, calculated as:

$$OMCost\_diff_{s,pt,year} = OMCost\_scen_{s,pt,year} - OMCost\_ref_{s,cc\_pt,year} \quad (19)$$

Operation and maintenance costs for both scenario and reference vehicles are discounted using the discount rate pertaining to the perspective, specified in the subsequent section.

Finally, **total cost difference** of vehicles in the policy scenario versus reference are given as the sum of technology cost difference, energy cost difference, and operation and maintenance cost difference:

$$TotalCost\_diff_{OEM,s,pt,year,age} = C\_opt\_diff_{OEM,s,pt,year,age} + EnCost\_diff_{OEM,s,pt,year,age} + OMCost\_diff_{s,pt,year} \quad (20)$$

5.3 Perspectives and Parameters

To assess the impact of different possible policy options, the DIONE TCO and payback module carries out cost comparisons between the respective policy scenarios and a Reference scenario. To this aim, costs are framed in two perspectives, which represent the perception of a vehicle buyer, i.e., the end-user, and a social perspective. These differ in a number of settings as described below and summarized in Table 2.

The **social** perspective represents the costs society faces through the introduction of a LDV CO_2 emission reduction target. They are calculated by comparing total costs (manufacturing costs, fuel savings, and O&M cost differences) over a vehicle lifetime of 15 years within each policy scenario to the aggregate costs occurring under the Reference scenario. Settings for the social perspective are:

- Discount Rate of 4%
- No markup on manufacturing costs (these include a 3% profit margin for manufacturers)
- No VAT

The **end-user** perspective shows the difference in total costs of ownership incurred by an end-user over a given time of vehicle usage. In the present analysis, costs for the first end-user over life years 1 to 5 of the vehicle, and of the second enduser over life years 6 to 10 have been focussed on. Settings for the end-user perspective are:

- Discount Rate of 11% for Cars and 9.5% for LCV
- 20% VAT included in O&M costs
- A markup factor of 1.4 for Cars and 1.11 for LCV is applied to convert technology costs into prices. This includes dealer margins, logistics and marketing costs.

Residual values can be considered for manufacturing costs which represent the non-depreciated part of the initial investment after a given number of years. This distributes up-front costs more evenly over vehicle lifetime.

Table 2: Input parameters specifying cost calculation perspectives

Element	Sub-category	Assumption	Notes
Discount Rate, %	Social	4%	This social discount rate is recommended for Impact Assessments in the Commission's Better Regulation guidelines [9].
	End user (cars)	11%	Consistent with the Reference Scenario 2016 [10].
	End-user (LCVs)	9.5%	Consistent with the Reference Scenario 2016 [10].
Depreciation	All		Based on [11].
Mark-up factor	Cars	1.40	Used to convert total manufacturing costs to prices, including dealer margins, logistics and marketing costs and relevant taxes*. Consistent with values used in previous IA analysis according to [12],[13]. The mark-up for LCVs excludes VAT, as the vast majority of new purchases of LCVs are by businesses, where VAT is not applicable.
VAT % rate	N/A	20%	Used to convert O&M costs including tax, to values excluding tax for social perspective.

Notes: * Average manufacturer profit margin is already accounted for in the cost-curves.

Payback Analysis is carried out as a year-wise version of the end-user perspective, with the same parameter settings. The aim of the end-user perspective is to calculate, for each individual vehicle segment and powertrain and at each point in time, the positive and negative costs associated with a users' decision to buy a more efficient vehicle than in the absence of the policy. This can involve buying a more efficient conventional car, but also a switch to a different car technology. This calculation also shows if an upfront investment can be (over-)compensated by fuel and operations savings, and what amount of extra costs or benefits accrues over time. For payback analysis, not all reference powertrains coincide with the reference powertrains set in the cost curves, which are SI for SI+HEV, SI PHEV, SI REEV, BEV, and FCEV and CI for CI+HEV, CI PHEV, CI and REEV. Instead, reference powertrains for payback analysis have been chosen such that assumed mileage patterns of each xEV type are similar to those of their conventional counterparts. According to the annual mileage assumptions used (taken from PRIMES-TREMOVE), there are two mileage categories, with relatively low mileage for SI and BEV versus relatively higher activity for CI, all PHEV and REEV powertrains as well as FCEV. Thus the base vehicles (called closest conventional powertrain, cc_pt, in Section 5.2) are:

— Reference scenario SI+HEV of same segment and year for SI+HEV and BEV, and

— Reference scenario CI+HEV of same segment and year for CI+HEV, SI PHEV, CI PHEV, SI REEV, CI REEV, and FCEV.

For vehicles which have an SI closest conventional powertrain for the cost curves, but replace a CI in the payback perspective (i.e., SI PHEV, SI REEV and FCEV), the price difference between SI and CI is subtracted in the analysis to take into account that they are assumed to replace a CI conventional rather than an SI car, the so-called re-baseline step. SI and CI price differences in Euro for the small, lower medium, upper medium and large car segment are RebaseCosts = {1000, 1400, 1800, 2500} and for the small, medium and large van segments they are RebaseCosts = {1000, 1400, 2500}. RebaseCosts are zero for all powertrains other than SI PHEV, SI REEV and FCEV, and for all powertrains in the social perspective and in aggregate views.

Finally, for all perspectives, comparisons of total vehicle cost under each policy scenario relative to the reference scenario are first carried out for each powertrain and segment separately. In order to summarize the overall cost effect of policy options and to allow comparison among different scenarios, a weighted fleet average is calculated both for the enduser and social perspective by weighting total costs per segment and powertrain by the respective fleet composition. This yields the **average costs or savings** per each new vehicle in a given year of analysis resulting from a respective policy option.

5.4 TCO and Payback Results

Table 3 illustrates total cost calculation in a social perspective. For each year of analysis (2025 and 2030) and vehicle age, all three cost types (technology costs, energy costs, and operation and maintenance costs) are calculated and averaged over all new vehicles. For example, the second line of the table gives costs of the new vehicles bought in 2025 during their second life year (i.e. in 2026). Average technology costs for both scenario and reference result from the DIONE cross-optimization. Average energy costs have been calculated in the DIONE fuel and energy cost module, and O&M costs have been determined as described in Section 5.1. The three cost types can then be aggregated and compared for policy scenarios relative to the reference scenario.

Similar results have been calculated for all the needed policy scenarios analysed for supporting the assessment of policy options for LDV CO_2 emission reduction, both for the social and enduser perspective.

Table 3: Exemplary results for annual net costs from a societal perspective

Year	Veh. Age	Avg Tech. cost	Avg Tech Cost REF	Avg Ener. Cost	Avg Energy Cost REF	Avg OpCost	Avg OpCosts REF
2025	1	1703	1323	655	721	1072	1060
2025	2	1703	1323	1270	1399	2102	2080
2025	3	1703	1323	1845	2034	3093	3060
2025	4	1703	1323	2372	2616	4046	4003
2025	5	1703	1323	2874	3171	4962	4910
2025	6	1703	1323	3336	3682	5842	5781
2025	7	1703	1323	3770	4164	6689	6619
2025	8	1703	1323	4165	4601	7504	7425
2025	9	1703	1323	4538	5015	8287	8200
2025	10	1703	1323	4873	5387	9040	8945
2025	11	1703	1323	5178	5726	9764	9661
2025	12	1703	1323	5471	6051	10460	10350
2025	13	1703	1323	5727	6335	11129	11012
2025	14	1703	1323	5988	6626	11773	11649
2025	15	1703	1323	6211	6873	12392	12262
2030	1	2283	1261	611	805	1065	1074
2030	2	2283	1261	1178	1551	2090	2106
2030	3	2283	1261	1707	2248	3075	3099
2030	4	2283	1261	2195	2892	4022	4053
2030	5	2283	1261	2645	3485	4933	4971
2030	6	2283	1261	3065	4038	5809	5853
2030	7	2283	1261	3450	4546	6651	6702
2030	8	2283	1261	3803	5012	7460	7518
2030	9	2283	1261	4137	5453	8239	8302
2030	10	2283	1261	4444	5859	8988	9056
2030	11	2283	1261	4725	6229	9707	9782
2030	12	2283	1261	4983	6571	10399	10479
2030	13	2283	1261	5218	6882	11065	11150
2030	14	2283	1261	5443	7180	11705	11795

6 Conclusions

In this report, we have presented a set of computational modules of the DIONE model family developed and run at EC JRC, which were used to support the assessment of economic impacts of different options for setting targets for light duty vehicle CO_2 emission reduction after 2020. Building on each other, the modules allow to construct vehicle emission reduction cost curves, identify an optimal distribution of efforts among the different powertrains and segments which compose the fleet, calculate additional manufacturing costs as well as fuel savings, and compute total additional costs or savings from emission reduction for specific vehicle types as well as the fleet averages.

The methodology has been applied to develop cost curves, and run cross-optimization scenarios with subsequent cost calculation from different perspectives for a rigorous analysis of the impacts of different post-2020 light duty vehicle CO_2 targets.

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List of abbreviations and definitions

ACEA	*European Vehicle Manufacturer Association*
ACO	*Ant Colony Optimization*
EU	*European Union*
EC	*European Commission*
GM	*General Motors*
ICE	*Internal Combustion Engine*
JAMA	Japanese Vehicle Manufacturer Association
JLR	Jaguar - Land Rover
LCV	*Light Commercial Vehicle*
LDV	*Light Duty Vehicle*
NEDC	*New European Driving Cycle*
OEM	*Original Equipment Manufacturer (here denoting "car manufacturer")*
O&M	*Operation and Maintenance*
PSA	*Peugeot Société Anonyme (Peugeot, Citroën, DS)*
TCO	*Total Cost of Ownership*
WLTP	*Worldwide Light duty vehicle Test Procedure*
xEV	*Advanced Electrified Vehicle (includes all PHEV, all REEV, BEV and FCEV)*

Powertrains:

SI+HEV	*Spark Ignition (Gasoline), including Hybrid Electric Vehicle*
CI+HEV	*Compression Ignition (Diesel), including Hybrid Electric Vehicle*
SI PHEV	*Spark Ignition (Gasoline) Plug-In Hybrid Electric Vehicle*
CI PHEV	*Compression Ignition (Gasoline) Plug-In Hybrid Electric Vehicle*
SI REEV	*Spark Ignition (Gasoline) Range-Extended Electric Vehicle*
SI REEV	*Compression Ignition (Gasoline) Range-Extended Electric Vehicle*
BEV	*Battery Electric Vehicle*
FCEV	*Fuel Cell Electric Vehicle*

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Annex 1. Cost Curve Parameters

All tables are for cost curves obtained on WLTP basis, excluding off-cycle technologies.

Cost curves for 2025

Table 1: ICEs cost curves (€) for 2025, for LOW cost scenarios.

Powertrain	Segment	Cost curve relative to vehicle baseline for SI+Hybrid and CI+Hybrid $y = C + c / (x - x_0)$						
		C	c	x_0	x_min = Min CO_2 reduction (%)	x_max = Max CO_2 reduction (%)	y_min = Min additional cost	y_max = Max additional cost
SI+Hybrid	Car: Small	-509.22	-273.08	0.536713	0.21%	46.86%	€1.56	€3,500.17
	Car: Lower Medium	-625.65	-314.48	0.503094	0.07%	42.79%	€0.29	€3,558.39
	Car: Upper Medium	-563.03	-275.77	0.490856	0.13%	43.30%	€0.27	€4,203.88
	Car: Large	-563.51	-272.48	0.484350	0.10%	43.41%	€0.20	€4,862.52
	LCV: Small	-501.18	-269.23	0.550490	1.35%	49.58%	€0.19	€4,419.15
	LCV: Medium	-849.93	-489.90	0.576550	0.02%	48.04%	€0.08	€4,242.60
	LCV: Large	-1092.70	-611.18	0.573391	1.76%	48.87%	€6.86	€6,122.31
CI+Hybrid	Car: Small	-668.35	-360.85	0.553916	1.91%	47.05%	€6.38	€3,659.54
	Car: Lower Medium	-887.92	-514.14	0.583127	0.54%	48.17%	€2.02	€4,182.90
	Car: Upper Medium	-899.79	-521.62	0.588496	1.16%	49.34%	€4.32	€4,584.49
	Car: Large	-1265.36	-764.80	0.607344	0.77%	48.76%	€10.15	€5,119.13
	LCV: Small	-654.15	-390.58	0.591460	0.73%	51.78%	€14.45	€4,650.72
	LCV: Medium	-700.70	-403.13	0.585647	1.45%	51.93%	€5.13	€5,371.87
	LCV: Large	-730.60	-425.88	0.586670	0.72%	53.47%	€4.32	€7,463.31

Table 2: ICEs cost curves (€) for 2025, for TYPICAL cost scenarios.

Powertrain	Segment	Cost curve relative to vehicle baseline for SI+Hybrid and CI+Hybrid $y = C + c / (x - x_0)$ C	c	x_0	x_min = Min CO_2 reduction (%)	x_max = Max CO_2 reduction (%)	y_min = Min additional cost	y_max = Max additional cost
SI+Hybrid	Car: Small	-758.88	-411.53	0.541893	0.21%	46.86%	€3.47	€4,856.20
	Car: Lower Medium	-971.92	-498.00	0.513503	0.18%	43.49%	€1.28	€5,363.88
	Car: Upper Medium	-830.85	-411.21	0.496298	0.29%	43.30%	€2.55	€5,666.04
	Car: Large	-845.96	-414.39	0.490670	0.10%	43.41%	€0.29	€6,483.61
	LCV: Small	-740.40	-402.63	0.553940	1.35%	49.58%	€4.61	€6,181.57
	LCV: Medium	-1302.66	-762.53	0.585512	0.02%	48.61%	€0.12	€6,365.63
	LCV: Large	-1524.45	-850.35	0.572356	1.76%	48.53%	€8.25	€8,245.92
CI+Hybrid	Car: Small	-919.67	-498.82	0.556732	1.91%	47.05%	€8.16	€4,867.56
	Car: Lower Medium	-1169.31	-674.09	0.580614	0.54%	48.17%	€2.58	€5,647.99
	Car: Upper Medium	-1187.73	-687.56	0.587751	1.16%	49.34%	€5.53	€6,098.28
	Car: Large	-1718.29	-1020.93	0.606590	1.76%	48.76%	€15.05	€6,858.29
	LCV: Small	-880.39	-522.95	0.591282	0.05%	51.78%	€4.78	€6,239.68
	LCV: Medium	-981.48	-566.66	0.588026	1.45%	51.93%	€6.57	€7,259.14
	LCV: Large	-986.15	-573.74	0.585648	0.72%	53.47%	€5.68	€10,274.02

Table 3: ICEs cost curves (€) for 2025 for HIGH cost scenarios.

Powertrain	Segment	Cost curve relative to vehicle baseline for SI+Hybrid and CI+Hybrid $y = C + c / (x - x_0)$						
		C	c	x_0	x_min = Min CO_2 reduction (%)	x_max = Max CO_2 reduction (%)	y_min = Min additional cost	y_max = Max additional cost
SI+Hybrid	Car: Small	-1236.58	-665.97	0.551078	1.61%	46.86%	€8.18	€6,838.06
	Car: Lower Medium	-1357.72	-695.82	0.512898	0.18%	44.10%	€3.66	€8,316.59
	Car: Upper Medium	-1186.18	-590.91	0.497629	0.27%	43.30%	€7.82	€7,957.46
	Car: Large	-1234.59	-608.04	0.492593	0.10%	43.41%	€2.26	€9,166.29
	LCV: Small	-1118.85	-584.81	0.552108	3.10%	49.58%	€3.44	€9,262.10
	LCV: Medium	-1895.40	-1103.40	0.582243	0.02%	48.61%	€0.35	€9,578.07
	LCV: Large	-2109.18	-1156.18	0.563024	1.76%	48.32%	€10.42	€12,382.19
CI+Hybrid	Car: Small	-1213.94	-672.96	0.558787	0.62%	47.05%	€3.96	€6,411.74
	Car: Lower Medium	-1651.64	-963.85	0.587819	0.54%	48.17%	€3.26	€7,434.00
	Car: Upper Medium	-1609.29	-930.44	0.587851	1.16%	49.34%	€5.22	€8,240.19
	Car: Large	-2032.41	-1208.24	0.593403	0.24%	48.76%	€12.01	€9,382.20
	LCV: Small	-1261.00	-752.84	0.594541	0.05%	51.78%	€6.29	€8,553.61
	LCV: Medium	-1418.96	-824.60	0.592056	1.45%	51.93%	€8.81	€9,908.82
	LCV: Large	-1389.78	-809.80	0.586633	0.72%	53.47%	€7.74	€14,201.83

Table 4: xEVs cost curves (€) for 2025 (% CO2 reduction for PHEV/REEV, % energy reduction for BEV/FCEV) for LOW cost scenarios.

Powertrain	Segment	Cost curve relative to ICE baseline for xEVs $y = ax^2 + bx + c / (x - x_0)$ a	b	c	x_0	x_min = Min reduction (%)*[1]	x_max = Max reductio n (%)*	y_min = Min additional cost[2]	y_max = Max additional cost
SI PHEV	Car: Small	-14,341.7403	16,864.6322	-20.1920	0.8815	78.82%	87.02%	€4,600.69	€5,567.07
	Car: Lower Medium	-12,747.0678	16,184.6754	-12.0167	0.8656	76.91%	85.89%	€5,041.80	€6,193.77
	Car: Upper Medium	-15,714.3389	18,609.2958	-14.5698	0.8676	76.31%	86.06%	€5,192.11	€6,186.83
	Car: Large	-19,198.0476	22,630.3072	-15.7983	0.8611	74.72%	85.43%	€6,342.84	€7,330.45
	LCV: Small	-8,799.1233	11,706.9429	-11.9084	0.8615	75.76%	85.73%	€3,949.37	€5,796.76
	LCV: Medium	-8,175.4161	12,336.2208	-8.9496	0.8702	78.43%	86.69%	€4,795.46	€6,809.66
	LCV: Large	-22,118.4043	26,111.2319	-15.4299	0.8961	82.78%	89.34%	€6,688.19	€9,766.35
CI PHEV	Car: Small	-13,896.3160	16,559.9911	-20.9633	0.8980	81.71%	88.64%	€4,529.92	€5,482.12
	Car: Lower Medium	-16,580.7632	18,778.7068	-27.2679	0.8914	80.45%	87.94%	€4,704.57	€5,835.86
	Car: Upper Medium	-17,611.8038	19,534.7835	-30.5485	0.8934	80.56%	88.08%	€4,670.73	€5,847.92
	Car: Large	-22,209.6468	24,285.7690	-33.6393	0.8850	79.06%	87.32%	€5,692.79	€6,967.45
	LCV: Small	-10,231.1200	12,682.3560	-13.6426	0.8975	82.44%	89.28%	€3,699.98	€5,525.80
	LCV: Medium	-13,948.0121	16,676.0157	-15.8723	0.9029	83.04%	89.81%	€4,462.70	€6,426.21
	LCV: Large	-27,693.4018	30,123.6218	-22.8983	0.9023	83.05%	89.83%	€6,228.89	€9,217.84
SI REEV	Car: Small	-24,381.2919	27,530.2954	-10.0850	0.9134	85.78%	90.69%	€5,866.16	€6,403.05
	Car: Lower Medium	-26,180.1708	30,065.5477	-7.9481	0.9060	84.56%	90.14%	€6,842.16	€7,449.65
	Car: Upper Medium	-31,090.8639	34,923.0903	-8.9285	0.9077	84.21%	90.31%	€7,498.77	€7,866.08
	Car: Large	-37,980.2196	42,465.9564	-10.0960	0.9036	83.17%	89.90%	€9,195.08	€9,377.75
	LCV: Small	-16,915.3375	20,677.6554	-7.7012	0.8989	83.69%	89.61%	€5,605.45	€7,033.43
	LCV: Medium	-20,854.6367	25,663.2940	-5.7126	0.9093	85.49%	90.72%	€6,847.33	€8,292.29
	LCV: Large	-53,094.2036	57,586.8151	-10.7206	0.9289	88.46%	92.70%	€9,634.38	€11,835.55
CI REEV	Car: Small	-30,781.1386	33,103.6508	-16.6794	0.9304	87.70%	92.17%	€5,678.80	€6,191.80

[1] Refers to the x-axis (% CO_2 reduction) start point for these curves which have been offset so as to compare with equivalent conventional vehicle

[2] Refers to the y-axis (additional manufacturing cost) start point for these curves which have been offset so as to compare with equivalent conventional vehicle

Powertrain	Segment	Cost curve relative to ICE baseline for xEVs $y = ax^2 + bx + c / (x - x_0)$							
		a	b	c	x_0	x_min = Min reduction (%)*[1]	x_max = Max reduction (%)*	y_min = Min additional cost[2]	y_max = Max additional cost
CI REEV	Car: Lower Medium	-34,886.5618	37,450.0869	-19.5417	0.9260	86.91%	91.74%	€6,549.99	€7,168.01
	Car: Upper Medium	-35,985.8128	39,099.7266	-18.0620	0.9260	86.93%	91.83%	€7,129.36	€7,744.11
	Car: Large	-47,050.9138	50,188.0831	-24.0476	0.9211	85.94%	91.29%	€8,783.07	€9,354.52
	LCV: Small	-25,915.7542	28,769.5955	-10.0912	0.9288	88.18%	92.54%	€5,438.90	€6,848.72
	LCV: Medium	-34,205.5168	37,416.5806	-11.8644	0.9323	88.57%	92.88%	€6,568.68	€8,023.86
	LCV: Large	-61,153.5543	64,235.8716	-17.0280	0.9316	88.59%	92.87%	€9,271.40	€11,529.80
BEV	Car: Small	-23,659.8705	22,024.9265	-10.0281	0.8049	73.93%	79.56%	€3,486.61	€3,576.05
	Car: Lower Medium	-36,526.7561	34,005.8303	-15.0687	0.8094	73.67%	79.80%	€5,435.87	€5,170.22
	Car: Upper Medium	-46,813.5093	42,810.5492	-22.9778	0.8125	74.29%	79.98%	€6,297.93	€6,017.21
	Car: Large	-70,371.7462	65,081.4573	-29.1712	0.8181	74.03%	80.34%	€9,986.86	€8,823.35
	LCV: Small	-22,168.9963	20,697.1300	-10.5529	0.7958	73.24%	79.07%	€3,414.90	€4,356.41
	LCV: Medium	787,164.0662	-1,147,659.093	4,777,460	-10.529	72.42%	78.39%	€6,078.58	€6,756.10
	LCV: Large	1,276,383.580	-1,918,766.576	29,014,161	-38.982	72.98%	78.83%	€9,847.63	€10,938.47
FCEV	Car: Small	-30,909.2367	28,699.6739	-33.0971	0.6280	49.59%	60.49%	€6,874.75	€7,431.39
	Car: Lower Medium	-40,017.4794	37,076.7305	-65.7548	0.6481	49.87%	61.55%	€8,977.75	€9,652.38
	Car: Upper Medium	-47,973.4762	44,261.4429	-79.0472	0.6470	50.60%	61.53%	€10,673.95	€11,483.89
	Car: Large	-59,414.2851	55,224.4889	-135.0298	0.6698	50.79%	62.74%	€13,556.02	€14,428.06
	LCV: Small	-29,296.4886	27,186.2241	-26.1331	0.6105	48.75%	59.92%	€6,496.62	€7,877.54
	LCV: Medium	-36,873.7507	33,056.5601	-41.1983	0.6086	48.22%	59.43%	€7,679.16	€9,275.97
	LCV: Large	-52,125.6336	46,106.9224	-61.0379	0.6111	48.73%	59.82%	€10,543.54	€13,218.71

Table 5: xEVs cost curves (€) for 2025 (% CO_2 reduction for PHEV/REEV, % energy reduction for BEV/FCEV) for TYPICAL cost scenarios.

Powertrain	Segment	Cost curve relative to ICE baseline for xEVs $y = ax^2 + bx + c / (x - x_0)$ a	b	c	x_0	x_min = Min reduction (%)	x_max = Max reduction (%)	y_min = Min additional cost	y_max = Max additional cost
SI PHEV	Car: Small	-19,736.5809	21,698.4648	-40.6450	0.8854	78.82%	87.02%	€5,258.77	€6,580.64
	Car: Lower Medium	-14,514.5486	18,395.6012	-18.3119	0.8665	76.91%	85.89%	€5,768.26	€7,413.95
	Car: Upper Medium	-18,271.7833	21,469.3176	-22.5311	0.8688	76.31%	86.06%	€5,955.78	€7,374.66
	Car: Large	-21,498.7994	25,500.5342	-23.4947	0.8619	74.72%	85.43%	€7,271.72	€8,789.71
	LCV: Small	-10,512.5268	13,714.4375	-18.6241	0.8623	75.76%	85.73%	€4,551.16	€7,100.53
	LCV: Medium	-10,991.8580	15,416.1211	-16.9575	0.8709	78.43%	86.69%	€5,547.59	€8,394.12
	LCV: Large	-19,684.9341	25,443.2530	-16.5449	0.8959	82.78%	89.34%	€7,827.57	€12,287.24
CI PHEV	Car: Small	-18,214.8939	20,731.9589	-31.9478	0.8998	81.71%	88.64%	€5,181.24	€6,382.19
	Car: Lower Medium	-20,212.7602	22,482.1343	-35.7783	0.8915	80.45%	87.94%	€5,430.71	€6,937.94
	Car: Upper Medium	-21,409.5720	23,401.3995	-41.1655	0.8940	80.56%	88.08%	€5,438.28	€7,027.23
	Car: Large	-24,661.2318	27,295.4763	-39.4189	0.8843	79.28%	87.32%	€6,592.15	€8,423.36
	LCV: Small	-12,631.4010	15,320.2745	-17.8322	0.8976	82.44%	89.28%	€4,297.92	€6,706.76
	LCV: Medium	-16,905.8283	19,951.7542	-21.2063	0.9029	83.04%	89.81%	€5,213.66	€7,873.41
	LCV: Large	-32,438.7730	35,316.9763	-30.3261	0.9023	83.05%	89.83%	€7,364.16	€11,532.80
SI REEV	Car: Small	-30,791.2146	34,041.3241	-18.0092	0.9151	85.78%	90.69%	€6,874.83	€7,661.85
	Car: Lower Medium	-30,031.0000	34,559.3370	-11.8629	0.9065	84.56%	90.14%	€7,961.68	€8,952.69
	Car: Upper Medium	-36,481.6163	40,779.8688	-14.0497	0.9086	84.21%	90.31%	€8,676.93	€9,349.13
	Car: Large	-42,899.0554	48,214.3190	-15.2123	0.9042	83.17%	89.90%	€10,627.76	€11,235.55
	LCV: Small	-19,750.7314	24,079.6326	-11.6540	0.8994	83.69%	89.61%	€6,530.52	€8,565.15
	LCV: Medium	-26,927.4667	32,122.2564	-11.1696	0.9099	85.49%	90.72%	€8,006.57	€10,168.49
	LCV: Large	-52,576.6641	59,089.7306	-11.1073	0.9287	88.46%	92.70%	€11,387.90	€14,790.42
CI REEV	Car: Small	-39,492.8509	41,734.5493	-24.2319	0.9315	87.70%	92.17%	€6,678.33	€7,329.05
	Car: Lower Medium	-41,085.6643	44,034.6604	-23.4344	0.9256	86.91%	91.74%	€7,663.59	€8,551.04
	Car: Upper Medium	-43,773.7565	47,096.5482	-24.5790	0.9264	86.93%	91.83%	€8,305.64	€9,222.53

Powertrain	Segment	Cost curve relative to ICE baseline for xEVs $y = ax^2 + bx + c / (x - x_0)$							
		a	b	c	x_0	x_min = Min reduction (%)	x_max = Max reductio n (%)	y_min = Min additional cost	y_max = Max additional cost
CI REEV	Car: Large	-51,691.1857	55,761.1726	-26.7127	0.9204	86.09%	91.29%	€10,159.34	€11,212.25
	LCV: Small	-31,985.4030	35,098.7593	-13.0956	0.9289	88.18%	92.54%	€6,360.64	€8,254.42
	LCV: Medium	-42,977.8786	46,402.4174	-16.3085	0.9324	88.57%	92.88%	€7,717.40	€9,764.61
	LCV: Large	-72,819.8032	76,401.8918	-22.7166	0.9316	88.59%	92.87%	€11,007.51	€14,294.78
BEV	Car: Small	-31,227.1236	28,831.6492	-13.7201	0.8055	73.93%	79.56%	€4,432.47	€4,498.96
	Car: Lower Medium	-53,261.3637	48,244.9960	-21.6868	0.8104	73.67%	79.80%	€6,930.63	€6,291.36
	Car: Upper Medium	583,673.4849	-891,920.7963	6,832,952	-18.857	74.29%	79.98%	€8,135.42	€7,786.15
	Car: Large	-86,802.1514	81,157.0954	-38.6062	0.8186	74.03%	80.34%	€13,000.67	€11,674.09
	LCV: Small	-27,751.5028	25,903.6834	-13.1932	0.7958	72.56%	79.07%	€4,383.33	€5,454.66
	LCV: Medium	703,201.6545	-1,044,783.517	13,598,021	-33.652	71.64%	78.39%	€7,921.79	€8,627.62
	LCV: Large	-86,409.7940	79,712.4153	-33.7626	0.7942	71.72%	78.83%	€13,159.42	€14,218.22
FCEV	Car: Small	-43,564.8193	40,521.1931	-48.4322	0.6301	49.59%	60.49%	€9,734.63	€10,426.79
	Car: Lower Medium	-58,251.5695	53,843.0672	-104.9447	0.6525	49.87%	61.55%	€13,046.56	€13,881.71
	Car: Upper Medium	-70,349.3810	64,999.5981	-122.8329	0.6507	50.60%	61.53%	€15,726.88	€16,732.52
	Car: Large	-88,307.0386	81,921.1746	-224.8283	0.6759	50.79%	62.74%	€20,166.30	€21,254.78
	LCV: Small	-40,611.9108	37,911.2379	-35.1118	0.6109	47.45%	59.92%	€9,135.34	€10,865.82
	LCV: Medium	-50,311.3342	45,822.3457	-52.1732	0.6083	46.75%	59.43%	€10,839.58	€12,873.52
	LCV: Large	-75,193.8411	66,055.9423	-86.7215	0.6116	46.35%	59.82%	€15,048.60	€18,500.18

Table 6: xEVs cost curves (€) for 2025 (% CO_2 reduction for PHEV/REEV, % energy reduction for BEV/FCEV) for HIGH cost scenarios.

Powertrain	Segment	Cost curve relative to ICE baseline for xEVs $y = ax^2 + bx + c / (x - x_0)$ a	b	c	x_0	x_min = Min reduction (%)	x_max = Max reduction (%)	y_min = Min additional cost	y_max = Max additional cost
SI PHEV	Car: Small	-22,471.3120	25,231.6529	-52.1089	0.8849	78.82%	87.02%	€6,478.91	€8,378.96
	Car: Lower Medium	-19,812.2014	24,066.5281	-31.1732	0.8674	76.91%	85.89%	€7,128.82	€9,564.04
	Car: Upper Medium	-23,180.0678	26,969.5214	-33.7161	0.8694	76.31%	86.06%	€7,401.92	€9,464.14
	Car: Large	-26,809.1410	31,705.7766	-32.3354	0.8620	74.72%	85.43%	€9,021.27	€11,212.08
	LCV: Small	-12,740.9723	16,743.6598	-30.0977	0.8630	75.76%	85.73%	€5,677.69	€9,430.33
	LCV: Medium	-12,904.9158	18,554.1438	-26.5053	0.8713	78.43%	86.69%	€6,956.24	€11,131.25
	LCV: Large	-25,849.9010	32,938.1627	-26.4674	0.8959	82.78%	89.34%	€9,949.55	€16,419.73
CI PHEV	Car: Small	-22,310.0354	25,480.1384	-38.9783	0.8993	81.71%	88.64%	€6,398.84	€7,997.62
	Car: Lower Medium	-24,612.3262	27,661.8139	-39.2197	0.8899	80.45%	87.94%	€6,777.55	€8,881.05
	Car: Upper Medium	-26,718.6481	29,410.5248	-45.3692	0.8922	80.56%	88.08%	€6,865.59	€9,059.79
	Car: Large	-29,540.5373	33,327.9734	-39.9563	0.8821	79.28%	87.32%	€8,330.59	€10,857.88
	LCV: Small	-12,623.7624	16,615.3901	-21.0827	0.8972	82.44%	89.28%	€5,425.66	€8,820.05
	LCV: Medium	-18,450.5675	22,839.9152	-25.5345	0.9027	83.04%	89.81%	€6,617.67	€10,370.81
	LCV: Large	-40,730.3411	44,593.6593	-40.1101	0.9023	83.05%	89.83%	€9,480.00	€15,342.16
SI REEV	Car: Small	-36,111.4860	40,594.1039	-24.4863	0.9153	85.78%	90.69%	€8,716.61	€9,891.26
	Car: Lower Medium	-35,941.6006	41,890.4074	-14.9236	0.9061	84.56%	90.14%	€10,009.57	€11,534.40
	Car: Upper Medium	-47,374.5561	52,379.6400	-20.7997	0.9089	84.21%	90.31%	€10,829.30	€11,843.64
	Car: Large	-54,672.2438	61,074.2443	-19.3456	0.9039	83.17%	89.90%	€13,253.59	€14,125.43
	LCV: Small	-21,463.8146	27,410.4648	-16.7366	0.8995	83.69%	89.61%	€8,226.43	€11,279.19
	LCV: Medium	-32,859.3388	39,532.0712	-16.8547	0.9101	85.49%	90.72%	€10,130.00	€13,352.94
	LCV: Large	-70,412.4799	78,302.8035	-17.9358	0.9288	88.46%	92.70%	€14,579.32	€19,592.36
CI REEV	Car: Small	-48,728.5938	51,868.4337	-27.1542	0.9307	87.70%	92.17%	€8,512.83	€9,369.63
	Car: Lower Medium	-53,387.9007	57,024.8006	-26.5717	0.9246	86.91%	91.74%	€9,703.12	€10,949.07
	Car: Upper Medium	-57,887.5299	61,786.5265	-28.6226	0.9255	86.93%	91.83%	€10,462.08	€11,718.52

Powertrain	Segment	Cost curve relative to ICE baseline for xEVs $y = ax^2 + bx + c / (x - x_0)$ a	b	c	x_0	x_min = Min reduction (%)	x_max = Max reduction (%)	y_min = Min additional cost	y_max = Max additional cost
CI REEV	Car: Large	-67,858.3711	72,704.0903	-28.8237	0.9192	86.09%	91.29%	€12,786.93	€14,193.46
	LCV: Small	-36,306.6614	40,764.1118	-15.4663	0.9286	88.18%	92.54%	€8,059.20	€10,758.17
	LCV: Medium	-50,281.6702	55,159.8823	-19.1047	0.9321	88.57%	92.88%	€9,816.79	€12,721.27
	LCV: Large	-91,547.4804	96,408.1214	-28.9591	0.9315	88.59%	92.87%	€14,170.45	€18,821.28
BEV	Car: Small	-37,144.5930	35,430.4429	-14.3034	0.8043	73.26%	79.56%	€6,231.75	€6,231.47
	Car: Lower Medium	391,495.4495	-601,424.4438	4,688,972	-18.780	72.96%	79.80%	€9,879.67	€9,184.06
	Car: Upper Medium	-76,956.1793	71,602.1137	-35.2916	0.8122	73.60%	79.98%	€11,489.78	€10,750.04
	Car: Large	-111,910.3504	106,267.3839	-33.8466	0.8154	74.03%	80.34%	€17,786.74	€15,894.56
	LCV: Small	819,347.0609	-1,209,725.186	8,951,049	-19.055	72.56%	79.07%	€5,964.25	€7,478.76
	LCV: Medium	888,522.1284	-1,350,664.658	-15,281,683	29.9596	71.64%	78.39%	€10,789.02	€11,838.65
	LCV: Large	-110,724.5460	103,665.5569	-42.4897	0.7940	71.72%	78.83%	€17,946.26	€19,534.33
FCEV	Car: Small	-53,739.5205	50,662.9065	-58.9310	0.6293	48.30%	60.49%	€12,370.69	€13,306.82
	Car: Lower Medium	-74,055.9461	68,551.5158	-141.4743	0.6534	48.53%	61.55%	€16,713.79	€17,837.10
	Car: Upper Medium	-88,419.8066	82,591.0631	-149.2298	0.6494	49.28%	61.53%	€20,226.88	€21,576.27
	Car: Large	-105,319.3916	102,449.9045	-175.1725	0.6645	50.79%	62.74%	€25,984.26	€27,491.57
	LCV: Small	-48,080.5194	46,347.7317	-41.2113	0.6101	47.45%	59.92%	€11,518.93	€13,912.30
	LCV: Medium	252,162.0155	-252,188.1380	5,064,454.64	-65.582	46.75%	59.43%	€13,707.90	€16,560.12
	LCV: Large	-90,709.5945	81,774.2574	-105.5764	0.6108	46.35%	59.82%	€19,131.58	€24,012.22

Table 7: xEVs cost curves (€) for 2025 (% CO_2 reduction for PHEV/REEV, % energy reduction for BEV/FCEV) for VERY LOW cost scenarios.

		Cost curve relative to ICE baseline for xEVs $y = ax^2 + bx + c / (x - x_0)$							
Powertrain	**Segment**	**a**	**b**	**c**	**x_0**	**x_min = Min reduction (%)**	**x_max = Max reduction (%)**	**y_min = Min additional cost**	**y_max = Max additional cost**
	Car: Small	-9,658.4540	11,994.2422	-20.4336	0.8816	78.82%	87.02%	€3,673.69	€4,886.74
	Car: Lower Medium	-7,663.9524	10,907.8236	-12.1238	0.8657	76.91%	85.89%	€3,990.99	€5,418.98
	Car: Upper Medium	-10,228.4180	12,929.5285	-14.6293	0.8676	76.31%	86.06%	€4,052.52	€5,366.67
SI PHEV	Car: Large	-12,692.4151	15,926.7479	-15.7625	0.8610	74.72%	85.43%	€4,965.03	€6,351.46
	LCV: Small	-4,716.9745	7,485.1669	-11.9076	0.8615	75.76%	85.73%	€3,093.41	€5,178.13
	LCV: Medium	-2,757.1757	6,719.6583	-9.0046	0.8702	78.43%	86.69%	€3,723.83	€6,018.67
	LCV: Large	-12,901.1690	16,504.5670	-15.5335	0.8961	82.78%	89.34%	€5,054.11	€8,555.52
	Car: Small	-8,897.3749	11,352.8363	-20.2149	0.8978	81.71%	88.64%	€3,603.53	€4,763.47
	Car: Lower Medium	-11,150.9349	13,128.2389	-26.3068	0.8912	80.45%	87.94%	€3,661.98	€5,028.03
	Car: Upper Medium	-11,697.4074	13,387.3009	-29.3863	0.8932	80.56%	88.08%	€3,543.32	€4,978.29
CI PHEV	Car: Large	-15,178.8269	17,004.7288	-32.1241	0.8846	79.06%	87.32%	€4,314.97	€5,912.43
	LCV: Small	-5,728.2909	7,932.9995	-13.4881	0.8974	82.44%	89.28%	€2,841.83	€4,861.58
	LCV: Medium	-8,333.3463	10,752.1022	-15.6906	0.9028	83.04%	89.81%	€3,411.53	€5,619.00
	LCV: Large	-19,139.8412	21,082.8101	-22.6900	0.9022	83.05%	89.83%	€4,616.04	€7,977.46
	Car: Small	-14,884.7327	17,749.2583	-10.7431	0.9136	85.78%	90.69%	€4,475.13	€5,389.90
	Car: Lower Medium	-15,971.2203	19,557.8349	-8.4331	0.9062	84.56%	90.14%	€5,264.71	€6,315.90
	Car: Upper Medium	-20,043.3621	23,584.2708	-9.3217	0.9078	84.21%	90.31%	€5,790.75	€6,672.89
SI REEV	Car: Large	-25,070.9011	29,243.2147	-10.5164	0.9037	83.17%	89.90%	€7,133.76	€7,963.27
	LCV: Small	-8,539.9411	12,130.3678	-7.8255	0.8990	83.69%	89.61%	€4,321.20	€6,116.95
	LCV: Medium	-9,555.9214	14,119.6708	-5.8649	0.9094	85.49%	90.72%	€5,240.70	€7,143.27
	LCV: Large	-32,838.3214	36,901.6939	-10.8974	0.9289	88.46%	92.70%	€7,192.24	€10,104.66
	Car: Small	-20,264.2678	22,306.7850	-16.1435	0.9303	87.70%	92.17%	€4,288.99	€5,144.34
CI REEV	Car: Lower Medium	-23,569.2587	25,826.6145	-18.9343	0.9258	86.91%	91.74%	€4,986.08	€5,995.27
	Car: Upper Medium	-23,748.3168	26,524.7871	-17.4654	0.9259	86.93%	91.83%	€5,434.70	€6,479.66

Powertrain	Segment	Cost curve relative to ICE baseline for xEVs $y = ax^2 + bx + c / (x - x_0)$ a	b	c	x_0	x_min = Min reduction (%)	x_max = Max reduction (%)	y_min = Min additional cost	y_max = Max additional cost
CI REEV	Car: Large	-32,687.4271	35,450.2502	-23.1292	0.9210	85.94%	91.29%	€6,711.31	€7,819.04
	LCV: Small	-16,127.2895	18,681.4443	-9.9961	0.9288	88.18%	92.54%	€4,151.42	€5,883.66
	LCV: Medium	-22,041.3702	24,871.1946	-11.7472	0.9323	88.57%	92.88%	€4,996.37	€6,850.80
	LCV: Large	-42,511.9703	45,004.3790	-16.8933	0.9316	88.59%	92.87%	€6,860.92	€9,727.72
BEV	Car: Small	-15,796.5381	14,583.9173	-9.5490	0.8047	73.93%	79.56%	€2,275.34	€2,606.62
	Car: Lower Medium	-23,724.1146	21,993.6956	-13.4977	0.8088	73.67%	79.80%	€3,514.69	€3,668.42
	Car: Upper Medium	-31,439.8545	28,347.3798	-21.3343	0.8121	74.29%	79.98%	€4,016.09	€4,211.91
	Car: Large	-45,940.6629	42,348.4655	-24.5028	0.8168	74.03%	80.34%	€6,492.46	€6,161.80
	LCV: Small	-14,985.9053	13,897.6621	-10.3218	0.7958	73.24%	79.07%	€2,283.41	€3,450.43
	LCV: Medium	-28,353.7616	25,828.4244	-17.2164	0.7907	72.42%	78.39%	€4,064.84	€5,153.26
	LCV: Large	1,275,183.562	-1,889,144.264	14,526,511.1	-19.838	72.98%	78.83%	€6,479.74	€8,268.14
FCEV	Car: Small	-30,905.6685	28,697.9775	-33.0947	0.6280	49.59%	60.49%	€6,874.77	€7,431.62
	Car: Lower Medium	-40,031.4436	37,082.6787	-65.7779	0.6481	49.87%	61.55%	€8,977.39	€9,651.13
	Car: Upper Medium	-47,982.4903	44,264.6497	-79.0580	0.6470	50.60%	61.53%	€10,673.34	€11,482.65
	Car: Large	-59,408.9945	55,221.3328	-135.0153	0.6698	50.79%	62.74%	€13,555.70	€14,427.97
	LCV: Small	-29,288.1229	27,181.4892	-26.1308	0.6105	48.75%	59.92%	€6,496.28	€7,877.61
	LCV: Medium	-36,878.3531	33,059.3317	-41.1998	0.6086	48.22%	59.43%	€7,679.44	€9,276.04
	LCV: Large	-52,125.2039	46,106.4900	-61.0378	0.6111	48.73%	59.82%	€10,543.43	€13,218.60

Cost curves for 2030

Table 8: ICEs cost curves (€) for 2030, for LOW cost scenarios.

Powertrain	Segment	Cost curve relative to vehicle baseline for SI+Hybrid and CI+Hybrid $y = C + c / (x - x_0)$ C	c	x_0	x_min = Min CO_2 reduction (%)	x_max = Max CO_2 reduction (%)	y_min = Min additional cost	y_max = Max additional cost
SI+Hybrid	Car: Small	-395.00	-215.03	0.545141	0.22%	48.47%	€1.04	€3,160.76
	Car: Lower Medium	-441.01	-227.25	0.514734	0.17%	45.89%	€1.98	€3,630.54
	Car: Upper Medium	-384.04	-196.75	0.511986	0.29%	46.41%	€2.47	€3,722.97
	Car: Large	-377.57	-190.09	0.506730	0.92%	46.62%	€4.52	€4,318.24
	LCV: Small	-416.35	-237.60	0.570475	0.01%	50.91%	€0.26	€3,453.18
	LCV: Medium	-665.41	-383.20	0.584911	0.92%	50.48%	€0.25	€4,118.51
	LCV: Large	-784.56	-433.20	0.577031	2.60%	50.82%	€1.66	€5,511.67
CI+Hybrid	Car: Small	-527.51	-289.47	0.561687	1.91%	48.79%	€6.00	€3,394.25
	Car: Lower Medium	-714.15	-421.39	0.593885	0.54%	50.11%	€1.90	€3,826.17
	Car: Upper Medium	-733.40	-436.69	0.603698	1.16%	51.33%	€4.07	€4,096.58
	Car: Large	-1049.51	-649.28	0.621359	0.77%	50.73%	€8.59	€4,641.02
	LCV: Small	-590.20	-367.16	0.616737	0.73%	53.65%	€12.23	€3,984.39
	LCV: Medium	-639.09	-383.77	0.610500	1.45%	53.74%	€4.83	€4,612.85
	LCV: Large	-676.92	-411.52	0.611469	0.72%	55.24%	€4.07	€6,295.05

Table 9: ICEs cost curves (€) for 2030, for TYPICAL cost scenarios.

Powertrain	Segment	Cost curve relative to vehicle baseline for SI+Hybrid and CI+Hybrid $y = C + c / (x - x_0)$ C	c	x_0	x_min = Min CO_2 reduction (%)	x_max = Max CO_2 reduction (%)	y_min = Min additional cost	y_max = Max additional cost
SI+Hybrid	Car: Small	-586.42	-321.42	0.550132	0.22%	48.47%	€0.18	€4,323.40
	Car: Lower Medium	-648.79	-328.95	0.515652	1.03%	45.25%	€2.14	€4,561.23
	Car: Upper Medium	-563.04	-290.24	0.516166	0.29%	46.41%	€2.49	€5,009.25
	Car: Large	-531.21	-275.03	0.508895	0.32%	46.62%	€12.70	€5,917.91
	LCV: Small	-582.75	-331.67	0.568889	0.01%	50.63%	€0.43	€4,717.67
	LCV: Medium	-920.67	-532.97	0.584803	0.92%	50.17%	€5.33	€5,495.55
	LCV: Large	-1125.86	-631.67	0.580070	2.60%	50.62%	€14.27	€7,424.92
CI+Hybrid	Car: Small	-744.62	-414.88	0.570553	1.91%	48.79%	€7.72	€4,273.32
	Car: Lower Medium	-976.75	-582.39	0.600161	0.54%	50.11%	€2.44	€4,900.82
	Car: Upper Medium	-982.67	-587.02	0.605761	1.16%	51.33%	€5.23	€5,365.23
	Car: Large	-1460.86	-899.28	0.627238	1.76%	50.73%	€14.25	€6,034.63
	LCV: Small	-806.47	-501.46	0.618804	0.05%	53.65%	€4.52	€5,284.60
	LCV: Medium	-911.63	-552.08	0.616011	1.45%	53.74%	€6.22	€6,113.88
	LCV: Large	-897.82	-544.78	0.610349	0.72%	55.24%	€5.37	€8,510.34

Table 10: ICEs cost curves (€) for 2030 for HIGH cost scenarios.

Powertrain	Segment	Cost curve relative to vehicle baseline for SI+Hybrid and CI+Hybrid $y = C + c / (x - x_0)$ C	c	x_0	x_min = Min CO_2 reduction (%)	x_max = Max CO_2 reduction (%)	y_min = Min additional cost	y_max = Max additional cost
SI+Hybrid	Car: Small	-871.31	-479.06	0.550136	0.18%	48.21%	€2.40	€6,172.80
	Car: Lower Medium	-939.04	-483.38	0.517610	0.31%	45.32%	€0.42	€6,568.14
	Car: Upper Medium	-808.90	-421.67	0.517063	0.29%	46.41%	€11.28	€7,149.59
	Car: Large	-805.09	-410.08	0.510575	0.32%	46.62%	€3.21	€8,446.26
	LCV: Small	-919.36	-502.76	0.568528	3.10%	51.28%	€16.00	€8,099.23
	LCV: Medium	-1322.48	-765.80	0.581636	0.92%	50.17%	€15.41	€8,262.17
	LCV: Large	-1666.34	-925.27	0.578810	2.60%	50.62%	€7.53	€11,076.27
CI+Hybrid	Car: Small	-1022.67	-585.53	0.575982	0.62%	48.79%	€5.04	€5,623.00
	Car: Lower Medium	-1364.19	-816.89	0.603420	0.54%	50.11%	€1.79	€6,617.57
	Car: Upper Medium	-1333.46	-806.90	0.607272	0.26%	51.33%	€0.92	€7,251.86
	Car: Large	-1664.09	-1008.73	0.607634	0.72%	50.73%	€16.00	€8,385.78
	LCV: Small	-1175.09	-735.92	0.623555	0.05%	53.65%	€6.02	€7,276.18
	LCV: Medium	-1271.80	-769.33	0.615448	1.45%	53.74%	€8.43	€8,588.87
	LCV: Large	-1295.11	-787.58	0.611839	0.72%	55.24%	€7.41	€11,965.14

Table 11: xEVs cost curves (€) for 2030 (% CO_2 reduction for PHEV/REEV, % energy reduction for BEV/FCEV) for LOW cost scenarios.

Powertrain	Segment	a	b	c	x_0	x_min = Min reduction (%)	x_max = Max reduction (%)	y_min = Min additional cost	y_max = Max additional cost
		Cost curve relative to ICE baseline for xEVs $y = ax^2 + bx + c / (x - x_0)$							
SI PHEV	Car: Small	-12,376.0460	14,582.9647	-19.0039	0.8874	79.19%	87.45%	€3,985.60	€4,745.91
	Car: Lower Medium	-11,953.4905	14,668.6281	-13.9921	0.8772	77.29%	86.69%	€4,332.09	€5,076.12
	Car: Upper Medium	-13,969.1629	16,291.4060	-16.7264	0.8807	76.70%	87.06%	€4,421.58	€5,162.48
	Car: Large	-16,650.2227	19,460.8513	-16.7925	0.8746	75.17%	86.55%	€5,363.59	€6,072.41
	LCV: Small	-6,965.0542	9,603.1376	-10.7458	0.8687	76.17%	86.32%	€3,388.69	€4,792.28
	LCV: Medium	-7,446.0309	10,889.1268	-8.2079	0.8765	78.77%	87.25%	€4,081.35	€5,598.92
	LCV: Large	-13,391.7134	17,636.9854	-7.7478	0.9047	83.58%	90.26%	€5,543.01	€7,797.93
CI PHEV	Car: Small	-11,718.3258	14,067.7181	-20.8831	0.9042	81.83%	89.03%	€3,923.35	€4,655.39
	Car: Lower Medium	-14,892.5480	16,540.8512	-32.2342	0.9002	80.58%	88.40%	€4,010.71	€4,877.03
	Car: Upper Medium	-16,483.6653	17,617.2408	-41.5200	0.9045	80.68%	88.56%	€3,917.08	€4,815.70
	Car: Large	-19,102.4715	20,624.9381	-38.1030	0.8939	79.20%	87.82%	€4,739.23	€5,706.41
	LCV: Small	-8,282.6518	10,439.5625	-12.6613	0.9026	82.56%	89.70%	€3,147.57	€4,519.79
	LCV: Medium	-10,920.9368	13,361.7168	-14.4922	0.9074	83.15%	90.21%	€3,764.52	€5,226.93
	LCV: Large	-17,434.2775	20,472.9391	-14.2060	0.9059	83.16%	90.22%	€5,168.33	€7,333.95
SI REEV	Car: Small	-19,456.7841	22,341.7348	-7.5427	0.9168	86.07%	91.03%	€4,959.89	€5,342.52
	Car: Lower Medium	-23,694.3435	26,759.9308	-8.8182	0.9143	84.86%	90.75%	€5,778.01	€6,028.42
	Car: Upper Medium	-27,072.7945	30,208.6187	-9.8704	0.9173	84.52%	91.06%	€6,324.89	€6,483.18
	Car: Large	-32,631.0442	36,334.9806	-10.1076	0.9132	83.52%	90.74%	€7,714.19	€7,677.56
	LCV: Small	-12,465.6431	16,009.3270	-5.7816	0.9041	84.02%	90.09%	€4,766.35	€5,803.49
	LCV: Medium	-18,466.7625	22,427.4060	-5.1030	0.9140	85.77%	91.14%	€5,773.00	€6,786.17
	LCV: Large	-37,028.8980	41,652.6458	-5.2341	0.9347	88.99%	93.32%	€7,894.55	€9,379.07
CI REEV	Car: Small	-23,376.6310	25,700.8466	-13.1986	0.9338	87.81%	92.46%	€4,794.75	€5,135.41
	Car: Lower Medium	-28,451.0953	30,725.8625	-18.9702	0.9312	87.04%	92.09%	€5,514.08	€5,925.98
	Car: Upper Medium	-30,531.7169	33,079.4334	-19.3998	0.9319	87.05%	92.18%	€5,988.20	€6,385.83

Powertrain	Segment	Cost curve relative to ICE baseline for xEVs $y = ax^2 + bx + c / (x - x_0)$							
		a	**b**	**c**	x_0	**x_min = Min reduction (%)**	**x_max = Max reductio n (%)**	**y_min = Min additional cost**	**y_max = Max additional cost**
CI REEV	Car: Large	-41,674.2100	43,863.9407	-30.2404	0.9283	86.08%	91.66%	€7,334.18	€7,677.99
	LCV: Small	-20,777.4601	23,354.6675	-9.0715	0.9324	88.29%	92.85%	€4,613.76	€5,620.55
	LCV: Medium	-27,403.4007	30,272.9242	-10.6918	0.9356	88.68%	93.18%	€5,524.47	€6,533.16
	LCV: Large	-41,164.6023	44,921.8461	-10.1100	0.9343	88.70%	93.16%	€7,680.34	€9,198.32
BEV	Car: Small	-20,401.0361	18,883.4361	-8.2866	0.8120	74.76%	80.22%	€2,827.32	€2,838.38
	Car: Lower Medium	-33,663.9919	30,728.3387	-18.5150	0.8208	74.61%	80.52%	€4,435.58	€4,094.48
	Car: Upper Medium	-41,788.6448	37,959.2550	-19.2198	0.8202	75.18%	80.67%	€5,199.92	€4,808.70
	Car: Large	-64,770.0592	58,733.1453	-41.2243	0.8345	75.32%	81.32%	€7,999.94	€6,858.24
	LCV: Small	-18,673.5441	17,445.4020	-7.9767	0.8019	74.00%	79.66%	€2,797.05	€3,428.01
	LCV: Medium	-35,293.1882	32,503.3542	-13.0945	0.7981	73.35%	79.12%	€5,033.70	€5,383.06
	LCV: Large	1,049,564.331	-1,595,104.030	18,842,677.8	-29.946	73.93%	79.57%	€8,246.45	€8,718.62
FCEV	Car: Small	-24,648.0531	23,111.5768	-27.9452	0.6364	50.45%	61.17%	€5,590.44	€6,017.24
	Car: Lower Medium	-32,899.2518	29,829.5608	-83.3781	0.6667	50.79%	62.25%	€7,188.63	€7,699.52
	Car: Upper Medium	-37,368.2731	34,799.7180	-66.4835	0.6570	51.61%	62.32%	€8,478.69	€9,096.33
	Car: Large	-48,801.1328	43,807.3472	-196.4375	0.6966	51.92%	63.60%	€10,696.56	€11,358.10
	LCV: Small	-23,195.3471	21,895.2003	-20.3530	0.6171	49.52%	60.52%	€5,314.52	€6,337.22
	LCV: Medium	-28,926.9766	26,490.1206	-31.2294	0.6147	48.95%	60.00%	€6,273.77	€7,458.09
	LCV: Large	-41,306.8504	37,035.3853	-49.4499	0.6181	49.46%	60.39%	€8,576.98	€10,516.50

Table 12: xEVs cost curves (€) for 2030 (% CO_2 reduction for PHEV/REEV, % energy reduction for BEV/FCEV) for TYPICAL cost scenarios.

Powertrain	Segment	Cost curve relative to ICE baseline for xEVs $y = ax^2 + bx + c / (x - x_0)$ a	b	c	x_0	x_min = Min reduction (%)	x_max = Max reduction (%)	y_min = Min additional cost	y_max = Max additional cost
SI PHEV	Car: Small	-17,142.0195	19,192.1179	-35.4823	0.8907	79.19%	87.45%	€4,806.06	€5,846.74
	Car: Lower Medium	-15,542.6142	18,479.4403	-26.2888	0.8799	77.29%	86.69%	€5,245.61	€6,301.08
	Car: Upper Medium	-17,662.2875	20,287.8199	-28.5687	0.8830	76.70%	87.06%	€5,410.89	€6,479.15
	Car: Large	-19,768.9068	23,315.4333	-26.0470	0.8760	75.17%	86.55%	€6,576.17	€7,702.06
	LCV: Small	-8,910.9750	11,989.7800	-17.5816	0.8697	76.17%	86.32%	€4,139.49	€6,103.45
	LCV: Medium	-9,010.0216	13,286.7730	-12.3112	0.8769	78.77%	87.25%	€5,030.54	€7,199.15
	LCV: Large	-14,822.4437	20,515.6505	-10.9557	0.9048	83.58%	90.26%	€7,008.76	€10,312.81
CI PHEV	Car: Small	-15,353.6734	17,931.5877	-29.5751	0.9054	81.83%	89.03%	€4,747.43	€5,661.80
	Car: Lower Medium	-18,027.8184	20,121.4785	-37.8447	0.8992	80.58%	88.40%	€4,924.93	€6,087.56
	Car: Upper Medium	-19,537.3868	21,223.0926	-47.0908	0.9030	80.68%	88.56%	€4,904.79	€6,116.60
	Car: Large	-22,963.3668	25,085.0748	-47.3016	0.8933	79.41%	87.82%	€5,929.97	€7,331.94
	LCV: Small	-9,799.8795	12,553.6981	-15.4907	0.9021	82.56%	89.70%	€3,897.36	€5,719.58
	LCV: Medium	-12,829.7311	16,021.8645	-18.6806	0.9077	83.15%	90.21%	€4,712.24	€6,702.23
	LCV: Large	-21,862.6933	25,856.4137	-19.3800	0.9060	83.16%	90.22%	€6,645.10	€9,680.02
SI REEV	Car: Small	-24,071.3991	27,662.2440	-11.5136	0.9175	86.07%	91.03%	€6,197.70	€6,766.04
	Car: Lower Medium	-28,391.6766	32,284.7972	-13.5834	0.9152	84.86%	90.75%	€7,160.15	€7,609.56
	Car: Upper Medium	-34,229.9360	37,905.0118	-17.4962	0.9188	84.52%	91.06%	€7,809.46	€8,177.40
	Car: Large	-38,083.6609	42,994.8574	-15.5555	0.9141	83.52%	90.74%	€9,539.52	€9,807.33
	LCV: Small	-15,342.1092	19,718.8203	-9.0734	0.9046	84.02%	90.09%	€5,903.16	€7,400.50
	LCV: Medium	-22,379.2904	27,426.1192	-7.6773	0.9143	85.77%	91.14%	€7,213.17	€8,763.39
	LCV: Large	-43,319.4766	49,667.8365	-7.4258	0.9348	88.99%	93.32%	€10,105.36	€12,458.21
CI REEV	Car: Small	-29,188.6569	32,157.6051	-15.9835	0.9337	87.81%	92.46%	€6,036.52	€6,457.80
	Car: Lower Medium	-35,833.9406	38,641.7879	-24.2746	0.9311	87.04%	92.09%	€6,897.35	€7,500.20
	Car: Upper Medium	-38,353.4309	41,483.4724	-26.0334	0.9321	87.05%	92.18%	€7,480.95	€8,087.88

Powertrain	Segment	Cost curve relative to ICE baseline for xEVs $y = ax^2 + bx + c / (x - x_0)$							
		a	b	c	x_0	x_min = Min reduction (%)	x_max = Max reduction (%)	y_min = Min additional cost	y_max = Max additional cost
CI REEV	Car: Large	-44,320.2576	48,294.0406	-26.6630	0.9257	86.22%	91.66%	€9,127.46	€9,826.48
	LCV: Small	-26,237.8384	29,410.1033	-11.5450	0.9322	88.29%	92.85%	€5,752.46	€7,107.19
	LCV: Medium	-32,697.2144	36,512.9512	-13.7450	0.9358	88.68%	93.18%	€6,957.17	€8,390.07
	LCV: Large	-51,636.4552	56,639.9990	-13.9406	0.9343	88.70%	93.16%	€9,908.15	€12,142.86
BEV	Car: Small	-28,335.1198	26,359.9797	-11.8346	0.8130	74.76%	80.22%	€4,030.21	€3,979.19
	Car: Lower Medium	-47,443.2361	43,544.3639	-25.1726	0.8216	74.61%	80.52%	€6,413.04	€5,825.41
	Car: Upper Medium	-56,068.2626	51,815.0684	-26.7178	0.8211	75.18%	80.67%	€7,650.16	€7,106.88
	Car: Large	-83,535.8269	77,808.7704	-51.3347	0.8344	75.32%	81.32%	€11,846.31	€10,436.96
	LCV: Small	-24,539.6567	23,225.1774	-10.0115	0.8019	73.34%	79.66%	€3,992.39	€4,657.14
	LCV: Medium	569,019.1604	-858,706.0242	11,981,431.8	-35.478	72.60%	79.12%	€7,323.55	€7,571.71
	LCV: Large	1,328,607.142	-2,015,789.804	20,336,404.8	-25.456	73.93%	79.57%	€11,964.86	€12,617.47
FCEV	Car: Small	-34,797.5638	32,512.7588	-43.3173	0.6398	50.45%	61.17%	€7,856.87	€8,378.01
	Car: Lower Medium	-47,306.3311	42,965.5322	-126.0527	0.6709	50.79%	62.25%	€10,392.47	€11,014.39
	Car: Upper Medium	-54,531.7977	50,893.0748	-102.4579	0.6608	51.61%	62.32%	€12,449.11	€13,206.23
	Car: Large	-71,429.0777	64,554.6185	-297.7795	0.7015	51.92%	63.60%	€15,894.88	€16,705.08
	LCV: Small	-31,870.6135	30,234.8803	-27.1411	0.6175	48.24%	60.52%	€7,398.17	€8,664.25
	LCV: Medium	-39,438.4843	36,509.3219	-40.4158	0.6147	47.50%	60.00%	€8,770.57	€10,258.45
	LCV: Large	-57,443.3860	51,881.7083	-64.5186	0.6178	49.46%	60.39%	€12,084.08	€14,628.86

Table 13: xEVs cost curves (€) for 2030 (% CO_2 reduction for PHEV/REEV, % energy reduction for BEV/FCEV) for HIGH cost scenarios.

		Cost curve relative to ICE baseline for xEVs $y = ax^2 + bx + c / (x - x_0)$							
Powertrain	**Segment**	**a**	**b**	**c**	**x_0**	**x_min = Min reduction (%)**	**x_max = Max reduction (%)**	**y_min = Min additional cost**	**y_max = Max additional cost**
SI PHEV	Car: Small	-25,080.6795	26,512.5024	-72.2030	0.8952	79.19%	87.45%	€5,946.58	€7,487.51
	Car: Lower Medium	-19,786.9148	23,284.6799	-38.7160	0.8801	77.29%	86.69%	€6,545.29	€8,146.10
	Car: Upper Medium	-21,987.7586	25,224.9363	-39.9571	0.8829	76.70%	87.06%	€6,778.82	€8,390.23
	Car: Large	-25,314.5542	29,587.2925	-36.3244	0.8758	75.17%	86.55%	€8,257.50	€9,927.72
	LCV: Small	-11,514.0054	15,195.8797	-30.8026	0.8709	76.17%	86.32%	€5,190.26	€8,175.94
	LCV: Medium	-11,474.2193	16,775.9273	-21.7116	0.8778	78.77%	87.25%	€6,363.93	€9,637.07
	LCV: Large	-17,662.5217	25,134.3378	-16.6428	0.9050	83.58%	90.26%	€8,996.06	€13,934.12
CI PHEV	Car: Small	-17,610.7967	21,104.2443	-33.6953	0.9044	81.83%	89.03%	€5,885.22	€7,138.48
	Car: Lower Medium	-20,657.8635	23,852.1450	-35.0064	0.8952	80.58%	88.40%	€6,197.78	€7,870.04
	Car: Upper Medium	-22,939.9633	25,674.2048	-43.8426	0.8987	80.68%	88.56%	€6,258.88	€7,983.42
	Car: Large	-28,004.7781	31,205.9957	-45.1012	0.8897	79.41%	87.82%	€7,597.36	€9,579.79
	LCV: Small	-11,167.6856	14,884.6245	-20.3587	0.9019	82.56%	89.70%	€4,956.12	€7,604.94
	LCV: Medium	-16,405.4365	20,497.0478	-24.8152	0.9071	83.15%	90.21%	€6,043.84	€8,929.47
	LCV: Large	-28,622.5413	33,773.4195	-27.2027	0.9059	83.16%	90.22%	€8,655.33	€13,044.63
SI REEV	Car: Small	-30,647.1623	35,151.1734	-18.4672	0.9185	86.07%	91.03%	€7,905.16	€8,788.21
	Car: Lower Medium	-39,164.8268	43,538.3337	-22.9712	0.9160	84.86%	90.75%	€9,093.76	€9,829.61
	Car: Upper Medium	-46,752.7288	50,754.8510	-27.3526	0.9193	84.52%	91.06%	€9,846.74	€10,445.27
	Car: Large	-52,680.9530	58,063.8830	-23.3252	0.9143	83.52%	90.74%	€12,030.38	€12,416.91
	LCV: Small	-17,865.0556	23,588.3695	-14.7291	0.9050	84.02%	90.09%	€7,480.94	€9,821.89
	LCV: Medium	-28,959.1102	35,281.8194	-12.9672	0.9147	85.77%	91.14%	€9,218.23	€11,614.95
	LCV: Large	-54,971.4985	63,239.4058	-10.9152	0.9348	88.99%	93.32%	€13,066.70	€16,661.39
CI REEV	Car: Small	-38,556.2118	42,227.4319	-21.2792	0.9338	87.81%	92.46%	€7,748.09	€8,318.78
	Car: Lower Medium	-47,371.4782	50,859.6493	-27.4459	0.9296	87.04%	92.09%	€8,838.36	€9,715.81
	Car: Upper Medium	-50,263.9831	54,165.9046	-27.7202	0.9302	87.05%	92.18%	€9,524.79	€10,380.05

Powertrain	Segment	Cost curve relative to ICE baseline for xEVs $y = ax^2 + bx + c / (x - x_0)$ a	b	c	x_0	x_min = Min reduction (%)	x_max = Max reductio n (%)	y_min = Min additional cost	y_max = Max additional cost
CI REEV	Car: Large	-59,879.3542	64,581.8617	-28.7995	0.9241	86.22%	91.66%	€11,637.06	€12,574.71
	LCV: Small	-31,901.2840	36,126.9257	-14.8569	0.9320	88.29%	92.85%	€7,340.88	€9,347.45
	LCV: Medium	-43,127.7595	47,900.9393	-17.9895	0.9354	88.68%	93.18%	€8,945.20	€11,043.76
	LCV: Large	-68,197.7404	74,590.0374	-19.0104	0.9342	88.70%	93.16%	€12,907.73	€16,169.81
BEV	Car: Small	-34,119.7385	32,814.2276	-12.3163	0.8116	74.12%	80.22%	€5,764.54	€5,623.61
	Car: Lower Medium	-59,625.4121	56,168.6963	-28.5906	0.8202	73.92%	80.52%	€9,309.11	€8,449.94
	Car: Upper Medium	-73,963.1454	69,366.0004	-31.0647	0.8201	74.52%	80.67%	€11,050.62	€10,058.62
	Car: Large	-106,722.7018	101,838.8500	-35.7253	0.8280	75.32%	81.32%	€16,637.18	€14,618.53
	LCV: Small	-28,898.2555	28,465.5914	-11.8897	0.8015	73.34%	79.66%	€5,531.41	€6,529.72
	LCV: Medium	718,466.6850	-1,073,189.552	8,040,549.92	-18.849	72.60%	79.12%	€10,181.97	€10,630.88
	LCV: Large	-105,027.2321	99,592.1209	-32.6218	0.8016	72.72%	79.57%	€17,323.03	€17,720.01
FCEV	Car: Small	-40,757.8839	38,817.0012	-49.7397	0.6380	49.19%	61.17%	€9,600.29	€10,335.94
	Car: Lower Medium	-56,888.6589	52,261.0612	-145.9009	0.6680	49.47%	62.25%	€12,806.63	€13,677.77
	Car: Upper Medium	-65,795.4181	62,044.4715	-121.7275	0.6590	50.32%	62.32%	€15,378.66	€16,431.14
	Car: Large	-78,287.7661	76,504.4240	-167.9633	0.6793	51.92%	63.60%	€19,665.99	€20,839.82
	LCV: Small	-35,582.7551	35,216.4782	-30.6468	0.6163	48.24%	60.52%	€8,979.11	€10,800.77
	LCV: Medium	-43,737.3926	42,435.2837	-44.7866	0.6132	47.50%	60.00%	€10,672.31	€12,837.75
	LCV: Large	-68,178.6781	62,547.5807	-80.5804	0.6170	47.11%	60.39%	€14,887.24	€18,507.01

Table 14: xEVs cost curves (€) for 2030 (% CO_2 reduction for PHEV/REEV, % energy reduction for BEV/FCEV) for VERY LOW cost scenarios.

Powertrain	Segment	Cost curve relative to ICE baseline for xEVs $y = ax^2 + bx + c / (x - x_0)$ a	b	c	x_0	x_min = Min reduction (%)	x_max = Max reduction (%)	y_min = Min additional cost	y_max = Max additional cost
SI PHEV	Car: Small	-7,551.2967	9,749.0923	-19.3697	0.8875	79.19%	87.45%	€3,186.78	€4,223.65
	Car: Lower Medium	-6,798.6798	9,478.9890	-14.4330	0.8769	77.29%	86.69%	€3,403.51	€4,486.60
	Car: Upper Medium	-8,291.9691	10,647.9183	-16.8212	0.8807	76.70%	87.06%	€3,433.07	€4,558.55
	Car: Large	-9,880.3803	12,782.5808	-16.7501	0.8746	75.17%	86.55%	€4,167.36	€5,364.46
	LCV: Small	-2,708.9921	5,396.1794	-10.7610	0.8687	76.17%	86.32%	€2,653.26	€4,334.17
	LCV: Medium	-1,683.5971	5,156.3252	-8.2980	0.8766	78.77%	87.25%	€3,142.10	€4,992.22
	LCV: Large	-3,551.1616	7,767.7441	-7.8467	0.9048	83.58%	90.26%	€4,170.83	€6,922.51
CI PHEV	Car: Small	-6,506.3420	8,836.8003	-19.8582	0.9038	81.83%	89.03%	€3,121.04	€4,092.20
	Car: Lower Medium	-8,968.6296	10,640.7134	-30.5694	0.8998	80.58%	88.40%	€3,085.67	€4,237.93
	Car: Upper Medium	-10,181.3926	11,346.1821	-39.0948	0.9039	80.68%	88.56%	€2,936.44	€4,138.70
	Car: Large	-11,627.1580	13,215.9660	-35.6426	0.8933	79.20%	87.82%	€3,536.49	€4,888.87
	LCV: Small	-3,491.4211	5,589.0013	-12.4647	0.9025	82.56%	89.70%	€2,405.17	€4,008.59
	LCV: Medium	-4,869.1255	7,226.6644	-14.2513	0.9074	83.15%	90.21%	€2,842.97	€4,597.85
	LCV: Large	-8,335.7873	11,242.3192	-13.9290	0.9059	83.16%	90.22%	€3,779.21	€6,385.05
SI REEV	Car: Small	-9,321.2527	12,215.1440	-8.2665	0.9171	86.07%	91.03%	€3,764.96	€4,574.53
	Car: Lower Medium	-12,637.7971	15,724.8909	-9.7335	0.9147	84.86%	90.75%	€4,389.69	€5,178.92
	Car: Upper Medium	-15,559.7878	18,721.6638	-10.5171	0.9172	84.52%	91.06%	€4,849.08	€5,631.84
	Car: Large	-18,791.9531	22,630.0169	-10.7833	0.9135	83.52%	90.74%	€5,930.75	€6,686.39
	LCV: Small	-3,678.2013	7,311.3953	-5.9701	0.9041	84.02%	90.09%	€3,665.53	€5,122.22
	LCV: Medium	-6,168.5225	10,235.4052	-5.3295	0.9141	85.77%	91.14%	€4,368.35	€5,921.22
	LCV: Large	-14,886.9372	19,645.3338	-5.3815	0.9347	88.99%	93.32%	€5,853.02	€8,160.86
CI REEV	Car: Small	-12,160.3834	14,493.2541	-12.5903	0.9336	87.81%	92.46%	€3,591.21	€4,327.59
	Car: Lower Medium	-16,029.1670	18,340.9294	-18.0632	0.9309	87.04%	92.09%	€4,130.36	€5,010.03
	Car: Upper Medium	-17,293.4232	19,881.6306	-18.3856	0.9316	87.05%	92.18%	€4,515.11	€5,418.84
	Car: Large	-26,032.9245	28,329.1646	-28.5292	0.9280	86.08%	91.66%	€5,527.48	€6,506.42

Powertrain	Segment	Cost curve relative to ICE baseline for xEVs $y = ax^2 + bx + c / (x - x_0)$ a	b	c	x_0	x_min = Min reduction (%)	x_max = Max reduction (%)	y_min = Min additional cost	y_max = Max additional cost
CI REEV	LCV: Small	-10,349.9149	12,891.2237	-8.9440	0.9324	88.29%	92.85%	€3,500.51	€4,880.46
	LCV: Medium	-14,045.5967	16,879.2581	-10.5343	0.9356	88.68%	93.18%	€4,147.58	€5,632.33
	LCV: Large	-21,077.7071	24,773.2969	-9.9334	0.9342	88.70%	93.16%	€5,607.64	€7,836.13
BEV	Car: Small	-11,900.0684	11,109.4351	-7.7555	0.8117	74.76%	80.22%	€1,758.27	€2,043.89
	Car: Lower Medium	-19,144.7893	17,591.0050	-15.8684	0.8196	74.61%	80.52%	€2,683.53	€2,837.07
	Car: Upper Medium	-24,395.5419	22,147.4445	-17.2596	0.8195	75.18%	80.67%	€3,116.90	€3,290.51
	Car: Large	-37,577.3693	34,260.8321	-32.6312	0.8323	75.32%	81.32%	€4,899.45	€4,704.91
	LCV: Small	-10,898.2556	10,347.0656	-7.7267	0.8018	74.00%	79.66%	€1,797.04	€2,686.04
	LCV: Medium	-20,831.8662	19,403.6886	-12.5149	0.7979	73.35%	79.12%	€3,195.27	€4,029.36
	LCV: Large	1,049,007.716	-1,572,819.991	13,170,371.6	-21.403	73.93%	79.57%	€5,171.29	€6,467.65
FCEV	Car: Small	-24,660.2278	23,116.2753	-27.9541	0.6364	50.45%	61.17%	€5,589.77	€6,015.76
	Car: Lower Medium	-32,903.5413	29,831.7489	-83.3895	0.6667	50.79%	62.25%	€7,188.70	€7,699.37
	Car: Upper Medium	-37,351.6462	34,792.7671	-66.4612	0.6570	51.61%	62.32%	€8,479.39	€9,098.07
	Car: Large	-48,811.3110	43,811.0217	-196.4884	0.6966	51.92%	63.60%	€10,695.97	€11,356.83
	LCV: Small	-23,192.3365	21,894.0067	-20.3522	0.6171	49.52%	60.52%	€5,314.66	€6,337.56
	LCV: Medium	-28,941.6438	26,497.5362	-31.2343	0.6147	48.95%	60.00%	€6,273.93	€7,457.43
	LCV: Large	-41,305.9049	37,034.4175	-49.4496	0.6181	49.46%	60.39%	€8,576.73	€10,516.25

Annex 2. Assessment of technology related comments from car manufacturers

Introduction

In 2016 several bilateral meetings with automotive OEMs were organised at technical level to discuss the findings of a DG CLIMA commissioned study "Improving understanding of technology and costs for CO_2 reductions from cars and LCVs in the period to 2030 and development of cost curves" ([3], the "study" hereafter). Following these meetings, the JRC has been requested to assess the technology related comments from car manufacturers (OEMs) on the study.

The main aims of the study were i) to generate an updated list of CO_2 improvement technologies for cars and LCVs, their costs and CO_2 savings potential, and ii) to construct cost curves on this basis.

The study has been based on an extensive literature survey, on the outputs of selected detailed vehicle simulations, and on the feedback from 36 stakeholders. In particular, during the study 5 OEMs (BMW, Fiat, Honda, Hyundai, McLaren), 2 manufacturer associations (ACEA, JAMA), 6 engineering consultancies, 12 automotive suppliers and 3 research/academic organisations were involved.

After the finalisation of the study additional feedback was received from 12 OEMs (BMW, Daimler, Fiat, Ford, GM, Honda, Hyundai, JLR, PSA, Toyota, Volvo, VW). The additional feedback is mainly based (i) on a draft of the final study report (status 28-07-2015), (ii) on the final version of the Excel file that includes the techno-economic data for all considered technologies, and (iii) on one exemplary page of "Technologies applicable in 2015 to Compression Ignition Internal Combustion Engine vehicles (including hybridisation) for the lower-medium car segment" that was used in earlier iterations of stakeholder consultation during the course of the study.

The aim of our present assessment is to (i) check the alignment between the new comments received and the assumptions of the original study, (ii) analyse the validity of recurring critical comments, and (iii) evaluate the need for further action.

In the following we describe the assessment and report the conclusions achieved.

Assessment

The assessment is based on the following material and information sources: Information provided to the OEMs (see above), final study report (status 25-02-2016), material provided by the OEMs, selected other studies that were used as input ([17],[18],[19]), JRC expertise, analyses of CO2MPAS[3] model outputs, and additional runs of the JRC cost curve model.

Overall, the feedback from the OEMs on the approach and many of the assumptions of the study was positive. The feedback on some detailed aspects of the study was constructive and occasionally backed-up with in-depth analyses. Most of the comments focused on car technologies which can reduce CO_2 emissions under test cycle conditions. Only one OEM also provided feedback on off-cycle technologies. The format of the OEMs' feedback and its level of detail was very heterogeneous.

Evaluation of general comments

Besides detailed comments on technologies (treated in the next section) several OEMs also provided more general comments. We consider all of them as non-critical for the study. Here we describe the most important ones that were shared by several OEMs.

[3] CO2MPAS: CO_2 Model for PAssenger and commercial vehicles Simulation, is the model developed at JRC, and used in the implementation of Eu Regulations 1152-1153/2017 (see [7],[21] for more information)

A number of OEMs pointed out that some portions of the technology related costs, especially the indirect costs such as R&D related expenditures, are uncertain and can vary a lot from technology to technology (and company to company). This is fully in line with the study approach, which recognises uncertainty in both directions (under- and overestimation of costs). For each vehicle configuration, 3 cost curves have been developed, describing the situation for typical (= central), low, and high cost estimates for the different technologies[4].

Most OEMs highlighted that many of the technologies considered in the study will already have to be implemented for reaching the 2020 targets. That is fully in line with the study as all cost curves relate to improvements and costs over a 2013 baseline vehicle. Also the developed cost curves, through a baseline adjustment, integrate information on technologies that were already deployed in parts of the fleet in 2013[5].

Several OEMs mentioned that some of the technologies are incompatible with each other. That is fully in line with the approach to technology compatibility taken in the cost curve study, which lists all incompatible technologies in an incompatibility matrix contained in the study's Excel file. None of the comments received contradicted any of the compatibilities/incompatibilities of this matrix. Also OEMs emphasised that due to technology overlap, some combinations of technologies can lead to lower total reduction when combined (as the single reduction steps cannot be simply multiplied with each other). That is fully in line with the study and considered in the construction of the cost curves through scaling for overlapping technologies[3].

Several OEMs pointed out that one of their model-year 2015 versions in a given car segment is much better than the average car in the same segment in 2013 that was used for the 2013 baseline of the cost curve study. That is fully in line with the study[6].

Evaluation of detailed technology comments

Most of the OEMs provided detailed comments on technology cost and CO_2 reduction assumptions of the study. In our assessment we distinguish five types of comments for each of the two dimensions (cost/ CO_2 reduction potential):

- no feedback,
- the technology is already deployed or its deployment is planned,
- the study assumptions for a given technology are either explicitly agreed or even seen as too pessimistic,
- the study assumptions for a given technology are seen as slightly too optimistic,
- the study assumptions for a given technology are seen as much too optimistic.

The differentiation between slightly and much too optimistic is in most cases a rather qualitative judgement based on the OEMs' feedback. The rating concerning the CO_2 reduction potential considers both comments related to the feasibility as well as CO_2 reduction impact of a given technology. If 4 or more OEMs stated that they consider the study assumptions (slightly or much) too optimistic for the costs and/or CO_2 improvement of a given technology, we have further analysed the cost/ CO_2 reduction assumptions of that technology. This approach was further supported by the fact that assumptions that were challenged by only one, two, or three OEMs were often at the same time confirmed by several others.

[4] This is described in Chapter 8.1.5.3 of the study. The typical, low, and high cost estimates for each technology, derived from an uncertainty analysis, are provided in the Excel-file with the techno-economic assumptions.

[5] This is described in Annex A6.2 of the study

[6] The differences are explained by the progress from 2013 to 2015 and the fact that the study correctly uses the average of all newly registered vehicles in the given segment for the baseline while the OEMs typically refer to their best version only.

Based on this assessment methodology, the following 4 technologies were identified for further analysis: mild weight reduction, medium weight reduction, strong weight reduction, aerodynamics improvement 2.

For "Mild weight reduction (10% from the whole vehicle)", 5 OEMs stated that the cost assumption was too optimistic, while 5 OEMs considered the CO_2 improvement potential of this measure as too optimistic. On the other hand, 2 OEMs stated that this measure has been deployed or will be deployed in their vehicles without commenting on the detailed cost/CO_2 reduction assumptions.

The assumptions on CO_2 reduction potentials as well as cost assumptions of the two other weight reduction measures, "medium" and "strong" with 20% and 30% weight reduction from the whole vehicle, respectively, were seen as too optimistic by almost all of the OEMs. The assumptions of the cost curve study for the weight reduction measures are based on an earlier "down-weighting study"[20], which also featured a stakeholder consultation, although less exhaustive than the one performed for the study. The "down-weighting" study itself heavily relies on three studies that were originally performed for the US market ([22],[23],[24]). The "down-weighting study" added extra costs when deriving European cost and corresponding weight reduction factors. However, in the light of the overwhelmingly negative OEM comments on the weight measures, the level of extra costs added may not have been high enough. The weight measure 3 is described in the study as follows: "Strong weight reduction concerns weight shedding, as compared to existing designs, of greater than 30% on the entire vehicle. This will typically require fundamental changes to the structural parts, such as replacing conventional bodies for aluminium or composite space-frames. Although considerably lighter, potentially even allowing the use of downsized powertrains, these technologies add significant cost to the vehicle. For this reason, lightweighting mechanisms of this magnitude are usually reserved for performance vehicles and no marketplace examples exist between a model and its predecessor. Lightweighting strategies would need to apply throughout the vehicle and thus this technology is not forecast until 2025". That seems to indicate that this weight measure may only be valid for niche applications in the near to medium time frame.

CO2MPAS analytical results [25] indicate that the CO_2 impact of weight reduction measures in general may be lower than what was assumed in the cost curve study.

Two OEMs considered the cost assumption for "Aerodynamics improvement 2 (Cd reduced by 20%)" as overly optimistic, while 7 OEMs stated that the CO_2 reduction potential was overestimated. On the other hand there were also 4 OEMs that agreed with the cost assumption of this measure.

To evaluate the impact of these critical points, the JRC cost curve model was re-run for the WLTP[7] for 2025 and 2030 for all car and LCV[8] segments and their respective powertrain configurations (224 combinations and 3 cost scenarios for each combination). Differing from the original study, the following modified techno-economic assumptions were used for the 4 technologies/measures that required further analysis:

- for the measure "Mild weight reduction (10% from the whole vehicle)", the CO_2 improvement potential was reduced by one third (e.g. if in the original study it was assumed to be 6.6% for a given vehicle variant, the assumption in the re-run was 4.4% etc.); this lower CO_2 improvement assumption is similar to our own CO2MPAS analytical results (see [25]),
- for the measure "Medium weight reduction (20% from the whole vehicle)" the CO_2 improvement was reduced by 4 percentage points (e.g. if in the original study it was assumed to be 12.4% for a given vehicle variant, the assumption in the re-

[7] Post 2020 targets will likely be based on WLTP. Hence, these cost curves will matter most for any related impact assessment work.

[8] While the OEM comments focussed on cars, we also applied the same modifications to the 4 measures within the LCV cost curves in order to assess the impact of the comments assuming that their logic also applies to LCV

run was 8.4% etc.) and its costs were doubled; these modifications reflect comments on the feasibility and cost impact of this measure; the resulting newly assumed cost and CO_2 reduction assumptions are similar to what for example IKA (2014) has used and the CO_2 improvement assumption is similar to our own CO2MPAS analytical results (see [25]),

- the measure "Strong weight reduction (30% from the whole vehicle)" was eliminated, reflecting the overwhelmingly pessimistic OEM feedback on the feasibility of such a large weight reduction (within any reasonable additional cost) as well as the description of this weight measure within the cost curve study (see citation above),
- for the measure "Aerodynamics improvement 2 (Cd reduced by 20%)", the CO_2 improvement potential was reduced by 1 percentage point (e.g. if in the original study it was assumed to be 5% for a given vehicle variant, the assumption in the re-run was 4% etc.); this lower CO_2 improvement assumption is similar to our own CO2MPAS analytical results (see [25]).

The newly generated cost curves were then compared with the original curves of the cost curve study in order to assess the impact of these modifications.

The analysis reveals that the ranges of the newly created cost curves overlap with the ones of the original cost curves, and the difference between the "old" and the "new" curves is compatible with the uncertainty in the estimation of the cost and CO_2 reduction. The newly created low cost curve does not intersect with the original high cost[2] curve. We have analysed all results for the 2025 and 2030 WLTP (with and without off-cycle technologies) cost curves. In none of the 224 analysed cases the newly created low cost curve intersects with the original high cost curve. Also in all of the cases the original high cost curve is well above the new typical cost curve for most of the CO_2 reduction ranges[9].

For several measures, especially electric vehicles and hybrids, several OEMs pointed out that the study assumed too high costs. Moreover, a few OEMs mentioned that they are working on additional measures that are not listed in the cost curve study. These were however not further considered in our assessment. Hence, the assessment approach that we applied can be considered conservative as we focused on the downside potential of measures and not their upside potential.

Conclusions

We carried out an assessment of the technology related comments from car manufacturers on the cost curve study. Overall the OEM comments validated the study approach and most of its assumptions. Recurring OEM comments questioned the assumptions for 4 measures, arguing they may be overly optimistic in the cost curve study. Three of the measures were weight reduction and one aerodynamics related. After evaluating the validity of the OEMs' critical comments and comparison with JRC data and other studies, we performed a re-run of the JRC cost curve model with modifications on the assumptions for 3 measures and elimination of one of the measures (the most ambitious weight reduction measure). The newly generated cost curves were then compared with the original curves of the cost curve study in order to assess the impact of these modifications.

We found that the ranges of the newly created cost curves overlap with the ones of the original cost curves. This indicates that the bandwidth of scenarios in the cost curve study is large enough to accommodate for the impact of critical comments that were voiced by several OEMs. Our assessment approach can be considered conservative as we assessed the impact of the critical comments but not the impact of comments that mentioned lower costs or higher/ more CO_2 reduction potentials, in particular as regards especially electric vehicles and hybrids.

[9] In 73% of the cases these two curves do not intersect. For the cases with intersection the crossing point is well above CO_2 reduction levels of 40%.

We conclude that the cost curves from the study seem overall reasonable and can constitute an appropriate input to assess the additional cost of vehicle improvements needed for meeting CO_2 targets with respect to a 2013 baseline vehicle portfolio.

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