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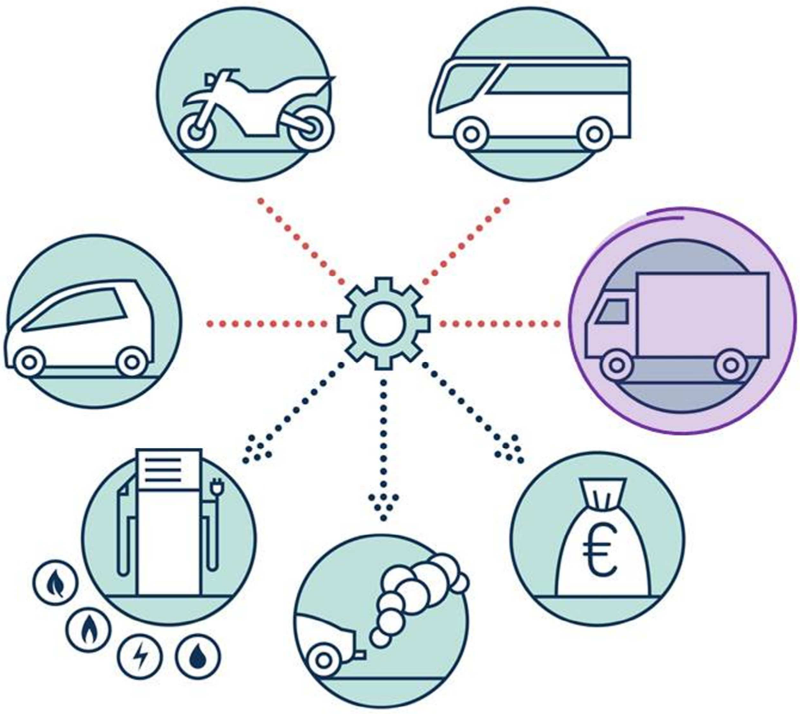

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Heavy duty vehicle CO_2 emission reduction cost curves and cost assessment – enhancement of the DIONE model

The present report describes a set of computational modules for assessing the costs of alternative CO_2 emission reduction targets for heavy duty vehicles. In particular, these modules allow constructing HDV emission reduction cost curves, identifying cost-optimal CO_2 emission reduction distributions over the different vehicle classes and powertrains concerned, and calculating additional manufacturing costs, fuel savings and total costs or savings resulting for different regulation scenarios.

The modules have first been developed in the context of the European Commissions' impact assessment for post-2020 CO_2 targets for light duty vehicles in 2017. They have been further adapted and supplemented in order to support the impact assessment for potential heavy duty vehicle CO_2 emission standards for 2025 and 2030 in Europe.

Contents

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The development of the cost curves and cost assessment methodology has been closely linked to the work on a study ([5]) commissioned by DG CLIMA. The authors are therefore grateful to the study team, in particular to Eelco den Boer, Stefan Hausberger, Martin Rexeis, Pelopidas Siskos and Felipe Rodriguez for providing input data and feedback.

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Executive summary

The European Union (EU) is committed to reducing its greenhouse gas emissions and energy consumption. In this line, the aim of transport decarbonisation has recently been reconfirmed in the European Commission's Communication on a low-emission mobility strategy [1]. In November 2017, the European Commission proposed a regulation setting CO_2 emission performance standards for light duty vehicles (cars and vans) for the period up to 2030 [2]. As indicated in the accompanying impact assessment [3], further measures are needed in the road transport sector, in particular for heavy duty vehicles (HDV), which are currently responsible for about a quarter of CO_2 emissions from road transport in the EU and some 6% of total EU CO_2 emissions.

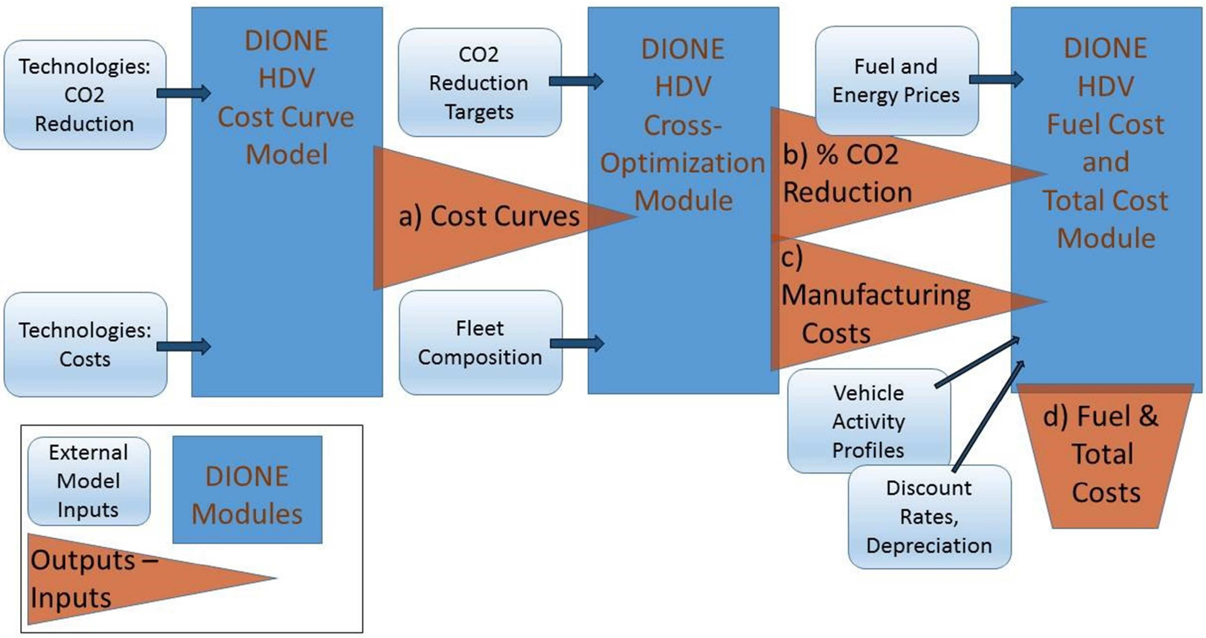
An important step of policy formulation is to evaluate the costs a policy causes and the corresponding impacts on affordability for users and OEM competitiveness. With its DIONE model, the European Commission's Joint Research Center (JRC) provides a modelling framework to assess the costs of vehicle CO_2 emission standards [4], first developed within the framework of the 2017 light duty vehicle impact assessment. These modules have been adapted and further extended with a view to assessing the costs of HDV emission standards. Main HDV modules are:

— DIONE HDV Cost Curve Model: Develops HDV cost curves which describe the costs of reaching different levels of CO_2 emission reduction for each HDV class and powertrain

— DIONE HDV Cross-Optimisation Module: Identifies cost-optimal strategies to reach given emission targets, building on the cost curves; outputs respective additional HDV manufacturing costs

— DIONE HDV Fuel Cost and Total Cost Module: Calculates the fuel savings for the optimised vehicles and the change of total costs of ownership caused by a CO_2 standard, from different perspectives (i.e., first user, second user, society).

Figure 1: Flowchart of DIONE HDV modules



The interaction between the modules, as well as inputs needed and outputs produced, are sketched in Figure 1.

The DIONE modules (blue boxes) are run one after the other. In a first step, the cost curve model produces a) HDV CO_2 reduction cost curves for each vehicle class, powertrain, year of analysis, and cost scenario considered. These curves are provided to the cross-optimisation module, which outputs b) optimal CO_2 reduction and c) additional manufacturing costs for each vehicle class and powertrain. On this basis, in a third step the fuel and total cost module calculates d) fuel savings of the vehicles and combines them with manufacturing costs to derive changes in total costs of ownership.

The light blue boxes indicate external inputs needed to run the modules. Most of this data has been provided within a study on behalf of DG CLIMA which is documented in [5].

Ample use has been made of the DIONE HDV modules for preparing the EC impact assessment for HDV CO_2 standards. Some 80 final cost curves have been developed, and several hundred cross-optimisation scenarios have been run to explore sensitivities. This report provides technical documentation of the DIONE HDV modules and documents the cost curves developed within the analysis.

1 Introduction

The European Union (EU) 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 reconfirmed by the EU's ratification of the Paris agreement in 2016 [6]. With its Communication on a low-emission mobility strategy [1], the European Commission has reinforced its commitment to transport decarbonisation and stressed the need to increase the efficiency of the transport system, deploy low-emission alternative energy for transport, and move towards low- and zero-emission vehicles. While the EU has set CO_2 emission targets for cars and vans (defined by the European Regulations 443/2009 and 510/2011), and post-2020 targets have been proposed in 2017 [2], heavy duty vehicle (HDV) CO_2 emissions are not yet regulated in the EU.

To support the analysis of potential HDV CO_2 standards, the JRC has further developed its DIONE model suite. It consists of the DIONE Fleet Impact Model which can be used for vehicle fleet projections (see [7],[8]), the DIONE Cost Curve Model for developing vehicle CO_2 reduction cost curves, the DIONE Cross-Optimisation Module which determines cost-optimal allocation of CO_2 reduction efforts to the different vehicle types within a fleet, and the DIONE Fuel and Energy Cost and TCO Module employed to determine variable and total costs under different scenarios. For an overview of the modules, see the description in the Executive Summary and Figure 1. All but the first module have first been developed within the context of the European Commission's impact assessment for light duty vehicle CO_2 standards and have been documented in [4]. These modules have been adapted and extended to support the assessment of manufacturing and operating costs of heavy duty vehicles in the framework of the European Commission's impact assessment of heavy duty vehicle CO_2 standards. A total of 80 final cost curves for HDV have been developed, and several hundred scenarios have been run to explore policy options and their costs.

This report provides technical documentation of the enhancements made and results obtained. The following sections 2 throughout 4 present, one by one, the DIONE HDV Cost Curve Model, HDV Cross-Optimisation Module, and HDV Fuel Cost and Total Cost Module, along with input data used, calculations run and exemplary results obtained. The report concludes with a short summary.

2 HDV Cost Curve Development

A large number of technologies exist that can be employed for reducing the energy consumption and CO_2 emissions of heavy duty vehicles throughout the next decades. Components that can be improved with regard to energy consumption include the engine, tyres, transmission, axles, aerodynamic drag and auxiliaries. Different technologies can be combined into bundles in order to achieve higher emission reductions. Fitted on the basis of such bundles, CO_2 emission reduction cost curves provide a continuous functional description of the costs associated with reaching given CO_2 reductions for different HDV classes and powertrains. For each vehicle class considered, the cost curves express the costs of reaching given CO_2 reductions, relative to a 2016 new HDV of the same class with a diesel powertrain. The cost curves form the basis for assessing CO_2 reduction costs, optimal distributions of efforts over different vehicle classes and powertrains, fuel savings and total costs of ownership arising under different levels of CO_2 reduction.

The European Commission Joint Research Center's DIONE Cost Curve Model, first developed within the context of light duty vehicle emission reduction assessment [4], was further enhanced for developing HDV CO_2 reduction cost curves. This work and its outcomes are presented below. Where algorithms and settings were kept as in the previous work and have already been documented, details are not repeated here, but the reference is given.

2.1 Vehicle Classes and Cost Scenarios Covered

Compared to light duty vehicles, heavy duty vehicles serve a much wider range of purposes, including urban, regional and long-haul transport of goods as well as specific services in construction or municipalities. Therefore, HDV are diversified and highly customised vehicles, which hampers type approval CO_2 certification as carried out for LDV. While HDV certification legislation is under way, and the VECTO tool has been developed to simulate HDV fuel consumption, rigorous data on vehicle efficiencies and their past trend is lacking.

The cost curve model relies on input data on available technologies, their CO_2 reduction potentials and costs, as well as their compatibility. Such data was provided for the four VECTO vehicle classes 4, 5, 9 and 10 (see Table 1) within a study on behalf of the European Commission's Directorate General for Climate Action [5]. In 2012, these classes were responsible for about 65% to 70% of total HDV CO_2 emissions including buses and coaches [9].

Table 1: Vehicle groups considered in this analysis

Vehicle group	Axle configuration	Chassis configuration	Technically permissible maximum laden mass (tons)
4	4x2	Rigid	>16
5	4x2	Tractor	>16
9	6x2	Rigid	all weights
10	6x2	Tractor	all weights

Within [5], for each technology and vehicle group, an estimate of manufacturing costs in 2025 was given. Typical CO_2 reduction potentials were assessed for the four vehicle groups and for two VECTO cycles, i.e. regional delivery and long-haul, with low and representative load each. Applying a weighting of potentials skewed towards either regional delivery (RD) or long-haul (LH), two sub-group values were calculated for each technology. Based on these estimates, cost curves can be constructed for eight sub-groups (Class 4 RD, Class 4 LH, Class 5 RD, Class 5 LH, Class 9 RD, Class 9 LH, Class 10 RD, Class 10 LH) and two powertrains (Diesel, LNG), giving rise to a total of 16 cost curves for each year and cost scenario. The base year is set to 2016.

As an initial assessment for 2030, improvement factors α for cost development and β for CO_2 reduction have been defined. Technologies available in 2030, their CO_2 improvements and costs will need to be revised and cost curves updated as more data becomes available. Input data was further transformed as described below. Additional cost scenarios were developed starting from the thorough assessment of typical costs.

In total, three cost curve scenarios were considered:

a) The **typical** scenario uses input data for the 2025 CO_2 reduction potentials and costs of each technology as well as 2016 technology uptake based on best available information as collected within the project [5]. Maximum technology uptake is set to 100% for all technologies. 2030 inputs were generated based on the 2025 estimates as described below.

b) A **medium-cost** scenario was designed to reflect possible limitations of technology uptake by 2025. Maximum technology uptake was set to less than 100% for a number of technologies, based on expert assessment within the project [5] and information provided by OEM. The medium-cost scenario covers only 2025 as it was assumed that by 2030, all technologies become fully available, thus cost curves converge with the typical case.

c) A **high-cost** scenario was added which took on board additional technology cost and potential information as well as concerns regarding possible limitations in market uptake of technologies received from OEM after the presentation of the first set of curves. 2025 high technology costs were quantified within the study [5]. CO_2 reduction potentials of each technology were derived from the typical values by applying reduction factors defined in the same study, based on the feedback gathered from manufacturers.

As a result of this work, 80 final cost curves have been developed, including 48 curves for 2025 (8 sub-groups * 2 powertrains * 3 cost scenarios) and another 32 for 2030 (8 sub-groups * 2 powertrains * 2 cost scenarios). Parameters for these curves are included in Annex 1. On top of the curves used for the work at JRC, an equivalent set of typical and high-cost curves with adapted settings was produced as an input for scenario runs with the PRIMES-TREMOVE model. Differences were, e.g., that due to PRIMES-TREMOVE model requirements cost curve base year was 2005, and that HDV using full hybrid technology were framed as a separate powertrain, whereas full hybridisation is included as one technology option for diesel and LNG vehicles in the JRC approach.

2.2 Input Data Transformation

To correctly assess technology-based future CO_2 reduction potentials and costs, any possible technology uptake limits need to be considered. This regards both technological improvement already exploited in the base year of analysis and limits to future uptake of each technology. In the cost curve approach developed for LDV, base year technology uptake was taken into account via post-processing, reducing the combined CO_2 reduction and costs of each technology bundle by the technology potential already exploited and the costs already faced in the cost curve base year (baseline adjustment step described in [4]). Full technology availability was assumed. Thus, maximum uptake of each technology was set to 100%.

With a view to HDV, there are concerns regarding maximum technology uptake due to the possibly limited availability of a number of technologies in 2025. Therefore, the need arose to take into account maximum technology uptake rates of less than 100%. Such limits $tuMax$ were defined for the medium-cost and high-cost scenarios within [5].

The handling of maximum uptake of less than 100% required a different treatment than the post-processing approach applied in the LDV model, as these are characteristics of individual technologies and need to be taken into account at single technology level. As maximum uptake had to be implemented in the input data to the cost curve model, it was also decided to include 2016 technology uptake at this stage.

To this aim, the **unavailable share** $\mathrm{tu_{m,y,cs}}$ of CO_2 reductions and costs between the base year 2016 and the target year, due to previous uptake or maximum uptake limits, is calculated for each technology as:

$$\mathrm{tu_{m,y,cs}} = \min((1 - \mathrm{tuMax_{m,y,cs}} + \mathrm{tu2016_m}), 1) \quad (1)$$

for each technology m, year y and cost scenario cs, based on maximum technology uptake rates $\mathrm{tuMax_{m,y,cs}} \leq 100\%$ and base year technology uptake $\mathrm{tu2016_m}$ as provided within the project [5].

CO_2 **savings potentials** of each technology m in each target year y within each cost scenario cs are then calculated starting from the typical (typ) values for 2025:

$$\mathrm{Potential_{m,y,cs}} = \mathrm{Potential_{m,2025,typ}} * \left(1 - \mathrm{ReductionFactor}_{m,cs}\right) * \left(\beta_y - \mathrm{tu_{m,y,cs}}\right), \quad (2)$$

where $\beta_{2025} = 1$ and $\beta_{2030} = 1.1$ and $\mathrm{ReductionFactor}_{m,cs} = 0$ for $\mathrm{cs} = \{typical, medium\}$ and as defined within [5] for $\mathrm{cs} = \mathrm{high}$.

Target year manufacturing costs are determined as

$$\mathrm{Cost_{m,y,cs}} = \mathrm{Cost_{m,2025,base(cs)}} * (\alpha_y - \mathrm{tu_{m,y,cs}}), \quad (3)$$

where the base cost scenarios used are $\mathrm{base(typical)} = \mathrm{base(medium)} = \mathrm{typ}$ and $\mathrm{base(high)} = \mathrm{high}$, with input values for both the typical and high cost scenarios defined in [5] as described above. Moreover, $\alpha_{2025} = 1$ and $\alpha_{2025} = 0.95$.

The transformed input data, consisting of tuples of CO_2 savings potentials and technology costs $(\mathrm{Potential_{m,y,cs}}, \mathrm{Cost_{m,y,cs}})$, is fed into the DIONE cost curve model. To develop a cost curve, in a first step, optimisation is carried out to identify cost-optimal packages of CO_2 reduction technologies for each vehicle sub-group, powertrain and year. Then, cost curves are fit to the set of solutions. These steps are described below.

2.3 Identifying Optimal Technology Packages

The DIONE cost curve model applies an optimisation algorithm which combines Ant Colony Optimisation and Local Search to identify optimal technology packages for reducing CO_2 emissions. Given the set of available CO_2 reduction technologies with their potentials and costs as well as a list of incompatibilities, the problem consists in finding, among all possible packages (i.e., subsets of combinations of these technologies), the set of optimal configurations which have minimal total costs and maximum total CO_2 reduction. The algorithm finds Pareto optimal technology packages which 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). It outputs these packages along with their combined CO_2 reductions and costs. The approach has been thoroughly documented in [4].

2.4 Parameter Transformation

In the development of HDV cost curves, 2016 technology uptake is taken into account in the input data as described in section 2.2. Thus firstly, there is no need to carry out the baseline adjustment step applied in the LDV model (as documented in [4]). Since maximum HDV technology uptake of less than 100% has been introduced into the model, it has to be kept in mind that optimal technology bundles derived for HDV have a slightly different interpretation than those resulting from previous work on LDV, where an on/off approach was pursued (a technology could be present in a bundle, or absent). In the HDV approach, the presence of a technology in a bundle can indicate that, e.g., 75% of the 2025 new fleet will have this technology but 25% will not, thus the bundle costs and total CO_2 reductions are interpreted as the average costs and CO_2 savings of including the respective technologies for the new fleet share where they are applicable. In contrast, for LDV technology bundle costs represented the costs of adding all technologies contained in the bundle to any given vehicle of the respective segment and powertrain.

Secondly, it was found in [5] that for HDV, multiplication of technology potentials does not lead to a substantial overassessment of the reductions achieved through a technology bundle. Thus, scaling for technology overlap, as previously applied to LDV technology bundles, can be skipped as well.

Thirdly, as no HDV with advanced electrified powertrains (xEV) are considered at this stage, the further two post-processing steps applied for xEV battery scaling and for re-baselining xEV powertrains to base year conventional vehicles are obsolete as well.

In sum, there is no need to post-process the optimal technology bundles' parameters found by the optimisation routine for HDV.

2.5 Cost Curves

Once optimal technology bundles have been identified, CO_2 emission reduction cost curves are constructed within the DIONE Cost Curve Model by fitting a curve that best represents them. The cost curves provide a continuous functional description of the costs associated with reaching given CO_2 reductions (in % versus a 2016 new diesel HDV of the same sub-group) for a given HDV sub-group and powertrain. The cost curve fitting approach was applied as presented in [4]. The functional form of the HDV cost curves is

$$c(x) = C + \frac{c}{x - x_0} + b * x \qquad (4)$$

where the parameters C, c, x_0 and b are found by the fit.

The analytical form of HDV cost curves given in equation (4) differs by the term b*x from the one used for light duty vehicles with internal combustion engine powertrain presented in [4]. This is due to the fact that initial tests with the previous expression showed that the fits obtained were not satisfactory, as the HDV optimal solutions curve appeared more flat on the left hand side, and more linear on the right hand side. Different functional forms were tested to fit the optimal HDV solutions, and the simplest and most efficient one was found using the additional linear term in x.

80 cost curves have been developed, covering 8 HDV sub-groups, diesel (DSL) and liquid natural gas (LNG) powertrains, the years 2025 and 2030, and three cost scenarios (typical, medium-cost and high-cost). All parameters for these curves can be found in Annex 1.

Fitted cost curves for 2025 are shown in Figure 2 and Figure 3. As can be seen, the medium-cost curves have a narrower area of definition than both the typical and high ones, and in some cases intersect or overlap with the high-cost curve. This is due to the fact that in the medium-cost curve, for many technologies a reduced 2025 maximum possible penetration was assumed. The potential of single technologies is therefore lower than in the typical and high-cost cases, such that more and in particular more costly technologies need to be picked at lower CO_2 reduction rates. Thus the flat portion of the curve is shorter and maximum achievable CO_2 reduction is significantly lower.

Figure 2: Fitted cost curves for HDV of the sub-groups 4 RD, 5 LH, 9 RD and 10 LH, for Diesel (left) and LNG powertrain (right) in 2025, for cost scenarios typical (blue), medium-cost (green), and high-cost (red).

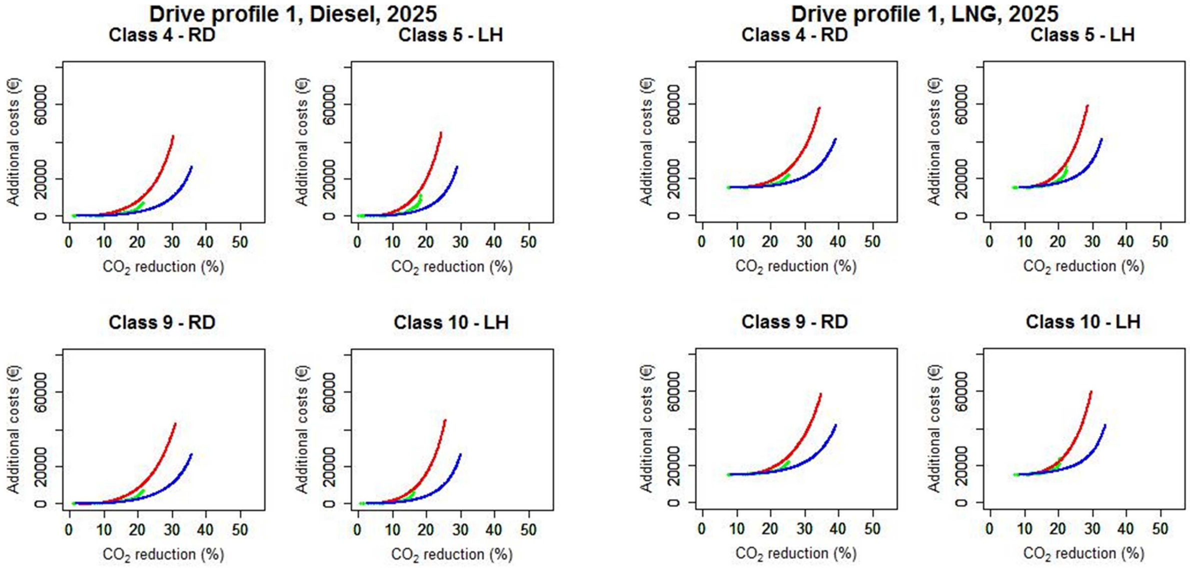
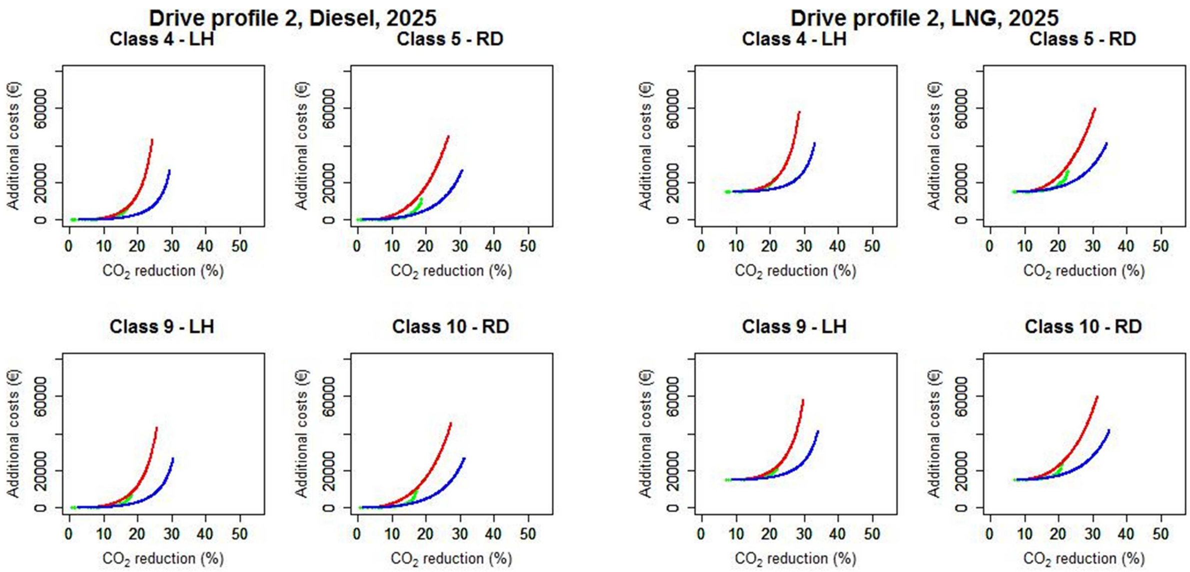


Figure 3: Fitted cost curves for HDV of the sub-groups 4 LH, 5 RD, 9 LH and 10 RD, for Diesel (left) and LNG powertrain (right) in 2025, for cost scenarios typical (blue), medium-cost (green), and high-cost (red).



3 HDV Cross-Optimisation

Cross-optimisation is carried out to determine the cost-minimizing distribution of CO_2 reduction over powertrains and vehicle classes, given a fleet CO_2 reduction target and a fleet composition scenario as well as cost curves.

In the DIONE Cross-Optimisation Module developed for LDV in [4], the analysis was carried out on a manufacturer level, starting from scenarios of manufacturer fleet composition as well as manufacturer-specific CO_2 reduction targets derived from assumptions on future CO_2 standard design. This approach turned out to be not viable for the HDV case, as less data is available and no experience exists with past regulation which might serve as a basis for detailed regulation design. Moreover, the present analysis did not cover the total new HDV fleet but was undertaken only for eight sub-classes of HDV composing what is called the "regulated fleet" in the following.

The DIONE Cross-Optimisation Module was therefore adapted for the analysis of overall HDV CO_2 reduction targets for the sum of new registrations in the eight sub-groups under scrutiny as described in the following Section 3.1. Analysis of the 2016 new HDV registrations in classes 4, 5, 9 and 10 suggests that OEM fleet composition is more or less proportional to total market composition, which supports transferability of the present results to individual OEM.

For HDV, different alternative optimisation approaches were implemented, as illustrated in Table 2. For each variant, the approach is described and exemplary cases are presented in the following sections. In the original approach, a target is set at the level of the (regulated) fleet, and optimisation aims at meeting this target at lowest possible technology cost. Alternative variants were developed both with regard to the target structure and with regard to the optimisation parameter:

- Apart from setting a target for the regulated fleet as a whole, it was considered to set separate targets for the eight HDV sub-groups. This approach is documented in Section 3.2. Moreover, targets were mostly set in relative terms (% CO_2 reduction), but alternatively can also be given in absolute terms (gCO_2 per km or per tkm), as described in Section 3.4.
- As regards optimization approaches, an additional variant was added where optimality is defined as minimisation of social costs, i.e., the sum of technology costs and fuel savings, which is presented in Section 3.3. Technically, social and technology cost-based optimization can be combined with each target structure respectively, resulting in all combinations given in Table 2. Combinations where no section is indicated have not been implemented.

Table 2: Cross-optimisation variants

<table>
<tr><th colspan="3"></th><th colspan="2">Cross-optimisation variant</th></tr>
<tr><th colspan="3"></th><th>Technology Costs</th><th>Social Costs</th></tr>
<tr><td rowspan="4">CO_2 reduction target structure</td><td rowspan="2">Fleet Target</td><td>Relative (%)</td><td>Section 3.1 (Original Version)</td><td>Section 3.3</td></tr>
<tr><td>Absolute (gCO_2)</td><td>Section 3.4</td><td></td></tr>
<tr><td rowspan="2">Sub-group target</td><td>Relative (%)</td><td>Section 3.2</td><td>Section 3.3</td></tr>
<tr><td>Absolute (gCO_2)</td><td></td><td></td></tr>
</table>

3.1 Technology cost cross-optimisation with fleet target

Formally the description of the cross-optimisation problem with a CO_2 standard to be fulfilled across the regulated fleet (in this case composed of the eight included classes) is the following:

A target year new HDV fleet is composed of sub-groups $s_j, j = 1, \dots, 8$ (classes 4, 5, 8 and 9 with an RD and a LH profile each). Each vehicle can have one of two powertrains $p_k, k = 1,2$ (DSL, LNG). Cross-optimisation is run over the $i = 1, \dots, N$ sub-group/powertrain combinations which contribute to reaching a given CO_2 reduction target. With a fleet-wide target set, cross-optimisation is run over all $N = 16$ sub-group/powertrain combinations.

The CO_2 reductions for each sub-group/powertrain combination, called x_i , are the independent variables of the problem. They are associated with cost functions $c_i(x_i)$ resulting from the DIONE cost curve model. The possible values of x_i are restricted by the cost curve definition interval (x_{min_i}, x_{max_i}), calculated by the optimisation algorithm from the technology packages with the lowest and highest CO_2 reduction.

The problem consists in finding the $x^{opt} = (x_1^{opt}, \dots x_N^{opt})$ minimizing the manufacturing costs of CO_2 emission reduction technology, subject to the constraint that a given CO_2 reduction target is met. Manufacturing costs are calculated from the cost curves for each sub-group/powertrain combination i, weighted by their shares p_i:

$$C = \sum_{i=1}^{N} p_i \cdot c_i\,(x_i) \qquad (5)$$

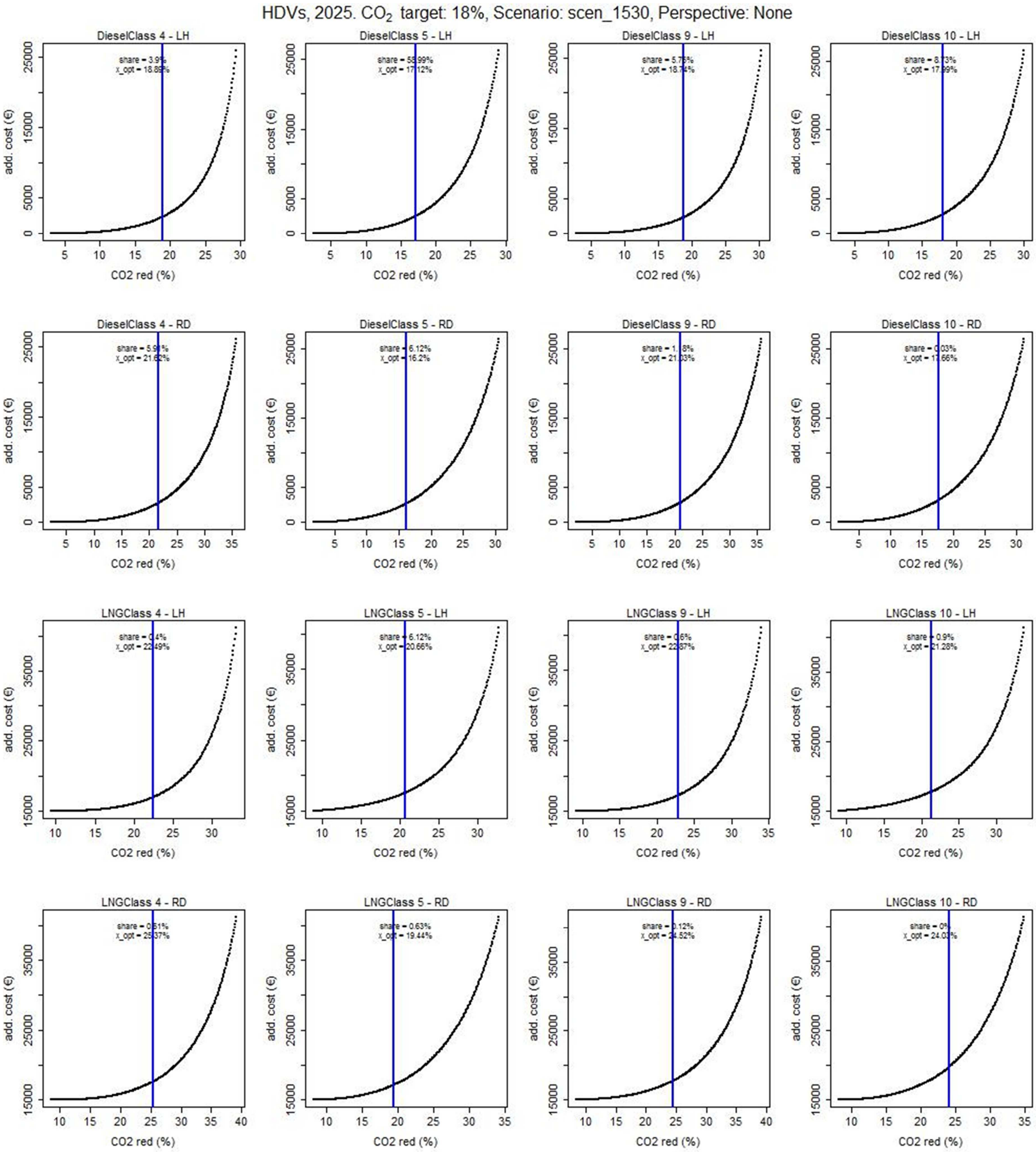
which has to be minimised subject to the constraint that the overall total CO_2 reduction R needs to be at least as high as the target value, T_{CO_2}, that is:

$$R = \sum_{i=1}^{N} p_i \cdot x_i \geq T_{CO_2} \qquad (6)$$

An optimisation routine solving this problem was implemented using the *constrOptim* algorithm of the library {stats} in R which solves the linear constrained optimisation problem in x_i, finding the set of optimal points x^{opt}.

An example of cost curves along with solutions found for fleet target based manufacturing costs cross-optimisation is shown in Figure 4. It relates to a fleet target of 18% CO_2 reduction to be reached in 2025 compared to 2016, using typical cost curves. Each panel represents the cost curve (in black), and an optimal solution found (blue bar) for one of the 16 vehicle sub-group/powertrain combinations, e.g., the first panel refers to sub-group 4LH DSL vehicles. CO_2 savings are plotted on the x-axis, and additional cost, in this case the manufacturing cost of technologies reducing CO_2 emissions, on the y-axis. Within the frames, the shares of the HDV sub-group/powertrain categories within the regulated fleet as well as the solutions found for the respective sub-group and powertrain are printed. In the example given, e.g., the share of sub-group 4LH DSL vehicles is 3.9%, and the optimal CO_2 reduction in this segment is 18.89%. In the example given, the solutions found for DSL optimal CO_2 reductions range from 16.2 to 21.6%, while for LNG, they are between 19.4 and 25.4%. The costs of these CO_2 reductions range from 2,200 to 3,100 Euros for DSL and from 16,900 to 19,600 Euros for LNG HDV.

Figure 4: Technology cost cross-optimisation results for 2025, fleet target 18%, typical costs



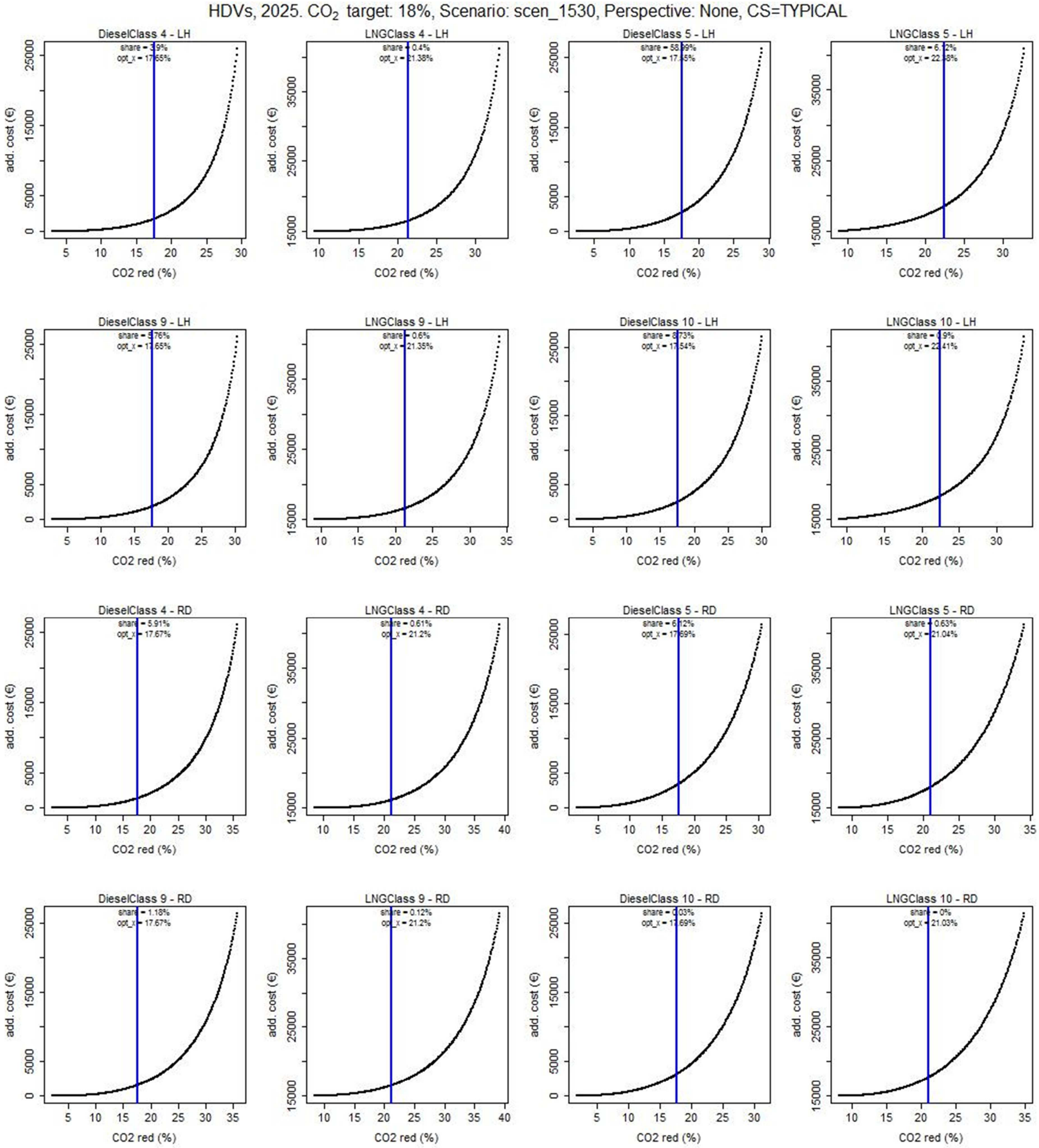
3.2 Technology cost cross-optimisation with sub-group targets

For HDV, the option of setting CO_2 targets for vehicle sub-groups separately was implemented. This implies that optimisation is carried out for just the two powertrains (DSL, LNG) in each of the eight sub-groups separately. Technically, diverging from the fleet approach described in the previous section, cross-optimisation is run including only the $N = 2$ powertrains within a sub-group. In this case the shares of DSL and LNG vehicles in each sub-group are normalised such that $\sum_{i=1}^{N} p_i = 1$. The cross-optimisation consists in running eight sub-group s_j cross-optimisations separately.

This version became the standard optimisation approach used for the work carried out to support the impact assessment for HDV CO_2 standards. In general, the same %CO_2 reduction target was set for each sub-group. The requirement for each sub-group to reach a given target separately is a more binding constraint than the requirement to meet the same target over the complete regulated fleet, as the latter allows for higher reductions occurring in some sub-groups to compensate for lower reductions achieved elsewhere. Consequently, it could be noticed that some of the more ambitious 2030 reduction targets could not be reached in some sub-groups, resulting in an under-fulfilment of the target at fleet level, whereas the same target level was achievable under fleet-wide optimisation.

An example of sub-group target cross-optimisation results can be seen in Figure 5, again setting a fleet target of 18% CO_2 reduction to be reached in 2025 compared to 2016, using typical cost curves. When comparing to the previous Figure 4, note that the order in which the segment/powertrain panels are arranged has changed, as the present algorithm addresses both powertrains within a given sub-group before proceeding to the next sub-group. In this case, the range of optimal CO_2 reductions found for DSL vehicles is 17.54 to 17.69%, and for LNG vehicles 21.03 to 22.42%. This exemplifies that a sub-group target leads to solutions in a much narrower range than a fleet-wide target of the same level. Costs found for the different sub-groups range from 1,300 to 3,400 Euros for DSL and from 16,000 to 18,500 Euros for LNG HDV.

Figure 5: Technology cost cross-optimisation results for 2025, sub-group target 18%, typical costs



3.3 Social cross-optimisation

HDV differ strongly from LDV with regard to their usage, as they run much higher annual and lifetime mileages. Therefore, fuel consumption is an important determinant of their economics. While for LDV, cross-optimisation was carried out on the basis of additional manufacturing costs only as described in the above sections, for HDV a second cross-optimisation perspective was introduced which determines the optimal distribution of CO_2 reduction efforts on the basis of manufacturing costs minus fuel savings. This perspective is called social cross-optimisation.

To consider fuel savings in the optimisation, they can be included in the target function, making use of the fact that a relative reduction in CO_2 emissions results from a reduction in fuel consumption by the same percentage, which translates into a proportional reduction in fuel costs. Lifetime vehicle fuel costs $BaseFC_i$ of the 2016 base vehicle of the respective powertrain and sub-group, prior to applying any efficiency improvements, can be determined as the product of vehicle mileage, reference vehicle specific energy consumption, and discounted, mileage weighted price of the respective fuel (input data on vehicle activities and energy consumption were provided within the project [5], settings see Table 4):

$$BaseFC_i = \mathrm{RefEnCons}_i * act_i * FP_i \ , \tag{7}$$

where $\mathrm{RefEnCons}_i$ is the energy consumption of the 2016 reference vehicle (MJ/100km), act_i is total lifetime activity of the respective HDV sub-group (km), and FP_i is the activity weighted, discounted fuel price of the respective fuel for each HDV sub-group (Eur/MJ), derived from fuel price trajectories of the PRIMES-TREMOVE model.

We then introduce fuel savings over vehicle lifetime as an extra term into the cost function. As fuel savings are proportional to CO_2 reduction, these can be calculated as the total fuel expenses of the base vehicle $BaseFC_i$ times CO_2 reduction x_i determined from the cross-optimisation. The total cost function becomes

$$TC = \sum_{i=1}^{N} p_i \cdot [c_i\,(x_i) - BaseFC_i * x_i]. \tag{8}$$

The term $BaseFC_i * x_i$ is linearly increasing in CO_2 reduction. In the case of HDV, additional manufacturing costs are usually overcompensated by fuel savings such that the term $c_i(x_i) - BaseFC_i * x_i$ becomes negative. The problem, framed as a minimisation of costs, in fact becomes a maximisation of savings. Figure 6 shows an example of social cross-optimisation at typical technology costs, where $c_i(x_i) - BaseFC_i \cdot x_i$ is represented. It can be seen that the term (additional manufacturing costs – fuel savings) is negative over the complete area of definition of the cost curves for all sub-group/powertrain combinations. It is also evident that the curves exhibit cost minima. By definition, at $\mathrm{x}_i = x_{min_i}$ the cost curve gradient is zero, i.e., for each i,

$$\frac{d\,(c_i(x_{min,i}) - BaseFC_i * x_{min,i})}{dx_i} = 0 \tag{9}$$

which, using the functional form of the cost curves in (4), yields:

$$\mathrm{X}_{min_i} = x_{0i} \pm \sqrt{\frac{c_i}{b_i - BaseFC_i}} \tag{10}$$

Since X_{min_i} is required to fall within the area of definition of the cost curves (x_{min_i}, x_{max_i}), and since x_{0i} is always greater than x_{max_i} (see cost curve parameters given in Annex 1), only the 'minus' variant of equation (10) is a feasible solution. Thus there is a unique minimum of the 'social' cost curve for all i (provided the factor under the square root is positive).

Under the optimisation approach formulated in Section 3.1, the choice of cost minima is the optimal solution if it satisfies the constraints, thus the cross-optimisation algorithm will set $x_i^{opt} = \mathrm{X}_{min_i}$ as long as this fulfils the constraint given in (6), i.e., as long as

$$\sum_{i=1}^{N} p_i \cdot x_{min,i} \geq T_{CO_2} \quad (11)$$

holds (thus as long as the weighted combination of CO_2 reductions in all sub-classes at the cost minimum is greater than or equal to the target value). Except in the case of equality, this means that the target would be overshot in the model, which is unlikely to happen in practice.

Therefore, in order to avoid overshooting the target, whenever (11) holds as an inequality, the constraint needs to be inverted. In these cases, to force the cross-optimisation to reach the established target the original constraint of equation (6) is replaced by:

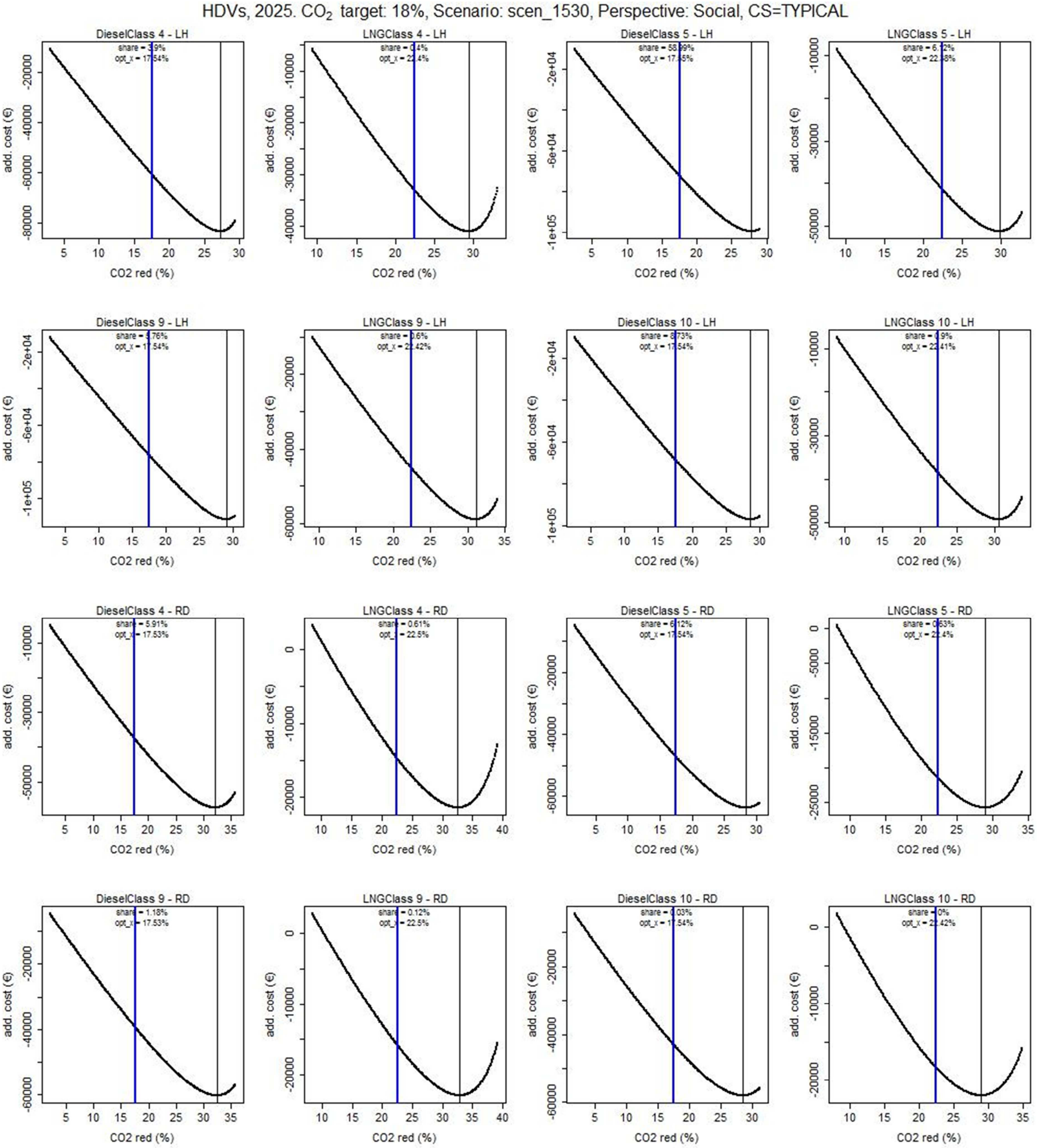
$$R = \sum_{i=1}^{N} p_i \cdot x_i \leq T_{CO_2}. \quad (12)$$

Cross-optimisation then proceeds to identify the x_i minimizing TC as described in Section 3.1 or 3.2, depending on whether a fleet-wide or sub-group target is set.

The situation is illustrated Figure 6, for the same settings as in the previous figures (18% target for 2025, typical costs). As before, the x-axis shows CO_2 reduction, but differently from previous Figure 4 and Figure 5, the additional costs on the y-axis now refer to additional manufacturing costs minus fuel savings. The figure shows that cost minima (indicated by the black bars) occur at higher CO_2 reduction values than the optimal solution not overshooting the target (blue vertical bars), therefore in this case the constraint (12) was applied.

The range of optimal CO_2 reductions found for DSL vehicles in the example is 17.53 to 17.55%, and for LNG vehicles 22.38 to 22.5%, i.e., results for the different sub-groups of the same powertrain are even closer than in the technology cost based sub-group target cross-optimisation presented in the previous sections. Technology cost ranges are very similar to the solution found there, although the optimisation parameter in this case is technology costs minus fuel savings, which ranges from -37,000 to -76,000 Eur/vehicle for DSL and from -15,000 to -45,000 Eur/vehicle for LNG powertrains, the negativity indicating that these are savings over vehicle lifetime.

Figure 6: Social cross-optimisation results for 2025, sub-group target 18%, typical costs



3.4 Utility-based absolute targets

Finally, a cross-optimisation option was developed that allows taking into account the utilities of different vehicle classes. For this purpose, vehicle utility was defined as the product of payload times activity (tons*kilometres, tkm) during a life year of an HDV of a given sub-group. The rationale of such an approach is to incentivise higher relative CO_2 emission reductions in highly active or heavily loaded vehicle classes, as this will have a stronger impact on real world CO_2 emissions than the same proportional reduction in vehicles with lower tkm. This optimisation is carried out to gain insight into how OEM could optimise the distribution of CO_2 reduction efforts over the different sub-groups of their new fleets. Therefore technology cost is chosen as the cross-optimisation parameter. While such analysis will eventually need to be run on OEM level, first runs were carried out at total regulated fleet level.

In order to implement this approach, a given %CO_2 reduction target $\mathrm{T_{CO_2}}$ is translated into an absolute target $\mathrm{ABS\_T_{CO_2}}$ in terms of average HDV tCO_2 on the fleet level. This is done by multiplying the %target by the weighted sum of the product of payload $\mathrm{pl_i}$, annual activity $\mathrm{act_i}$ and 2016 reference vehicle CO_2 emissions (gCO_2/km) $\mathrm{RefCO2_i}$ over all HDV sub-groups:

$$ABS\_T_{CO_2} = T_{CO_2} * \sum_{i=1}^{N} p_i * pl_i * act_i * RefCO2_i], \tag{13}$$

where reference vehicle emissions were calculated from the energy consumption of the respective vehicles

$$\mathrm{RefCO2_i} = \mathrm{RefEnCons}_i * Conv_i. \tag{14}$$

Input data such as payloads pl_i, activities act_i and reference vehicle energy consumption $\mathrm{RefEnCons}_i$ as well as conversion factors $Conv_i$ of the fuels diesel and LNG (gCO_2/MJ) were taken from [5].

Where either a unique target is given for the fleet as a whole, or the same % target is applied for each sub-group, it suffices to place this % target outside the sum as done in equation (13). This was the case for all scenarios analysed so far, whereas in principle differentiated sub-group targets could be handled as well.

In analogy to the target, the constraint needs to be transformed as well:

$$R = \sum_{i=1}^{N} p_i \cdot X_{min,i} * pl_i * act_i * BaseCO2_i \geq ABS\_T_{CO_2} \tag{15}$$

Equation (15) is valid in case of technology cost cross-optimisation, replacing the previous constraint given in (6).

If social cross-optimisation is carried out (as described in Section 3.3), considering additional manufacturing costs and fuel savings, a potential overshooting of the target needs to be prevented. As before, if

$$\sum_{i=1}^{N} p_i \cdot X_{min,i} * pl_i * act_i * BaseCO2_i \geq ABS\_T_{CO_2}, \tag{16}$$

the constraint needs to be inverted, and the following equation replaces the constraint previously given in (12):

$$R = \sum_{i=1}^{N} p_i \cdot x_i * pl_i * act_i * BaseCO2_i \leq ABS\_T_{CO_2}. \tag{17}$$

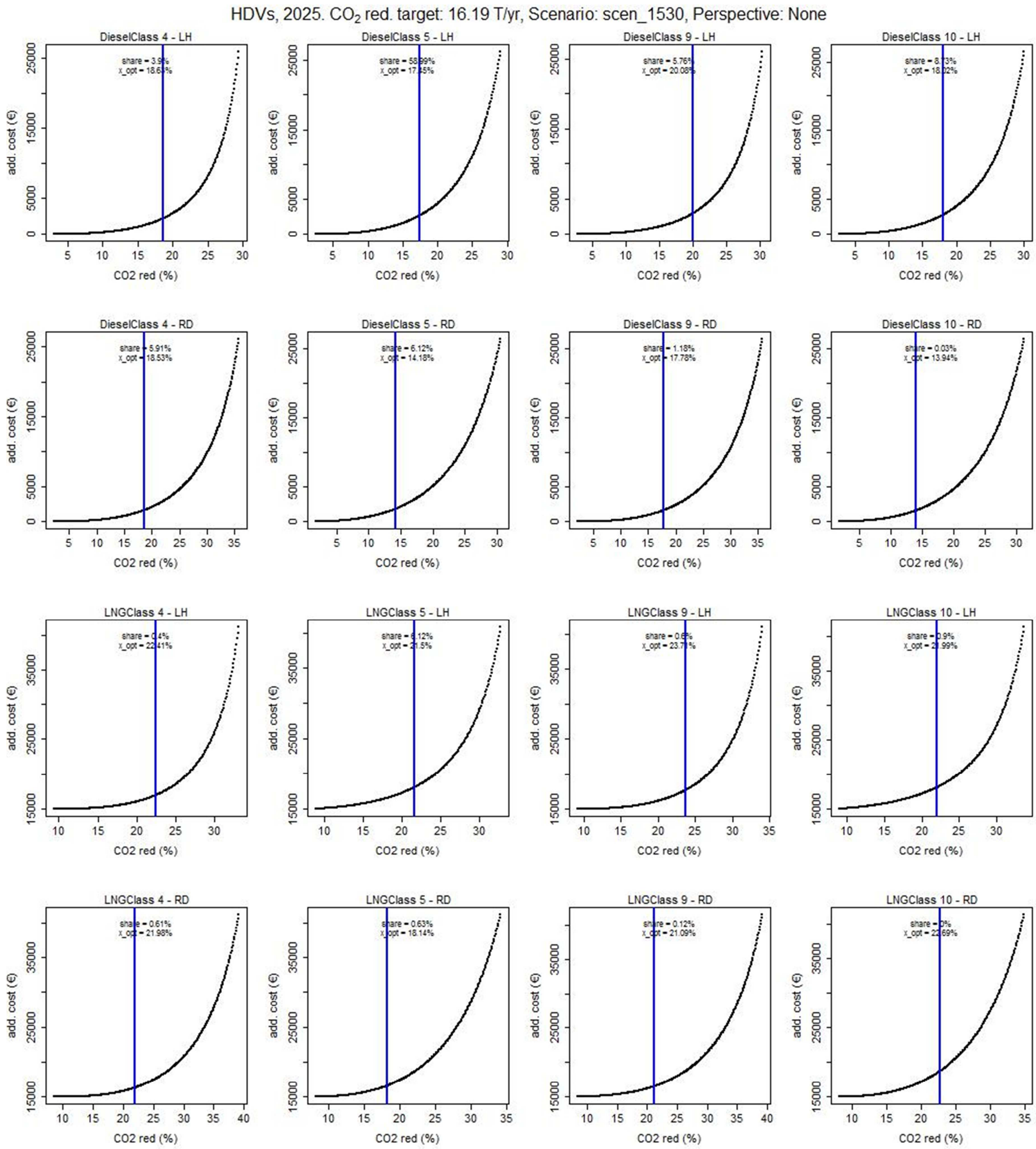
With these settings, the cross-optimisation routine searches for an optimal distribution of CO_2 reduction efforts over vehicle sub-groups, taking into account their payloads and activities. It will thus attribute higher reductions to sub-groups providing more utility.

An example of outcomes for an 18% reduction target by 2025, translated into a fleet-wide absolute target of 16.2 tCO_2 per HDV and year, is shown in Figure 7. Comparing with the cross-optimisation carried out for equivalent relative sub-group targets, all other settings equal, as presented in Figure 5, it can be seen that higher reductions are allocated to most LH sub-groups which have higher utilities, whereas in RD sub-groups less effort tends to be made. For example, in sub-group 9LH, which has the highest utility-weighted 2016 CO_2 emissions, DSL powertrain CO_2 reduction is 14% higher under the utility based target (at 20.08%) than under the constant sub-group target (17.65%).

As could be expected, compared to a class-based constant target, the spread of CO_2 reduction over the sub-classes is larger under a utility-based absolute target approach, as the algorithm allows allocating efforts over a larger range of vehicle classes. For the exemplary case of an 18% CO_2 reduction target in 2025 versus 2016, Figure 5 shows a maximum range of efforts of little more than 1%pts over all sub-groups for a given powertrain (i.e., 17.54 to 17.69% reduction for the DSL HDV and 21.03 to 22.42% for LNG), whereas the fleet based outcomes shown in Figure 7 have a range of roughly 6%pts over the sub-groups (i.e., 13.94 to 20.08% for DSL and 18.14 to 23.71% for LNG HDV of the different sub-groups).

Average additional manufacturing costs are slightly lower than under fixed sub-class targets, as shifts among classes allow for a more cost-efficient distribution of efforts, but the effect is small, e.g. 1% lower average additional manufacturing costs for the exemplary scenario.

Figure 7: Technology cost cross-optimisation results for 2025, absolute target for 18% relative target, typical costs



3.5 Cross-Optimisation Scenario Runs

As the range of cross-optimisation options presented in the previous Sections 3.1 through 3.4 shows, a number of settings are available for each cross-optimisation run.

In particular, choices need to be made

- On the structure of the CO_2 reduction targets:
    - Do they have to be met by the fleet as a whole, or by sub-groups?
    - Are they to be met as a relative (% compared to base year emissions), or as an absolute target (in tCO_2)?
- On the cross-optimisation perspective:
    - Should only additional manufacturing costs be optimised, or social costs (including fuel savings)?

Table 3 illustrates again the possible combinations of these settings, indicating which options have been run by EC JRC to support the analysis of HDV CO_2 targets. An "x" signifies that these settings have been implemented for a range of scenarios, and the bold "**XX**" indicates that this option has been identified as the main variant for the impact assessment, used for most of the analysis. Empty cells mean that a combination of settings has not been explored. As pointed out in Section 3.4, the absolute target version has been developed to examine optimal OEM strategies under a target that they have to fulfil on the level of their respective new fleets, thus while technically feasible, neither the sub-group target approach nor the social perspective have a useful interpretation in this regard and have therefore not been taken forward.

Table 3: Cross-optimisation variants employed (x) and chosen as the standard variant (**XX**)

<table>
<tr><td colspan="3"></td><td colspan="2">Cross-optimisation approach</td></tr>
<tr><td colspan="3"></td><td>Technology Costs</td><td>Social Costs</td></tr>
<tr><td rowspan="4">CO_2 reduction target structure</td><td rowspan="2">Fleet Target</td><td>Relative</td><td>x</td><td>x</td></tr>
<tr><td>Absolute</td><td>x</td><td></td></tr>
<tr><td rowspan="2">Sub-group target</td><td>Relative</td><td>x</td><td>XX</td></tr>
<tr><td>Absolute</td><td></td><td></td></tr>
</table>

Apart from the technical settings, a cross-optimisation run is defined by the CO_2 reduction target level, where a reference case and seven different target structures for 2025 and 2030 have been considered, as well as by the choice of cost curves, three sets of which (typical, medium-cost, high-cost) have been developed and used in the present analysis.

4 HDV Fuel Cost and Total Cost Calculation

4.1 Perspectives and Parameters

To assess the impact of different possible regulations, the DIONE HDV Fuel Cost and Total Cost Module computes the fuel costs and total costs under different scenarios and from different perspectives, i.e., for the first vehicle user, the second user, and the social perspective. These perspectives vary with regard to time frames, depreciation of additional manufacturing costs, and discount rates as well as taxes considered for calculating fuel costs. Settings for the three perspectives are specified in Table 4.

Table 4: Total cost calculation settings

	Enduser 1	Enduser 2	Social
HDV life years	1 - 5	6 - 15	1 - 15
Discount rate	9.5%	9.5%	4%
Depreciation	56%	44%	100%
VAT	excluded	excluded	excluded
Excise duty	included	included	excluded

4.2 Method and Results

For each of the $i = 16$ sub-group/powertrain combinations, fuel savings under a given scenario in a target year are calculated compared to a reference vehicle. As before, the reference vehicle for each sub-group/powertrain is defined as a 2016 new diesel vehicle of the same sub-group. Energy Consumption $RefEnCons_i$ of the reference vehicles (in MJ/km) as well as conversion factors of the fuels diesel and LNG (gCO_2/MJ) $Conv_i$ are taken from [5]. Reference Vehicle 2016 CO_2 emissions $RefCO2_i$ are calculated according to equation (14). For each regulation scenario, target year $y = 2025, 2030$ CO_2 emissions are computed using the scenario specific optimal CO_2 reduction of the sub-group/powertrain resulting from cross-optimisation:

$$CO2_{y,i} = RefCO2_i \; * x_i \tag{18}$$

Target year HDV energy consumption results as:

$$EnCons_{y,\,i} = CO2_{y,i} \,/Conv_i \tag{19}$$

Then, fuel savings of target year HDV with respect to the reference vehicles are calculated for each sub-group/powertrain. This is done on the basis of activities which are constant for all vehicles within the same sub-group, regardless of powertrain and scenario, but change due to the perspective p taken (first user, second user or social). Target year energy consumption varies by scenario and year, whereas the weighted fuel prices differ by scenario, year and perspective. Fuel savings result as:

$$FS_{y,i,p} = act_{i,p} * (RefEnCons_i * RefFP_i - EnCons_{y,\,i} * FP_{y,i,p} \tag{20}$$

Fuel prices of the reference vehicles $RefFP_i$ and of the target year vehicles $FP_{y,i,p}$ are calculated as the activity-weighted discounted fuel prices over the perspective period (settings see Table 4), based on a fuel price trajectory from PRIMES-TREMOVE. Activities are the sum of annual vehicle mileages available from [5] over the vehicle life years covered by the perspective.

Average fuel savings of a target year new vehicle result as the weighted sum over vehicle sub-groups/powertrains:

$$FS_{y,p} = \sum_{i=1}^{16} FS_{y,i,p} * p_i. \tag{21}$$

Similarly, average additional manufacturing costs as resulting from the cross-optimisation approaches presented in Sections 3.1, 3.2 and 3.4 can be derived:

$$C_y = \sum_{i=1}^{16} c_i * p_i \tag{22}$$

From these variables, the average total additional costs of ownership can be calculated for each scenario and perspective, taking into account the share of initial additional manufacturing costs depreciated $d_p = [0;1]$ within the perspective timeframe. Apart from manufacturing and fuel costs, no other cost types could be considered due to insufficient data availability.

$$TCO_{y,p} = C_y * d_p - FS_{y,p} \tag{23}$$

As HDV have a relatively high fuel consumption, (23) typically yields a negative result, indicating that upfront manufacturing costs for CO_2 reduction are overcompensated by fuel savings over the perspective periods under investigation, thus there is a net benefit.

Finally, it can be expected that HDV efficiency will continue to increase, as observed in the past, even if no HDV CO2 standard is adopted. Such autonomous development, as modelled in a reference scenario, has to be subtracted from scenario outcomes to derive the changes that can be attributed to the respective HDV CO_2 standards modelled in each scenario. To this aim, outcomes from equations (21) to (23) are calculated both for the reference (REF) as for the policy scenario (S), and the difference is derived as shown below for TCO, and done analogously for fuel savings and costs separately:

$$\mathrm{TCO'}_{y,p,S} = \mathrm{TCO}_{y,p,S} - \mathrm{TCO}_{y,p,REF} \tag{24}$$

Main results from this calculation are the additional manufacturing costs and fuel costs separately, as well as TCO, for each of the scenarios alone or relative to the reference scenario. Table 5 shows exemplary outcomes for reference and three policy scenarios targeting a 13, 18 and 23% CO_2 reduction of the 2025 new fleet versus 2016, derived from the social optimisation perspective under a sub-group target based cross-optimisation approach.

Table 5: Exemplary fuel and total cost results for social sub-group target cross-optimisation, 2025

Scenario	TCO Perspective	CO_2 red. target	Tech. Cost (EUR)	Fuel Savings (EUR)	Total Cost (EUR)
REF	Social	0.11257	857.0621	46258.71	-45401.7
REF	Enduser1	0.11257	479.9548	36194.83	-35714.9
REF	Enduser2	0.11257	377.1073	26963.48	-26586.4
scen_1020	Social	0.13	1715.289	55253.65	-53538.4
scen_1020	Enduser1	0.13	960.5617	43998.92	-43038.4
scen_1020	Enduser2	0.13	754.7271	32754.21	-31999.5
scen_1530	Social	0.18	3944.916	76872	-72927.1
scen_1530	Enduser1	0.18	2209.153	61362.23	-59153.1
scen_1530	Enduser2	0.18	1735.763	45675.64	-43939.9
scen_2032	Social	0.23	8196.533	97798.12	-89601.6
scen_2032	Enduser1	0.23	4590.059	77894.33	-73304.3
scen_2032	Enduser2	0.23	3606.475	57986.54	-54380.1

Similar results were calculated to evaluate different policy options in the framework of the EC impact assessment for HDV CO_2 standards. In this context, vehicle sub-group target cross-optimisation in the social perspective (described in Section 3.3) was the most widely used approach. However a large number of other scenarios was run as well to guarantee robustness of results. A large number of scenario runs was carried out, differentiating all possible settings. As an example, vehicle sub-group target cross-optimisation was run for eight CO_2 target scenarios (reference plus seven CO_2 standard scenarios), three cost curve scenarios (typical, medium-cost, high-cost), two cross-optimisation settings (social, technology cost based), and three fuel and total cost perspectives (Enduser 1, Enduser 2, Social), i.e., for 144 settings in total. A large number of further runs was carried out employing the alternative cross-optimisation approaches.

5 Conclusions

In this report, we have presented the modules of the EC JRC DIONE model which have been developed and applied to assess the impacts of heavy duty vehicle (HDV) CO_2 standards on vehicle manufacturing and user costs. These modules allow developing HDV CO_2 emission reduction cost curves, calculating the optimal allocation of emission reduction efforts to different HDV sub-groups, and computing additional manufacturing, fuel and total costs or savings.

These modules have been employed to provide insight into the costs of possible CO_2 standards for eight significant HDV sub-groups of both diesel and LNG type in 2025 and 2030. To this end, 80 final HDV cost curves have been developed, which have been the basis of several hundred cross-optimisation scenario runs with subsequent total cost calculation from different user perspectives, providing a knowledge base for assessing different HDV CO_2 targets.

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List of abbreviations and definitions

ACO	Ant Colony Optimisation
DSL	Diesel
EC	European Commission
EU	European Union
HDV	Heavy Duty Vehicle
LNG	Liquid Natural Gas
Sub-group	All HDV belonging to the same VECTO class and drive profile, regardless of their powertrain, i.e., DSL and LNG
TCO	Total Cost of Ownership
VECTO	Vehicle Energy Consumption Calculation Tool
xEV	Advanced Electrified Vehicle

List of figures

List of tables

Annex 1. Cost Curve Parameters

Cost curves for the typical cost scenario

Table 1: HDV CO_2 reduction cost curves (€) for 2025 and typical cost scenario.

		Cost curves relative to 2016 DSL HDV $y = C + c / (x - x_0) + bx$							
Powertrain	**Segment**	**C**	**c**	**x_0**	**b**	**x_min = Min reduction (%)*[1]**	**x_max = Max reduction (%)***	**y_min = Min additional cost[2]**	**y_max = Max additional cost**
DIESEL	Class 4 - RD	-6858.17	-3000	0.432749	-20250.1	2.20%	35.88%	0.00	26,426.04
	Class 5 - LH	-7241.55	-2600	0.353667	-26814.4	2.46%	29.09%	0.00	26,362.90
	Class 9 - RD	-8826.26	-4000	0.449175	-24667.9	2.02%	35.89%	0.00	26,609.84
	Class 10 - LH	-6820.77	-2500	0.363077	-22929.9	2.57%	30.10%	0.00	26,556.48
	Class 4 - LH	-3829.23	-1300	0.332362	-15654	3.04%	29.51%	0.00	26,426.04
	Class 5 - RD	-12192.2	-5000	0.408645	-33786.1	1.71%	30.64%	0.00	26,362.90
	Class 9 - LH	-4507.42	-1600	0.349533	-16760.3	2.76%	30.54%	0.00	26,609.84
	Class 10 - RD	-11967.9	-5000	0.416041	-33046.5	1.72%	31.38%	0.00	26,556.48
LNG	Class 4 - RD	7744.418	-3800	0.476598	-28775.4	8.56%	39.19%	15,000.00	41,331.54
	Class 5 - LH	9723.252	-2000	0.381343	-17512.6	8.80%	32.77%	15,000.00	41,268.40
	Class 9 - RD	7103.193	-4000	0.481996	-25637.9	8.39%	39.20%	15,000.00	41,515.34
	Class 10 - LH	9916.83	-1900	0.389785	-13865.9	8.91%	33.73%	15,000.00	41,461.98
	Class 4 - LH	11656.61	-1500	0.37239	-21766.4	9.35%	33.17%	15,000.00	41,331.54
	Class 5 - RD	734.7305	-7000	0.464173	-49422.8	8.10%	34.23%	15,000.00	41,268.40
	Class 9 - LH	10946.26	-1800	0.388794	-21879.6	9.08%	34.15%	15,000.00	41,515.34
	Class 10 - RD	989.1538	-7000	0.471287	-48449.4	8.11%	34.93%	15,000.00	41,461.98

[1] Refers to the x-axis (% CO_2 reduction) start point for these curves
[2] Refers to the y-axis (additional manufacturing cost) start point for these curves

Table 2: HDV CO_2 reduction cost curves (€) for 2030 and typical cost scenario.

Powertrain	Segment	C	c	x_0	b	x_min = Min reduction (%)	x_max = Max reduction (%)	y_min = Min additional cost	y_max = Max additional cost
		Cost curves relative to 2016 DSL HDV $y = C + c / (x - x_0) + bx$							
DIESEL	Class 4 - RD	-6246.58	-3000	0.471918	-18721.6	2.45%	39.43%	0.00	25,013.44
	Class 5 - LH	-6512.58	-2600	0.389589	-24320.9	2.73%	32.35%	0.00	24,938.70
	Class 9 - RD	-8069.76	-4000	0.489174	-22300.2	2.24%	39.40%	0.00	25,188.84
	Class 10 - LH	-6152	-2500	0.399035	-20868.7	2.86%	33.37%	0.00	25,122.13
	Class 4 - LH	-3429.3	-1300	0.365986	-14322.5	3.38%	32.67%	0.00	25,013.44
	Class 5 - RD	-11103.3	-5000	0.447038	-30414.7	1.90%	33.92%	0.00	24,938.70
	Class 9 - LH	-4067.41	-1600	0.384154	-14966.1	3.06%	33.75%	0.00	25,188.84
	Class 10 - RD	-10922.6	-5000	0.454138	-29867.7	1.91%	34.64%	0.00	25,122.13
LNG	Class 4 - RD	30065.72	-1800	0.567522	-14750.9	21.96%	51.54%	32,000.00	57,013.44
	Class 5 - LH	30692.97	-1500	0.502109	-18233.8	22.18%	45.88%	32,000.00	56,938.70
	Class 9 - RD	29501.82	-2900	0.587098	-24582.4	21.80%	51.52%	32,000.00	57,188.84
	Class 10 - LH	30337.37	-1500	0.51076	-15918.3	22.29%	46.69%	32,000.00	57,122.13
	Class 4 - LH	32002.08	-1000	0.491985	-16633.2	22.71%	46.14%	32,000.00	57,013.44
	Class 5 - RD	28611.18	-3500	0.551428	-32624.4	21.52%	47.13%	32,000.00	56,938.70
	Class 9 - LH	31455.29	-1200	0.505809	-16574.8	22.45%	47.00%	32,000.00	57,188.84
	Class 10 - RD	28691.38	-3500	0.556999	-32207.5	21.53%	47.71%	32,000.00	57,122.13

Cost curves for the medium cost scenario

Table 3: HDV CO_2 reduction cost curves (€) for 2025 and medium cost scenario.

		Cost curves relative to 2016 DSL HDV $y = C + c / (x - x_0) + bx$							
Powertrain	**Segment**	**C**	**c**	x_0	**b**	**x_min = Min reduction (%)**	**x_max = Max reduction (%)**	**y_min = Min additional cost**	**y_max = Max additional cost**
DIESEL	Class 4 - RD	-1725.46	-451.648	0.257951	-7844.38	0.94%	21.46%	17.94	7,013.27
	Class 5 - LH	-1259.05	-257.718	0.202373	-6986.42	0.14%	18.35%	13.50	11,102.50
	Class 9 - RD	-1750.84	-459.289	0.257805	-8567.12	0.84%	21.45%	18.72	7,026.49
	Class 10 - LH	-746.708	-138.261	0.178203	-5924.49	0.76%	16.49%	18.72	8,698.38
	Class 4 - LH	-1363.13	-275.34	0.198012	-8496.93	0.80%	17.00%	17.94	7,013.27
	Class 5 - RD	-1667.74	-355.159	0.211138	-8728.49	0.12%	18.65%	13.50	11,102.50
	Class 9 - LH	-1280.51	-274.766	0.209491	-8116.43	0.76%	18.14%	18.72	7,026.49
	Class 10 - RD	-1098.15	-214.458	0.189839	-7920.22	0.74%	17.06%	18.72	8,698.38
LNG	Class 4 - RD	13689.91	-456.812	0.294665	-10030.9	7.38%	25.22%	15,017.94	21,918.77
	Class 5 - LH	14124.94	-267.224	0.241796	-9563.73	6.63%	22.27%	15,013.50	26,008.00
	Class 9 - RD	13742.7	-444.636	0.293503	-10144.9	7.29%	25.21%	15,018.72	21,931.99
	Class 10 - LH	14630.26	-129.013	0.217316	-6934.51	7.21%	20.49%	15,018.72	23,603.88
	Class 4 - LH	14138.31	-278.259	0.237189	-11172	7.25%	20.97%	15,017.94	21,918.77
	Class 5 - RD	13797.42	-367.755	0.250289	-11807.8	6.61%	22.56%	15,013.50	26,008.00
	Class 9 - LH	14211.96	-265.497	0.247434	-9811.76	7.21%	22.06%	15,018.72	21,931.99
	Class 10 - RD	14385.71	-201.299	0.228385	-9086.72	7.19%	21.03%	15,018.72	23,603.88

Cost curves for the high cost scenario

Table 4: HDV CO_2 reduction cost curves (€) for 2025 and high cost scenario.

Powertrain	Segment	Cost curves relative to 2016 DSL HDV $y = C + c / (x - x_0) + bx$ C	c	x_0	b	x_min = Min reduction (%)	x_max = Max reduction (%)	y_min = Min additional cost	y_max = Max additional cost
DIESEL	Class 4 - RD	-19921.2	-8145.32	0.405616	-59621.2	2.20%	30.58%	0.00	43,480.02
	Class 5 - LH	-28880.7	-10128.3	0.346706	-104204	2.46%	24.48%	0.00	45,017.07
	Class 9 - RD	-30110.6	-13566.5	0.446453	-84997.1	2.02%	31.11%	0.00	43,658.34
	Class 10 - LH	-24436.4	-8659.7	0.350636	-86146.9	2.57%	25.62%	0.00	45,161.98
	Class 4 - LH	-9496.68	-2807.48	0.287503	-46803.3	3.04%	24.39%	0.00	43,480.02
	Class 5 - RD	-74294.4	-36034.2	0.483119	-177131	1.71%	26.68%	0.00	45,017.07
	Class 9 - LH	-11127.1	-3500.75	0.309696	-46476.4	2.76%	25.72%	0.00	43,658.34
	Class 10 - RD	-52980.6	-24153.2	0.454487	-131007	1.72%	27.44%	0.00	45,161.98
LNG	Class 4 - RD	-6810.54	-10818.7	0.459814	-82944.3	8.56%	34.41%	15,000.00	58,152.70
	Class 5 - LH	-17846.2	-14884.1	0.409146	-153418	8.80%	28.67%	15,000.00	59,689.75
	Class 9 - RD	-21351.6	-19980.8	0.512097	-122899	8.39%	34.91%	15,000.00	58,331.25
	Class 10 - LH	-12585.4	-12505.3	0.411109	-126263	8.91%	29.74%	15,000.00	59,834.90
	Class 4 - LH	7322.903	-3225.84	0.332885	-62017.5	9.35%	28.58%	15,000.00	58,152.70
	Class 5 - RD	-121078	-87553.5	0.623107	-313927	8.10%	30.73%	15,000.00	59,689.75
	Class 9 - LH	5278.97	-4032.31	0.354998	-61029.6	9.08%	29.84%	15,000.00	58,331.25
	Class 10 - RD	-60170.9	-42636.6	0.546172	-203531	8.11%	31.45%	15,000.00	59,834.90

Table 5: HDV CO_2 reduction cost curves (€) for 2030 and high cost scenario.

Powertrain	Segment	C	c	x_0	b	x_min = Min reduction (%)	x_max = Max reduction (%)	y_min = Min additional cost	y_max = Max additional cost
		Cost curves relative to 2016 DSL HDV $y = C + c / (x - x_0) + bx$							
DIESEL	Class 4 - RD	-15668.5	-6880.67	0.435393	-43971.5	2.45%	33.94%	0.00	41,075.32
	Class 5 - LH	-24651.1	-9519.29	0.379431	-87258.5	2.73%	27.50%	0.00	42,523.82
	Class 9 - RD	-22733.9	-10836	0.471843	-61413	2.24%	34.46%	0.00	41,245.29
	Class 10 - LH	-21244.9	-8306.54	0.384536	-73158.2	2.86%	28.67%	0.00	42,658.63
	Class 4 - LH	-8238.12	-2698.78	0.318596	-36626	3.38%	27.31%	0.00	41,075.32
	Class 5 - RD	-48778.7	-23871.5	0.487223	-116021	1.90%	29.75%	0.00	42,523.82
	Class 9 - LH	-9222.29	-3186.95	0.339839	-35404.6	3.06%	28.73%	0.00	41,245.29
	Class 10 - RD	-40382.8	-19316.7	0.476379	-97363.7	1.91%	30.50%	0.00	42,658.63
LNG	Class 4 - RD	27324.34	-5504.61	0.548315	-54964.8	21.96%	47.15%	32,000.00	73,075.32
	Class 5 - LH	29163.54	-7615.43	0.503545	-109073	22.18%	42.00%	32,000.00	74,523.82
	Class 9 - RD	24619.35	-8668.79	0.577474	-76766.2	21.80%	47.57%	32,000.00	73,245.29
	Class 10 - LH	29044.73	-6645.16	0.507628	-91447.2	22.29%	42.93%	32,000.00	74,658.63
	Class 4 - LH	32918.38	-2159.01	0.454877	-45782.3	22.71%	41.85%	32,000.00	73,075.32
	Class 5 - RD	12226.45	-19097.3	0.589779	-145026	21.52%	43.80%	32,000.00	74,523.82
	Class 9 - LH	31628.84	-2549.57	0.471872	-44255.9	22.45%	42.98%	32,000.00	73,245.29
	Class 10 - RD	15958.13	-15453.4	0.581103	-121705	21.53%	44.40%	32,000.00	74,658.63

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