Ricardo
Energy & Environment

Improving understanding of technology and costs for CO2 reductions from cars and LCVs in the period to 2030 and development of cost curves

Service Request 4 to LDV Emissions Framework Contract

Report for DG Climate Action
Ref. CLIMA.C.2/FRA/2012/0006

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Contact:

Nikolas Hill
Ricardo Energy & Environment
Gemini Building, Harwell, Didcot, OX11 0QR,
United Kingdom

t: +44 (0) 1235 75 3522
e: nikolas.hill@ricardo.com

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Authors:

Nikolas Hill, Elisabeth Windisch, Felix Kirsch, Gareth Horton and Craig Dun (Ricardo Energy & Environment);Stefan Hausberger and Claus Matzer (TU Graz);Ian Skinner (TEPR);Alberto V. Donati, Jette Krause and Christian Thiel (EC JRC);Peter Wells (for the Peer Review) (Cardiff Business School).

Approved By:

Sujith Kollamthodi

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Executive summary

Introduction

Regulatory targets for reduction of tailpipe CO_2 emissions from passenger cars and light commercial vehicles (LCVs) have been set for the period up to 2021 in the European Union. It is now important to begin work on the potential size and format of the post-2020 targets for light duty vehicles (LDVs).

The aim of this project was to develop a more detailed understanding of the technologies that are available now and that are likely to be available in the period up to 2030 for controlling passenger car and LCV CO_2 emissions for different vehicle segments. The final output from the project was to develop and present cost curves (for 2015, 2020, 2025 and 2030) by segment and powertrain type on a WLTP basis to support policy analysis on potential future regulatory targets for CO_2 emissions from LDVs post-2020.

To achieve the overall aims of the study it was necessary to gather and test available data on the cost and performance of CO_2 reducing technologies with stakeholders and develop a methodological approach for estimating their trajectories in performance and cost to 2030.

Establishing an appropriate baseline and segmentation

A fundamental starting point to the work involved establishing an appropriate baseline for the analysis, and confirming the appropriate LDV segmentation. This was achieved through evaluation of available literature, stakeholder views and analysis of the most recently available EEA car and van CO_2 monitoring databases to establish baseline performance and characteristics for the study analysis. The work also built upon previous analysis for the Commission for the recently completed LDV downweighting study (Ricardo-AEA, 2015). In addition, to support the setting of the baseline and later analysis, a dataset was purchased from IHS Global Insight detailing the estimated penetration levels of CO_2 reducing technologies into the marketplace by 2013. The result of this analysis was the establishment of the following segmentation for the project, including four segments for passenger cars and three for LCVs:

- Small Cars [A+B segment]
- Lower Medium Cars [C segment]
- Upper Medium Cars [D segment]
- Large Cars [Others]
- Small LCVs [<1.8t GVW]
- Medium LCVs [1.8-<2.5t GVW]
- Large LCVs [2.5-3.5t GVW]

Developing a list of CO_2 reducing technologies

Other early tasks for the project included the identification of a suitable list of CO_2 reducing technologies for LDVs, relevant for the period up to 2030, which was achieved via a preliminary review of available literature and initial discussions with key expert stakeholders. This list of technologies also included those expected to have beneficial impacts on fuel consumption/CO_2 emissions in the real-world, but that don't show such savings over regulatory cycles/testing protocols. Such 'off-cycle' technologies (e.g. including those qualifying as eco-innovations) have not been included in previous similar analysis for the Commission. Additional (on- and off-cycle) technologies were also added to the list as the project progressed, e.g. where they were identified in later more detailed discussions with stakeholders. The final full list included over 80 technologies taken forward for analysis in the cost-curves, plus additional information gathered on xEV powertrain components used to establish the future costs and performance of these vehicle types (i.e. including PHEVs, REEVs, BEVs and FCEVs).

Gathering and reviewing evidence on CO_2 reducing technologies and stakeholder consultation

The main part of the project involved the gathering, review and analysis of data (as well as more qualitative information) on CO_2 reducing technologies from the literature, and through stakeholder consultation in various forms. The stakeholder consultation activities included the following elements:

- *Gap-filling:* questionnaires and interviews used to gather specific information on technology performance and costs from key organisations.
- *Delphi Survey:* used to gather feedback and seek agreement with expert stakeholders on key aspects of the proposed methodology for developing cost estimates for technologies.
- *Validation*: obtaining feedback from key expert stakeholders on draft findings and on the initial data/assumptions for the performance and costs of technologies.
- *Interviews and ad-hoc communications*: used to gather both general feedback on a range of relevant areas, or specific information on key data, methodologies or other assumptions

This aspect of the project was particularly challenging due to sometimes conflicting views on the performance and costs of different technical options between different stakeholders, and also with information available in the literature. In such considerations, higher priority/weighting was given to data derived using more rigorous and transparent methodologies (such as the tear-down based cost estimates developed for the US EPA/NHTSA (EPA & NHTSA, 2012) and for ICCT (FEV, 2013a), (FEV, 2012)) and those given by expert industry stakeholders over less detailed information available in the wider public literature. (For many technologies, the estimated manufacturing costs were significantly lower than those used in previous cost-curve analysis for the Commission.) Unfortunately, the approach adopted by the majority of OEMs, i.e. to only provide generalised feedback via their trade association, somewhat hampered the ability to explore in more detail the reasons for disagreement with some of the cost estimates (e.g. those derived by tear-down studies) for certain technologies. In contrast, a significant number of automotive suppliers provided useful feedback / key data for the project.

For technical options for reducing off-cycle CO_2 emissions, the challenge in many cases was in finding *any* relevant CO_2 reduction and cost estimates, rather than on resolving conflicting sometimes information. For these technical options, the gap-filling and wider interviews with OEMs and their suppliers were critical to obtaining key data. Even so, some options could not be taken forward into the cost-curve analysis due to lack of data on their costs and/or CO_2 reducing performance. Overall, significant revisions were made to the original draft data/assumptions for all technical options following feedback from the data validation process and interviews with stakeholders in the consultation phase.

The following list provides a general summary of some of the key actions taken as a result of this consultation process. In addition, the feedback received was also factored into the more qualitative discussions provided in various sections across the main report:

- Amendments to assumptions on the CO_2 benefits of technologies to reflect lower than optimal initial market average performance and improvements over time;
- Amendments to the initially proposed cost-curves in terms of their assignment to different technologies and moving to continuous, rather than stepped cost-curves;
- Amendments to the assumed costs of individual technologies based on feedback;
- Revisions to some of the key technology component costs and learning rates used in the advanced xEV analysis; and
- Influencing decision-making on the exclusion/inclusion and setting of a range of other cost elements / considerations in the overall analysis.

Exploration of factors influencing future technology costs

Additional work was also carried out to explore the various factors that have an influence on the future costs of CO_2 reducing technologies from LDVs:

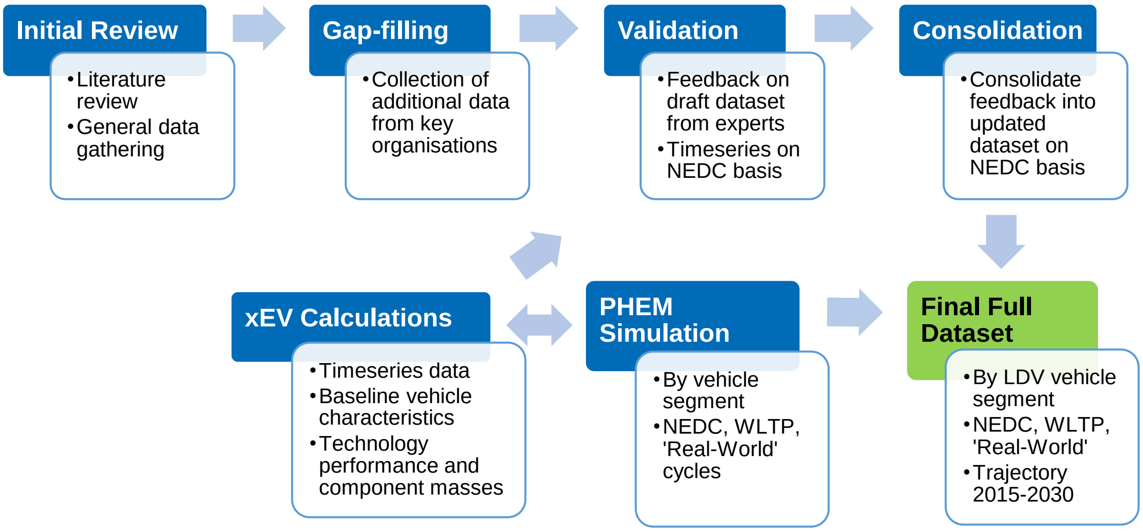
- Development of an evidence base on measures that OEMs and suppliers take to mitigate the costs associated with CO_2 reduction technologies;
- Exploration of the variation between ex-ante and ex-post cost estimates;
- Exploration of the potential impacts of alternative powertrain deployment scenarios.

The outputs and conclusions from these work elements were fed into the final methodological approaches used to estimate the future costs of CO_2 reducing technologies.

Analysis of the CO_2 benefits associated with each technology

The following Figure ES1 below provides a summary of the overall methodological approach and process used to develop the estimates of the CO_2 benefits associated with different technologies.

Figure ES1: Summary of the methodology to estimating the CO_2 benefits of technologies



An essential part of the overall work programme involved the simulation of the impacts of different technologies on the fuel consumption/CO_2 emissions from different LDV segments, powertrain types and test cycles (including NEDC, WLTP and real-world cycles). This work was conducted by TU Graz using the PHEM model and involved the definition, setting-up, calibrating and running of in the end around 2500 simulations of individual technologies with different LDV segments and powertrains, as well as a number of technology packages. The outputs from this analysis were critical to the project for a number of reasons, including:

a) Providing cross-corroboration of CO_2 savings from the literature or stakeholders for particular technical options;

b) Providing evidence to estimate the potential variation in specific CO_2 savings for different vehicle segments (and powertrain types) based on the different baseline characteristics;

c) Allowing the estimation of CO_2 savings potentials on a WLTP-basis for different technologies from the primarily NEDC-based CO_2 savings information available in the literature/from stakeholders;

d) Informing development of suitable correction factors for the cost-curves to account for overlaps in the action of compatible technologies (i.e. by comparing the results of the technology package simulations with estimates of combined CO_2 reductions based on individual technology results).

During the course of the project TU Graz also performed a range of other analysis in order to provide verification checks for the developed cost-curves / the cost-curve input data assumptions, this included using information from currently deployed vehicle types, as well as a limited programme of component testing and simulation.

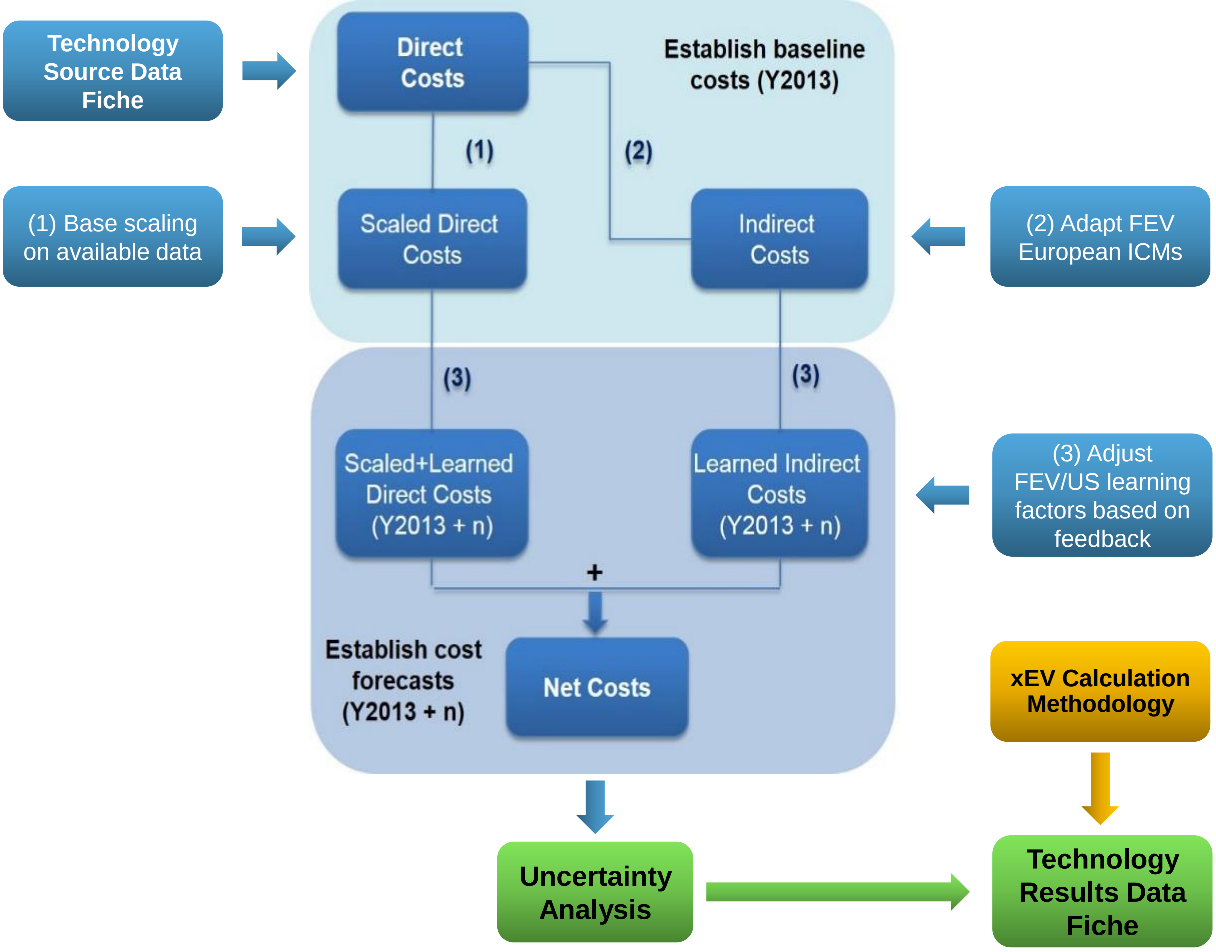
For advanced xEVs, a slightly different approach was adopted, which involved the development of estimates for the additional costs and CO_2 /energy reducing performance of these powertrains for different time periods from information on individual components (i.e. batteries, motors, fuel cells, and a range of other xEV components) scaled to different LDV segments.

Final methodological development and technology analysis results

The following schematic in Figure ES2 presents a summary of the final methodological approach developed for estimating the future costs of different technologies, based on the feedback from the stakeholder consultation. (A summary of the final methodological approach for estimating the CO_2 performance of different technologies has already been presented above in the previous sub-section.)

The outcomes from the data gathering, analysis and wider consultation activities from the cost perspective included a finalised set of direct manufacturing costs (DMC) and a refined methodological approach to estimate the future costs of individual technical options. This approach also included the development and refinement of learning curves and indirect cost multipliers (ICMs) assigned to different technologies, and the development of segment multipliers (SM) used to scale costs between different LDV segments. These elements, together with estimates for their respective uncertainties were utilised in a statistical uncertainty analysis using a Latin Hypercube Sampling (LHS) approach to derive estimates for the typical, low and high costs of technologies for different segments and years.

Figure ES2: Schematic of the final technology cost calculation methodology



As already indicated, a slightly different approach was adopted for advanced xEVs, that developed estimates for the additional costs of these powertrains from information on individual sub-systems/components scaled to different LDV segments. The specific assumptions used in this analysis were gathered from existing available literature (including other recent studies by Ricardo Energy & Environment) and tested with stakeholders. In addition, a series of alternative xEV deployment scenarios were used to explore the potential range in possible future costs based on a simplified learning methodology applied to individual xEV components. The result was a set of typical, low and high estimates for the costs of different xEV powertrain types by vehicle segment and year.

Development and verification of cost curves

The final outputs from the LHS uncertainty analysis of technology costs and the combination of data from the PHEM simulations and consolidated CO_2 reductions by technology were used to generate a series of 252 cost-curves on a WLTP basis using a cost-curve model newly developed by JRC. This included different combinations of powertrain type (conventional, PHEV, REEV, BEV, FCEV), LDV segment, and year (2015, 2020, 2025 and 2030), as well as providing separate cost-curves with/without off-cycle technologies included. As part of this process, a number of post-processing steps were also applied to the data output from the cost curve model, including:

1. Adjustment of the initial dataset to correct for already deployed technologies in the 2013 baseline;
2. Correcting for battery/H_2 storage cost savings in maintaining electric /hydrogen range (xEVs only);
3. Correcting for overlaps in technologies (based on analysis of the outputs of the PHEM simulation of technology packages by TU Graz);
4. Re-baselining xEV powertrain cost-curves relative to 2013 conventional powertrains (xEVs only).

The final set of cost-curve equations for the entire set of core WLTP-based cost-curves is being provided alongside this report in an Excel summary file to complement the Technology Results Data Fiche. This MS Excel based fiche of information provides all the key outputs/results from the project, including the final set of costs and CO_2 performance figures for individual technology options, as well as key datasets used to derive them (e.g. the DMCs, learning curves, ICMs, segment multipliers and their uncertainties input to the LHS analysis).

In addition, a number of additional cost-curves were also developed to provide sensitivities/comparisons, including comparisons of NEDC-based cost curves for lower medium cars with those generated in other previous work for the Commission and cost-curves illustrating the impact of switching between the typical, low and high technology cost estimates.

Overall it is concluded that the revised cost-curve approach (supported by a detailed analysis of technology costs and vehicle simulations) provides a good compromise between the two alternative extremes, i.e.: (i) a full simulation/testing programme (relatively vastly more expensive to feed a similar number of cost-curves compared to the anticipated improved accuracy), and (ii) simple cost-curve generation without post-processing corrections (too simplistic leading to significant over-estimation of potential improvements for SI engines in particular). However, it is believed that the current approach could potentially be further enhanced by a lower level programme of additional selected simulations and tests to build on the work that was possible/already carried out under this project and could then better inform the adjustment for technology overlaps in the development of the final cost-curves.

The final task for this project involved also consideration of the need/potential to adjust the developed average (mass-market) cost-curves to other vehicle segments or manufacturers. In the course of the engagement undertaken within the project, stakeholders were asked for their views on whether there was a case for adjusting the analysis for a particular vehicle segment or manufacturer. In particular, engagement was carried with small volume manufacturers, as these were mentioned as a set of manufacturers for which an adjustment might be appropriate. In addition, an assessment of the assumptions used in relation to performance cars in the analysis undertaken in support of the 2017-2025 US CAFE regulations was carried out, as such cars were mentioned as potentially being appropriate for an adjustment in the analysis.

Overall, the analysis concluded that it was not appropriate or possible to develop a generic correction factor for either small volume manufacturers or performance cars more widely for the analysis undertaken within this study. In both cases, more work would be needed to explore whether suitable, more specific factors could be identified, but even then it is likely that subjective judgement would be required, thus questioning the added value of such additional work.

Given the relatively small numbers of vehicles involved, it is unlikely that such work would be sufficiently cost-effective and so other options, such as the derogations for some of these manufacturers in the Regulation itself, might remain more appropriate for dealing with such manufacturers / segments.

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Table of abbreviations

Abbreviation	Description
A	Cross sectional area in [m²]
a, b	weighting factors in [-]
AMT	Automated Manual Transmission
AT	Automatic Transmission
BEV	Battery Electric Vehicle
BMEP	Brake Mean Effective Pressure
C_1	FC of PHEV with cycle start of full charged battery in [l/100 km]
C_2	FC of PHEV with empty battery in [l/100 km]
CADC	Common Artemis Driving Cycle
C_d x A	Road load from air resistance in [s²/m²]
CI engines	Compression-ignition engines
CNG	Compressed Natural Gas
CO_2	Carbon dioxide
D_a	Assumed average distance between two battery charges, suggested: 25 km
DCT	Double/Dual Clutch Transmission
DMC	Direct Manufacturing Cost
D_e	Electric range in [km]
DIN	Deutsches Institut für Normung
EE	Electric Engine
EEC	Electric Energy Consumption
EGR	Exhaust Gas Recirculation
FC	Fuel Consumption
FCEV	Fuel Cell Electric Vehicle
FC_{norm}	Normalized fuel consumption in [(g/h)/kW$_{rated}$]
fr0, fr1	Road load from rolling resistance in [-], [s/m]
FTP-75	Federal Test Procedure
GHG	Greenhouse gas
HBEFA	Handbook Emission Factors for Road Transport
HDV	Heavy Duty Vehicle
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
ICM	Indirect Cost Multiplier
LCV	Light Commercial Vehicle
LDV	Light Duty Vehicle (i.e. cars and LCVs)
Li-ion	Lithium-ion (i.e. battery chemistry)
Li-S	Lithium-Sulphur (i.e. battery chemistry)
m_{CADC}	CADC test mass in [kg]
m_{NEDC}	NEDC test mass in [kg]
$m_{permissible\_max}$	maximum permissible mass in [kg]

Abbreviation	Description
MT	Manual Transmission
$m_{unloaden}$ (DIN)	unladen mass DIN in [kg]
$m_{unloaden}$ (EU)	unladen mass EU in [kg]
$m_{unloaden\_max}$	maximum unladen mass in [kg]
MW	Motorway
m_{WLTC}	WLTC test mass in [kg]
$m_{WLTC\_best\_case}$	WLTC best case test mass in [kg]
$m_{WLTC\_worst\_case}$	WLTC worst case test mass in [kg]
n	Engine speed in [min^{-1}]
NEDC	New European Driving Cycle
n_{idle}	Idling speed in [min^{-1}]
n_{norm}	Normalized engine speed in [-]
NO_x	Nitrogen Oxides
n_{rated}	Rated engine speed in [min^{-1}]
OEM	Original Equipment Manufacturer
PC	Passenger Cars
P_e	Effective engine power in [kW]
PHEM	Passenger car and Heavy duty Emission Model
PHEV	Plug-In Hybrid Vehicle
PM	Particulate Matter
P_{norm}	Normalised engine power in [-]
P_{rated}	Rated engine power in [kW]
R&D	Research and Development
RWC	Real-world Driving Cycle
RDE	Real Driving Emissions
REEV	Range Extended Electric Vehicle
RRC	Rolling Resistance Coefficient in [kg/ton]
RWC	Real World Cycle
SCR	Selective Catalytic Reduction
SI engines	Spark-ignition engines
SOC	State Of Charge in [-]
SUV	Sport Utility Vehicle
TUG	Technical University Graz
UF	Utility Factor in [-]
VCR	Variable compression ratio
WLTC	Worldwide harmonized Light vehicles Test Cycle
WLTP	Worldwide harmonized Light vehicles Test Procedure
WR	Weight Reduction
RPA	Relative positive acceleration in [m/s^2]

1 Introduction and context

Ricardo Energy & Environment together with our partners CAIR, TEPR and TU Graz have been commissioned to provide technical support to improve the understanding of technology and costs for CO_2 reductions from cars and light commercial vehicles in the period to 2030, and the development of cost curves. The project was commissioned by the European Commission's DG Climate Action.

This Final Report provides a summary of the findings of the work completed during the course of the project. The report has been structured to provide the following elements:

- Summary of the context of the work undertaken (this Section 1);
- Establishment of the baseline and segmentation, and the list of technical options (Sections 2 to 3);
- Gathering and review of the evidence on the costs and performance of CO_2 reducing technologies (Section 4);
- Exploration of the costs and CO_2 benefits of the identified technologies, the final methodological development and the results of the technology analysis (Sections 5 to 7);
- The development and verification of cost-curves (Section 8);
- A high-level summary of the project findings (Section 9);

1.1 General context

In 2007, the Commission proposed the introduction of a regulatory framework for reducing the average CO_2 emissions of the new car fleet, and the development of a similar framework for light commercial vehicles (LCVs; i.e. including vans)[1]. This culminated in regulatory targets for tailpipe CO_2 emissions for cars (Regulation (EC) 443/2009[2]) and LCVs (Regulation (EU) 510/2011[3]). Both Regulations set provisional targets for 2020 (following on from earlier targets at 2015 for cars and 2017 for LCVs), which were confirmed and adopted in amendments to the original Regulations in 2014[4]. These targets are 95 gCO_2/km for cars, to be met by 2021, and a target of 147 gCO_2/km for 2020 for LCVs. Both of these proposals underlined that there was public and stakeholder support for setting targets beyond 2020.

It is important to begin work on the potential size and format of the post-2020 targets, as soon as possible, with the revised Regulations committing the Commission to undertake a review of the potential targets, modalities and other aspects of the post-2020 regulatory framework in 2014. An extensive set of studies previously undertaken for the Commission has underpinned the development of these Regulations, with many completed under the previous framework contract on LDV emissions.

This project is part of a work programme to support the development of a post-2020 regulatory regime for addressing car and LCV CO_2 emissions. In order to identify the most cost-effective post-2020 targets it is important to have a detailed understanding of the technologies that are available now and that are likely to be available in the near future for controlling passenger car and LCV CO_2 emissions for different vehicle segments. Only then is it possible to develop challenging but achievable CO_2 performance targets for each vehicle type. Challenging targets are needed in order to ensure that CO_2 emissions from light duty vehicles (LDVs) continue to decline at a rate that is consistent with meeting the EU's long-term GHG reduction objectives, which require at least a 60% reduction in transport sector GHG emissions compared to 1990 levels to be achieved by 2050, according to the 2011

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[1] European Commission (2007), Results of the review of the Community Strategy to reduce CO_2 from passenger cars and light commercial vehicles (COM(2007) 19, 2007)

[2] Regulation (EC) 443/2009 of the European Parliament and of the Council setting emission performance standards for new passenger cars (Passenger Car CO_2 Regulation) [2009] OJ L140/1

[3] Regulation (EU) 510/2011 setting emission performance standards for new light commercial vehicles as part of the Union's integrated approach to reduce CO_2 emissions from light-duty vehicles (Van CO_2 Regulation) [2011] OJ L145/1

[4] Regulation (EU) No 333/2014 amending Regulation (EC) No 443/2009 to define the modalities for reaching the 2020 target to reduce CO_2 emissions from new passenger cars; Regulation (EU) No 253/2014 amending Regulation (EU) No 510/2011 to define the modalities for reaching the 2020 target to reduce CO_2 emissions from new light commercial vehicles

Transport White Paper[5]. Challenging targets will also provide the most benefit to consumers, as a result of improved fuel efficiency.

1.2 Objectives of the study

The objectives of this study are summarised as follows:

1. Establish an appropriate baseline relative to which the costs and performance of CO_2 reducing technologies will be assessed, including a relevant vehicle segmentation.
2. Develop a list of technologies that could be applied to cars and LCVs between 2020 and 2030 to reduce their CO_2 emissions, including both on- and off-cycle emissions.
3. Collate, understand and confirm, as far as is possible, the costs and CO_2 reduction potential associated with these technologies.
4. Develop and present of cost curves for 2015, 2020, 2025 and 2030 by segment.

The resulting report will address these objectives in a comprehensive and detailed manner, thereby providing guidance for policy formulation.

1.3 Methodology overview

The following sections provide a summary of the work completed under this project, covering each of the technical tasks specified in the Commission's Terms of Reference. The report has been structured into seven main technical chapters, following this introduction, summarising the work completed:

- **Chapter 2:** Establishing a baseline and appropriate vehicle segmentation;
- **Chapter 3:** Producing a list of technologies to reduce LDV CO_2 emissions;
- **Chapter 4:** Gathering and reviewing evidence on the costs and performance of CO_2 reducing technologies;
- **Chapter 5:** Exploration of factors influencing future technology costs;
- **Chapter 6:** Analysis of the CO_2 benefits associated with each technology;
- **Chapter 7:** Final methodological development and technology analysis results;
- **Chapter 8:** Development and verification of cost curves.

Additional supporting information is also provided in the report Appendices, and in accompanying MS Excel files also provided to the Commission alongside this report.

1.4 Peer review

A separate peer review was commissioned as part of the project and will be published alongside it. An initial peer review on the interim report (which included the majority of the work completed) was provided by Peter Wells (CAIR, Cardiff University) following the submission of the interim report. The final peer review of the fully completed project work documented in this final report is provided in Appendix 7.

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[5] European Commission (2011) *Roadmap to a Single European Transport Area – Towards a competitive and resource-efficient transport system* (White Paper, COM(2011) 144, 2011)

2 Establishing a baseline and appropriate vehicle segmentation

2.1 Overview of the methodology for establishing the baseline and segmentation

The project had to establish the most appropriate baseline to be used in the analysis. An assessment was also required of the difference in technology deployment between the new baseline and the baseline year used in the previous analysis of cars (TNO et al., 2011) and LCVs (TNO et al., 2012).

In order to establish this baseline this task was split into three components:

i. Identify datasets that can be used to develop the baseline
ii. Establish an appropriate vehicle segmentation
iii. Use the data sources and revised vehicle segmentation to develop a new baseline

The objective of the work was to provide the following outputs to be used in later project tasks:

- New LDV baseline for the cost-curve analysis
- Updated vehicle segmentation for cars and LCVs

The following subsections provide a detailed summary of our approach in each of each of these areas and conclusions for this project task.

2.2 Identification of datasets used to develop the baseline

Establishing a robust baseline that can be used for a reference point is a key requirement for ensuring that the analysis of the potential cost of CO_2 reduction is as accurate as possible. Over- or under-estimating the current levels of deployment of technologies will impact directly on the accuracy of any subsequent estimates of the costs and potential savings. By tracking the extent to which technologies are already present, we avoid double-counting of technology costs and benefits, as well as gaining a more detailed insight into possible uptake rates for use in projections of the fleet development.

Since the definition of the baseline and segmentation used for this study was fundamental to underpin the work to be carried out in later tasks, these aspects were defined at the start of the project, and agreed with the Commission.

Below is a brief summary of the main sources identified and used for the purposes of defining the baseline and segmentation of LDVs for this project. Of particular note, it was necessary to define the baseline characteristics (and indeed additional costs) of advanced xEV powertrains[6] separately using a more detailed methodology. This is described further in Section 2.4.2.

a) *The most recent versions of the car and van/LCV CO_2 monitoring databases:* the most recent databases available from the EEA's website (EEA, 2014) (EEA, 2014a) were the provisional 2013 databases;
b) *Updated datasets on the penetration of CO_2 reducing technology into the EU LDV Fleet:* updated data was sourced from IHS Automotive on the penetration of CO_2 reducing technology into the EU LDV fleet in 2002, 2010 and 2013;
c) *Information on the relative costs of CO_2 reducing technologies for different segments:* Information available in (FEV, 2013a) and other related reports by FEV for ICCT provides bottom-up estimates of the costs of CO_2 reducing technologies for a range of different car segments;
d) *Information to facilitate the estimation of baseline characteristics of advanced xEV powertrains:* Since the currently available xEV models are not fully representative of the average characteristics of the different vehicle segments it was necessary to gather additional information in order to estimate average baseline characteristics and assess the current default technology available in such models;

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[6] Advanced xEV powertrains are defined as PHEVs, REEVs, BEVs, FCEVs and FC-REEVs for the purposes of this study.

e) *Information available in from other analysis for DG CLIMA:* this included data provided in earlier CO_2 technology cost assessments in (TNO et al., 2011) and (TNO et al., 2012), as well as analysis conducted more recently by Ricardo-AEA *et al.* (2015) on downweighting of LDVs;

f) *Other assorted sources of supporting information and data*.

2.2.1 Cleaning the CO_2 monitoring databases

In order to effectively analyse and use the provisional 2013 car (EEA, 2014) and LCV (EEA, 2014a) CO_2 monitoring databases for the purposes of this project, it was necessary to apply extensive cleaning/corrections and develop methodologies to allocate the vast majority of available models (in terms of percentage of total registrations) to segments. This was a very time-consuming process and the following list provides a brief summary of some of the actions taken. A more detailed summary of the methodology used to clean the monitoring databases and assign models to different categories and segments is provided in Appendix 1.

- **Reduction in size (car only):** The car datasets are not organised efficiently: several entries - a total of 1.4 million rows across the four years - show only one registration. Single registrations (1.3% total) were removed to manage the database size to a manageable length for analysis.
- **Erroneous values:** Brand names were normalised across Member State entries where there was some variation to facilitate comparisons, and corrections made to erroneous values.
- **Allocating entries to models:** the field ‘Cn’ (commercial name[7]) includes ~30,000 different strings. It was not uncommon to find the field empty, or that it contained misspellings or unreadable fonts (as the spreadsheet was completed in various alphabets and included special characters). In many occasions, the make and model combination was a bad match (i.e. wrong make for the model). Corrections were applied where possible.
- **Allocating models to segments:**
  - *Car:* There is no definitive way of allocating vehicles to segments. In particular, the size boundaries between the A, B, C, and D-segment vehicles are not clear and there are differences of opinion regarding which segment a given vehicle falls into. In reality the range of models available on the market results in a continuous spectrum of vehicles, with models available at almost every length from 2.5 to 5 metres.
    The long term trend that a given model becomes larger each time it is updated further complicates the issue. For example, the 2012 Mercedes A-Class is almost 0.7 metres longer than the original 1997 version (a 20% increase), effectively moving it from B-segment to C-segment.
  - *LCV:* typical segmentation is carried out according to mass.
- **Erroneous values identification and amendment:** several entries present values which are not credible (e.g. mass below 300 kg or more than 50% difference with respect to model average). A number of routines were used to apply appropriate corrections.

2.3 Establishing an appropriate vehicle segmentation

The objective of this sub-task was to establish whether the currently used segmentation for cars and LCVs was still appropriate, or if an alternative was desirable for the purposes of this study and future supporting analysis in this area. It was agreed with the Commission at the project kick-off meeting that any updated vehicle segmentation needed to fulfil the following three key criteria:

1. Is the segmentation appropriate to sufficiently capture differences between costs and CO_2 reduction potential for different types of car and light commercial vehicles;
2. Can it be readily understood, can it be characterised using publically available datasets as far as possible;
3. Is it manageable and proportionate (i.e. did not unreasonably expand on the number of resulting cost-curves that would need to be developed).

The following sub-sections provide a summary of the background research and analysis used to define the final segmentation that was used in this project for passenger cars and LCVs.

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[7] http://www.eea.europa.eu/data-and-maps/data/co2-cars-emission/monitoring-of-co2-emissions-from

2.3.1 Segmentation for passenger cars

In Europe vehicle segments for passenger cars do not have any formal characterisation or regulations, instead they tend to be based on comparison to well-known brand models. In fact for most countries (with a few exceptions for countries with high quality of vehicle registration databases) there is no car market segmentation information available, from either central or national sources[8]. However, whilst there is no formal description (e.g. defined by specific objective criteria like engine size, dimensions or weight), there is a general European-level market segmentation that is used for passenger cars of at least nine categories:

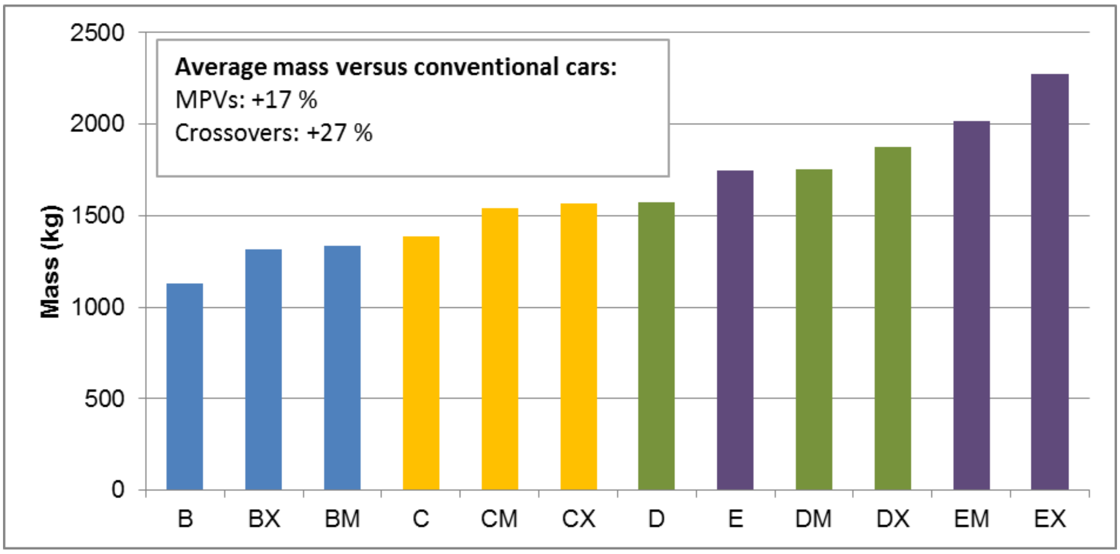
A: Mini cars
B: Small cars
C: Lower medium cars
D: Upper medium cars
E: Executive cars
F: Luxury cars
S: Sport coupés
M: Multi-purpose vehicles
J: Sport utility cars (including off-road vehicles)

Vehicles in the B, C and D categories account for by far the greatest proportion of the car fleet in the European Union (~82% of registrations according to our analysis of the 2013 CO_2 monitoring database), which has been used as a justification for using these segments as a basis for the small, medium and large car categories in previous analysis for the Commission (TNO et al., 2011).

However, over recent years there has been a significant rise in so-called cross-over vehicles and other new vehicle categories. The potential to use a more disaggregated level of segmentation was therefore explored for cars as part of the parallel study on vehicle mass reduction carried out for DG CLIMA (Ricardo-AEA et al, 2015) in order to better understand market trends in vehicle mass and likely future potential and costs of mass reduction. This aspect was particularly important for the consideration of mass reduction, as illustrated in Figure 2.1 below, and also has potentially important impacts on overall vehicle aerodynamics.

There are potentially also restrictions in the applicability of the results based on the previous 'small', 'medium', and 'large' passenger car segmentation for the higher-end executive, luxury and sports segments, and for larger SUVs and compact utility vehicles (CUVs). In such vehicles it is expected that there might be particular sensitivity to impacts on certain vehicle characteristics, performance and utility parameters that are harder to achieve/maintain with certain technology applications/combinations.

Figure 2.1: Average mass by segment as defined in the EC "Downweighting" study (Ricardo-AEA, 2015)



Notes: **-M= Multi-Purpose Vehicles (MPVs)** that can be allocated to a conventional class according to their size or to the model they relate to. For example, the Golf Plus is a medium size MPV related to the Volkswagen Golf,

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[8] 'Transport data collection supporting the quantitative analysis of measures relating to transport and climate change (TRACCS)', Final project report by Emissia, IVL Sweden and Infras for DG Climate Action, December 2013.

therefore allocated to CM. **-X = Crossovers** (also sometimes known as crossover utility vehicles - CUVs) that, as with MPVs, have been allocated to the segment according to their size or the base model they are derived from.

However, other than for mass reduction (and aerodynamics to a lesser degree), it is not anticipated that for other technological options there will be very significant differences between vehicles in conventional passenger car segments and those in the equivalent crossover and MPV segments. In contrast, there are strong reasons to expect greater similarities in other technologies (and their costs) within the ‘native’ segment to which the MPV or CUV sub-type belongs. Therefore, it was judged that it may be more appropriate to include such vehicles in their ‘native’ segment. On the other hand, it was considered more important to be able to distinguish the segments above the D-segment as these vehicles are all generally larger, heavier and more powerful than those in segments A-D, and are also predominantly more expensive higher-end/premium brand vehicles. This would also allow for keeping to a maximum of four segments for passenger cars, which was deemed the maximum practical number possible for the cost-curve analysis. Adding further categories would rapidly increase the number of possible cost-curve combinations to unmanageable numbers (see Section 8).

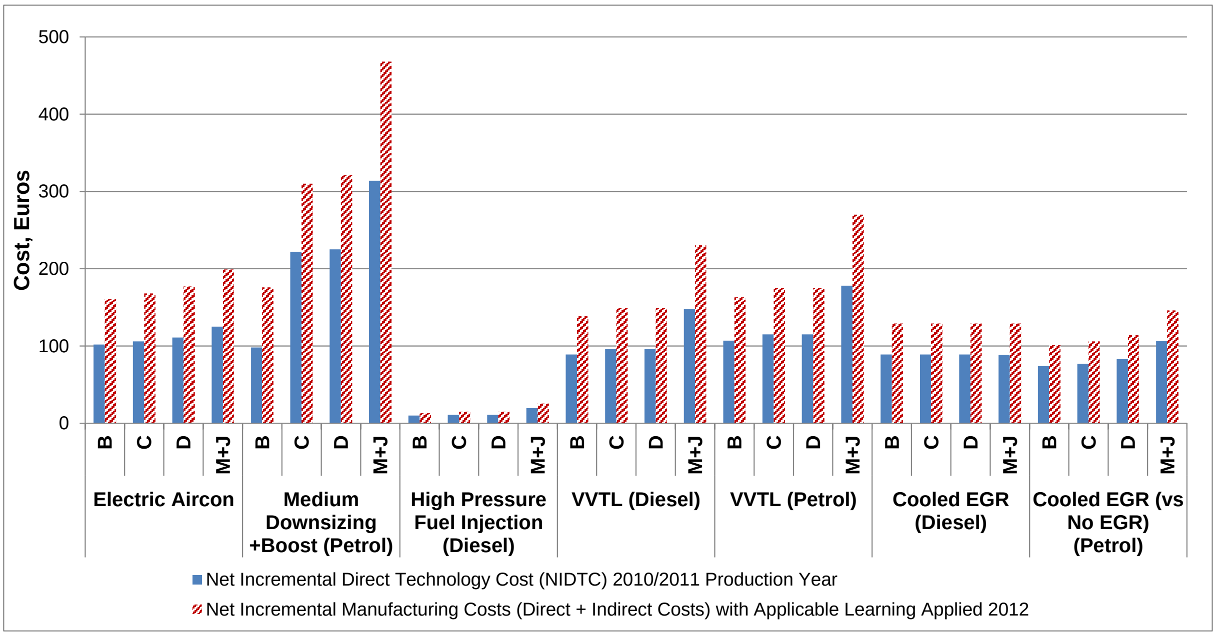
The indications from the information reviewed in the available literature also suggested that it was unlikely that significantly greater accuracy would result by expanding the number of segments significantly beyond current levels. This is because all available estimates to date for the alternative costs of CO_2 reducing technologies have used simple scaling factors to convert central estimates to different market segments. Any additional segments would require further assumptions to be made in this respect.

A further consideration was the consistency of the analysis resulting from this project with the segmentation that has been developed for modelling under the recently completed TRACCS project (Emisia, 2013), which provides the following segmentation, based on the first four of the five main categories also used in ACEA’s segmentation[9]:

- Small (corresponds broadly to A and B segments)
- Lower-Medium (C segment)
- Upper-Medium (D segment)
- Executive (E and F segments)
- Other (the remaining segments)

A review of (FEV, 2013a) and other related work by FEV for ICCT also showed that the costs for larger (than D) segment vehicles appear to have significantly higher technology costs (versus the differences between B, C and D) – as illustrated in Figure 2.2 below. It was concluded that this supported the proposal to split these out into a single separate segment.

Figure 2.2: Comparison of selected technology costs for different car segments



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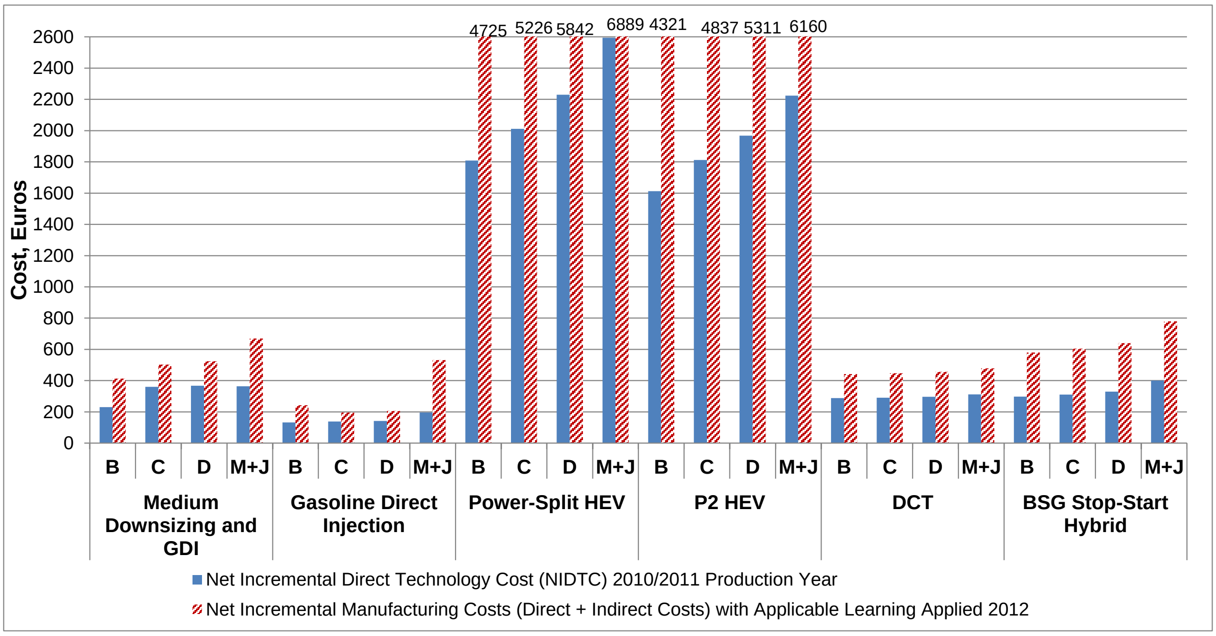
[9] http://www.acea.be/statistics/tag/category/segments-body-country



The final segmentation for cars is presented in Table 2.1 below, and is broadly comparable with that used/defined in the TRACCS project.

Table 2.1: Final segmentation for passenger cars

Segment	Description	Examples
Small [A+B]	Includes MPV and Cross-over vehicles based on A and B segment vehicles	Fiat 500, Smart Fortwo, Renault Twingo, Ford Fiesta, VW Polo, Opel Corsa, Peugeot 208, Toyota Yaris, Citroen C3
Lower Medium [C]	Includes MPV and Cross-over vehicles based on C segment vehicles	VW Golf, Ford Focus, Opel Astra, Nissan Qashqai, BMW 1-Series, Renault Megane, M-B A-Class, Renault Scenic
Upper Medium [D]	Includes MPV and Cross-over vehicles based on D segment vehicles	BMW 3-Series, VW Passat, Audi A4, M-B C-Class, Peugeot 508, BMW X3, Audi Q5, Ford Mondeo, Volvo XC60
Large [Others]	Includes vehicles from all other European car segments	M-B E-Class, BMW 5-Series, Audi A6, Volvo V70, VW Touareg, Porsche Cayenne, L-R Range Rover Sport

2.3.2 Segmentation for LCVs

For LCVs, in contrast to cars, there does not seem to be a compelling reason to increase the number of segments – particularly since, from a review of the CO_2 monitoring database, the market appears to be dominated by less than ten base models (comprising over 90% of sales). It could also potentially be argued that the smallest segment comprises vehicles that are so similar to passenger cars that it might not be significantly different enough to warrant a different cost-curve. [However, comparison with data on technology penetration (see Section 2.4.1.2), shows that there is a significant difference in the technology deployment levels and therefore the CO_2 reduction potential already taken compared to the average for equivalent sized cars].

Currently, the segmentation for light commercial vehicles is based on the N_1 'Class' defined by the vehicle's reference mass (unladen). However, it has been suggested that this current classification leaves particular models that are close to the boundaries prone to shifts between categories due to small net mass changes that do not fundamentally change the vehicles' utility basis for the marketplace. This is likely to be exacerbated in the future through application of technology - e.g. mass reduction measures, or the addition of heavier hybrid / electric technologies.

Therefore we investigated possible alternatives to this classification using the LCV CO_2 monitoring database to explore trends in Total Permitted Maximum Laden Mass (TPMLM), body type and payload capacity. The results of the analysis have been plotted in Figure 2.3 and Figure 2.4. Whilst the investigation of payload capacity yielded no obvious useful trends, the analysis suggests that segmentation using TPMLM may be a better alternative, as this metric should read across more directly to the vehicle's utility. Considering the charts below, there also already seems to be specific TPMLM points that are represented in the marketplace and a fairly natural break at around the 1.8-1.9 tonne and at 2.5 tonne mark that already corresponds quite well with the current N_1 'Class' categories, and also versus the previously identified car segments (i.e. car-derived vans or van-derived cars).

Figure 2.3: Share of new Van/LCV registrations by N1 vehicle class and total permitted maximum laden mass for 2013 and 2014

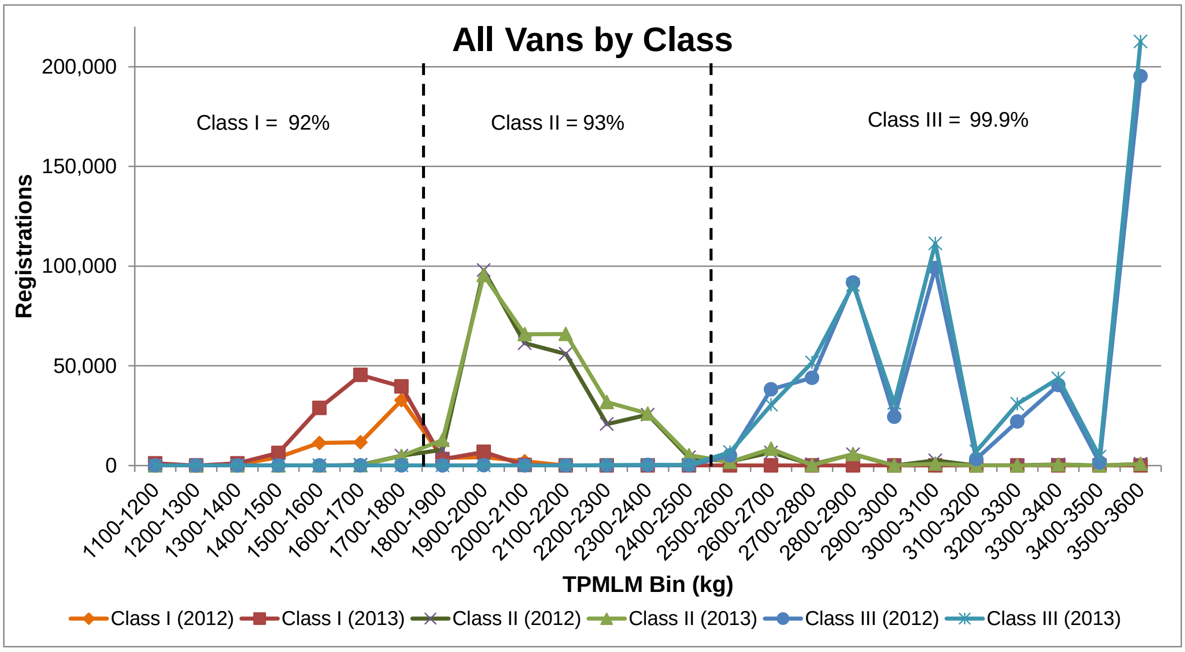
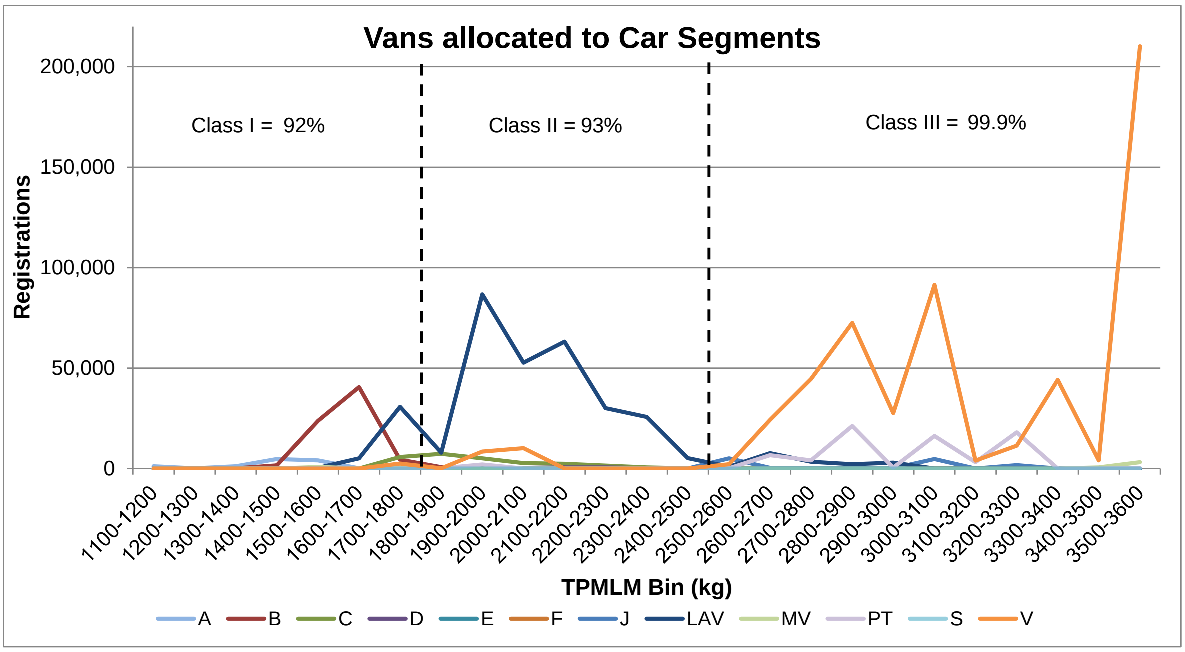


Figure 2.4: Share of new Van/LCV registrations by equivalent car segment and total permitted maximum laden mass for 2013



Notes: Allocation to car segments based on models identified as car-derived, or otherwise: LAV = 'Leisure Activity Vehicle', MV = Minivan style (e.g. small/lightweight like Piaggio), PT = 'Pick-up truck' style. V = traditional van.

The final recommended segmentation for LCVs that was agreed with DG CLIMA was therefore to use a segmentation based on TPMLM, and this is presented in Table 2.2 below.

Table 2.2: Final segmentation for light commercial vehicles

Segment	Definition	Examples
Small [<1.8t GVW]	Vehicles with a gross vehicle weight (GVW) / TPMLM less than 1.8 tonnes	Fiat Fiorino, Dacia Dokker Van, Peugeot Bipper, Citroen Nemo, Piaggio Porter, Fiat Qubo, Fiat Strada
Medium [1.8-<2.5t GVW]	Vehicles with a GVW / TPMLM of 1.8 to <2.5 tonnes	Citroen Berlingo, Renault Kangoo, VW Caddy Van, Peugeot Partner, Fiat Doblo, Toyota Hilux
Large [2.5-3.5t GVW]	Vehicles with a GVW / TPMLM of 2.5 to 3.5 tonnes	Ford Transit, M-B Sprinter, VW Transporter, Fiat Ducato, Renault Master, Iveco Daily, Opel Vivaro, M-B Vito

Notes: GVW = Gross Vehicle Weight, TPMLM = Total Permitted Maximum Laden Mass

2.3.2.1 Limitations

It has been noted that the 2013 CO_2 monitoring data for LCVs should be considered incomplete with regard to multi-stage vehicles. ACEA has indicated that these represent a significant proportion of registrations for certain segments (i.e. Class III) and certain manufacturers. There is therefore concern that their omission in monitoring data may have a notable impact on overall estimates. ACEA statistics (ACEA, 2015) for LCV registrations in 2013 show 1,376,859 vehicles, in comparison to 1,240,539 in the 2013 monitoring database, which may indicate up to 11% of all registrations may be missing from the 2013 monitoring database. It is assumed that a significant proportion of these may be multi-stage vehicles. However, without specific data on their characteristics it is difficult to say what level of impact this would have on the overall analysis.

2.4 Development of the new baseline

Using the information and analysis carried out, as summarised in the previous sections, we developed the new baseline for which the deployment of technology and its costs will be estimated. As indicated earlier, this baseline is based on the 2013 technology uptake from the available data.

In this section we provide a summary of the baseline with the level of take up of the full range of technologies quantified for each vehicle size/type category for the most recent year possible (i.e. 2013).

In order to establish the technology baseline for conventional vehicles (including hybrids) Ricardo Energy & Environment explored with the major data providers the availability of datasets/analysis to update the technology penetration analysis performed previously for the Commission and reported in (TNO et al., 2012a). This resulted in the purchase of an updated dataset from IHS Automotive in a similar format, but adding some additional technical options and providing data also for 2013.

This technology deployment was set out for petrol and diesel cars and LCVs and also by market segment. However, due to the terms of the contract with IHS Automotive, only the aggregated results are allowed to be shared in a public form. A summary of the analysis on this dataset is presented in the following Section 2.4.1 (with additional data tables in Appendix 1); the full dataset was also provided to the Commission together with the contractual terms for its internal use for this project.

Setting the baseline also includes the wider characteristics of the vehicles in the final car and LCV segments, which has been achieved via comparison to the most recently available CO_2 monitoring datasets (i.e. for 2013) in terms of CO_2 performance, power, and vehicle mass. As well as capturing historic improvements due to the deployment of technologies, this baseline should also intrinsically include non-specific technological improvements and benefits accrued due to test-cycle flexibilities to date. It will also include the impacts of the employment of additional changes to vehicle specifications required by other European legislation to date (e.g. on safety, daytime running lights, etc.).

Some validation of the baseline assumptions for technology uptake was also carried out with stakeholders in conjunction with the data collection and stakeholder engagement activities conducted (see Section 4).

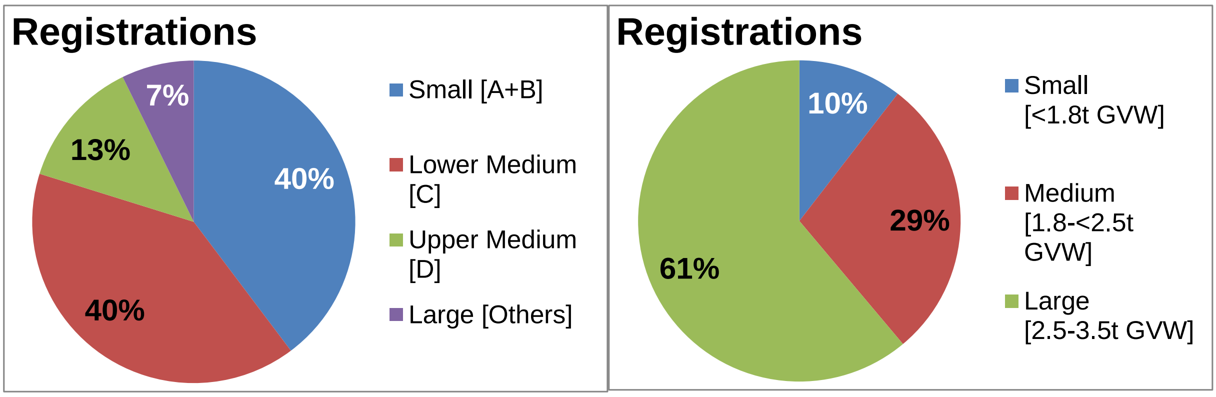
For plug-in electric vehicles (and forthcoming hydrogen fuel-cell electric vehicles) – all such vehicles are generally referred to as *'xEVs'* – Ricardo Energy & Environment conducted a separate analysis of the models currently available (and some important models pending imminent release) in order to establish baseline performance and technology specification.

2.4.1 Baseline for conventional vehicles

2.4.1.1 Baseline characteristics of conventional vehicles

Following the cleaning process and agreement with the Commission on the updated segmentation to be used in the analysis, the cleaned 2013 CO_2 monitoring databases were used to calculate the average baseline characteristics for the different segments and fuel types for this study. This included the respective numbers and shares of registrations (see Figure 2.5 and Table 2.3), as well as registration-weighted averages for vehicle footprint (in M^2) and vehicle unladen mass (in kg) (see Table 2.4), and for CO_2 emissions (in g/km) and peak power (in kW) (Table 2.5). These are all summarised in the following figure and tables.

Figure 2.5: Share of EU LDV registrations by segment in 2013



Passenger Cars **Light Commercial Vehicles**

Notes: Calculated from the provisional 2013 CO_2 monitoring databases for cars and LCVs.

Table 2.3: Number of vehicle registrations by fuel type and segment in 2013

	Registrations, #			Registrations, % Total		
Segment	**Petrol**	**Diesel**	**Total**	**Petrol**	**Diesel**	**Total P+D***
Small Car [A+B]	2,874,561	1,016,705	4,055,774	71%	25%	**96%**
Lower Medium Car [C]	1,432,868	2,519,168	3,999,939	36%	63%	**99%**
Upper Medium Car [D]	225,674	1,092,952	1,326,904	17%	82%	**99%**
Large Car [Others]	139,549	614,136	754,073	19%	81%	**100%**
Average Car	**4,672,652**	**5,242,961**	**10,136,690**	**46%**	**52%**	**98%**
Small LCV [<1.8t GVW]	12,574	110,548	**127,428**	10%	87%	**97%**
Medium LCV [1.8-<2.5t GVW]	8,639	306,649	**326,581**	3%	94%	**97%**
Large LCV [2.5-3.5t GVW]	2,009	684,778	**688,732**	0%	99%	**100%**
Average LCV	**23,222**	**1,101,975**	**1,142,741**	**2%**	**96%**	**98%**

Notes: Calculated from the provisional 2013 CO_2 monitoring databases for cars and LCVs. Totals are for registration records that could be allocated to a fuel and segment and are therefore not inclusive of all records.
* The remaining vehicles are mainly fuelled by LPG, gas, E85 or electric.

The results of this analysis have been used to inform a range of other calculations, including the development of the xEV baseline performance and costs (see Section 2.4.2 as well as later chapters), as well as for calibrating the PHEM simulation analysis of technology performance carried out by TU Graz (see Section 6). Finally, these parameters were also used to define the baseline/root of the cost-curves that were developed (see Section 8).

Table 2.4: Average Unladen Mass and Footprint by LDV segment in 2013

	Unladen Mass, kg			Footprint, m^2		
Segment	**Petrol**	**Diesel**	**Average**	**Petrol**	**Diesel**	**Average**
Small Car [A+B]	1,091	1,244	**1,132**	3.6	3.7	**3.6**
Lower Medium Car [C]	1,380	1,510	**1,463**	4.1	4.1	**4.1**
Upper Medium Car [D]	1,523	1,659	**1,636**	4.3	4.3	**4.3**
Large Car [Others]	1,582*	1,926	**1,862**	4.1	4.7	**4.6**
Average Car	**1,215**	**1,538**	**1,390**	**3.8**	**4.2**	**4.0**
Small LCV [<1.8t GVW]	1,091	1,191	**1,181**	3.6	3.7	**3.7**
Medium LCV [1.8-<2.5t GVW]	1,374	1,450	**1,450**	4.2	4.2	**4.2**
Large LCV [2.5-3.5t GVW]	1,863	2,023	**2,023**	4.5	5.7	**5.7**
Average LCV	**1,263**	**1,780**	**1,761**	**3.9**	**5.1**	**5.1**

Notes: Calculated from the provisional 2013 CO_2 monitoring databases for cars and LCVs.
* Discussion with ICCT has suggested that based on their dataset the average mass of large petrol cars should be between 1,700 and 1,800 kg.

Table 2.5: Average Peak Power and CO_2 emissions by LDV segment in 2013

	Peak Engine Power, kW			NEDC CO_2 emissions, g/km		
Segment	**Petrol**	**Diesel**	**Average**	**Petrol**	**Diesel**	**Average**
Small Car [A+B]	61	66	**62**	118.4	104.4	**114.5**
Lower Medium Car [C]	92	91	**91**	136.4	124.0	**128.5**
Upper Medium Car [D]	120	113	**114**	151.3	134.1	**137.0**
Large Car [Others]	183	143	**151**	181.7	162.3	**165.9**
Average Car	**78**	**96**	**87**	**127.4**	**126.8**	**126.8**
Small LCV [<1.8t GVW]	56	57	**57**	135.5	105.4	**109.4**
Medium LCV [1.8-<2.5t GVW]	72	68	**68**	154.8	135.4	**134.0**
Large LCV [2.5-3.5t GVW]	101	95	**95**	188.4	204.7	**204.6**
Average LCV	**66**	**83**	**83**	**147.2**	**175.4**	**173.8**

Notes: Calculated from the provisional 2013 CO_2 monitoring databases for cars and LCVs.

2.4.1.2 Baseline technology for conventional vehicles

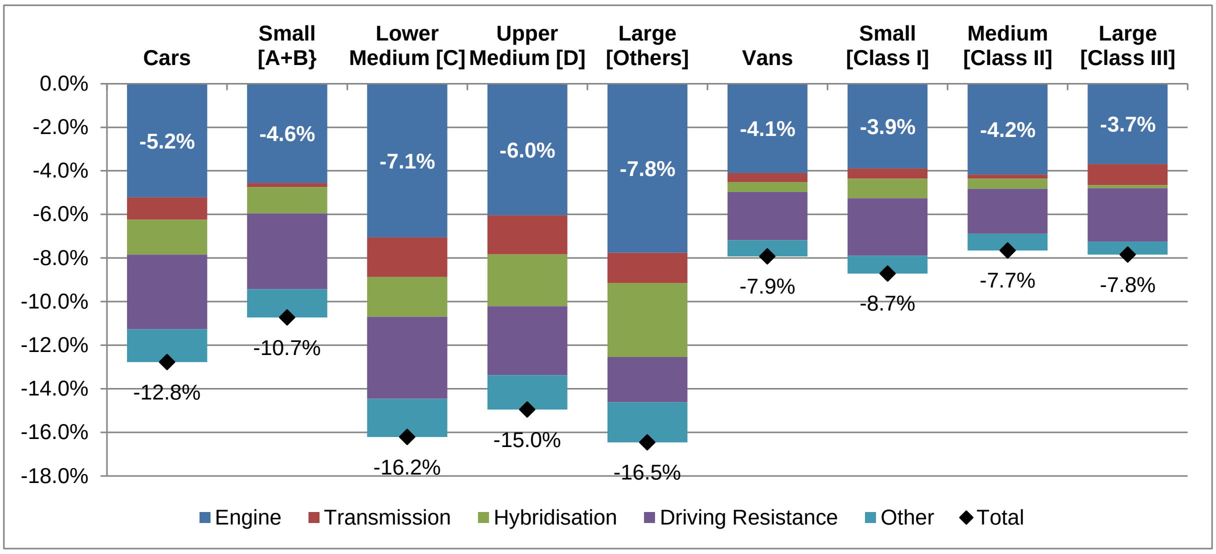
Besides defining the baseline characteristics of the vehicles, it is also important to be able to account for the degree to which CO_2 reducing technologies have been deployed in the current fleet.

There are two key considerations here: (1) accounting for deployed technology so that there is no double-counting in CO_2 savings potential and their corresponding costs; and (2) ensuring there is a clear reference against which the CO_2 savings for different technical measures can be compared.

In order to satisfy the first consideration, Ricardo Energy & Environment purchased a dataset from IHS Automotive that provided an update and expansion of previous analysis for the Commission (TNO et al., 2012a) in providing estimates of the penetration of CO_2 reducing technologies into the car and LCV fleet in 2002, 2010 and in 2013. The new analysis was split by vehicle segment, however only the aggregated data for all cars and for all LCVs (i.e. with no vehicle size-specific information) is allowed to be published in the public domain (see Appendix 1). Using this dataset, Ricardo Energy & Environment estimated the CO_2 savings due to the technology application between 2002 and 2013, which is summarised in Figure 2.6 and Figure 2.7 below. These figures show significant differences between segments in both the overall estimated CO_2 savings, and the degree to which different types of technologies are applied.

This dataset was used with the baseline CO_2 emissions calculated from the EEA CO_2 monitoring database (earlier Table 2.5) to calibrate the final cost-curves (see Section 8.1) to the 2013 situation (and also adjusted to a WLTP basis). In this way it was possible to capture the non-technology related improvements to CO_2 emissions, whilst at the same time avoiding double-counting savings due to different degrees of deployment of a range of the different technical measures for CO_2 reduction that were included in the cost-curves.

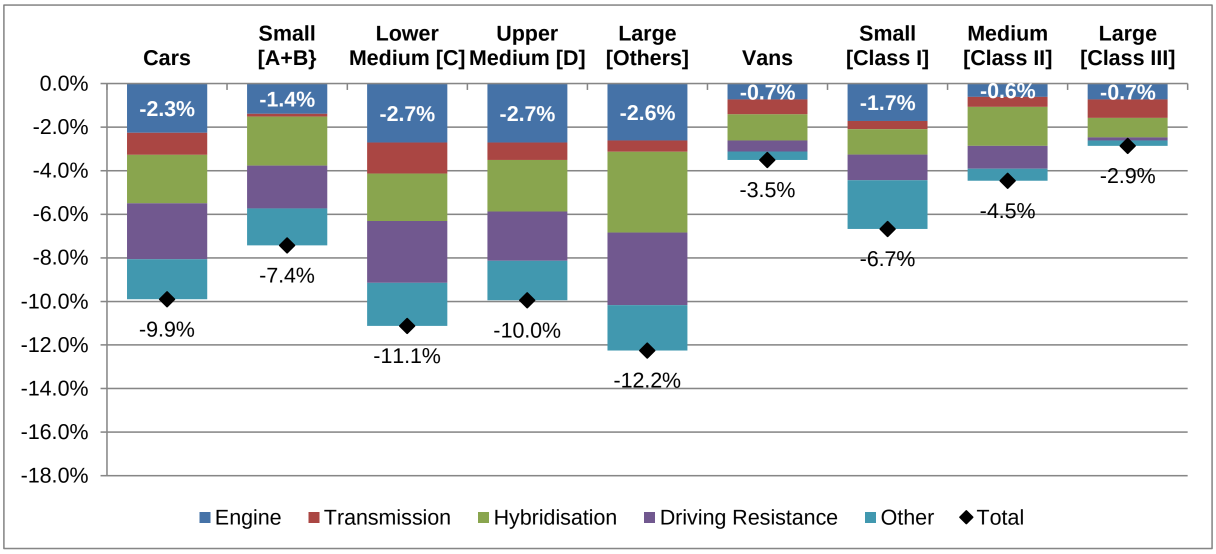
Figure 2.6: Comparison of estimated NEDC-based CO_2 savings from deployed technologies for petrol vehicles vs 2002



Source: Ricardo Energy & Environment analysis of data provided by IHS Automotive on technology penetration. Includes content supplied by IHS Automotive; Copyright © IHS Automotive, August 2014. All rights reserved.

Notes: The Ricardo Energy & Environment analysis used to derive the above chart uses the final assumptions on CO_2 reduction potential of technologies for 2015 based on the final analysis carried out in this study.

Figure 2.7: Comparison of estimated NEDC-based CO_2 savings from deployed technologies for diesel vehicles vs 2002



Source: Ricardo Energy & Environment analysis of data provided by IHS Automotive on technology penetration. Includes content supplied by IHS Automotive; Copyright © IHS Automotive, August 2014. All rights reserved.

Notes: The Ricardo Energy & Environment analysis used to derive the above chart uses the final assumptions on CO_2 reduction potential of technologies for 2015 based on the final analysis carried out in this study.

The second key consideration was to set a baseline technology configuration to which the CO_2 savings of the technologies being investigated could be compared. Since most technologies are only partially deployed (to a greater or lesser degree) in the 2013 fleet, it was necessary to set a baseline configuration that provided a consistent reference point excluding ALL the technical measures under consideration. Hence, in terms of some of the basic technology characteristics of petrol and diesel vehicles, these were set to be essentially unchanged since the previous report for cars (TNO et al., 2011) and LCVs (TNO et al., 2012) – as presented in Table 2.6. In reality, the average configuration in the 2013 fleet is somewhat different, with many engines with some degree of downsizing (sometimes with fewer cylinders) and direct-injection, start-stop, and many with transmissions with six or seven gears (and hence some degree of gear-ratio optimisation vs models in previous years). However, these are excluded from the baseline configuration so that the savings for the application of single technologies can be estimated correctly and consistently.

Table 2.6: Baseline technology for passenger cars

Baseline Technology	SI-Petrol			CI-Diesel		
	Engine layout	Fuel system	Gearbox	Engine layout	Fuel system	Gearbox
Small Car [A+B]	4 cylinder in-line	Multi point injection	5 speed manual	4 cylinder in-line	Common rail direct injection	5 speed manual
Lower Medium Car [C]	4 cylinder in-line	Multi point injection	5 speed manual	4 cylinder in-line	Common rail direct injection	5 speed manual
Upper Medium Car [D]	4/6 cylinder in-line	Multi point injection	5 speed manual (automatic)	4/6 cylinder in-line	Common rail direct injection	5 speed manual (automatic)
Large Car [Others]	4/6 cylinder in-line	Multi point injection	5 speed manual (automatic)	4/6 cylinder in-line	Common rail direct injection	5 speed manual (automatic)
Small LCV [<1.8t GVW]	4 cylinder in-line	Multi point injection	5 speed manual	4 cylinder in-line	Common rail direct injection	5 speed manual

Baseline Technology	SI-Petrol			CI-Diesel		
	Engine layout	Fuel system	Gearbox	Engine layout	Fuel system	Gearbox
Medium LCV [1.8-<2.5t GVW]	4 cylinder in-line	Multi point injection	5 speed manual	4 cylinder in-line	Common rail direct injection	5 speed manual
Large LCV [2.5-3.5t GVW]	4/6 cylinder in-line	Multi point injection	6 speed manual	4 cylinder in-line	Common rail direct injection	6 speed manual

2.4.2 Baseline for alternative powertrain types

The objective of the project was to develop an analysis that provided self-consistent and representative values for cost and CO_2 reducing performance for different vehicle segments and powertrain types. The situation for alternative powertrains is complicated by the fact that there are only relatively few models available in the marketplace. The characteristics (performance, specification, etc.) and costs of these models are therefore not directly representative of or comparable to the average vehicles in their market segments. For dedicated gas-fuelled vehicles, the situation should be relatively straightforward, in that the majority of the vehicle will/can be identical to a petrol-equivalent. However, the situation is more complex for advanced xEVs. For the purposes of this study, these are defined to include:

- PHEVs – Plug-in Hybrid Electric Vehicles;
- REEVs – Range Extended Electric Vehicles;
- BEVs – Battery Electric Vehicles;
- FCEVs – (Hydrogen) Fuel Cell Electric Vehicles;

For such powertrains, as their underlying baseline technology performance/specification improves, this can alter the performance and cost of the baseline vehicle in a more complex way. This is even before any of the additional energy/CO_2 reducing technologies that are also compatible with other vehicle powertrains are considered (e.g. driving resistance reduction technologies for all powertrain types, engine/transmission technologies for PHEVs and REEVs).

A particularly important example of this is that the costs (per kWh storage) and the energy density (in kg/kWh or litres/kWh) of batteries used in electric vehicles are expected to change significantly in the next 15 years, which will affect the underlying overall cost and efficiency of a ‘baseline’ vehicle. Not only that, but there are likely to be changes in other aspects of the market offering, like the electric range of such vehicles, which will affect both the mass (and therefore energy consumption) and cost of the vehicle.

In order to characterise such vehicles in a consistent way and account for such changes it was necessary to develop a more complex bottom-up analysis of these vehicle types. The methodology employed built upon that defined in previous work for the Commission (TNO et al., 2011), updating key datasets (e.g. assumptions on battery costs, electric range, etc.) and expanding the analysis in some areas (e.g. adding fuel cell electric vehicles, estimates for costs and performance of advanced battery chemistries).

Fundamentally the methodology allows for the estimation of the total system cost and net additional vehicle cost for different LDV vehicle segments and powertrain types. The following Table 2.7 provides a summary of the segments and powertrain types modelled using this approach, and a list of the system components included in the analysis. For each system component, an estimate of its cost and mass was used. In some cases these figures were fixed components that varied only according to vehicle segment; in other cases, system component costs were scaled/estimated via a more complex calculation depending on other vehicle characteristics (e.g. average power for the segment, desired electric range, etc.).

Table 2.7: Summary of the vehicle segments, powertrain types and system components included in the baseline xEV powertrain analysis

Segments	ICE system components	Other xEV system components
Small Car	Baseline Petrol Engine+Transmission	Wiring Harness
Lower Medium Car	Baseline Diesel Engine+Transmission	Regenerative Braking System
Upper Medium Car	PHEV Petrol Engine+Transmission	HVAC (standard / incl. heat pump)
Large Car	PHEV Diesel Engine+Transmission	Motor (body / in-wheel)
Small LCV	REEV Petrol Engine+Transmission	Inverter
Medium LCV	REEV Diesel Engine+Transmission	Boost converter
Large LCV	Baseline Petrol Aftertreatment	EV gearbox (single-/multi-speed)
Powertrains	Baseline Diesel Aftertreatment	Battery (Li-ion / Adv. chemistry)
Petrol PHEV	Fuel tank	Control unit
Diesel PHEV		On-board charger
Petrol REEV		Fuel cell stack
Diesel REEV		Fuel cell peripherals
BEV		Hydrogen storage
FCEV		
FC REEV		

A summary of the full data tables of assumptions on mass, cost, etc. for different xEV system components is provided in Appendix 2. This includes the initial time-series assumptions for how these components are projected to change, although the future cost estimates have now been superseded by the powertrain deployment scenario analysis carried out in the project (see Section 5.4).

In order to estimate the overall baseline energy consumption/ CO_2 emissions and costs of ‘average’ xEV powertrains, and how these are likely to change in the future (up to 2030), it was necessary to also consider a number of other key parameters, as summarised in Table 2.8 below.

Table 2.8: Summary of key parameters used to define the performance and costs of xEVs

Parameter	Description	Impact area
All-electric range	Driving range for which the vehicle can travel entirely on electricity from a full battery over the standard NEDC test-cycle	Cost, Mass, net MJ/km
% electric km	For PHEVs and REEVs what proportion of the vehicle’s operation is assumed to be in all-electric mode	net MJ/km
Available SOC (State Of Charge)	The percentage share of the battery that is available for all-electric operation (the remainder being reserved)	Cost, Mass, net MJ/km
Scaling for ICE	Maximum power rating of the ICE as a percentage of the maximum power of an equivalent performance conventional ICE vehicle	Cost, Mass, net MJ/km
Scaling for Motor	Maximum power rating of the motor as a percentage of the maximum power of an equivalent performance	Cost, Mass, net MJ/km

Parameter	Description	Impact area
	conventional ICE vehicle	
Scaling for Fuel Cell	Maximum power rating of the fuel cell as a percentage of the maximum power of an equivalent performance conventional ICE vehicle	Cost, Mass, net MJ/km
Scaling battery costs per kWh (vs BEV)	Scaling factor used to estimate the battery costs (in € per kWh) of different powertrain types, relative to those for a BEV, i.e. costs per kWh are higher for HEV, PHEV, etc.	Cost
% change in MJ/km for electric drive vs ICE	2013 baseline assumption for the percentage reduction in average energy consumption of the xEV powertrain type operating in full electric mode, relative to an equivalent conventional ICE.	Cost, Mass, net MJ/km
% change in MJ/km vs ICE (charge sustaining)	2013 baseline assumption for the percentage reduction in average energy consumption of the xEV powertrain type operating in electric charge sustaining mode (i.e. similar to HEV operation), relative to an equivalent conventional ICE.	net MJ/km
Hydrogen range	Range the vehicle can travel entirely on hydrogen from a full battery over the standard NEDC test-cycle.	Cost, Mass, net MJ/km

The assumptions for the values of the key parameters provided in Table 2.8 were based primarily on a number of key sources as follows, with tables of specific values provided in Appendix 2:

1. (TNO et al., 2011)*:* Used to define the initial assumptions for many of the parameters, with key assumptions updated using more recent data sources;
2. *Public data on xEV models in the marketplace:* Used to calibrate key parameters like ICE/engine/motor scaling, available SOC, electric range, performance of 2013 xEVs relative to conventional models in the marketplace, etc.
3. (Ricardo-AEA, 2013)*:* Updated estimates for current and anticipated future costs of batteries, fuel cell systems, hydrogen storage, etc.
4. (ACEA et al, 2014)*:* Current estimates for average xEV battery costs and specifications.
5. (JEC, 2013) *and* (JRC, 2011)*:* Various data on the costs and specifications of xEVs.

The public data on xEV models in the marketplace was also used to identify any baseline technologies applied as standard to current xEVs, and included information on the following models presented in Table 2.9. The information gathered on these different models was also used to sense-check the outputs of the bottom-up derivations of performance, mass and costs of baseline xEVs.

Table 2.9: xEVs models for which public information on performance and specifications were gathered

Powertrain	Models	Market Segment	Year
BEV Cars	BMW i3	B. Super Mini	2013
	Citroën C-Zero	A. Mini	2013
	Ford Focus Electric	C. Lower Medium	2013
	Mercedes-Benz B-Class Electric Drive	C. Lower Medium	2014
	Mercedes-Benz SLS AMG	S. Sports coupe	2013
	Mitsubishi i-MiEV	A. Mini	2013
	Nissan Leaf	C. Lower Medium	2013
	Peugeot iOn	A. Mini	2013
	Renault Fluence Z.E.	D. Upper Medium	2013
	Renault ZOE	B. Super Mini	2013
	Smart Fortwo Electric Drive coupe	A. Mini	2013
	Tesla Model S	F. Luxury Saloon	2013
	Th!nk City	A. Mini	2013
	Volkswagen e-Golf	C. Lower Medium	2013
	Volkswagen e-up!	A. Mini	2013
PHEV / REEV Cars	Audi A3 e-tron	C. Lower Medium	2014
	BMW i3 with range extender	B. Super Mini	2013
	BMW i8	S. Sports coupe	2013
	Mitsubishi Outlander GX3h PHEV	J. SUV / 4x4	2013
	Opel Ampera 'Positiv' EV	C. Lower Medium	2013
	Porsche Panamera S E-Hybrid	F. Luxury Saloon	2013
	Toyota Prius Plug-in Hybrid	C. Lower Medium	2013
	Volkswagen Golf GTE	C. Lower Medium	2014
	Volvo V60 Plug-in Hybrid	D. Upper Medium	2013
FCEVs	Honda FCX Clarity	D. Upper Medium	2013
	Hyundai Tuscon Fuel Cell	J. SUV / 4x4	2013
	Mercedes-Benz B-Class F-Cell	C. Lower Medium	2011
	Toyota Mirai	D. Upper Medium	2015
BEV LCVs	Citroën Berlingo Van Electric	N1 CL2	2013
	Mercedes-Benz Vito E-Cell	N1 CL3	2013
	Nissan e-NV200 Cargo Van Accenta	N1 CL2	2013
	Peugeot Partner Electric Van	N1 CL2	2013
	Piaggio Porter	N1 CL1	2013
	Renault Kangoo Van Z.E.	N1 CL2	2013

A summary of the final results of the estimated baseline performance and vehicle masses for the different powertrain types for lower medium cars are presented in Table 2.10 below. Similar results were also calculated for the different vehicle segments. A summary of the estimated mass breakdown of the PHEV, REEV, BEV and FCEV systems for 2013 lower medium cars is also presented in Figure 2.8.

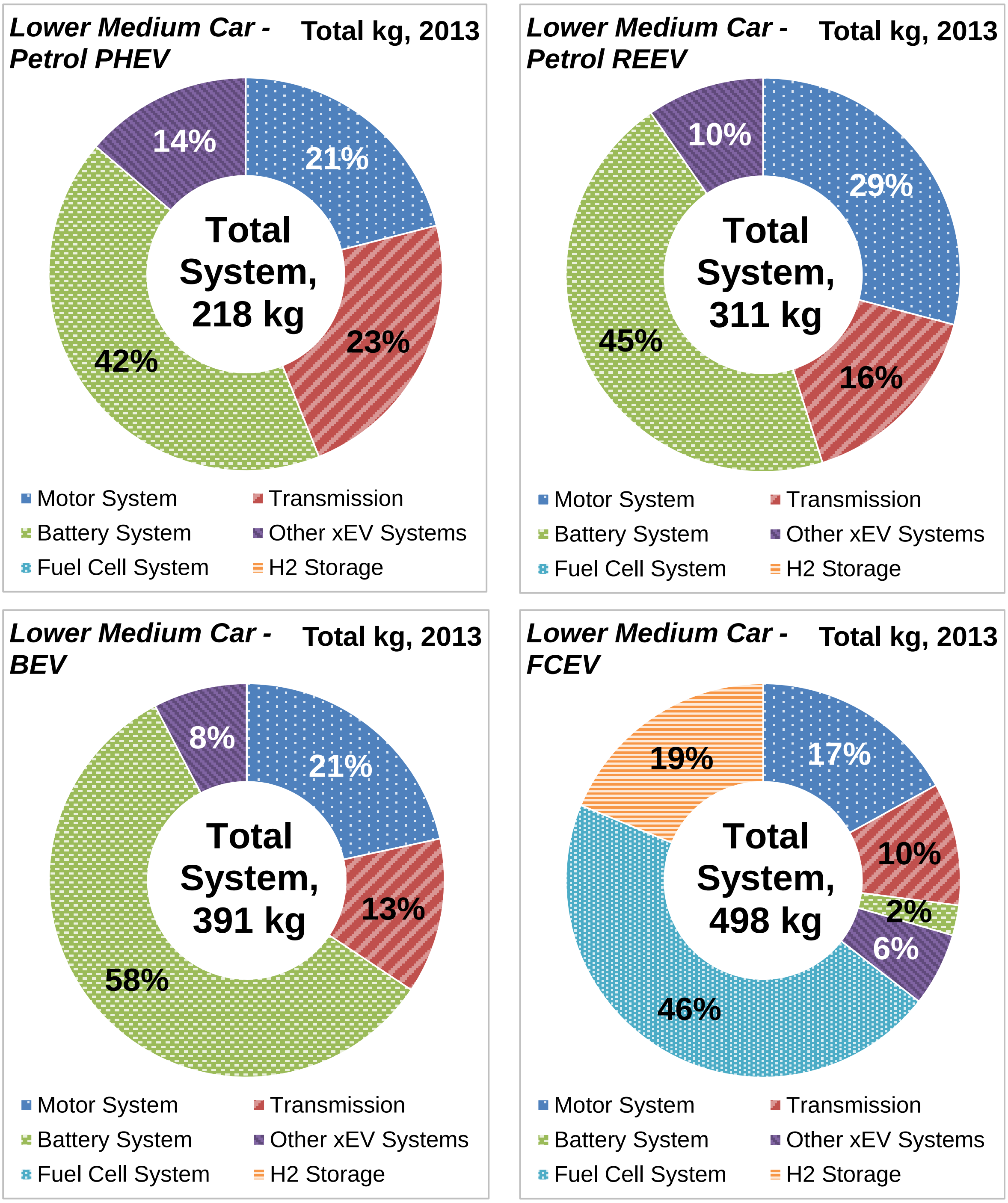
The analysis of xEV powertrain costs and energy/CO_2 reductions is further discussed in Section 4.5, with an exploration of the impact on total xEV costs of alternative powertrain deployment scenarios presented and discussed later in section 5.4.

Table 2.10: Baseline MJ/km and additional vehicle mass by xEV powertrain type for lower medium cars

Parameter	Powertrain	2013	2020	2025	2030
Electric NEDC MJ/km	Petrol PHEV	0.51	0.49	0.48	0.48
	Diesel PHEV	0.51	0.49	0.48	0.48
	Petrol REEV	0.49	0.46	0.45	0.45
	Diesel REEV	0.49	0.46	0.45	0.45
	BEV	0.42	0.41	0.40	0.39
	FCEV	0.49	0.45	0.45	0.44
Charge sustaining NEDC MJ/km	Petrol PHEV	1.37	1.31	1.29	1.28
	Diesel PHEV	1.22	1.16	1.15	1.14
	Petrol REEV	1.55	1.46	1.44	1.42
	Diesel REEV	1.37	1.29	1.27	1.26
	BEV	0.00	0.00	0.00	0.00
	FCEV	0.93	0.84	0.83	0.82
Overall NEDC MJ/km	**Petrol PHEV**	**0.80**	**0.76**	**0.75**	**0.74**
	Diesel PHEV	**0.74**	**0.71**	**0.70**	**0.70**
	Petrol REEV	**0.70**	**0.66**	**0.65**	**0.64**
	Diesel REEV	**0.66**	**0.63**	**0.62**	**0.61**
	BEV	**0.42**	**0.41**	**0.40**	**0.39**
	FCEV	**0.93**	**0.84**	**0.83**	**0.82**
Battery Size, kWh	Petrol PHEV	10.2	9.7	9.6	9.5
	Diesel PHEV	10.2	9.7	9.6	9.5
	Petrol REEV	15.5	14.6	14.4	14.3
	Diesel REEV	15.5	14.6	14.4	14.3
	BEV	24.9	37.4	39.0	40.9
	FCEV	1.4	1.3	1.2	1.2
Additional Vehicle Mass*, kg	Petrol PHEV	106	60	36	21
	Diesel PHEV	133	87	63	48
	Petrol REEV	210	140	103	81
	Diesel REEV	226	156	119	97
	BEV	134	122	48	7
	FCEV	241	127	99	72
Total Vehicle Mass, kg	**Petrol PHEV**	**1,569**	**1,523**	**1,498**	**1,483**
	Diesel PHEV	**1,596**	**1,550**	**1,525**	**1,511**
	Petrol REEV	**1,673**	**1,603**	**1,566**	**1,543**
	Diesel REEV	**1,689**	**1,619**	**1,582**	**1,560**
	BEV	**1,597**	**1,585**	**1,510**	**1,470**
	FCEV	**1,703**	**1,589**	**1,561**	**1,535**

Notes: * Relative to equivalent average conventional ICE vehicle.

Figure 2.8: 2013 Estimated xEV system breakdown by mass for Baseline 2013 Lower Medium Car



3 Producing a list of technologies to reduce LDV CO_2 emissions

3.1 Technologies reducing on-cycle CO_2 emissions

3.1.1 Overview of methodology for identifying technologies on-cycle CO_2 emissions

The objective of this task was to produce a list of technologies that could be used to reduce LDV CO_2 emissions under the official test cycle (anticipated to be the WLTP after 2020) in the period 2025 to 2030. These could be technologies that are currently available, or expected to be available in the near future, or those that have been proposed or are under development and could feasibly be introduced to the marketplace in this period.

This task was split into the following three components:

i. Review of existing list of technologies as applied in previous projects;
ii. Produce a list of existing or proposed technologies that could be used to reduce test cycle LDV CO_2 emissions in the period to 2025 to 2030;
iii. Finalise the list of on-cycle technologies to be taken forward in the analysis.

The following subsections provide a summary of the work carried out and findings from this task.

3.1.2 Summary of the work completed and results

The previous analyses of CO_2 reducing technologies for the Commission (e.g. (TNO et al., 2011), (TNO et al., 2012)) formed the starting point for the identification of relevant technologies for this project. However, in total, well over 300 individual sources were identified and reviewed in the process of identifying and gathering information on CO_2 reducing technologies for LDVs, in addition to information identified through the project's stakeholder engagement exercise. The data gathering and engagement processes are discussed in more detail later in Section 4.

Summaries of the final list of over 50 technologies are provided in Table 3.1 to Table 3.5 below. Technologies initially identified that were not taken forward are discussed in Section 3.1.2.1, together with the reasons for their final exclusion. More detailed descriptions of the individual technologies are provided in the Final Technology Results Fiche Excel Worksheet provided alongside this report, which also includes some market examples and a summary of their identified deployment in the marketplace where available (also discussed further in Section 7).

The Technology Results Data Fiche also provides technology compatibility tables that summarise the compatibility of different technologies (e.g. where they overlap / duplicate technology or effects) according to how they have been defined for this analysis. These tables also provide an indication of the compatibility/relevance of different technologies with different LDV segments and powertrain types.

Table 3.1: Final list of on-cycle engine technologies taken forward in the analysis

#	Description	Tech ID	Additional information
1	Dedicated Natural Gas Vehicle	CNG	Versus comparable petrol vehicle
2	Combustion improvements for SI engines: Level 1	G-WALL	Gas-wall heat transfer reduction
3	Combustion improvements for SI engines: Level 2	COMPR	Compression ratio increase due to continuous combustion chamber improvements
4	Combustion improvements for SI engines: Level 3	VCR	Variable compression ratio (VCR)
5	Combustion improvements for CI engines: Level 1	COMB1	Improvement of compression ratio, expansion ratio, combustion chamber architecture, injection timing, rate shaping, air: fuel ratio control, air/fuel mixing.
6	Combustion improvements for CI engines: Level 2	COMB2	Injection pressures: increased and individual management
7	Combustion improvements for CI engines: Level 3	VCR-D	Variable compression ratio (VCR)
8	Direct injection - homogeneous	DI-H	
9	Direct injection - stratified charge & lean burn	DI-SC	
10	Thermodynamic cycle improvements (a)	TCYCLE-A	Split cycle PCCI/HCCI/RCCI CAI
11	Thermodynamic cycle improvements (b)	TCYCLE-B	Efficient cycles (e.g. Atkinson, Miller, Liberalto)
12	Cylinder deactivation	CYLD	Via valve actuation or mechanical disconnection
13	Mild downsizing (15% cylinder content reduction) + boost	DS-MLD	Includes compensatory increase in boost
14	Medium downsizing (30% cylinder content reduction) + boost	DS-MED	Includes compensatory increase in boost
15	Strong downsizing (>=45% cylinder content reduction) + boost	DS-STG	Includes compensatory increase in boost
16	CI Mild downsizing (15% cylinder content reduction)	DS-MLD-D	Includes compensatory increase in boost
17	CI Medium downsizing (30% cylinder content reduction)	DS-MED-D	Includes potential cylinder deletion and increase in boost
18	CI Strong downsizing (>=45% cylinder content reduction)	DS-STG-D	Includes potential cylinder deletion and compensatory increase in boost
19	Cooled EGR for SI	C-EGR	Low pressure cooled EGR vs no EGR
20	Cooled EGR for CI	C-EGR-D	Low pressure cooled EGR vs uncooled EGR
21	Cam-phasing	CAM-P	Includes various types of VVT systems
22	Variable valve actuation and lift for SI	VVA	aka VVTL
23	Variable valve actuation and lift for CI	VVA-D	aka VVTL
24	Engine friction reduction: Level 1	E-FRIC1	Engine low friction design and materials for 20% reduction in engine friction
25	Engine friction reduction: Level 2	E-FRIC2	Advanced engine friction reduction for up to 40% total reduction in engine friction.

Table 3.2: Final list of on-cycle transmission technologies taken forward in the analysis

#	Description	Tech ID	Additional information
1	Improved Manual Transmission	IMP-MT	Minor improvements to current manual transmissions
2	Automated manual transmission (AMT)	AMT	
3	Dual clutch transmission (DCT)	DCT	
4	Continuously variable transmission (CVT)	CVT	
5	Optimising gearbox ratios / downspeeding	GEAR-R	
6	Further optimisation or gearbox increasing to 8+ gears	GEAR-R2	Increased number of gears for advanced automatic / dual clutch transmissions
7	Downspeeding via slip controlled clutch and DMF* removal	DSPD	
8	Multi-speed gearbox for xEVs	xEV-GEAR	

* DMF = Dual Mass Flywheel

Table 3.3: Final list of on-cycle driving resistance reduction technologies taken forward in the analysis

#	Description	Tech ID	Additional information
1	Mild mass reduction	WR-MLD	10% reduction from the whole vehicle
2	Medium mass reduction	WR-MED	20% reduction from the whole vehicle
3	Strong mass reduction	WR-STG	30% reduction from the whole vehicle
4	Aerodynamics improvement 1	AERO-1	Cd reduced by 10%
5	Aerodynamics improvement 2	AERO-2	Cd reduced by 20%
6	Low rolling resistance tyres 1	LRRT1	For an average 15% reduction in rolling resistance
7	Low rolling resistance tyres 2	LRRT2	For an average 30% reduction in rolling resistance (i.e. a further 15% on Level 1)
8	Reduced driveline friction 1	D-FRIC1	Mild reduction in losses to achieve ~20% friction reduction.
9	Reduced driveline friction 2	D-FRIC2	Up to 50% friction reduction using extreme measures.
10	Low drag brakes	LD-BRAKE	

Table 3.4: Final list of on-cycle hybridisation technologies taken forward in the analysis

#	Description	Tech ID	Additional information
1	Start-stop system	S-STOP	e.g. BSG, Enhanced starter, Direct starter, ISG
2	Micro hybrid - start-stop, plus regenerative braking	H-MCR	e.g. also new ultra-capacitor-based systems
3	Mild electric hybrid - torque boost for downsizing	H-MLD	e.g. 48V mild hybrids, Honda’s IMA system, etc.
4	Full electric hybrid - with limited full electric operation	H-FLL	Can operate electric drive for short distances, e.g. power-split hybrid, P2 hybrid.
5	Air hybrid	H-AIR	e.g. as developed by PSA and Bosch
6	Flywheel hybrid	H-FLY	e.g. KERS system

Table 3.5: Final list of other on-cycle technologies taken forward in the analysis

#	Description	Tech ID	Additional information
1	Thermal management	T-MAN	
2	Thermo-electric waste heat recovery	WHR-TELEC	
3	Secondary heat recovery cycle	WHR-CYCL	i.e. organic rankine cycle (ORC)
4	Kinetic waste energy recovery	WHR-BAT	e.g. TIGERS (Turbogenerator Integrated Gas Energy Recovery System)
5	Auxiliary systems efficiency improvement	AUX-CAR	General electrification of engine accessories, efficient water pump, etc. Combines thermal/other/EPS improvements and includes a move to 48V for later periods.
6	Auxiliary (thermal) systems improvement	AUX-THERM	Thermal: Coolant, oil pump, valve, thermostat
7	Auxiliary (other) systems improvement	AUX-OTHER	Other: Lubrication (variable / electric pump), vacuum (variable / electric pump), FIE
8	Electrical assisted steering (EPS, EPHS)	EAS	

3.1.2.1 On-cycle technologies not taken forward in the final analysis

A number of possible additional on-cycle technologies were identified during the project, but were excluded from the final list taken forward in the cost-curve development. These options and the reasons for their exclusion are summarised in Table 3.6 below.

Table 3.6: Other on-cycle technologies not taken forward in the analysis

Technologies	Reason for exclusion
Micro CNG turbine	No information could be identified on the potential costs nor CO_2 benefits of this option.
VVT and VVL	Variable valve timing and variable valve lift technologies are covered/included within other separately defined technology groups (i.e. cam-phasing and VVA).
Steer-by-wire and brake-by-wire	It was theorised that the future use of steer-by-wire or brake-by-wire systems may lead to the possibility of mass reduction and therefore improved fuel efficiency. However, no information has been identified on either the costs or possible weight/fuel consumptions savings.
In-wheel motors for xEVs	Information from public sources suggested initially that additional mass/CO_2 savings and cost-reductions might be achieved through the use of in-wheel motors for advanced xEVs (mainly BEVs, REEVs and possibly also FCEVs). However, feedback from the stakeholder consultation suggested that such benefits were likely not unique to this technical solution and were more a function of the sophistication of the current available systems. These were not split out as a separate technology for xEVs therefore.
Various xEV improvements	Various options for xEVs, including drivetrain improvements, reduced battery mass and battery system improvements were included separately within the xEV analysis.

Technologies	Reason for exclusion
Embedded wireless charging infrastructure	Should widespread adoption of wireless charging embedded in major roads become a reality, this could lead to the significant down-sizing of electric vehicle batteries for reduced costs and mass/energy consumption. However, the infrastructure costs would be likely to be very high and it was also judged wireless in-road charging was not to be likely implemented to a sufficient degree by 2030 to enable these battery size reductions.
Liquid air engine for waste heat recovery	No information could be identified on the potential cost of this option, and the costs of other measures with similar impacts were also already available.
Various NO_x control technologies	It was initially thought that there may be room for optimisations of engine fuel consumption by allowing the increase of engine-out NO_x emissions, which could be controlled using various aftertreatment technologies (i.e. NO_x catalysts/traps or SCR) to keep tailpipe emissions within the regulatory limits. However, after an initial review and discussion with internal and external experts early on in the project, it was judged that such technologies would be needed mainly to achieve the likely future RDE (real-world driving emission) testing requirements later in the decade, and in-use testing to ensure compliance with air quality pollutant limits set in the regulations. Further investigation of these technologies was therefore halted at this stage in favour of investigating more promising options.

3.2 Technologies reducing off-cycle CO_2 emissions

3.2.1 Overview of methodology for identifying technologies off-cycle CO_2 emissions

In addition to factors (and technologies) that can affect CO_2 impacts measurable under the standard test-cycles, there are also a range of factors (and technologies) that affect the so-called ‘real-world’ CO_2 performance of LDVs, for example the use of standard auxiliary equipment/loads that is not activated or captured (such as heating, ventilation and air-conditioning systems (HVAC), full headlights and power steering).

Off-cycle emissions can be controlled through the use of so-called ‘eco-innovations’, which have been provided for in the Regulations to allow for innovation in reducing ‘real-world’ CO_2 in areas that are not captured under the official testing protocol. The objective of this task was therefore to identify/develop a list of such technologies that can potentially reduce off-cycle CO_2 emissions for application up to 2030, and complements the development of the list of technical options to reduce on-cycle CO_2 emissions.

This task was split into the following two stages:

i. Identification of a list of existing or proposed eco-innovation technologies;
ii. Finalise the list of technologies to reduce off-cycle CO_2 to be taken forward in the analysis.

The following subsections provide summary of the work carried out and findings from this task.

3.2.2 Summary of the work completed and results

As for on-cycle technologies, the work completed involved an extensive review of publically available literature and information collected as part of the stakeholder engagement activities (discussed further in Section 4). The main starting point for the information gathering included a review of those technologies already granted ‘eco-innovation’ status for the purposes of compliance with the CO_2 Regulations for LDVs, and also those technologies identified in the work informing the US CAFE regulations (NHTSA, 2010) and (NHTSA, 2012).

Summaries of the final list of off-cycle technologies are provided in Table 3.7 below. Technologies initially identified that were in the end not taken forward are discussed in Section 3.2.2.1, together with the reasons for their final exclusion. As for the on-cycle technologies, more detailed descriptions of the individual technologies are provided in the Technology Results Data Fiche provided alongside this report.

This MS Excel workbook also provides technology compatibility tables that summarise the compatibility of different technologies with each other, as well as providing an indication of the compatibility/relevance of different technologies with different LDV segments and powertrains types, where appropriate.

Table 3.7: Final list of off-cycle technologies taken forward in the analysis

#	Description	Tech ID	Additional information
1	LED lighting	LED	
2	Solar roofs - cooling	SOLAR-C	e.g. as available as add-on for Toyota Prius
3	Solar roofs - battery charging	SOLAR-B	
4	Heat storage	HEAT-STOR	Off-cycle benefits of thermal management
5	Engine compartment encapsulation	ENG-ENCAP*	
6	Radar adaptive braking for energy recuperation	BAT-RDR	e.g. Tesla system, also used on Mercedes
7	High efficiency alternator	EFF-ALT	Intelligent alternator (variable output), high efficiency alternator
8	Improved MAC systems	IMP-MAC	
9	Improved HVAC - heat pump	REFL-PAINT	
10	Improved HVAC - heat pump	HP-HVAC	Mainly for EVs, PHEVs, FCEVs.
11	Cold storage evaporator	COLD-STOR	Allows air conditioning to function in engine idle-stop state.
12	Active seat ventilation	ACT-SEATV	
13	Localised air conditioning	LOCAL-AC	
14	Advanced cruise control	ADV-CC	Includes a range of types of adaptive cruise control.
15	Solar control glazing	GLAZE	
16	Eco-roll / coasting functionality	CST	e.g. via cruise-control, advanced start-stop
17	Active engine and transmission warm-up	ACT-WARMUP*	
18	Active aerodynamics 1 (for 3-5% drag / Cd improvement)	ACT-AERO-1*	e.g. active grill shutters, active wheel covers and active ride height control.
19	Tyre pressure monitoring systems (TPMS)	TPMS	Mandatory on all new LDVs since 2014
20	Fuel quality sensor	FQS	Allows optimisation of engine to changes in fuel quality to reduce air pollutant emissions and fuel consumption.
21	Model based control of engine and/or aftertreatment systems	M-CONTROL	Real-time optimisation to take into account local conditions and driver behaviour.

Notes: * Later in the project these technologies were identified as predominantly having on-cycle CO_2 savings under WLTP, due to differences in the procedure versus NEDC.

3.2.2.1 Off-cycle technologies not taken forward in the final analysis

A number of possible additional off-cycle technologies were identified during the project, but were excluded from the final list taken forward in the cost-curve development. These options and the reasons for their exclusion are summarised in Table 3.8 below.

Table 3.8: Other off-cycle technologies not taken forward in the analysis

Technologies	Reason for exclusion
Solar reflective paint	Whilst some data on CO_2 savings was available based on work carried out for the EPA and NHTSA in the US, it was not possible to confirm European savings potential, nor the costs of this option. It was also not clear whether this technology would be applicable to all vehicles. It therefore had to be excluded from the final technology set for the cost-curve development.
Regenerative shock absorbers	Whilst some data on CO_2 savings was available based on work carried out for the EPA and NHTSA in the US, and by the JRC for Europe it was not possible to identify any cost estimates for the technology from the literature nor stakeholder consultation exercise.
Improved steering pump (reduces idling losses)	No information could be identified on the potential cost of improved efficiency steering pumps (i.e. above the cost for electric- or electro-hydraulic power steering).
Battery management via navigation system	No information could be identified on the potential costs or CO_2 benefits of this option.
Efficient-routing via sat-nav information	No information could be identified on the potential cost of this option, nor confirmation of the level of likely real-world benefits (which would depend on the average level of use of the system).
Active aerodynamics 2 (for another 3-5% drag / Cd improvement)	Whilst some estimates were developed for the costs of active grille shutters for the first level of active aerodynamics potential, no other cost information for other measures (such as active wheel shutters and active suspension height) could be identified.
GLOSA, Green-Light Optimal Speed Advisory	Whilst the on-board vehicle system itself was likely to be relatively inexpensive, benefits would be reliant on the development and wide roll-out of more expensive infrastructure. Because of this, and the lack of actual information on CO_2 benefits and on-board costs, the decision to not progress further with this option was made at an earlier stage of the project.
Automated vehicles	No information could be identified on the likely costs or resulting CO_2 benefits of this option.

4 Gathering and reviewing evidence on the costs and performance of CO_2 reducing technologies

4.1 Overview of methodology for gathering and reviewing evidence on CO_2 reducing technologies

The following chapter provides a summary of the gathering and reviewing of evidence on the costs and performance of CO_2 reducing technologies. The Commission's specification for this project included a number of interrelated tasks focused on the topic of cost and CO_2 performance data for technologies that can be used to reduce emissions from passenger cars and LCVs. There was as a result a very high level of feedback between various tasks and sub-tasks to be completed for the project. The work described here has therefore been used as a basis to establish a robust evidence base, discussed further in this report chapter, in order feed into the estimate the CO_2 reduction benefits costs of **mass deployment** of the identified technologies, which is discussed in later report sections (6 and 7). Subsequent tasks refined these initial estimates into a form that was suitable for generating the cost curves (see later Section 8).

In order to achieve the objectives of the project a rigorous data collection, review and validation strategy was applied to ensure robust estimates were developed that could be used for future policy analysis. In order to achieve this, we used a multi-step process that included the following elements:

i. Literature review (Section 4.2);
ii. Incorporating/adapting the findings of the SR1 "Downweighting" study (Section 4.3);
iii. Development of vehicle technology fiches (Section 4.4);
iv. Development of estimates for the future CO_2 reduction potential and costs of xEV powertrains (Section 4.5)
v. Stakeholder engagement (Sections 4.6 to 4.8)

The following sections provide a summary the results of this work.

4.2 Literature review

An extensive literature review was conducted as part of this study which was an important first step in analysing the costs of the different types of vehicle technologies.

Whilst we were already aware of much of the literature in this area, we carried out a robust and comprehensive further search for literature sources, calling on the expertise and experience of all the consortium members. Given that a key focus of this project was to update and improve the existing cost estimates that were developed in 2011/12 as part of the TNO-led analysis for cars (TNO et al., 2011) and LCVs (TNO et al., 2012), it was also important to collate data from the most recent studies available that were not considered by these studies.

In the process of identifying, reviewing and collating data for the technical options identified in earlier tasks (see Section 3), data from over 200 individual sources were collated. However, the number of sources considered/reviewed during the process that did not yield specific cost or CO_2 data was even higher than this.

The following

Table 4**.1** provides a selection of some of key sources that have been reviewed as part of this project, in addition to the previous analysis performed for DG CLIMA (TNO et al., 2011) (TNO et al., 2012). Summaries of the studies of particular significance to our analysis, and how they deal with the key elements covered by this project, are presented in the following report subsections 4.2.1 to 4.2.5.

Table 4.1: Key literature reviewed

Author/ Year	Title	Brief description of content
FEV (2009)	EPA Light-Duty Technology Cost Analysis Pilot Study	Study commissioned by the US EPA performing a teardown of a passenger car in order to develop cost estimates of the components and fuel-saving component redesigns.
(FEV, 2013a) and (FEV, 2012)	Light-Duty Vehicle Technology Cost Analysis – European Vehicle Market (Phases 1 and 2)	Adaptation of the FEV 2009 study to European conditions; study commissioned by ICCT
(EPA & NHTSA, 2012)	Joint Final Technical Support Document: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards	Document outlining EPA's and NHTSA's approach for estimating vehicle technologies and costs as input towards the light-duty vehicle standards legislation for the model years 2012-2016.
ICCT (2012)	Summary of the EU cost curve development methodology	Combines the results from the fuel/GHG savings assessment from Ricardo 2012 with the FEV 2012 cost analysis. Based on these, the study computes cost curves for various vehicle segments.
(NRC, 2011) and (NRC, 2002)	Assessment of Fuel Economy Technologies for Light-Duty Vehicles. Committee on the Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy, National Research Council.	US Government tasked the National Research Council with a study to evaluate the effectiveness and impacts of the CAFE standards in 2001, which resulted in the first report in 2002. A cost-effectiveness analysis for new fuel saving technologies was carried out as part of the work. The NRC subsequently updated their analysis in a later report in 2011.
(IKA, 2012)	CO_2-Reduzierungspotentiale bei Pkw bis 2020	Study for the German Federal Ministry of Economic Affairs compiling data (sources include TNO et al. 2011, Mock 2010, FEV 2012, Ricardo 2012) to generate a table of costs, fuel savings and mass changes from each technology for three vehicle segments. These are then combined into technology packages. Based on the technology package costs and other developments baseline, optimistic and pessimistic scenarios for market share are calculated.

Author/ Year	Title	Brief description of content
(IKA, 2014)	CO_2-Emissionsreduktion bei Pkw und leichten Nutzfahrzeugen nach 2020. Study for BMWi.	Updated analysis by IKA considering technologies and developing cost curves for the post-2020 situation.
FEV (2012)	Light-Duty Vehicle Mass Reduction and Cost Analysis – Midsize Crossover Utility Vehicle	Study commissioned by the US EPA performing a teardown of a passenger car to specifically assess the potentials and costs for vehicle lightweighting. We have drawn upon our previous analysis of this report undertaken within our LDV downweighting study for DG CLIMA.
FEV (various)	Light-duty technology cost analysis, various technologies	Series of reports for the US EPA on Mild Hybrid and Valvetrain Technology, Advanced 8-Speed Transmissions, and Power-Split and P2 HEV Case Studies (2011-2013)
(FEV, 2014)	P2 Hybrid Electrification System Cost Reduction Potential Constructed on Original Cost Assessment	Downward revision of P2 hybrid system cost over FEV 2012 based on recent industry developments including improved design of case, launch clutch, coolant motor, and oil pump system. Such examples of revised cost estimates over short periods through improved design (rather than increased quantities produced) were taken into consideration when developing scenarios for longer term technology costs.

Notes: A complete list of the sources used to provide inputs to the cost and CO_2 dataset is provided in the accompanying technology fiche file.

4.2.1 TNO et al. (2006, 2011 & 2012)

4.2.1.1 General overview

These studies were carried out on behalf of the European Commission. The 2006 study focuses on the time horizon up to 2015, estimating the costs of reducing fleet average CO_2 emissions as part of the Commission's strategy at the time of achieving 120g CO_2 per km in 2012. The 2011 study focuses on the costs of meeting the 95 gCO_2/km target by 2020 and the implications of different strategies of effort-splitting between manufacturers based on different utility parameter designs. The 2012 study uses the same methodology to develop a largely analogous investigation into the feasibility of the 147 gCO_2/km target for LCVs for 2020. This summary concentrates on the general assessment of the costs of CO_2 reduction technologies used in the studies.

4.2.1.2 Segmentation

In TNO *et al*. 2006 and 2011, passenger cars have been divided into three segments: small, medium and large, where small covers the A and B segments, medium covers the C-segment, and large coves all segments above the C segment. For each segment and fuel type (petrol and diesel) a baseline vehicle without any fuel savings technologies is defined. The baseline corresponds to a typical 2002 vehicle.

In TNO et al. (2012), the standard European segmentation for LCVs by kerb weight category is used:

- Group I – kerb weight less than 1,305 kg
- Group II – kerb weight between 1,305 and 1,760 kg
- Group III – kerb weight above 1,760 kg

A 2010 baseline is used to create one representative vehicle for each LCV segment.

4.2.1.3 Technology coverage

The 2011 passenger car study identifies ten engine options, four transmission options, four hybridisation options, seven technologies for reducing tractive effort including three levels of lightweighting and four miscellaneous measures, making a total of 29 options. Only five engine options are applicable to diesel vehicles, so the diesel car technology list is shortened to 24 accordingly.

In the earlier 2006 study 27 similar options were identified. As explained in the 2011 study, these options were extended to include options which had become available in the meantime or were expected to become available in the time horizon up to 2020.

A separate chapter covers electric vehicles, developing cost and emission estimates for BEVs, PHEVs and REEVs in the three different segments.

The LCV study includes 30 technology options in its list, including a BEV and REEV option. The latter are, however, not included in the cost curve analysis. As in the car studies, plug-in electric drivetrains are discussed in a separate chapter.

All studies provide estimates of additional manufacturing costs and percentage CO_2 savings from each technology option.

4.2.1.4 Methodology for developing cost and CO_2 estimates

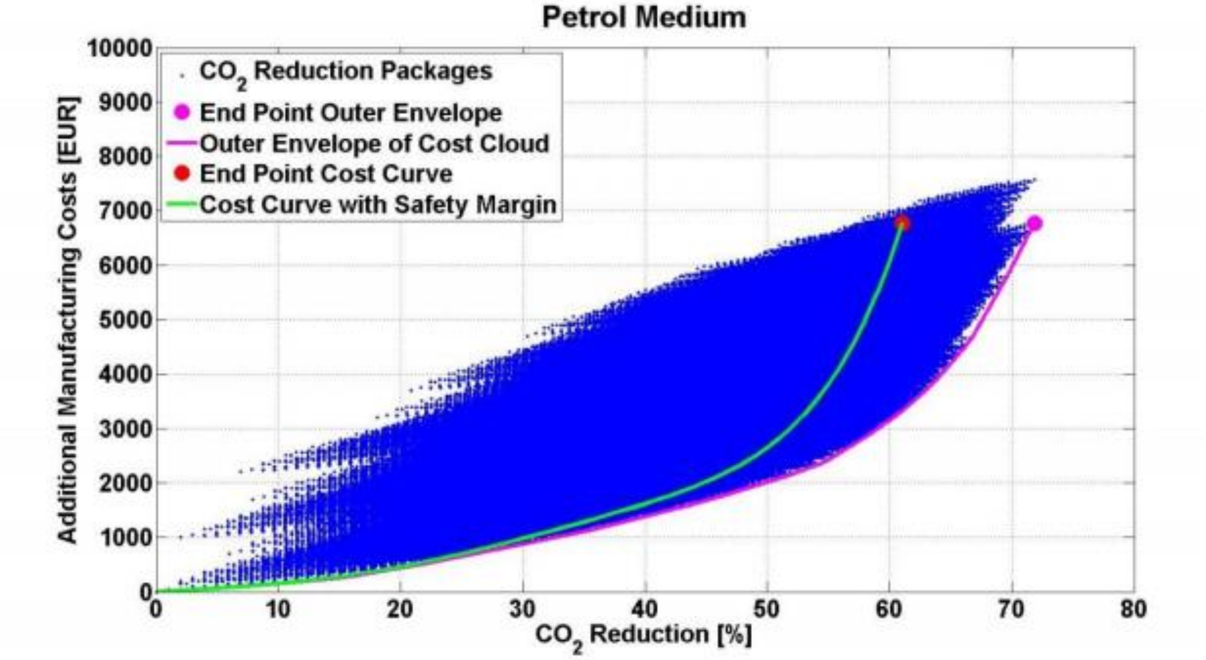
TNO *et al*. (2006) provides a summary of the literature reviewed on technology costs and CO_2 savings. This was complemented by a questionnaire sent to industry stakeholders (ACEA, CLEPA, etc.), some of which provided further quantified confidential input. Both inputs were used to create the final estimates used for the calculations. For the estimates in the 2011 study another literature review and stakeholder consultation were undertaken according to the same procedure.

Learning effects are only indirectly accounted for: cost estimations were based on survey results stemming from questionnaires sent out to industry stakeholders that were requested to take account of expected economies of scale and learning effects consistent with the assumption of large scale application. In the 2006 study the target period was 2008-2012, and in the 2011 study the target year given was 2020. TNO *et al*.'s equivalent study on light commercial vehicles (TNO et al., 2012) acknowledged that there can even be step changes in the cost of production as the amount produced increases. However, due to the large number of options and packages of various options, learning was not addressed in detail.

The 2006 study establishes an average translation factor between marginal manufacturer costs ('ex-factory' costs) for new emission reduction technologies and marginal retail price of 1.16 for passenger cars. This factor includes a 'manufacturing profit' – a mark-up of 0.05 – as well as dealer costs and profit – a mark-up of 0.11. Adding VAT results in a total mark-up of 1.44. The analysis does not, however, specify if the developed factor accounts for marginal indirect manufacturing costs other than the ones specifically mentioned, or whether these are already comprised in the marginal manufacturing costs. Direct and indirect manufacturing costs are not separated as such throughout the analysis. TNO *et al*.'s more recent studies in support of the confirmation of the 2020 targets, respectively for cars (TNO et al., 2011) and LCVs (TNO et al., 2012) follow this approach but apply slightly different mark-up factors for estimating retail prices depending on whether taxes and/or manufacturing profits are included. Again, direct and indirect manufacturing costs are not explicitly defined in the analyses.

In the next step, cost curves are created. These curves describe the least cost combinations of fuel saving technologies to achieve a given amount of CO_2 reduction. Incompatible technologies (e.g. it is impossible to apply level 1 downsizing and level 2 downsizing together) are excluded. In order to account for the risk of over-estimating fuel savings (e.g. by adding together the fuel savings from a technology that improves engine efficiency at part-load operation and another that reduces such part-load operation) a correction factor of 0.85 for petrol technologies and 0.95 for diesel technologies is introduced, reducing the fuel savings achieved by 15% and 5%, respectively, for the technology combinations with the highest levels of CO_2 saving. The correction factor is linearly reduced from 0.85/0.95 at the end of the curve, to 1 at the origin as the level of CO_2 savings of the technology combinations is reduced (see Figure 4.1).

Figure 4.1: Illustrative example of a cost curve (TNO et al., 2011)



TNO *et al*. (2011) features a section comparing the results of its cost curves to those of TNO *et al*. (2006). It is found that manufacturing costs for achieving a given level of abatement on petrol vehicles were estimated around 40%-80% higher in the 2006 study. For diesel vehicles, the earlier estimates were some 150%-200% higher. Note that some cost reduction should be expected, as the 2006 study estimated figures for 2008-2012 whereas the 2011 study estimated figures for 2020. However, TNO *et al*. (2011) still suggest that learning effects may be faster than anticipated: *"[T]he estimated costs for the application of available technologies at maturity are already lower than previously expected and could be expected to become lower over time."*

In TNO *et al*. (2011) a separate chapter develops cost and emission estimates for electric vehicles, including BEVs, PHEVs and EREVs in the three different segments, which have not been included in the above cost curves.

In the 2012 LCV study, the procedure for estimating cost curves was analogous. However, it did not draw on any cost data from the literature. Cost and CO_2 reduction estimates of the different LCV technologies were initially estimated within the study consortium. Then, feedback from industry stakeholders (including manufacturers, ACEA, CLEPA) was sought and assumptions adjusted in some cases. Similar to the car studies, a section comparing data shows that the costs of reducing CO_2 emissions from LCVs are estimated at far lower levels compared to older LCV studies (e.g. AEA *et al.* (2009))

4.2.1.5 Powertrain penetration

Assumptions concerning the level of uptake of different fuel saving technologies for meeting the 95 gCO_2/km target in 2020 amongst petrol and diesel passenger cars is not explicitly spelled out. However, the impact of different uptake levels of (plug-in) electric vehicles on the costs of meeting the 95 gCO_2/km target is examined in a set of sensitivities. The baseline assumption is zero penetration of electric vehicles (BEV, PHEV, REEV). The situation is analogous for the 2012 LCV study. The impact on including (plug-in) electric LCVs on the costs of meeting the target is examined in a sensitivity. Costs are substantially increased through the inclusion of 6%-18% electrification. The baseline assumption is zero penetration.

4.2.2 EPA studies (2008 – 2012)

4.2.2.1 General overview

The US Environmental Protection Agency (EPA) has conducted a number of studies into the future costs and CO_2 reduction potential of technologies for light duty vehicles, in order to support the development of the US LDV CO_2 emission standards. The reports of primary interest are those used to develop the 2017 and later model years (MY) LDV GHG emission standards.

Although a large number of reports have been published, the following key references provide a consolidated account of various supporting studies:

- EPA & NHTSA (2012) Joint Technical Support Document: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards[10]
- EPA (2011a) Computer Simulation of Light-Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020-2025 Timeframe[11].
- EPA (2009) Light-Duty Technology Cost Analysis Pilot Study[12]
- EPA (2008) Staff Technical Report: Cost and Effectiveness Estimates of Technologies Used to Reduce Light-duty Vehicle Carbon Dioxide Emissions[13]
- Regulatory Docket ID EPA-HQ-OAR-2010-0799.

4.2.2.2 Segmentation

For the studies on CO_2 reduction potential of technology packages, seven vehicle classes were included (EPA, 2011a).

1. Small (B-class) Car, such as the Toyota Yaris
2. Standard (D-class) Car, such as the Toyota Camry
3. Small Multi-Purpose Vehicle (MPV), such as the Saturn Vue
4. Full Sized Car, such as the Chrysler 300
5. Large MPV, such as the Dodge Grand Caravan
6. Light-Duty Truck (LDT), such as the Ford F150
7. Light Heavy-Duty Truck (LHDT), such as the General Motors HD3500

This represents two additional classes compared to the earlier analysis in EPA (2008). The inclusion of the small car class aimed to capture the engineering differences unique to small car classes.

4.2.2.3 Technology coverage

For the studies on CO_2 reduction potential of technology packages described in EPA (2011a):

- Hybrid vehicles will use an advanced hybrid control strategy, focusing on battery state of charge (SOC) management, but not at the expense of drivability
- Vehicles will use fuels that are equivalent to either 87 octane pump petrol or 40 cetane pump diesel.
- 2020–2025 vehicles will meet future California LEV III requirements for criteria pollutants, which are assumed to be equivalent to current SULEV II (or EPA Tier 2 Bin 2) levels.

The original 2008 analysis modelled advanced valvetrain technologies (such as variable valve timing and lift, cylinder deactivation), turbocharged and downsized engines, as well as 6 speed automatic transmissions, CVTs and dual clutch transmissions. The most recent project added several new engine and vehicle technologies, including: advanced, highly downsized, high BMEP turbocharged engines; high efficiency transmissions with 8 speeds and optimized shift strategies to maximize

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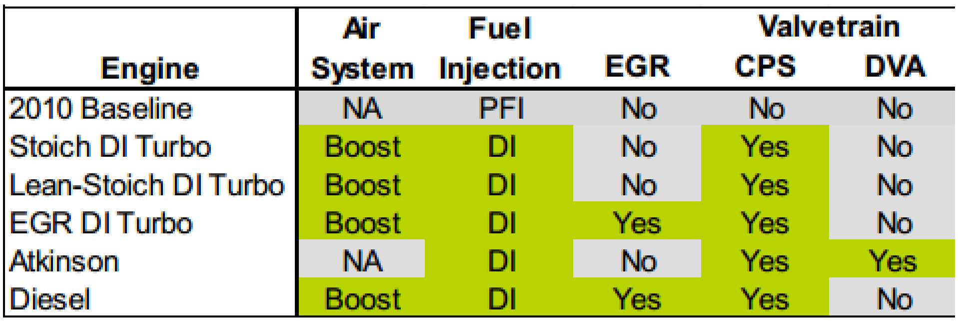
[10] http://www.epa.gov/otaq/climate/documents/420r12901.pdf
[11] http://www.epa.gov/otaq/climate/documents/420r11020.pdf
[12] http://www.epa.gov/otaq/climate/420r09020.pdf
[13] http://www.epa.gov/otaq/climate/420r08008.pdf

vehicle system efficiency; Atkinson-cycle engines for hybrids; Stop-start (or idle off) technology. Two main classes of hybrids were considered:

- Input powersplit hybrids. Examples of input powersplits in the market today include the Ford Fusion HEV and the Toyota Prius.
- P2 hybrids. An example of the P2 hybrid is the Hyundai Sonata Hybrid.

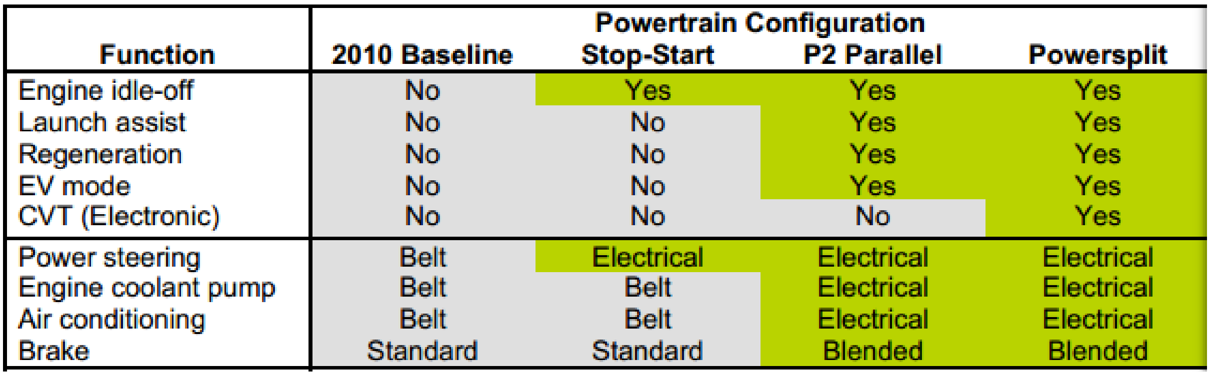
The technology packages considered were as follows:

Table 4.2: Engine technology package definition



Engine	Air System	Fuel Injection	EGR	Valvetrain CPS	Valvetrain DVA
2010 Baseline	NA	PFI	No	No	No
Stoich DI Turbo	Boost	DI	No	Yes	No
Lean-Stoich DI Turbo	Boost	DI	No	Yes	No
EGR DI Turbo	Boost	DI	Yes	Yes	No
Atkinson	NA	DI	No	Yes	Yes
Diesel	Boost	DI	Yes	Yes	No

Table 4.3: Hybrid technology package definition

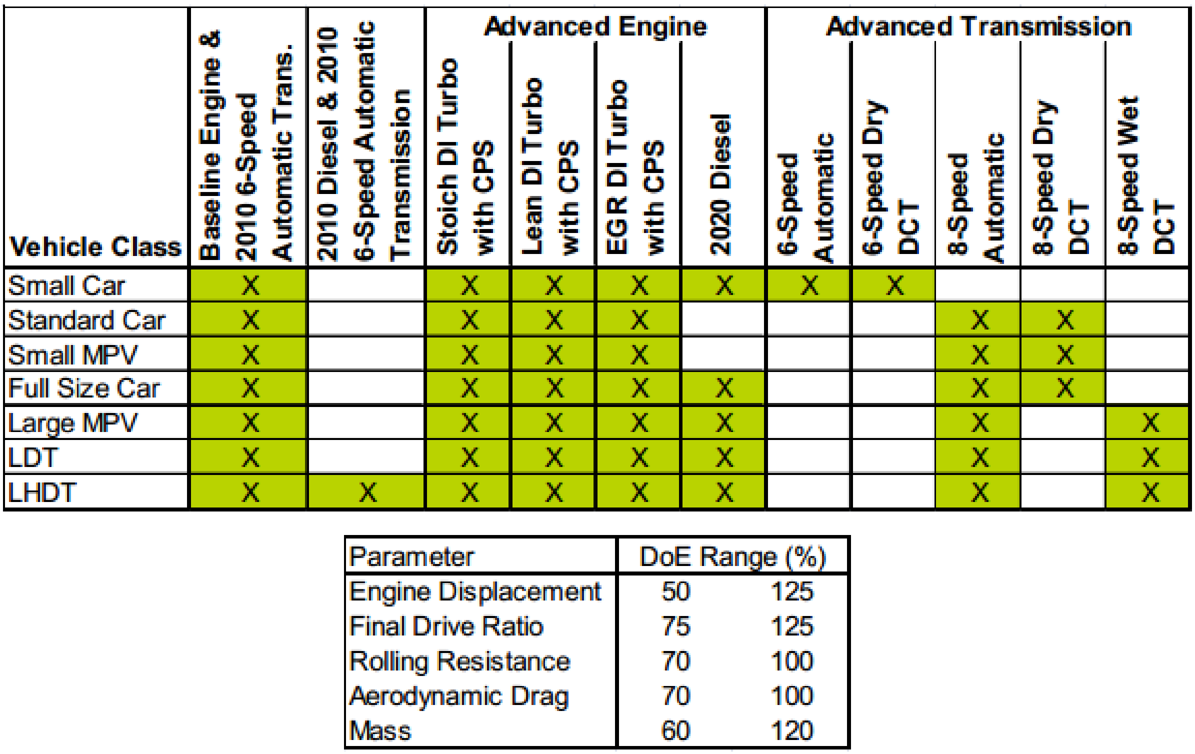


Function	Powertrain Configuration 2010 Baseline	Stop-Start	P2 Parallel	Powersplit
Engine idle-off	No	Yes	Yes	Yes
Launch assist	No	No	Yes	Yes
Regeneration	No	No	Yes	Yes
EV mode	No	No	Yes	Yes
CVT (Electronic)	No	No	No	Yes
Power steering	Belt	Electrical	Electrical	Electrical
Engine coolant pump	Belt	Belt	Electrical	Electrical
Air conditioning	Belt	Belt	Electrical	Electrical
Brake	Standard	Standard	Blended	Blended

Table 4.4: Transmission technology package definition

Transmission	Launch Device	Clutch
Baseline Automatic	Torque Converter	Hydraulic
Advanced Automatic	Multidamper Control	Hydraulic
Dry clutch DCT	None	Advanced Dry
Wet clutch DCT	None	Advanced Damp

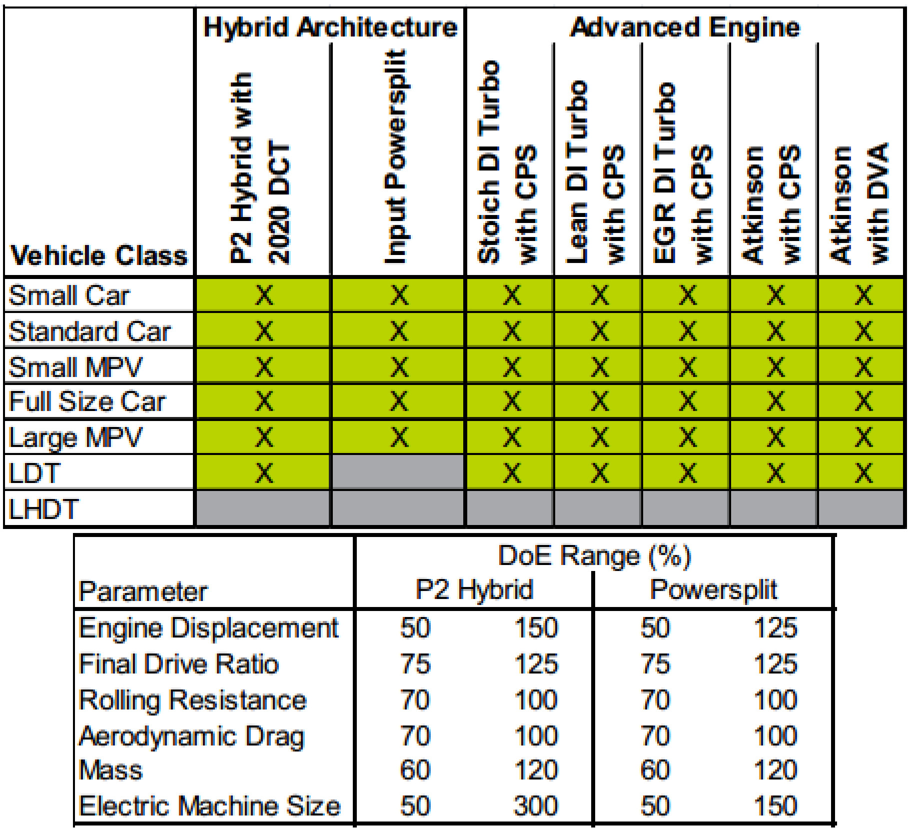
Table 4.5: Baseline and Conventional Stop-Start vehicle simulation matrix



Vehicle Class	Baseline Engine & 2010 6-Speed Automatic Trans.	2010 Diesel & 2010 6-Speed Automatic Transmission	Advanced Engine Stoich DI Turbo with CPS	Lean DI Turbo with CPS	EGR DI Turbo with CPS	2020 Diesel	Advanced Transmission 6-Speed Automatic	6-Speed Dry DCT	8-Speed Automatic	8-Speed Dry DCT	8-Speed Wet DCT
Small Car	X		X	X	X	X	X	X			
Standard Car	X		X	X	X				X	X	
Small MPV	X		X	X	X				X	X	
Full Size Car	X		X	X	X	X			X	X	
Large MPV	X		X	X	X	X			X		X
LDT	X		X	X	X	X			X		X
LHDT	X	X	X	X	X	X			X		X

Parameter	DoE Range (%)	
Engine Displacement	50	125
Final Drive Ratio	75	125
Rolling Resistance	70	100
Aerodynamic Drag	70	100
Mass	60	120

Table 4.6: P2 and Input Powersplit hybrid simulation matrix



Vehicle Class	Hybrid Architecture P2 Hybrid with 2020 DCT	Input Powersplit	Advanced Engine Stoich DI Turbo with CPS	Lean DI Turbo with CPS	EGR DI Turbo with CPS	Atkinson with CPS	Atkinson with DVA
Small Car	X	X	X	X	X	X	X
Standard Car	X	X	X	X	X	X	X
Small MPV	X	X	X	X	X	X	X
Full Size Car	X	X	X	X	X	X	X
Large MPV	X	X	X	X	X	X	X
LDT	X	▨	X	X	X	X	X
LHDT	▨	▨	▨	▨	▨	▨	▨

Parameter	DoE Range (%) P2 Hybrid		Powersplit	
Engine Displacement	50	150	50	125
Final Drive Ratio	75	125	75	125
Rolling Resistance	70	100	70	100
Aerodynamic Drag	70	100	70	100
Mass	60	120	60	120
Electric Machine Size	50	300	50	150

4.2.2.4 Methodology for developing cost and CO_2 estimates

To develop **CO_2 estimates**, the engineering consultancy Ricardo was commissioned by the EPA to develop vehicle computer simulations of specific technology packages to determine the energy consumption and CO_2 emission levels of future vehicles. The results are publically available in the Response Surface Models (RSM) tool for the US (2012)[14], and summarised in EPA (2011a) "Computer Simulation of Light-Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020-2025 Timeframe"[15]. This study assessed the effectiveness of a broad range of technologies including powertrain architecture (conventional and hybrid), engine, transmission, and other vehicle attributes such as engine displacement, final drive ratio, vehicle mass, and rolling resistance on seven light-duty vehicle classes.

The program team first developed a comprehensive list of potential technologies that could be in use on vehicles in the study timeframe, 2020–2025. These technologies were grouped by subject area, such as transmissions, engines, or vehicle, and prioritised based on the potential of the technology to improve GHG emissions, the state of development and commercialisation of the technology in the 2020-2025 timeframe and the current (2010) maturity of the technology. The selected options were then combined into technology packages for use in the vehicle performance simulations. Vehicles were assessed using three basic powertrain configurations: conventional start-stop, P2 hybrid, and Input Powersplit hybrid. A physics-based vehicle and powertrain system model was developed and implemented in MSC.Easy5™ (a commercially available software package widely used in industry for vehicle system analysis).

The U.S. D.O.T. Volpe Center contracted Argonne National Laboratory (ANL) to provide full vehicle simulation modelling support for the MYs 2017-2025 rulemaking. These were used to define the effectiveness of mild hybrids and used to update the effectiveness of advanced transmission technologies coupled with naturally-aspirated engines. This simulation modelling was accomplished using ANL's full vehicle simulation tool called "Autonomie," which is the successor to ANL's Powertrain System Analysis Toolkit (PSAT) simulation tool, and that includes sophisticated models for advanced vehicle technologies. The ANL simulation modelling process and results are documented in multiple reports that can be found in NHTSA's docket.

As a more practical alternative to full vehicle simulation, EPA developed a "lumped parameter model" that estimates the effectiveness of various technology combinations or "packages," in a manner that accounts for synergies between technologies. Vehicle simulation modelling performed for EPA by Ricardo was used to calibrate the lumped parameter model.

For the **cost estimates**, the consultancy FEV was commissioned to conduct tear-down studies. With these tear-down studies, incremental direct manufacturing costs were developed by comparing hardware differences among new technology configurations (i.e. the advanced technology offering) and against baseline vehicle technology configurations (i.e. current technology becoming the standard in the industry) having similar overall driving performance. Using comparison bill of materials, technical experts from both product and manufacturing engineering identified hardware differences between the two technologies as part of the teardown process. Components that were recorded as different were then evaluated using cost models that utilise data from comprehensive costing databases for raw materials, labour rates, manufacturing overhead, and mark-up costs. Where appropriate, results were scaled to other vehicle sizes and to similar technologies. Also, sensitivity analyses of key inputs such as raw material costs were performed. Marketplace validation was conducted at all stages of the analysis by cross-checking with data developed by entities and processes external to the team. The EPA relied on the results provided by FEV for estimating the cost of the technologies covered by the teardown studies.

Regarding the costs for HEVs, PHEVs, EVs, and FCEVs, the analysis for MY 2017-2025 was amended compared to the MY 2012-2016 rulemaking. This was due to both the rapid development of the technology, and the fact that analysis for the MYs 2012-2016 final rule employed a single $/kWh ($ per kilowatt-hour) estimate, and did not consider the specific vehicle and technology application for the battery. Specifically, batteries used in HEVs (high power density applications) versus EVs (high energy density applications) need to be considered appropriately to reflect the design differences, the

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[14] http://www.epa.gov/otaq/climate/documents/cs-tool-2012.zip
[15] http://www.epa.gov/otaq/climate/documents/420r11020.pdf

chemical material usage differences, and the differences in cost per kWh as the power to energy ratio of the battery changes for different applications.

To address these issues a battery cost model developed by Argonne National Laboratory (ANL) was used – available online[16]. This model allows users to estimate unique battery pack costs using user customised inputs. Costs and effectiveness values were developed for the mild and P2 HEV configuration, two different all-electric mileage ranges for PHEVs (20 and 40 in-use miles) and three different mileage ranges for EVs (75, 100 and 150 in-use miles).

To attain the final costs, the EPA developed indirect cost multipliers (ICMs). ICMs were developed as an alternative to the retail price equivalent (RPE) methodology which was considered to deal incorrectly with indirect cost components that may actually not be affected by vehicle modifications resulting from regulation (such as fixed depreciation costs, health care costs for retired workers, or pensions) (EPA, Automobile Industry Retail Price Equivalent and Indirect Cost Multipliers, 2009a). The factors were developed using an internal Delphi study involving EPA staff, and were subsequently peer-reviewed by three independent experts who expressed their support of the approach (EPA, Peer Review for the RTI Report, Automobile Industry Retail Price Equivalent and Indirect Cost Multipliers, 2009b). Depending on the complexity of the new technology introduced and on whether short- or long-term production effects are regarded, the developed ICMs account for:

- Production overhead (e.g. warranty, product development (R&D), depreciation and amortisation, maintenance and repair);
- Corporate overhead (general, retirement, health care);
- Selling costs (transportation, marketing, dealer support).

The approach groups all technologies into broad categories according to their complexity levels, and assumes that technologies within each group have the same ratio of indirect costs to direct costs. This simplification means that it is likely that direct costs for some technologies within a category will be higher and some lower than the estimate for the category in general (EPA & NHTSA, 2012). Table 4.7 shows a summary of which technologies are assigned to which complexity level.

The assignment of technologies to complexity levels as proposed in this study (see section 4.7) is based on EPA's complexity levels.

Table 4.7: Summary of technology designations complexity level used for the definition of ICMs

Low complexity	Medium complexity	High complexity 1	High complexity 2
• Passive aerodynamic improvements • Lubricant improvements • Mass reductions 3-10% • Aggressive shift logic engine • Friction reduction engine • Downsizing 6 speed auto transmissions • Low drag brakes • Electro-hydraulic power steering • Electric power steering • WT intake or coupled • Improved accessories	• 6-speed DCTs • Mass Reduction 15-20% • Turbocharging • Cylinder deactivation • VVT-dual cam phasing & Discrete variable valve lift • 8-speed auto and DCT transmissions • 12 volt start-stop systems • Active aerodynamic improvements • Converting OHV/SOHC to DOHC • Gasoline direct injection • Turbo downsizing • Turbo downsizing +EGR • Advanced Diesel	• Power-split hybrids • 2-mode hybrids • Plug-in hybrids (non-battery and charger) • Battery electric vehicles (non-battery and charger)	• Plug-in hybrids (battery) • Battery electric vehicles (battery)

Source: (EPA & NHTSA, 2012)

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[16] http://www.cse.anl.gov/batpac/about.html

Near-term ICM values account for differences in the levels of R&D, tooling, and other indirect costs that will be incurred. In the longer term, some of the indirect costs will no longer be attributable and therefore a lower ICM factor is applied. Furthermore, in the EPA approach, the same learning is applied to direct and indirect manufacturing costs. However, it is considered that only the warranty costs out of all indirect manufacturing costs should be subject to learning. Hence, different ICMs have been developed for warranty and non-warranty indirect cost items (see Table 4.8). The most recent ICMs were based on more up-to-date data compared to the earlier versions, in particular an updated value of the retail price equivalent (RPE) (changing from 1.46 to 1.5).

Table 4.8: Overview of non-warranty ICM factors applied in the EPA final rulemaking MY 2017-2025

Production Timeframe	Near term		Long term	
Technology complexity	Warranty	Non-Warranty	Warranty	Non-Warranty
Low	0.012	0.230	0.005	0.187
Medium	0.045	0.343	0.031	0.259
High1	0.065	0.499	0.032	0.314
High2	0.074	0.696	0.049	0.448

Notes: Long term is assumed to apply after 2018; Source: (EPA & NHTSA, 2012)

The ICMs cited in Table 4.8 allow for a profit allowance, at the average corporate profit rate of 6%. Whether to include profit in the multiplier has been topic of expert discussions and will depend on if profits are considered a cost of doing business.

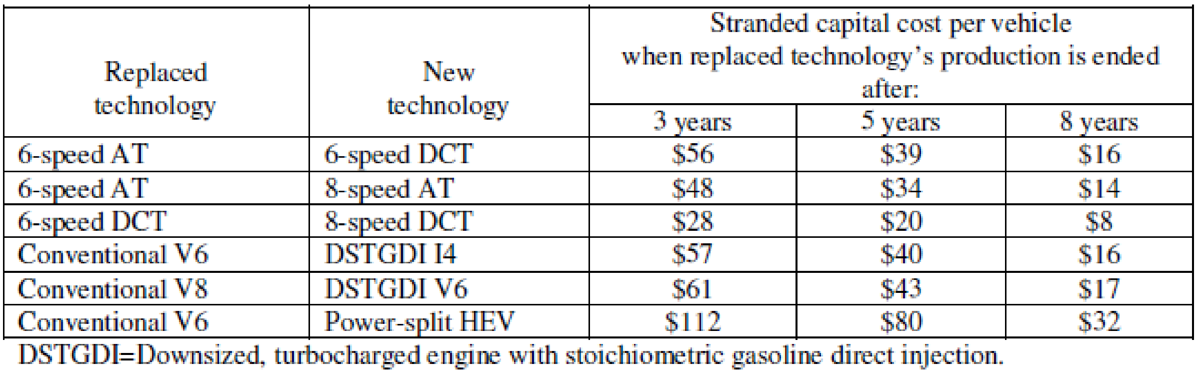
The scaling factors scale the direct incremental manufacturing costs between different vehicle segments. The scaling factors are based on the detailed cost analysis available for a vehicle segment (stemming from so-called ‘tear-down’ studies) as well as detailed vehicle component analysis for all vehicle segments. Final vehicle segment scaling factors are derived from scaling factors developed for each vehicle component, assembly, sub-system and system.

The EPA analysis (EPA & NHTSA, 2012) assumes that the level of cost reductions depends on where on the learning curve a technology’s learning progression is. The approach is a simplification of the traditional methodology applied in the EU study (EC, 2009) but is based on a higher learning rate of 0.8 (i.e. a 20% reduction in cost for each doubling in cumulative production, compared to the 0.90 and 0.85 for the downsizing and respectively hybridisation variant used in EC, 2009). Newly introduced technologies start off with “steep” learning (20% lower costs after two full years of implementation). Once two of these steep learning steps have occurred, learning at 3% per year becomes effective for five years. Beyond this the rate decreases to five years of learning at 2% per year, then five years at 1% per year. The step-wise learning approximates a volume-based logarithmic learning by assuming that production volumes of a given technology double within two years.

The above-described learning ‘schedule’ defining the intervals and frequency of cost reductions is varied in order to reflect that different technologies start at different points on the learning curve due to their different levels of maturity. For example, due to the nature of battery pack developments, the learning schedule for the latter is adapted to incorporate five steep learning steps although at a somewhat slower pace than every two years. This adapted schedule reflects that the learning of battery packs starts higher on the curve.

Since the production of automotive components is very capital-intensive, it is possible that capital investments in manufacturing facilities could become stranded (where their value is lost or diminished). A stranded capital analysis was performed for three transmission technology scenarios, two engine technology scenarios, and one hybrid technology scenario, as shown below in Table 4.9.

Table 4.9: EPA stranded capital analysis on transmission technology scenarios



Replaced technology	New technology	Stranded capital cost per vehicle when replaced technology's production is ended after:		
		3 years	5 years	8 years
6-speed AT	6-speed DCT	$56	$39	$16
6-speed AT	8-speed AT	$48	$34	$14
6-speed DCT	8-speed DCT	$28	$20	$8
Conventional V6	DSTGDI I4	$57	$40	$16
Conventional V8	DSTGDI V6	$61	$43	$17
Conventional V6	Power-split HEV	$112	$80	$32

DSTGDI=Downsized, turbocharged engine with stoichiometric gasoline direct injection.

4.2.2.5 Powertrain penetration

A baseline/reference fleet was developed in order to track the volumes and types of fuel economy-improving and CO_2-reducing technologies that are already present in the existing vehicle fleet. The baseline fleet in future years was then modelled using the OMEGA and CAFE models, which add technologies to vehicles in each of the baseline market forecasts such that each manufacturer's car and truck CAFE and average CO_2 levels reflect MY 2016 standards. This represents the light duty fleet from 2017-2025 in the absence of any new standards.

There are two fleet projections for the final rule, owing to the significant uncertainty associated with forecasting sales volumes, vehicle technologies, fuel prices, consumer demand, and so forth out to 2025. These factors, in the opinion of EPA, make it reasonable and appropriate to evaluate the impacts of the GHG standards using two baselines. For the first baseline, the forecast of the light vehicle market through MY 2025 based on (a) the vehicle models in the MY 2008 CAFÉ certification data, (b) the AEO2011 interim projection of future fleet sales volumes, and (c) the future fleet forecast conducted by CSM in 2009. The final rule also contains another market forecast using MY 2010 CAFE certification data, information from AEO 2012, and information purchased from LMC Automotive (formerly JD Power Forecasting). While there are some differences between these forecasts, they are not significant enough to change the conclusions of the analysis.

Technology and powertrain penetration under the proposed standards was modelled under an attribute-based standard. Under an attribute-based standard, every vehicle model has a performance target (fuel economy and CO_2 emissions for CAFE and CO_2 emissions standards, respectively), the level of which depends on the vehicle's attribute (footprint). The manufacturers' fleet average performance is determined by the production-weighted average (for CAFE, harmonic average) of those targets.

The mathematical functions for the proposed MYs 2017-2025 standards were based on an ordinary least-squares formulation, on sales-weighted data, using a fleet that has had technology applied, and after adjusting the data for the effects of mass-to-footprint. This was different to the previous approach under the MYs 2012-2016 final rules, where minimum absolute deviation, or MAD, was used instead since this mitigates the effect of outliers in a dataset. Subsequently, it was considered that all vehicles in the dataset were equally legitimate on-road designs, so there was no need to employ techniques to reduce the impact of outliers.

To estimate potential technology application in response to potential CAFE standards, NHTSA uses the CAFE Compliance and Effects Modelling System. It applies technologies incrementally as necessary to meet the fuel consumption reduction requirement, so the cost interaction between any particular technology and other technologies (cost synergies) must be defined.

Phase-in caps for some technologies are used to reflect real-world limitations such as engineering and development personnel and financial resources. Most technologies are available at a rate of either 85% or 100% beginning in 2016. Some advanced technologies expected to enter the market in the near future such as EGR Boost follow a 3% annual cap increase from 2016 to 2021, then, approximately 10% from 2021 to 2025. Diesels follow an annual 3% increase in phase-in cap through 2025. Hybrids follow a 3% annual increase from 2016 to 2021, then 5% from 2021 to 2025. PHEVs and EVs follow a 1% annual cap increase. Lower phase-in caps for Alternate Fuelled Vehicles

(AFVs) reflect additional investment in infrastructure that is required to achieve high levels of conversion to a new fuel type, as well as consumer response.

The scenarios that resulted are very detailed, and full account of them is available online in the regulatory docket.[17]

4.2.3 FEV for ICCT (2012 – 2014)

4.2.3.1 General overview

The International Council on Clean Transportation (ICCT) contracted with FEV to define the net incremental costs for a set of advanced light-duty vehicle technologies for the European vehicle market. The study was based on already existing cost analysis studies, performed by FEV for the EPA and hence for the North American vehicle market. The new cost models for the ICCT report are based off existing EPA models but account for key differences between North American and European manufacturing cost parameters, vehicle segment characteristics, and technology configurations. For example, in the EPA North American analysis, manufacturing processes and rates are based on data acquired from the United States. For the ICCT analysis, Germany's primary manufacturing methods and manufacturing cost structure/rates are used to support the European analysis. Since the cost models are based on manufacturing in advanced industrialized countries (i.e., U.S. and Germany), the calculated manufacturing costs tend to be on the conservative side. (FEV, 2013)

4.2.3.2 Segmentation

The study is carried out considering the following six European market segments (FEV, 2013):

- Subcompact, with an example being the VW Polo
- Compact/Small, with an example being the VW Golf
- Midsize, with an example being the VW Passat
- Midsize/Large, with an example being the VW Sharan
- Small/Midsize SUV/COV, with an example being the VW Tiguan
- Large SUV, with an example being the VW Touareg

4.2.3.3 Technology coverage

FEV's analysis for the European market was carried out in two phases. The following list states the technology configurations that were evaluated, stating also the baseline vehicle technology configuration against which it is compared, the latter being representative of the current state of design with similar overall driving performance. Components that are unique to the new technology, as well as components modified to account for the new technology adaptation, were identified and analysed to establish the incremental direct manufacturing costs. (FEV, 2013)

Phase 1 (FEV, 2013)

- Engine technology configurations
    - In-line four-cylinder (I4), Naturally Aspirated (NA), Port Fuel Injected (PFI) engine downsized to a smaller I4, Turbo, Gasoline Direct Inject (GDI) engine
    - V6, NA, PFI engine downsized to a I4, Turbo, GDI engine
    - V8, NA, PFI engine downsized to a V6, Turbo, GDI engine
- Transmission technology configurations
    - 5-Speed Automatic Transmission (AT) in comparison to a 6-Speed AT
    - 6-Speed AT in comparison to an 8-Speed AT
    - 6-Speed AT in comparison to a 6-Speed Wet, Dual Clutch Transmission (DCT)
- Hybrid Electric Vehicle (HEV) technology configurations
    - Belt Alternator Start (BAS) HEV in comparison to conventional powertrain vehicle
    - Power-Split HEV in comparison to a conventional powertrain vehicle

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[17] Regulatory Docket ID EPA-HQ-OAR-2010-0799

  - P2 HEV (i.e., single motor, twin clutch hybrid system) in comparison to a conventional powertrain vehicle

Phase 2 (FEV, 2012)

- Advanced Down-Sized Diesel Engine Technologies
  - High-Pressure (2500 bar) Injection System in comparison to an 1800 Injection System
  - Variable Valve Timing and Lift Valvetrain System in comparison to a Conventional Valvetrain System
  - High-Pressure EGR in comparison to a High- and Low-Pressure EGR System
- Advance Gasoline Engines
  - EGR High-Load Application in a Turbocharged Petrol Engine in comparison to a System without EGR
- 6-Speed Dry Dual Clutch Transmission in comparison to a 6-Speed Manual Transmission
- Start-Stop Hybrid System (with regenerative braking) in comparison to the same vehicle without the Start-Stop Technology
- Conversion and transformation of the Toyota Venza Mass-Reduction and Cost analysis completed for the United States Environmental Protection Agency into cost models representative of the technology in the European market.

Furthermore, in 2014, an update for the P2 hybrid electrification system costs was carried out (FEV, 2014).

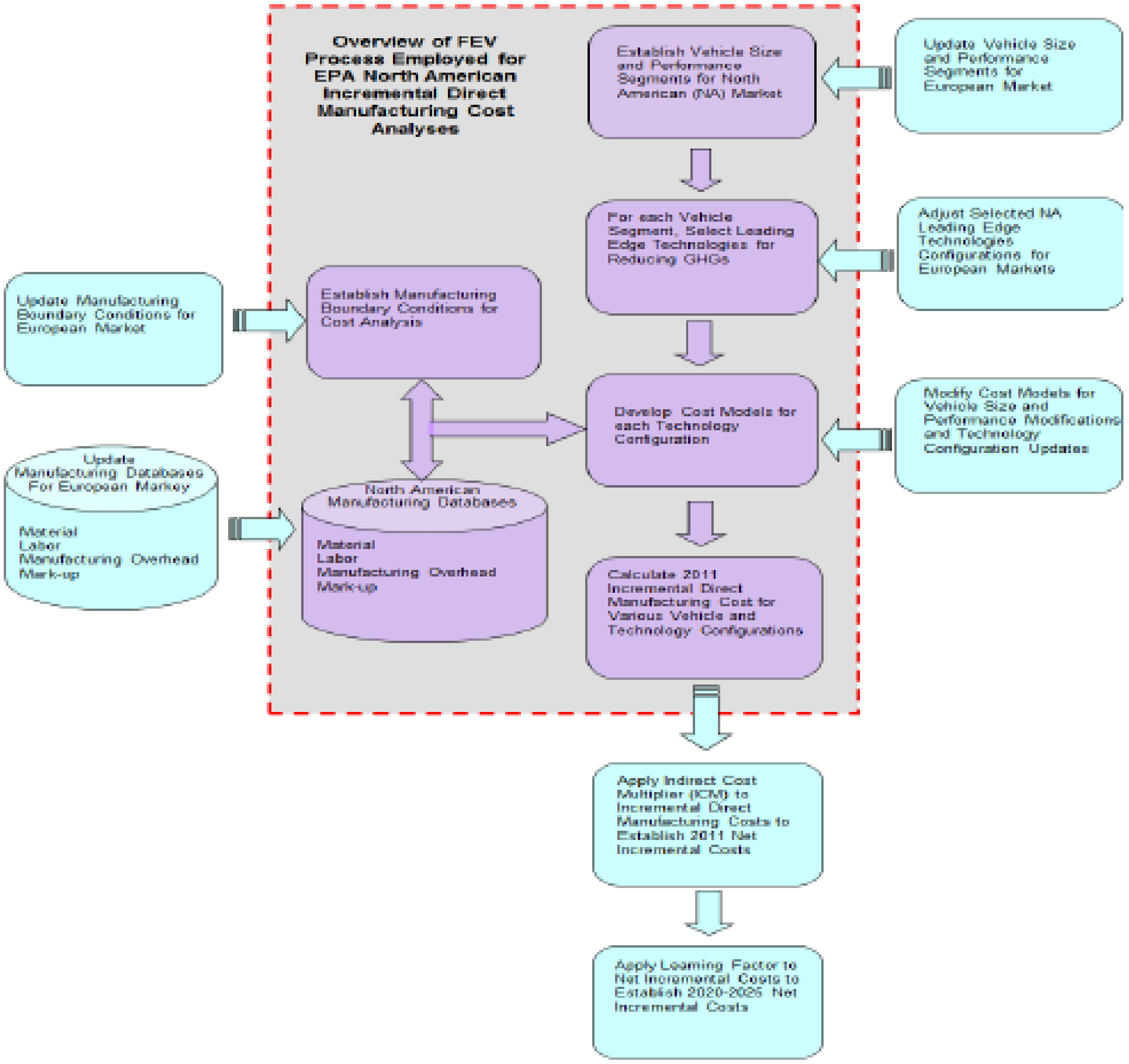
4.2.3.4 Methodology for developing cost and CO_2 estimates

As mentioned above, the foundation of FEV's analysis for the European market is based on previously completed teardown and cost analysis work conducted for the U.S. EPA, also completed by FEV. In order to tailor the **cost** analysis for the European market, the following process was applied, which highlights the adjustments that were made for the European market:

1. Establish manufacturing **boundary conditions for European market**.
2. Define suitable light-duty **vehicle categories for the European context**.
3. Develop **appropriate scaling factors** for each of the technologies under consideration for translation to the European vehicle segments
4. **Update costing databases** (e.g., material cost, labour cost, manufacturing overhead costs) **with European parameters**.
5. Run cost models with updated databases and scaling factors for each of the defined technology configurations and vehicle segments to establish incremental direct manufacturing costs.
6. Apply EPA-developed Indirect Cost Multipliers (ICMs) to each direct incremental manufacturing cost to establish net incremental costs.
7. Apply EPA-developed learning factors to net increment costs to account for product maturity differences (e.g., sales volume, design maturity, manufacturing maturity, etc.) between cost analysis boundary conditions and projected market boundary conditions.

The process of tailoring EPA's model to the European market is furthermore shown in Figure 4.2 below. It shows graphically where adjustments have been made. It also shows that indirect cost multipliers and learning factors were taken over from EPA's study (as described in 4.2.2.4) and left largely unadjusted for the European market in the Phase 1 and Phase 2 analysis.

Figure 4.2: Overview of the tailoring of EPA's model for North America to the European market (FEV, 2013)



The **ICM factors** have however subsequently been updated for the European market (FEV, 2013b). The development of these EU ICMs is founded on *i)* published indirect cost data from OEMs conducting business in Europe that allows the derivation of nominal ICM factors per indirect cost item and *ii)* an ICM calculator that adjusts nominal ICM factors specific to the technology being analysed. Three adjustment factor levels (A, B, and C) are defined for altogether five technology attributes (i.e. component complexity, integration in existing production line, integration in existing product concept, number of new/modified components and customer notice (affecting marketing costs)). An “A” level means that only a small adjustment is made to the nominal value, conversely, a “C” level signifies a large adjustment. In total a matrix of 105 adjustment factors is developed [for **3** *(factor levels)* **x 5** *(technology attributes)* **x 7** *(indirect cost items)*]. However, since not all indirect cost items are affected by all technology attributes, a little less than two-thirds of the values are 0. Table 4.10 shows the nominal ICM value for each indirect cost item as well as the respective minimum and maximum adjusted ICM values (assuming a combination of only “A” level adjustments or, respectively, “C” level adjustments for all technology attributes).

Table 4.10: Nominal and adjusted ICM factors in the updated FEV methodology

Indirect cost item	Nominal ICM	Minimum adjusted ICM *(AAA combination of adjustment factors)*	Maximum adjusted ICM *(CCC combination of adjustment factors)*
Warranty	0.050	0.075	0.185
R&D	0.060	0.018	0.264
Depreciation	0.080	0.000	0.120
Maintenance	0.030	0.000	0.045
Corporate Overhead	0.050	0.000	0.030
Marketing	0.060	0.000	0.090
Dealer selling support	0.130	0.000	0.078
Total cost contribution	**0.460**	**0.090**	**0.810**

Source: (FEV, 2013b)

Once the adjusted ICMs are established for the base year, adjustment factors with respect to production timing (again specific to each indirect cost item) are applied to arrive at production year dependent ICMs. The resulting ICMs are applied to baseline NIDMCs (Net Incremental Direct Manufacturing Costs). Resulting costs are not subject to any learning. Hence, production year adjustment factors already account for possible learning effects regarding indirect manufacturing costs.

EU-tailored ICMs do not include OEM profit, dealer profit support or transportation costs since FEV felt that these indirect cost components are not affected by future environmental regulations. Despite the limited scope of EU-tailored ICMs compared to the EPA ICMs, they are generally slightly higher at inception (2012 in this analysis), but then significantly drop-off towards 2025. This can be explained by the complete drop-off of selected indirect costs (i.e., R&D, Depreciation, Marketing, and Dealership) from year five onwards. In some cases the EU ICMs are even considerably higher for the base year – results that were said to be difficult to assess without understanding the variations in underlying assumptions which were used in development of the EPA ICMs.

Table 4.11 shows the three technology developments for which the highest difference between EU and EPA ICMs was identified (EU ICMs are learned accordingly where applicable). Of the remaining 14 analysed technologies, the average ICM ratio (EU/EPA) is 105% (with a minimum of 78% and a maximum of 138%).

Table 4.11: Comparison of EU and NA ICMs for technologies with highest Y2012 difference

Baseline Technology	New Technology	EU ICMs		EPA ICMs		ICM ration (EU/EPA)	
		2012	**2025**	**2012**	**2025**	**2012**	**2025**
5-Speed Automatic Transmission	6-Speed Automatic Transmission	0.495	0.062	0.242	0.192	**204%**	33%
6-Speed Automatic Transmission	6-Speed Dual Clutch Transmission	0.726	0.103	0.387	0.290	**187%**	35%
Conventional Diesel Engine	Downsized Conventional Diesel Engine (e.g. I4-I3, I6-I4, V8-I6)	0.560	0.074	0.242	0.192	**231%**	38%

Source: (FEV, 2013b)

Regarding EPA's **learning approach**, one modification was made relative to the methodology used by EPA: For new technology configurations which resulted in a savings relative to the baseline technology configuration, the learning factor was held constant at one for all production years evaluated. This signifies no change in cost savings as the technology matures. (In contrast, the EPA methodology treats new technology configurations, whether they result in a cost increase or decrease the same - hence, direct manufacturing cost savings over the baseline configuration will have less of a savings in the future relative to the present.)

(FEV, 2013b) furthermore provided an analysis on what would happen in case manufacturing was assumed not in Germany but in Eastern European countries, where labour rates are estimated to be on average 77% lower. Given resulting labour cost decreases, the cost reduction for most technologies analysed in (FEV, 2013b) is in the range of 15-20% (depending on the contribution of labour costs to the total manufacturing costs).

The FEV studies do not provide estimates for CO_2 reduction potentials for the analysed technologies.

4.2.3.5 Powertrain penetration

The FEV studies do not make their own explicit assumptions concerning the penetration of different powertrains/technologies in the future. The projections of future costs are based on the learning approach – a slightly adjusted approach to the one from EPA's study (see section 4.2.2.4 for EPA's approach and above for the modification carried out for FEV's analysis). This learning approach is based on assumptions regarding the year of volume manufacturing of the single technologies. Manufacturing costs as identified for this volume manufacturing production level are then projected backwards (or forwards) using the appropriate learning rates in order to establish costs for different points in time. The assumed year of volume manufacturing as well as the assumed development stage of the different technologies (and hence their penetration rates) are based on EPA's analysis (as described in section 4.2.2.5)

4.2.4 IKA (2012 & 2014)

4.2.4.1 General overview

The German Federal Ministry for Economic Affairs and Energy (BMWi) commissioned two studies carried out by IKA on the topic of cost and CO_2 reduction potential for light duty vehicles. IKA (2012) set out to estimate CO_2 reduction potentials and costs for passenger car technologies up to 2020 while IKA (2014) builds on this work, estimating CO_2 reduction potentials and costs beyond 2020 and up to 2030. Moreover, the 2014 study also includes LCVs in its analysis, drawing upon the 2010 IKA LCV study for BMWi, as well as the 2013 IKA LCV study for VDA.

The 2014 study basically extends the scenarios defined in the 2012 study beyond 2020. Assumptions on the development of technical progress as well as production cost reductions are drawn-out up to 2030. In addition, technology options are extended through the inclusion of PHEVs.

4.2.4.2 Segmentation

Both the 2012 and 2014 studies use the same type of segmentation, splitting the fleet into three segments. A and B-segment (European Commission definition (EC, 1999)) cars form SEG-1, C, D, M and J-segment cars form SEG-2, and E, F, and S-segment cars form SEG-3.

Based on linear extrapolation from past trends, is the studies forecasted that the market share of segment 1 vehicles will grow continuously up to 2030, mainly at the expense of segment 2 market share. The studies' results are presented both with the assumption of this continued trend towards smaller vehicle segments and without.

For LCVs, the standard European segmentation by kerb mass category is used:

- Group I – kerb weight less than 1.305 kg
- Group II – kerb weight between 1.305 and 1.760 kg
- Group III – kerb weight above 1.760 kg

No change over time in the market share of each LCV segment is forecast.

4.2.4.3 Technology coverage

In total, the studies cover 36 technologies. There are 13 engine technologies which include several different levels of variable valve timing, direct injection and downsizing, 4 hybrid technologies (micro, mild, full and plug-in, the latter only featuring in the 2014 study), 5 gearbox technologies, 5 miscellaneous technologies including auxiliaries electrification, thermal management, heat recovery systems and general friction reduction, and 9 technologies to reduce tractive effort including low resistance tyres and several levels of aerodynamic improvements and lightweighting.

4.2.4.4 Methodology for developing cost and CO_2 estimates

IKA (2014) states that the following sources for technology costs and fuel saving were used:

- Literature, including the main technical studies for the US EPA and the European Commission for informing CO_2 standards[18]
- Expert telephone interviews
- One workshop with members from industry and science for the discussion/validation of the compiled data

However, more specific information on the sources for the costs and CO_2 savings of individual measures or packages or how values from the literature were discussed with stakeholders and potentially revised is not provided.

The technology costs estimated are production costs. These are then multiplied by a mark-up factor. In IKA (2014) a standard mark-up factor of 1.6 is taken for estimating the impact on retail prices (in a set of sensitivities mark-up is varied between 1.2 and 2). The mark-up factor also incorporates the effect of VAT which averages around 20% across Europe.

IKA (2014) appears to apply a learning factor to capture technology cost reductions over time while the costs estimated in IKA (2012) were estimated directly for 2020 (the mark-up factor is varied, with the conservative scenario using higher mark-up than the progressive scenario in order to account for the effect of lower production volumes).

The different technologies are bundled into a total of five technology packages. TP1 is the most basic technology package consisting of the most basic fuel savings measures while TP5 is the technology package with the most extensive technology uptake and deepest levels of downsizing and lightweighting. Packages TP2 to TP5 also come as hybrid and plug-in hybrid variants.

Technology packages are:

- Plausible bundles of single technologies
- They can be applied in a combined way to the reference vehicles
- They represent alternative vehicle configurations
- In IKA (2014) it is assumed that production costs decrease + CO_2 reduction potential increases over time due to learning (depending on scenario)

The CO_2 reduction potential of these packages was defined by applying a ‘specifically defined correction factor’ in order to not overstate the potential when adding the individual reduction potentials of the technologies together. The factors used in IKA (2012) were 0.75-0.90 for petrol cars and 0.97-0.99 for diesel cars whereas the factors used in IKA (2014) aren’t stated.

A comparison of the cost and percentage CO_2 emission reductions between the 2012 and the 2014 study for the year 2020 reveals that data and assumptions between the two studies has indeed largely remained constant. Only in the case of small segment diesel cars costs were estimated some 15% lower for most technology packages in the 2014 study.

4.2.4.5 Powertrain penetration

After the technology packages and their costs were defined, uptake of these technology packages in the market was estimated, thus providing forecasts for resulting fleet average CO_2 reductions. IKA defined three scenarios based on energy price differences which result in different uptake levels of technology packages. The emissions reductions resulting from the level of uptake calculated under the three scenarios are defined as the ‘Economic Reduction Potential’.

- *Conservative scenario*: In the conservative scenario energy prices increase less than they have over the past 10 years. This leads to reduced fuel cost savings from each technology package. Since consumer technology uptake is driven by payback (see below) the conservative scenario results in lower technology uptake and thereby low reductions to fleet average CO_2 emissions. Moreover, the 2014 study assumes no learning effects or further CO_2 reductions from given technology packages towards 2025 and 2030 under the

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[18] The stated literature sources are (TNO et al., 2011), (TNO et al., 2012), as well as selected ATZ and MTZ articles.

conservative scenarios so technologies remain relatively expensive, further slowing their uptake.

- *Trend scenario*: In the trend scenario, energy prices increase in line with the change over the last 10 years, leading to greater economic viability of fuel saving technologies and hence greater uptake. Some learning assumed for 2025 and 2030.
- *Progressive scenario*: The progressive scenario assumes higher energy price increases than over the last 10 years which leads to the highest uptake of fuel saving technologies among the three scenarios. Moreover, the highest technology cost reductions towards 2025 and 2030 are assumed as the high demand for technologies induces steeper learning rates and economies of scale.

Uptake of technology packages is cost-based. In the 2012 study, discounted future savings were set against the additional technology costs to users. In the 2014 study the methodology was simplified to the requirement of an undiscounted payback over four years of ownership. Each of the three segments features four different use profiles: a high-mileage and a low-mileage profile each for commercial and private buyers. The differences in annual mileage affect the cost effectiveness of the technology package uptake. For commercial buyers (who account for 50% of new car purchases in Segments 1 and 2 and 80% in Segment 3 as well as 100% of LCV purchases) this is the only selection criterion for determining uptake of a technology package. Private buyers are split into five consumer types, differentiated by the extent of their willingness to pay extra for the technology packages. Uptake of battery electric vehicles is exogenously defined in a separate scenario. The base year for cars is 2010 (in both studies) and 2011 for LCVs.

4.2.5 US National Research Council (2002 & 2011)

4.2.5.1 General overview

In 2001, the US Government tasked the National Research Council with a study to evaluate the effectiveness and impacts of the CAFE standards. NRC (2002) reports the results of this study. Part of this work also addressed the case for tightened CAFE standards or other approaches for incentivising fuel economy. Therefore, a cost-effectiveness analysis for new fuel saving technologies was carried out.

NRC (2011) is an update of the technology assessments for fuel economy improvements and incremental costs contained in NRC (2002). It was requested in 2007 by the National Highway Traffic Safety Administration (NHTSA). The target was to also include technologies that has emerged since the publication of NRC (2002) and ‘estimate the efficacy, cost, and applicability of technologies that might be used over the next 15 years. It improved its methodology based on feedback from NRC (2002) and spells out its assumptions more clearly. 43 different technologies are assessed (NRC (2002) only covered 24).

4.2.5.2 Segmentation

Estimates are developed for three distinct vehicle categories: passenger cars, SUVs/minivans and pickup trucks. Costs are not differentiated by segment (e.g. within passenger cars) but some technologies are indicated to only be available for/applicable to larger passenger car segments. NRC (2011) highlights the issue of addressing an insufficient number of vehicle segments in the 2002 report.

In NRC (2011), technology cost estimates are developed for I4, V6 and V8 engines. More detailed modelling of the fuel consumption of different technology packages on different vehicle types is carried out as in several cases the aggregate benefit from a set of measures is less than the sum of savings from individual measures on their own.

4.2.5.3 Technology coverage

For passenger cars, 24 fuel saving technologies and their costs are covered. Most of these are engine technologies including various valve timing and injection configurations. Several transmission technologies such as gearboxes with higher number of gears are also included. In addition, there are various individual measures including an integrated starter-generator as first step towards hybridisation as well as 42V electrical system, 5% lightweighting, aerodynamic improvements, improved rolling resistance, and electric power steering.

In NRC (2011), a broad range of fuel saving technologies is covered, consisting of the following:

- Various engine technologies (adjustments to valves and injection)
- Transmission technologies
- Several modes of hybridisation: from start-stop to power split, P2 and PHEV
- Vehicle based measures: five levels of mass reduction, 10% aerodynamic improvements, improved rolling resistance
- Auxiliary improvements: electric power steering, higher voltage board system, improved appliances

4.2.5.4 Methodology for developing cost and CO_2 estimates

The report lists several sources from which it developed its cost estimates. These include:

- Meetings with manufacturers and suppliers
- Use of consultants for further information
- Derived own estimates based on expert judgement
- Stakeholders provided feedback to initial estimates, minor errors were corrected

The results tables list a lower and an upper bound estimate both for the fuel savings obtained through a specific technology and its costs. Cost estimates are given as ‘retail price equivalent’, i.e. the “incremental cost that applying the technology would add to the retail price of a vehicle”. However, there is no further explanation on assumed production costs and mark-up factors, etc. The study estimated technology prices at the time of writing. No forecasts have been made.

In NRC (2011) the following sources for the estimates were used:

- recent reports from regulatory agencies and other
- sources on the costs and benefits of technologies
- teardown studies of piece costs for individual technologies
- discussions with manufacturers and suppliers
- comparisons of vehicle retail prices and fuel consumption of comparable vehicles fitted with different technologies

As a first step, an estimate for long-run manufacturing cost was developed. A mark-up factor was then applied to those estimates in order to determine increase in average purchase price paid by the consumer. An average mark-up of 1.5 was assumed for parts purchased from suppliers. For technologies made in-house by manufacturers the assumed mark-up is 2.

While no deeper detail is provided about the assumptions under which the individual estimates were derived the discussion does acknowledge the importance of differing assumptions for results: *“Large differences in technology cost estimates can result from differing assumptions. These assumptions include whether costs are long- or short-term costs; whether learning by doing is included in the cost estimate; whether the cost estimate represents direct in-house manufacturing costs or the cost of purchasing a component from a supplier; and which of the other changes in vehicle design that are required to maintain vehicle quality have been included in the cost estimate. Cost estimates also depend greatly on assumed production volumes.”*

As in NRC (2002), no forecasts into the future have been made. *“The cost estimates represent estimates for the current (2009/2010) time period to about 5 years in the future.”*

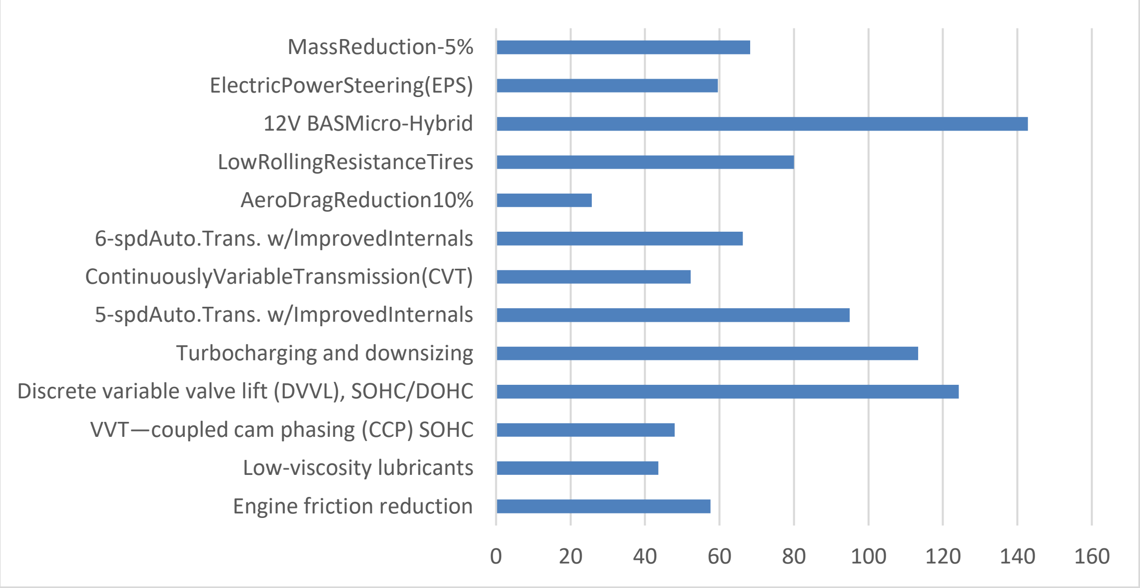
4.2.5.5 Powertrain penetration

The NRC studies examine the costs and emissions savings of technologies at a vehicle level. No subsequent fleet modelling is performed to assess costs of attaining a giving emission standard at a fleet level etc. Consequently, no estimates on powertrain penetration have been made.

4.2.5.6 Comparison of results

Out of the 24 technologies included in NRC (2002) and the 43 included in NRC (2011), 13 technologies feature in both datasets. The difference between the two estimates is illustrative of the impact of improved methodology and data availability, as well as cost reductions over time. In order to adjust for the impact of inflation, the comparison has been made after converting both sets of cost data to 2010 US dollars.

Figure 4.3: Index (2002=100) of technology cost estimates from NRC (2002) to NRC (2011), real prices



Overall, the comparison shows significant reductions in most technology costs. Only in the case of two of the most expensive technologies, namely ‘micro-hybrid’ and ‘turbocharging and downsizing’ the 2011 costs are significantly above the 2002 costs (a start-stop micro hybrid is estimated to cost around $350 in the 2002 study and $500 in the 2011 study, turbocharging and downsizing is estimated at $575 (2002) vs $650 (2011)). This may be partly attributable to the high mark-up (factor of 1.5-2) on production cost which NRC (2011) has explicitly accounted for. Due to the high costs of these measures, as a weighted average across all 13 measures cost estimates for 2011 are only 14% below 2002 estimates.

4.3 Integrating relevant information from the “Downweighting” study

4.3.1 Overview of methodology for integrating the downweighting study findings

This task involved the integration of relevant outputs from the “Downweighting” study conducted for the Commission (Ricardo-AEA, 2015) into the data collection and analysis process used for this project. This was therefore not a standalone task; rather, the Commission’s specification indicated that relevant information, outputs and results should be incorporated into this project where relevant. For this task the key findings and outputs captured and transferred across to this project have been outlined below.

4.3.2 Summary of the results for integration the downweighting study findings

Of particular importance are the new estimates for the costs associated with vehicle mass reduction developed in the “Downweighting” study (Ricardo-AEA, 2015), which have been used to form the basis of the estimates used in this new project. In particular, prior to the “Downweighting” study, the estimates for the costs of mass reduction were initially based on work carried out by TNO et al (TNO et al., 2011) (TNO et al., 2012), which provided estimates for the costs of reducing the mass of the vehicle body-in-white (BIW) by 10%, 20% and 40%. Separate estimates for the costs of mass reduction for all other possible components were also developed, but without any specific mass reduction target (note that these estimates were not developed for individual components or systems, but rather on the basis of combinations or groups of other components where it is possible to reduce mass). More recent research carried out in the USA and funded by the EPA and the NHTSA indicated that the cost estimates developed by TNO et al may now be too high.

Our research during the “Downweighting” study has led to the following findings:

- The previous TNO et al estimates for the costs of mass reduction are likely to be too high for use in developing a post-2020 regulatory regime for addressing CO_2 emissions from cars and light commercial vehicles;
- Many vehicles on the market today are already equipped with a wide variety of mass reduction measures, and hence this factor needs to be taken into account when developing the 2013 baseline vehicles (discussed earlier in section 2.4.1.2);
- The previous approach of separating out the costs of BIW mass reduction and other types of mass reduction is not the most appropriate way of addressing the potential costs associated with reducing the mass of vehicles. It is more appropriate to treat the vehicle as a whole and develop cost estimates for mass reduction on this basis. This is in line with the approach used by the US EPA, and has formed the basis of the analysis.
- New estimates for the costs of vehicle mass reduction have been developed based on 10%, 20% and 30% reductions in the **overall** mass of small, medium and large vehicles, using 2010 vehicles for baseline estimates. Note that whilst a 40% reduction in BIW mass is feasible, this level of mass reduction for whole vehicles is unlikely to be realistic (i.e. economically viable) in the 2020-2030 time period. The specific figures fed into this project’s analysis are summarised in Table 4.12.
- The cost estimates developed during the SR1 Downweighting study have been adjusted to bring them into line with the approach that we are using for this new study on LDV technologies. In particular, the estimates have been amended to address any changes in segmentation that we develop and to deal with updated baseline year.

Table 4.12: Summary of mass reduction costs from the SR1 Downweighting study utilised in this project

SR1 Segment	SR4 Segment	Reduction in total vehicle mass		
		10%	20%	30%
Small Cars	Small Cars	€ 31	€ 200	€ 738
Medium Cars	Lower Medium Cars	€ 39	€ 250	€ 923
Large Cars		€ 48	€ 300	€ 1,106
	Upper Medium Cars*	*€ 46*	*€ 286*	*€ 1,053*
	Large Cars*	*€ 52*	*€ 325*	*€ 1,199*
Small LCVs	Small LCVs	€ 38	€ 409	€ 2,044
Medium LCVs	Medium LCVs	€ 44	€ 477	€ 2,386
Large LCVs	Large LCVs	€ 83	€ 886	€ 4,429

Notes: Estimated based on extrapolation of the values for SR1 Large Cars, based on the combined weighted average mass of SR4 Upper Medium Cars and Large Cars relative to the mass of the individual SR4 segments.

4.4 Development of vehicle technology fiches

The objective of this task was originally to provide a summary fiche of information on the result of the review and extraction of key data from the identified literature for each of the technologies identified in earlier tasks (Section 3), including an attempt to bring the different datasets onto a similar cost basis.

It was originally hoped/anticipated that it might be possible to more fully disaggregate the different cost sub-components than has actually proved the case. For example, the detailed analysis by FEV for the US EPA and for ICCT, e.g. (FEV, 2013a) involved fully disaggregating a range of specific technologies into sub-components and used a range of assumptions on the breakdown of direct manufacturing costs into material, labour and other components, as well as detailed assumptions on indirect costs. The total costs were defined on a component basis and the final net costs were simply a comparison between the total costs for the baseline vehicle and the vehicle upgraded with the new technology. Therefore the relationships on the relative shares of the different cost components at the total system level could not be used/extrapolated in a valid way for other types of technology. Without access to more detailed underlying data (which FEV was not happy to provide), only the over-arching methodological approach using learning rates on the total direct manufacturing costs and the use of the already developed ICMs (indirect cost multipliers) was possible.

These ICMs have therefore been used to estimate the direct manufacturing cost (DMC) components for identified technology costs that were assumed to be on a total manufacturing cost basis. For example, discussions with experts TNO confirmed that the final technology costs produced under previous Commission studies, such as (TNO et al., 2011) and (TNO et al., 2012), were assumed to be on this basis. A summary of the development and review of the overall cost calculation methodology for the project via a Delphi Survey with experts is provided in later section 4.7.

The overall fiche of information has been split into two parts for better manageability:

1) **Technology Source Data Fiche (TSDF)**: Providing the input source data, references and initial transformations (i.e. to bring data onto the same basis). This is discussed further in this section;
2) **Technology Results Data Fiche (TRDF)**: A summary file providing the final analysis results – i.e. the output of uncertainty analysis with typical, low and high cost estimates for different technologies, as well as providing the scaling factors, learning rates and, ICMs used in the analysis, plus the assumed CO_2 reduction potentials for different segments, cycles and time periods. This file also provides summary descriptions of different technologies. This is discussed in later Section 7.

Due to the volume of information, both fiches have been provided to the Commission in full only as Excel files, with a limited selection of the information provided in the results fiche file also provided in Appendix 4 and 6. Both files have been provided also in their final forms alongside this report.

The project had to consider a higher number of individual technologies than originally envisaged. The identification and gathering of information on the costs and CO_2 reductions of these has involved the review of hundreds of individual sources, since only a few select major sources provide information on multiple technologies, and have not covered already most of the new technologies added for this project. As a result this has generated a very considerable amount of data in the source data fiche – almost 4000 rows of CO_2 and cost data in the main dataset, from 200 individual reference sources. Therefore it has only been feasible within the available project resources to carry out in-depth assessments of a small sub-set of the major sources (discussed in earlier Section 4.2). A high-level assessment of each of the individual data sources has also been performed, and is summarised in the source data fiche. This assessment provides indications by reference source on the following criteria:

A. General reference information:

1) Short name
2) Title
3) Publication year (or accessed year for website)
4) Link if available
5) Vehicle segments/types covered

B. Cost data:

1) Method basis (e.g. tear-down, expert review, internal data, comparison of prices, etc.)
2) Cost breakdown? (e.g. was the cost figure provided estimated from or broken down into sub-components?)
3) Cost basis (what basis were the overall cost figures provided in – e.g. direct manufacturing cost, total cost, retail price, etc.)
4) Currency and currency year
5) Cost year and/or whether estimates are provided for the change in costs over time or not.

C. CO_2 / energy reduction data:

1) Methodology basis (e.g. vehicle testing, simulation, internal data, general literature, etc.)
2) Test cycle/CO_2 savings basis (e.g. NEDC, WLTP, FTP-75, Real-world, etc.)
3) Year assumed for CO_2 reduction potential (i.e. current technology performance, or advanced/optimised future system)
4) Whether future improvements to the technical performance are anticipated/provided.

Further information is also provided for the specific data points in the source fiche where this was available. Clearly it has not been possible to deconstruct individual data points with almost 4000 entries, so many of the subsequent transformations necessary to bring the individual cost data onto the same basis have been performed automatically using the general data for the source or data point. Such transformations included:

- Converting costs to 2014 Euro basis (using Eurostat data on rates of inflation[19] and historical trends in currency conversion rates[20]),
- Converting to direct manufacturing cost or total cost basis using the final project ICMs (based on those developed by FEV for Europe – see Sections 4.7 and 7.3), and
- Forward- or reverse- learning of cost estimates to 2015 or 2020 cost basis using the finally agreed learning rates for individual technologies (discussed further in later Section 7).

In addition to these data fiches for conventional technologies, the information collated and used for the analysis of the future costs and energy consumption/CO_2 performance of baseline xEV powertrains has been provided in a separate file (see also Section 4.5). With key assumptions also included in Appendix 2 of this report.

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[19] http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=prc_hicp_aind&lang=en
[20] http://www.oanda.com/currency/historical-rates/

4.5 Estimating the future costs and CO_2 benefits of advanced xEV powertrains

Section 2.4.2 has already summarised the over-arching approach to characterising xEV powertrains and the development of estimates for the energy consumption and CO_2 performance and costs by using estimates for the costs and masses of individual components and scaling these to different segments using baseline vehicle characteristics. This section provides a further discussion of the calculation of the baseline CO_2 emissions and the initial estimates of the additional costs of different xEVs.

4.5.1 Energy consumption and CO_2 emissions of xEVs

The current baseline performance in terms of the energy consumption of xEV powertrains was estimated based on the relative improvement in energy consumption for a given xEV powertrain type compared to the average value for a given vehicle segment. This is summarised using the lower medium car values in the following Table 4.13. Direct CO_2 emissions from PHEVs and REEVs were simply calculated using standard fuel properties for petrol and diesel, and the assumed share of pure electric driving (see Appendix 2 for further detail on assumptions).

Table 4.13: Example for the estimation of the 2013 baseline xEV MJ/km for lower medium cars

Powertrain	Baseline MJ/km (Lower Medium Car)		Relative MJ/km for pure electric drive		Relative MJ/km for charge-sustaining drive	
	Total Av.	Petrol Av.	% of Baseline	MJ/km	% of Baseline	MJ/km
Baseline ICEV	1.75	1.89				
Petrol PHEV	1.75	1.89	29%	0.51	73%	1.37
Petrol REEV	1.75	1.89	28%	0.49	82%	1.55
BEV	1.75	-	24%	0.42	0%	0.00
FCEV	1.75	-	28%	0.49	53%	0.93

Improvements in energy consumption of baseline xEVs in future periods (see earlier Table 2.10) were estimated from a combination of the following two elements:

a. Anticipated improvements in overall electric drive efficiency based on data from (JRC, 2011);

b. Change in energy consumption resulting from a change (reduction) in overall mass of the xEV systems based on projected changes in mass of individual components (see Appendix 2)[21]. This included a first order correction to the battery-size/mass based on the initial calculation of energy consumption on electric drive and the required pure electric range.

A sensitivity was also conducted on how the mass of the battery might change (and therefore also its impact on overall vehicle efficiency and costs) if advanced battery chemistries (i.e. lithium sulphur or solid state batteries) were utilised versus the baseline assumption of further advances in conventional lithium ion based chemistries. The results of this for lower medium cars is presented in Table 4.18.

Table 4.14: Sensitivity on battery chemistry assumptions for xEV MJ/km, lower medium cars

Powertrain	2013	2020	2025	2030
Lithium-ion battery chemistries				
Petrol PHEV	0.796	0.757	0.749	0.744
Diesel PHEV	0.744	0.708	0.701	0.696
Petrol REEV	0.699	0.660	0.650	0.644
Diesel REEV	0.664	0.627	0.617	0.612
BEV	0.424	0.409	0.398	0.391

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[21] *Note*: for batteries this calculation base based on the dynamic between assumptions for the change in all-electric range for BEVs in different segments (see later Table 4.15), and improvements in the overall gravimetric energy density of the battery systems over time

Powertrain	2013	2020	2025	2030
FCEV	0.926	0.841	0.831	0.822
Advanced battery chemistries				
Petrol PHEV	0.796	0.748	0.743	0.740
Diesel PHEV	0.744	0.699	0.695	0.692
Petrol REEV	0.699	0.648	0.642	0.638
Diesel REEV	0.664	0.616	0.610	0.607
BEV	0.424	0.390	0.385	0.381
FCEV	0.926	0.840	0.830	0.822
% Change in MJ/km				
Petrol PHEV	0.0%	-1.2%	-0.8%	-0.6%
Diesel PHEV	0.0%	-1.2%	-0.8%	-0.6%
Petrol REEV	0.0%	-1.8%	-1.2%	-0.8%
Diesel REEV	0.0%	-1.8%	-1.1%	-0.8%
BEV	0.0%	-4.6%	-3.2%	-2.5%
FCEV	0.0%	-0.2%	-0.1%	-0.1%

4.5.2 Additional powertrain costs of xEVs

As indicated in earlier sections, the current baseline direct manufacturing costs of xEV powertrains was estimated based on the assumptions on the costs of individual components and the scaling factors for certain of these based on comparable baseline ICEVs (i.e. motors, batteries, etc.). The details of the assumptions utilised are provided in Appendix 2 (although the initial estimates on future cost reduction of key components has been superseded by the scenario analysis in Section 5.4).

Critical to the estimates of overall costs are the assumptions on all-electric range for xEVs. A summary of these assumptions is presented in Table 4.19 below. These electric range assumptions represent assumed indicative market averages, and in reality it is likely there will be a range of different market offerings available to suit different budgets/users. It is assumed that the average BEV range for small cars does not increase as fast or far as those of other segments, as this segment is particularly sensitive to cost, so improvements in battery cost and size/mass are more likely to be used to reduce the overall cost of the vehicle rather than increasing range/utility. Whilst certain models are likely to have longer range (e.g. the forthcoming 2017 Chevrolet Bolt), significant mass-market adoption for this segment in the period post-2020 will likely require cheaper lower-range models to also be available.

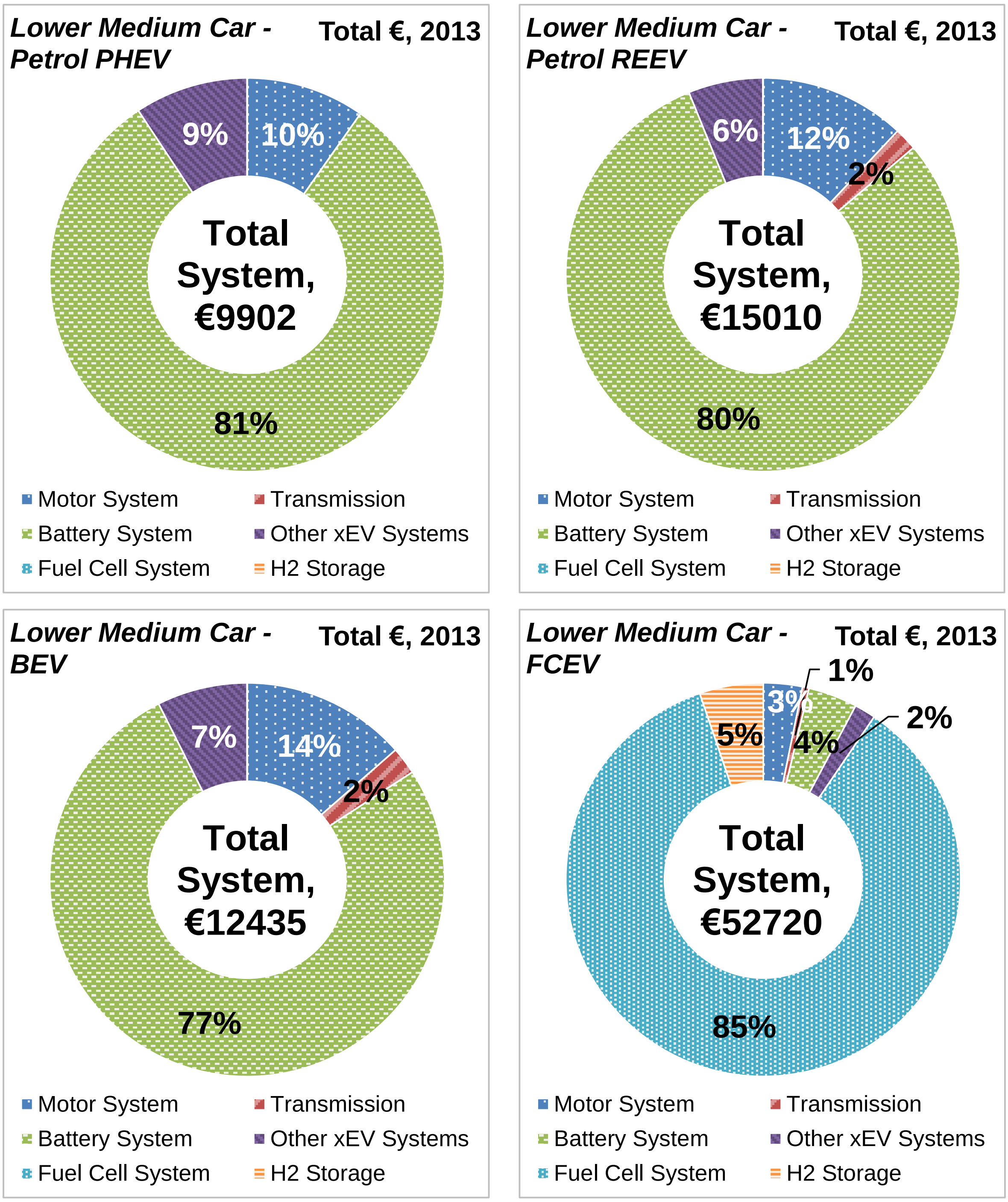
Table 4.15: Assumed all-electric range (km) for different xEV powertrain types

	Segment	2013	2020	2025	2030
PHEVs	All	50	50	50	50
REEVs	All	80	80	80	80
FCEVs*	All	5	5	5	5
BEVs					
	Small Car	150	200	210	220
	Lower Medium Car	180	280	300	320
	Upper Medium Car	200	300	330	360
	Large Car	250	400	425	450
	Small LCV	150	200	210	220
	Medium LCV	180	280	300	320
	Large LCV	200	300	330	360

Notes: * Nominal, for battery-sizing purposes

The indicative system cost breakdown for 2013 baseline vehicles derived using the xEV calculation methodology is provided for different xEV types in the following Figure 4.4 (costs are presented for petrol PHEVs and REEVs only; costs for diesel equivalents are similar). Although they have smaller battery packs, the costs per kWh for PHEVs /REEVs are roughly double those of BEVs, due to different cell power requirements. A larger SOC reserve is also required, further driving up system costs.

Figure 4.4: 2013 Estimated xEV system breakdown by cost for Baseline 2013 Lower Medium Car



As indicated for CO_2 /energy consumption reductions, a sensitivity was also conducted on how the cost of the battery might change if advanced battery chemistries (i.e. lithium sulphur or solid state batteries) were utilised versus the baseline assumption of further advances in conventional lithium ion based chemistries. The results of this analysis for lower medium cars are presented in Table 4.16 for the initial cost projection assumptions (see Section 5.4 for impacts of the powertrain scenario analysis on these). The ICMs assumed for xEVs are also presented in Table 4.17. It is assumed that these will be broadly similar to full HEVs for most powertrain types, but for FCEVs which are currently more complex and at an earlier stage of deployment, it is assumed the initial cost share will be higher (at the maximum value assumed by FEV in their analysis for ICCT, (FEV, 2013b)).

Table 4.16: Sensitivity on battery chemistry assumptions for xEV *additional direct manufacturing costs, lower medium cars 2013-2030**

Powertrain	2013	2020	2025	2030
Lithium-ion battery chemistries				
Petrol PHEV	€ 9,738	€ 5,348	€ 4,549	€ 4,041
Diesel PHEV	€ 9,399	€ 5,046	€ 4,254	€ 3,755
Petrol REEV	€ 14,156	€ 7,399	€ 6,188	€ 5,431
Diesel REEV	€ 13,870	€ 7,150	€ 5,945	€ 5,195
BEV	€ 9,644	€ 6,671	€ 5,541	€ 4,918
FCEV	€ 49,929	€ 19,573	€ 13,862	€ 11,337
Advanced battery chemistries (after current 2013 = Li-ion)				
Petrol PHEV	€ 9,738	€ 9,693	€ 4,526	€ 3,748
Diesel PHEV	€ 9,399	€ 9,394	€ 4,232	€ 3,461
Petrol REEV	€ 14,156	€ 13,906	€ 6,139	€ 4,982
Diesel REEV	€ 13,870	€ 13,661	€ 5,897	€ 4,746
BEV	€ 9,644	€ 14,576	€ 5,357	€ 4,197
FCEV	€ 49,929	€ 20,436	€ 13,861	€ 11,282
% Change in MJ/km				
Petrol PHEV	0.0%	81.2%	-0.5%	-7.3%
Diesel PHEV	0.0%	86.2%	-0.5%	-7.8%
Petrol REEV	0.0%	87.9%	-0.8%	-8.3%
Diesel REEV	0.0%	91.1%	-0.8%	-8.6%
BEV	0.0%	118.5%	-3.3%	-14.6%
FCEV	0.0%	4.4%	0.0%	-0.5%

Notes: The additional direct manufacturing costs take into account both the estimated costs of the xEV powertrain system, and the savings from any ICEV components downsized or no longer needed.

Table 4.17: Baseline assumed Indirect Cost Multipliers (ICMs) for different xEV powertrain types

	2013	2020	2025	2030
BEV	0.719	0.429	0.164	0.164
PHEV	0.719	0.429	0.164	0.164
REEV	0.719	0.429	0.164	0.164
FCEV	0.860	0.513	0.196	0.196

Notes: ICM includes an estimated 3% OEM profit margin, based on analysis of information from (VVA et al, 2015) and given stakeholders' views as expressed in the Delphi survey carried out for this study (see section 4.7).

4.5.2.1 Batteries

As part of the research and consultation activities carried out in this project, a range of material was gathered on the anticipated improvements in performance and costs of battery technologies. Feedback on the initial project assumptions on the trajectories in battery costs was also obtained from the consultation and validation process, which included producers of both BEVs and batteries.

The main factor influencing the speed of powertrain electrification is battery or energy storage technology. All four battery families (Lead, Nickel, Lithium and Sodium-based batteries) are used in the different levels of powertrain hybridisation/electrification. Start-stop functionality (also named micro-hybrid when energy recuperation/regeneration is also included) is generally powered by advanced lead-based batteries in almost all new ICE vehicles being placed on the market. Nickel and lithium-based batteries are a key determinant of the overall cost and performance of current HEVs, with lithium-based batteries currently being exclusively used for more advanced xEVs including plug-in vehicles (i.e. PHEVs, REEVs and BEVs) as well as FCEVs. Improving battery technology and reducing cost is widely accepted as one of the most important, if not the most important, factor that will affect the speed with which these vehicles gain market share. There is currently huge research and development activity underway, focusing on four key areas where breakthroughs are needed:

1. Reducing the cost (per kWh and per complete vehicle pack);
2. Increasing the specific energy (to improve vehicle range/performance for a given battery weight or reduce weight for a given battery kWh capacity);
3. Improving usable operational lifetime; and
4. Reducing recharging times

In the short- to mid-term, lithium ion battery technology is expected to form the principal basis of batteries for use in full HEVs (together with NiMH) and more advanced plug-in vehicles (i.e. PHEVs, REEVs and BEVs). However, a number of new technologies are being researched. In the medium term lithium-sulphur and solid-state advanced battery chemistries hold perhaps the most promise (up to five times the energy density of lithium ion). Responses to the consultation suggested that these advanced battery chemistries were highly unlikely to make it into vehicles before 2025 at the earliest (at least to any significant degree). The available literature and most respondents also indicated that although lithium-air has potentially greater potential (up to ten times lithium ion energy density), there are still many challenges to address and these batteries are expected to be many years from commercialisation (i.e. likely to only be available for application in vehicles well beyond 2030).

Research and interviews with both OEMs and a battery manufacturer indicated that whilst lithium-sulphur technologies have a very high energy density, the cycle lifetime is somewhat lower than lithium-ion chemistries. This means that this type of battery chemistry is more suited to vehicles with longer electric range/larger battery packs, as this means the number of cycles in the lifetime is less (since the distance travelled between charges is less). This is also part of the rationale for the approach that Tesla has adopted – i.e. using both cheaper and higher energy density lithium ion batteries (versus those used in other EVs) with lower cycle lives but much larger packs to mitigate for this.

A review of available literature, as well as previous analysis by Ricardo Energy & Environment (e.g. (Ricardo-AEA, 2013)), has shown that the costs for batteries (per kWh capacity) are expected to reduce by half in the next 10-15 years. Indeed the Gigafactory being built by Tesla in the US is anticipated to reduce the cost of batteries produced by some 30% purely through increased scale (Tesla Motors, 2014). This view on the level of likely battery cost reductions was also supported by most of the stakeholders that commented on battery technologies. Some respondents, particularly those more strongly advocating for FCEVs, indicated that they believe that this may be an over-estimate. However, other sources suggest that the rate of cost reduction could be even greater. For example, Volkswagen has recently indicated that they believe a 67% cost reduction in the battery packs for their electrified vehicles might be possible by moving to a single common design for all their models (Beene, 2015), as well as other factors. The EUROBAT R&D roadmap also has a target of reaching €200/kWh (US$260/kWh) by 2020 (current battery costs are estimated at €375/kWh). There are also numerous other examples of statements made by OEMs on the anticipated cost reductions and increases in electric ranges for the next generation of BEVs being introduced in the next five years, e.g. (Brogan, 2014), (Crosse, 2014), (Schmitt, 2014). Whilst it is important to treat such announcements with a degree of caution, the number and range of them seem to support the general consensus that a significant range increase and battery cost-reduction is possible and expected for BEVs in the period up to 2030 through a combination of improved chemistries and increased scale of manufacture. Such considerations were therefore also used to sense-check the outputs of the sensitivities on xEV component/powertrain cost explored using alternative powertrain deployment scenarios (see later Section 5.4).

In terms of battery costs for other types of xEVs, PHEV/REEV batteries cost more than BEV batteries, per kWh. This is because the power requirements place a proportionally larger demand on the smaller battery pack in a PHEV, so batteries with higher power must be used at a somewhat higher cost. This is also illustrated in the range costs for current battery packs presented in (ACEA et al, 2014). In this study we have assumed a cost differential of a factor of two between BEVs and PHEVs/REEVs per kWh capacity to account for this.

In terms of estimating the likely increases in electric range / battery capacity for BEVs in future years, a number of respondents indicated that this was more constrained by volume considerations, rather than mass, as there is only a finite volume available for them in different segments before significantly affecting utility. The projected improvements in both gravimetric and volumetric energy density of batteries was therefore factored into the assumptions used in the xEV powertrain analysis (see earlier Table 4.15).

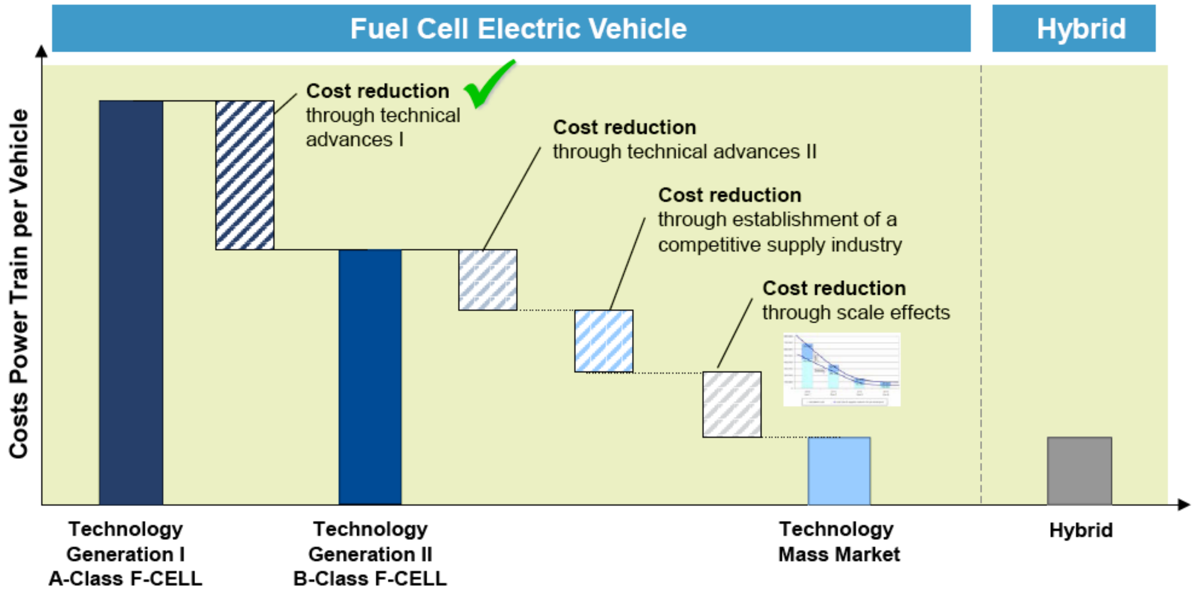
4.5.2.2 Hydrogen Fuel Cells

As for batteries, a range of material was gathered on the anticipated improvements in performance and costs of fuel cell and hydrogen storage technologies. Feedback on the initial project assumptions on the trajectories in battery costs was also obtained from the consultation and validation process, with included producers of both FCEVs and the fuel cells themselves.

While many manufacturers have active R&D programmes developing fuel cell technology, there are still a number of barriers to bringing the technology to the marketplace, including improvements to the costs and performance of fuel cells and reducing the cost of hydrogen storage.

Ricardo Energy & Environment has previously gathered information and tested assumptions on the projected future fuel cell and hydrogen storage costs in a number of projects, for example in recent work for ECF (Ricardo-AEA, 2013), where the assumptions used were also tested with/informed by industry experts. During the course of this current project Ricardo Energy & Environment sought further feedback from relevant OEMs and a fuel cell manufacturer to better understand and characterise the assumptions used in the xEV analysis. This review also included consideration/justification for the much higher rates of cost reduction anticipated for fuel cells, which is also summarised in Figure 4.5 below.

Figure 4.5: Cost reduction potentials of fuel cell technology (Daimler AG, 2013)



Source: (Daimler AG, 2013)

Since this project started, Toyota has commercially launched its Mirai FCEV in Japan and the US, with the European launch planned for later in 2015. This follows a number of FCEV models available from other manufacturers for lease or introduced in limited production, for example Honda produced a limited run of 200 FCX Clarity FCVs available for lease in California and Hyundai started limited production in February 2013 for lease to public and private fleets (and expects to build 1,000 vehicles for lease by 2015) (Hyundai, 2013)[22]. Some other manufacturers have similar expectations to launch commercially FCEVs in the next few years, including joint collaborations on the technology by a number of OEMs (Nissan, 2015). Although the cost of fuel cells (and FCEVs) is currently very high (even in relation to BEVs), there is an expectation that costs will reduce rapidly in the early years of commercial deployment. A recent study by the Carbon Trust (2012)[23] predicts that polymer fuel cell technology could achieve a step-change in cost reduction, with expected mass production costs coming down to around US$36/kW (current fuel cell system costs are around US$1,200/kW). This can also be compared to earlier figures form MacKinsey (2010), which suggested fuel cell stack costs could reach €43/kW as early as 2020. However, 5 years on this level of cost reduction now seems highly unlikely for 2020 and our analysis utilised slightly more conservative figures for the whole fuel cell system cost based on feedback from Daimler and ICCT from earlier work (Ricardo-AEA, 2013) as a starting point for the exploration of future cost reduction potential. Toyota have, however, also indicated that the cost of their next hydrogen-fuelled powertrain could be between one-third and one-fourth the cost of the current system in the Toyota Mirai FCEV (Automotive News, 2014).

A number of organisations commented (as part of the data validation and interview process) on the initial project assumptions on future fuel cell cost reduction and the rationale for the rapid cost reduction anticipated over the next 15 years. In particular, it has been noted that global automotive fuel cell production is currently measured in volumes of low 1000s. With Toyota, and soon Honda, Suzuki, Nissan, Daimler, etc. bringing fuel cells cars into production, then these volumes are likely to increase significantly. Compared to automotive lithium-ion battery technology, which is somewhat mature in terms of technology development supply chain and manufacturing, fuel cells are still undergoing rapid development of technologies, materials, system components, manufacturing processes and supply chain and hence have the potential for dramatic reduction in cost.

The fuel cell system cost constitutes of material cost, including precious metal, and manufacturing cost. The latter impacts the cost more than the former factor. The system currently requires a unique manufacturing process that not only satisfies unique specification requirement but also shortens the

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[22] Hyundai (2013). HYUNDAI CELEBRATES WORLD'S FIRST ASSEMBLY LINE PRODUCTION OF ZERO-EMISSIONS FUEL CELL VEHICLES. Retrieved on 20 March 2013 from http://www.hyundaipressoffice.co.uk/release/379/#

[23] Carbon Trust (2012). Polymer Fuel Cells – Cost reduction and market potential. Retrieved 14 March 2013 from www.carbontrust.com/about-us/press/2012/09/the-futures-bright-for-fuel-cells.

time for mass production. This is not a well-developed area, so it is believed that once it succeeds then it is expected that we would see cost reduction faster than for battery technologies.

There is also significant opportunity in aggregation of components across the industry with commodity components such as compressors, sensors, air/water separation, heat exchangers etc. already being used by multiple fuel cell system suppliers according to another stakeholder. In addition there are a number of FCEV components (such as air, fuel, thermal and control systems) that share significant synergies with petrol engines, so the development of a competitive supply chain with resulting cost reductions and volume increase seems reasonable to anticipate with the roll out of FCEVs.

According to the fuel cell manufacturer interviewed, the key challenge for reducing the cost of fuel cell stack technology is therefore primarily focused upon the materials used for the membranes, catalysts and diffusers in the cells plus the manufacturing techniques employed in producing the bipolar plates and the actual stack assembly process. In this area there are also some significant synergies between fuel cell and battery manufacture and assembly. There is therefore potential to transfer knowledge gained in the automated assembly of batteries (especially Li ion) to the fuel cell industry.

Such considerations have therefore been taken into account when assessing the material on fuel cell costs and performance and in sense-checking the results of the future xEV powertrain costs developed using the scenario-based learning approach outlined in later Section 5.4 of this report.

4.6 General stakeholder engagement activities

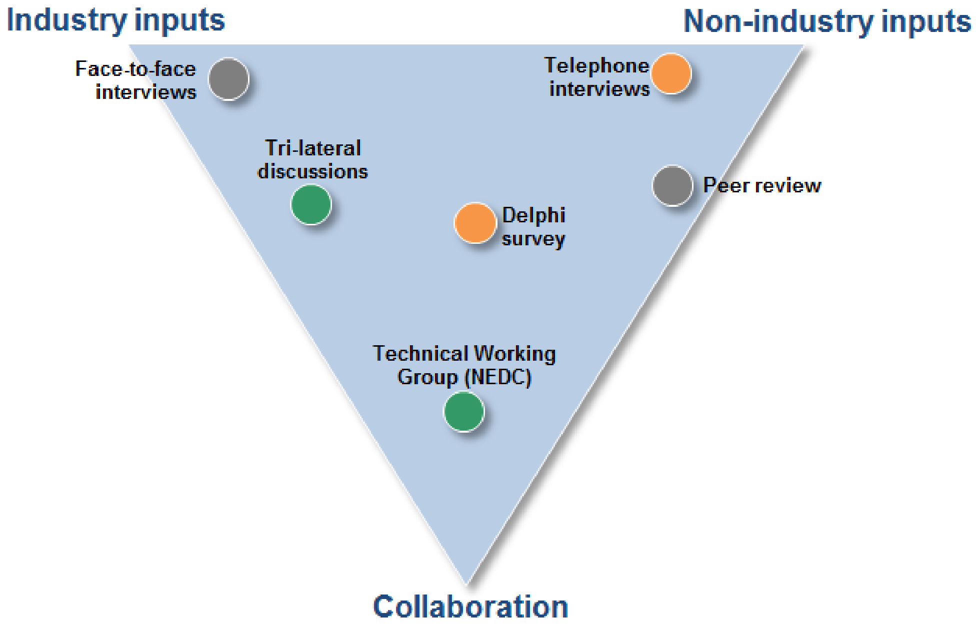
The data collated during desk research phase of the project was used as the starting point for the stakeholder engagement activities that were carried out in order to evaluate and cross-corroborate evidence on the costs associated with each technology of interest. Given both the high level of importance and the likely high level of sensitivity around the topics covered by this study, a multi-stranded approach to stakeholder consultation was essential in order to achieve a successful outcome for this project. A significant proportion of the overall project resources for this study was allocated to the consultation activities.

Our aim with all of the stakeholder engagement activities was to use the outputs from the early stages of this task, and other project tasks, as the basis for engaging stakeholders in discussions on the costs and performance of the different technologies. The outputs from these discussions were used to augment and refine the content of the source data fiche, which has then been used to inform other tasks in this study.

Whilst the primary aim of the consultation was supporting this task, it was also used to check and verify findings from earlier tasks (in Sections 2 and 3), as well as providing inputs to / views on key assumptions on other project tasks (e.g. on exploration of the variation in cost estimates and on powertrain deployment scenarios).

Our stakeholder engagement strategy was based on a combination of a range of face-to-face and telephone interviews, questionnaires and surveys, as illustrated in Figure 4.6 below.

Figure 4.6: Overview of stakeholder engagement methods



In planning and carrying out the consultation, the following elements and stages were employed:

A. Interviews/questionnaires with LDV technology experts:

1) *Stage 1: Gap-filling* exercise with specific technology experts/organisations (section 4.6.2);
2) *Stage 2: Validation* of draft assumptions and general discussions (section 4.8):
    - Direct feedback on specific assumptions on the draft dataset of technology costs and CO_2 reduction potential (section 4.8.1);
    - General interviews/questionnaire covering a range of project tasks / assumptions (section 4.8.2).

B. Delphi Survey: on key elements of the proposed future cost estimation methodology (section 4.7).

C. General ad-hoc discussions and meetings (section 4.6.1).

The overall objective for the exercise was to gather detailed information from OEMs, suppliers, automotive industry consultancies and other experts and discuss key assumptions. In doing so it was also a priority to clarify/establish the level of confidentiality for any provided feedback up-front, so that specific information or responses could be suitably anonymised if they were deemed sensitive (e.g. from a commercial perspective). The following tables provide a summary of the types of organisations responding to different aspects of the consultation process (see Table 4.18) and a full list of all the participating organisations (see Table 4.19), in order to preserve the requested confidentiality. A wide range of key experts and organisations were contacted earlier on in the project to inform them about the project, anticipated timings for the consultation and provide a preliminary invitation for participation.

Whilst a range of useful discussions and feedback were obtained from suppliers, automotive engineering consultancies and other experts, the vast majority of OEMs refused to participate directly in answering questions or providing feedback. Instead most OEMs preferred to respond indirectly through the European automotive industry association, ACEA. Whilst the cooperation of the relevant ACEA industry working group members was welcome and appreciated, this form of interaction somewhat hampered our ability to explore specific details and establish a better evidence base and insights from the industry.

A brief summary of the ad-hoc and gap-filling activities is provided in the following subsections, with more detailed summaries provided on the Delphi survey and validation/interview activities in subsequent report sections 4.7, and 4.8 respectively.

Table 4.18: Overview of participation in different activities by stakeholder type

Organisation Type	Gap-filling	Delphi	Validation	Total directly participating	Total not, or only indirectly, participating*
Engineering Consultancy		5	2	6	6
Automotive supplier	8		8	12	31
International Institution		1		1	1
Industry Association		2	1	2	5
NGO		3	2	3	3
OEM	2	2	3	5	12
Policy maker		2	1	3	2
Research/Academia		2	1	3	2
Technology developer	2			1	2
Sum	**12**	**17**	**18**	**36**	**64**

Notes: * Stakeholders contacted but who either failed to respond or declined direct participation with the study (e.g. preferring to respond via their industry association).

Table 4.19: Summary of stakeholder organisations participating in the engagement activities

Organisation	Organisation Type
ACEA	Industry association
AVL List GmbH	Engineering Consultancy
BMW	OEM
Cardiff University	Research/Academia
Continental	Automotive supplier
Controlled Power Technologies (CPT)	Automotive supplier
Dearman Engine Company	Automotive supplier
Delphi	Automotive supplier
Denso	Automotive supplier
European Commission	Policy maker
Faurecia	Automotive supplier
FEV GmbH	Engineering Consultancy
FIAT - Chrysler	OEM
fka Forschungsgesellschaft Kraftfahrwesen mbH Aachen	Engineering Consultancy
Gomecsys	Technology developer
Honda	OEM
Honeywell	Automotive supplier
Hyundai	OEM
Intelligent Energy	Automotive supplier

Organisation	Organisation Type
International Council on Clean Transportation (ICCT)	NGO
International Energy Agency	International Institution
JAMA	Industry association
JRC IET	Research/Academia
Liberalato	Automotive supplier
Low Carbon Vehicle Partnership	NGO
Mahle	Automotive supplier
McLaren Automotive Limited	OEM
Protean Electric Limited	Automotive supplier
Ricardo Plc	Engineering Consultancy
SP3H SAS	Technology development
TNO	Engineering Consultancy
Transport and Environment	NGO
US Environmental Protection Agency	Policy maker
WMG, Warwick University	Research/Academia
ZF Friedrichshafen	Automotive supplier

4.6.1 Ad-hoc discussions

As well as the range of formal interviews and responses to questionnaires/surveys, the project team also gathered information and understanding through a range of ad-hoc discussions with key experts, particularly early-on in the identification of technologies summarised in Section 3.

4.6.2 Gap-filling exercise

The objective of the gap-filling exercise was to identify areas where key data or understanding was poor or missing for the technologies identified to be taken forward in Section 3. Once a list of technologies/areas was identified, an evaluation/identification of key experts or organisations (e.g. technology developers, automotive suppliers or OEMs) believed to have particular knowledge /experience with the technology was carried out. A short-list of priority contacts was subsequently developed to overlap as much as possible with the identified gaps. Short questionnaires covering the relevant technologies were prepared and sent out to the target organisations, and were subsequently followed up with telephone-interviews, where organisations agreed to participate. The resulting data and understanding was used to refine the source data fiche and other relevant project assumptions.

4.7 Delphi survey on the cost methodology

This section gives an overview of the Delphi survey that was carried out as one stakeholder engagement activity in the frame of this study. A general introduction to the Delphi method is given in Box 1 below. The specific objectives of the Delphi survey for this study are outlined in 4.7.1, before the set-up and design of the survey are described in 4.7.2. The final section (4.7.3) gives an overview of the results of the survey. In Appendix 3 the Delphi survey documents sent to participants (the questionnaire and the 'technical annex') as well as the final feedback document can be found for further reference.

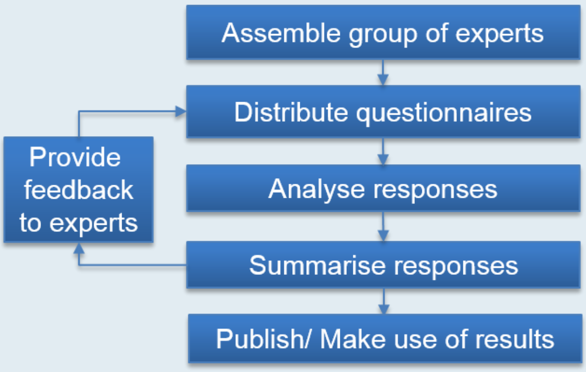
Box 1: General introduction to the Delphi method

The Delphi survey method originated in a series of studies conducted by the RAND Corporation in the 1950s (Okoli & Pawlowski, 2004). Since then it has found a multitude of applications, in such different sectors as telecommunications, public policy, automotive and health care[24].

The objective of a Delphi survey is to obtain the consensus of a group of experts on a specific question/problem. The method is mainly applied for analysing issues that are particularly complex and hence involve significant uncertainty. Frequently such issues concern forecasts of future developments that cannot be resolved by pure analytical methods as they are dependent on a multitude of undetermined or uncertain parameters. The researcher hence has to revert to a method of ‘last resort’, to judgemental information, to opinions from a group of experts that all have profound knowledge of the subject area and informed views on the issue in question.

The Delphi method allows the engaged expert panel to communicate anonymously via the administrator/organiser of the survey. The task of this administrator is to gather the opinions of the survey participants, collate these in an adequate format and distribute the anonymous summary to all participants. The survey participant then gets the opportunity to comment on the opinions/responses of the other participants, reconsider their view and/or revise their answer/statement to the issue being analysed. This iterative process can take the form of several rounds/stages. The number of times the participants are asked to review/revise their answers and collated feedback (i.e. the number of survey rounds/stages) can be either pre-defined, or, alternatively, set by the survey administrator throughout the process, who might decide to continue the process only until a certain level of consensus is agreed. A schematic overview of the Delphi survey process is shown in Figure 4.7.

Figure 4.7: The Delphi process



The role of the administrator in a Delphi survey is crucial. The administrator regulates all communication flows via gathering, summarising and distributing responses among all survey participants. It is the administrator who is responsible for recording and distributing opinions accurately hereby avoiding the introduction of any bias. The number of participants in the Delphi panel is dependent on the design of the survey and will be constrained by: i) what is manageable for the administrator; and ii) the number of experts with profound knowledge about the research topic in question. Generally the panel size requirements are modest (common are 10-20 participants; (Yousouf, 2007)). Of more importance is a certain dynamic among the group that allows for a consensus to be achieved on controversial issues.

The Delphi method has been criticised for (a) being unscientific, (b) having a low level of reliability of judgment among experts and therefore is dependent on the forecasts of the particular judges selected, (c) being sensitive to ambiguity in the questionnaire that is used for data collection in each round, and (d) the difficulty in assessing the degree of expertise incorporated into the forecast (Yousouf, 2007). It is therefore important to highlight that the outcome of a Delphi survey is not analytical evidence, but an aggregated opinion that is only as valid as the opinions of the experts who made up the panel. The outcome obtained by a Delphi survey is hence only as reliable as the opinions of the experts participating on the panel, reflecting the high importance that should be given to the selection of

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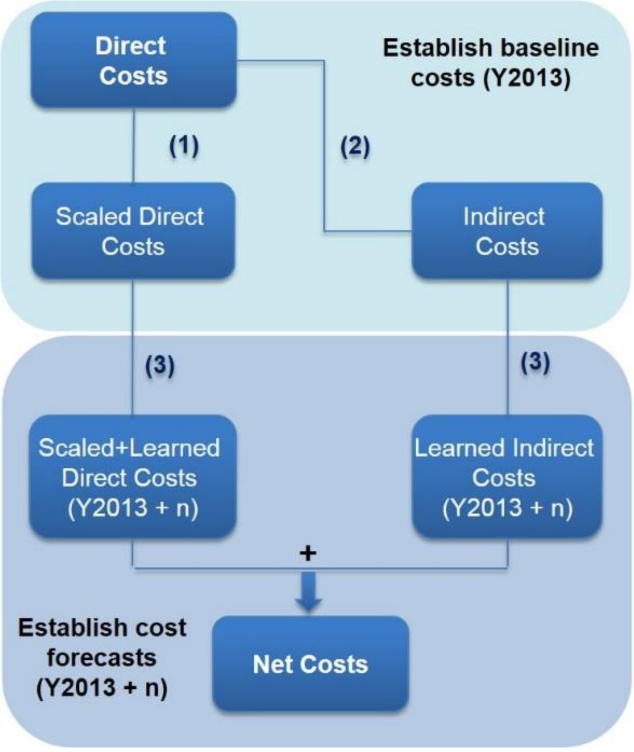
[24] (EICT, 2009), (Rayens & Hahn, 2000), (MDOT-CAR, 2012), (Clay-Wiliams & Braithwaite, 2009)

participating experts.

4.7.1 Objective of the Delphi survey in the frame of this study

The objective of the Delphi survey that was carried out in the frame of this study was to investigate issues concerning the proposed methodology for estimating and projecting technology costs. Before these issues are elaborated in more detail, the following Figure 4.8 gives a simplified overview of the overall cost estimation methodology proposed for this study.

Figure 4.8: Simplified sketch of the cost projection methodology



Broadly, the proposed estimation of future costs is a sequential process that departs from so-called '*direct* incremental technology costs'. These direct technology costs are incurred by the integration of a new technology into the vehicle, such as material and direct manufacturing costs. They can largely be obtained from previous studies, such as so-called *tear-down* studies that dismantled whole vehicles in order to explore these costs. The '*net* incremental technology costs' (the total net costs incurred due to the integration of a new technology and removal of the old one, which also includes non-direct factors), are then derived by applying the following factors to the direct incremental costs (as indicated in Figure 4.8 by (1), (2) and (3)):

1. **Scaling factors** that account for the fact that the cost of technologies might be different for different vehicle segments;
2. **Indirect cost multipliers (ICMs)** that account for cost items not directly attributable to the integration of the technology in a vehicle, such as R&D, overheads or selling costs; and
3. **Learning factors** that account for increasing efficiency of production (and better technology integration) over time/with increasing production volumes due to learning.

Applying scaling factors and indirect cost multipliers allows for the establishment of the correct baseline costs, i.e. the costs as incurred in the base year of the analysis (i.e. 2013). When applying learning factors, these base year costs are brought forward, to a future year, hence cost projections are developed.

Given the lack of precise information on the above and the significant amount of uncertainty they involve, the specific focus of the Delphi survey was to get experts' view on the above-listed factors/multipliers. More precisely, experts were asked their opinion on (among others) which specific values (from which sources) should be applied, in which way these should be applied, what these single factors should entail, and how they should be tailored to the single technologies. The aim was to achieve a consensus on specific methodological aspects of the technology cost estimation and projection that would allow the derivation of cost estimates that best possibly reflect reality.

4.7.2 Design and set-up of the survey

4.7.2.1 Selection of an expert panel

As discussed above, the outcome of a Delphi survey heavily relies on the expertise and knowledge of its single survey participants. The expert panel therefore has to be chosen carefully and only people that can demonstrate significant knowledge in the topic area(s) covered should participate.

The study team identified almost 40 potential participants from its pool of contacts as having extensive knowledge in the automotive industry and/or regarding technology cost estimation procedures. These 40 potential participants were either single persons or organisations/associations and were all similarly approached by the study team. Out of these approached contacts, 17 confirmed their availability in the timeframe for the Delphi survey and agreed to participate. This number was seen to be manageable for the specific design of the survey.

Table 4.20 shows the types of stakeholders these 17 individuals or organisations can be allocated to. It can be seen that the participants cover a wide range of stakeholders. This diversity was seen to be important in order to prevent any potential bias in the survey outcome that might favour a specific interest group.

Table 4.20: Delphi expert panel by type of stakeholder

Type of Stakeholder	Number
Policy maker	1
Research/Academia	2
Policy maker + Research/Academia	1
International Institution	1
(Automotive) Consulting	5
NGO	3
OEM	2
Car Manufacturers Association	2
Total	**17**

4.7.2.2 Survey schedule

The Delphi survey was scheduled with the objective of carrying out two questionnaire stages. These two stages would allow respondents to obtain and react to feedback on first stage responses and also for the study team to ask additional refining questions if needed. It was considered that more questionnaire stages would risk that participants lose their interest in the study or do not commit to participating given the increased time commitment that would have been necessary. Carrying out two stages also allowed the task to be finished within the time allocated by the overall time planning of this study.

The survey took place within a time frame of approximately 2.5 months (from making first contact with potential participants to sending out the final feedback), from October to December 2014. After the send-out of each questionnaire, participants were asked to return their answers within two weeks. This time period was then extended to 3 weeks due to the delays of some responses. Table 4.21 gives an overview of the overall schedule of the whole Delphi survey process within this study.

Table 4.21: Schedule of Delphi survey process

Milestone	Date/Deadline
First contact with potential survey participants	2/3 Oct 2014
Send out of stage 1 documents to participating experts	13 Oct 2014
Deadline for the return of stage 1 questionnaire (with extension)	27 Oct 2014 (3 Nov 2014)
Send out of stage 2 questionnaire (containing feedback of stage 1)	7 Nov 2014
Deadline for the return of stage 2 questionnaire (with extension)	21 Nov 2014 (1 Dec 2014)
Send out of final feedback	24 Dec 2014

Two survey participants contributed to the first stage questionnaire only since they could not meet the first (extended) deadline. Their responses were hence only included in the final feedback and were therefore not open for consideration to other survey participants before their response to the second stage questionnaire.

4.7.2.3 Design of the questionnaire and survey material

First stage documents

The **survey questionnaire** was set up in MS Word format and comprised four different sections that each comprised: (i) an introduction that gave the key background information on the topic being covered, and (ii) a set of questions on the specific issues related to the topic that were to be explored.

Next to the survey questionnaire, survey participants also received a '**technical annex**' that contained more detailed background information on the topics being covered as well as all references to the source material in case survey participants wished to look up specific details (see the stage 1 questionnaire as well as its technical annex in Appendix 3 of this report).

The questionnaire's four sections and broad content in the first stage of the Delphi process were the following:

1- Scaling factors:
   - 2 questions that asked for agreement/disagreement with the proposed scaling approach for different powertrains.

2- Indirect cost multipliers (ICM):
   - 2 questions that asked for agreement/disagreement with the proposed ICM approaches (of which the latter was conditional on the answer of the former);
   - 1 question that asked which cost components the multipliers should comprise;
   - 1 question that asked about the complexity level of each technology being analysed in order to be able to derive a corresponding ICM for the respective technology.

3- Learning factors:
   - 1 question that asked for the agreement/disagreement with the different proposed learning approaches;
   - 4 questions on the specifications of the learning approach and its potential tailoring to the different technologies (of which 3 were conditional on the answer of the first learning factor question);
   - 8 questions on how to apply learning to electric powertrains (of which every second question was conditional on the respective previous answer).

4- Other issues:

- 2 questions on manufacturers' strategies concerning cost reductions (of which the latter was conditional on the answer of the former);
- 2 questions on how cost out-turns might be different to cost expectations (of which the latter was conditional on the answer of the former);
- 4 questions on the cost curve methodology and its adequacy (of which every second question was conditional on the respective previous answer).

Finally, the questionnaire also provided some space for additional comments.

Second stage questionnaire

Based on the answers and feedback received to the first stage questionnaire, the questionnaire was adapted for the second stage before it was re-sent to the survey participants for reconsideration and possible revision of their initial answers. The following changes to the questionnaire's structure/content were made:

- The technical background information on the beginning of each section was shortened to only the key information, now called 'Reminders';
- Below each question a summary of the participants' stage 1 responses was given - either in graphical format (in the case where responses could be evaluated analytically), in written text format (in case feedback had to be summarised in a more qualitative way), or both;
- Where previous answers needed some clarification or additional specification, 'refining' questions were introduced in order to better gauge how a specific idea could potentially be implemented in practice. Altogether 8 refining questions were introduced into the 2nd stage questionnaire (of which one was conditional on a previous answer).

Final feedback

After the completion of the second stage, a final feedback document was established, again based on the questionnaire document. For each question feedback was given on: (i) whether participants had additional comments or revised their answers given the feedback that participants had received on the 1st stage questionnaire of the previous answers and (ii) answers that were obtained from the refining questions that were introduced in the second stage questionnaire. The final feedback furthermore contained an overview of the type of stakeholders that participated in the survey. (See the final feedback document in Appendix 3 of this report.)

4.7.3 Survey results

This section gives an overview of the results of the Delphi survey process. More detailed results per question as well as specific feedback by single respondents can be found in the final feedback document that was distributed to survey participants (see Appendix 3 of this report). The purpose of this section is to give the main outcomes of the survey only. The final sub-section gives more information on some general observations that were made throughout the survey process.

In the following the same structure as the survey questionnaire (and which was already presented above) is kept for the presentation of results. *[NB: The term 'majority' in the following is applied to all cases were at least half of the respondents that did not reply to a question with either 'No opinion/'Don't know' had the same opinion. Hence, the term does not give any indication on whether there was a large or small majority, or on the number of respondents that did actually have an opinion. Again, please refer to Appendix 3 of this report in order to identify all respective percentages.]*

4.7.3.1 Scaling factors

- A majority of respondents agreed with our proposed scaling approach for conventional and hybrid powertrains, i.e. the use of industry supplied information (where available) and the use of values tailored for the EU market (stemming from (FEV, 2013a)).
- Respondents did not have a common opinion with regards to which source (industry-provided values or values from (FEV, 2013a)) should be the preferred source, in case both were available.

- A majority of respondents agreed with our proposed scaling approach for advanced electric powertrains (PHEVs, REEVs, BEVs, and FEVs), i.e. estimating the additional costs of electric powertrain components based on the different power, performance and range characteristics for different segments (and the removal or scaling down of conventional powertrain components), similar to that already utilised in (TNO et al., 2011).

4.7.3.2 Indirect cost multipliers

- A majority of respondents agreed with the indirect cost multiplier approach for accounting for indirect manufacturing costs when introducing/integrating new CO_2 reduction technologies.
- A majority of respondents gave preference to the use of EU-tailored ICMs, as provided in (FEV, 2013b) (as compared to ICM values that have been used by EPA for the US market).
- Respondents were asked which cost items should be included in the ICMs and which ones should not. The following table gives information on which items should be included/not included (based on the majority of the respondents that had an opinion on the respective cost item). Regarding pension and healthcare costs no clear majority/consensus was obtained. The last column of the table shows which cost items were included in the EU-tailored values provided by (FEV, 2013b). It can be seen that the respondents' opinion diverges from FEV's approach only with respect to the manufacturer's profit allowance. A majority of stakeholders expressed the opinion that a manufacturer's profit allowance should be included to reflect that such profit allowance is essential for the sustainability of the business. This view was however heavily contested among survey participants and views expressed during the final stakeholder meeting carried out in the context of this study.

Table 4.22: Cost items that should be/not be considered as indirect costs and hence comprised in the ICMs

Cost item	Should be included	Currently included in FEV (2013b) values
Warranty costs	✓	✓
Research and development	✓	✓
Depreciation and amortisation	✓	✓
Maintenance and repair costs	✓	✓
Pension costs	?	
Health care costs	?	
General other overhead costs	✓	✓
Transportation costs		
Marketing costs	✓	✓
Dealer net profit allowance		
Dealer selling costs	✓	✓
Manufacturer's profit allowance	✓	

- Respondents who were in favour of the inclusion of manufacturer's profit allowance, proposed a mark-up factor of 5-10% to account for it.
- There was a slight change of mind regarding the inclusion/exclusion of transportation costs: In the stage 1 questionnaire a majority of respondents proposed to include them, in the second stage questionnaire (when a refining question on a possible mark-up factor was also asked) the majority of respondents believed that these costs should not be included (since none or only moderate cost increases would be expected).
- In the EPA's approach to ICMs (the basis for (FEV, 2013a), (FEV, 2013b)), technologies are classified according to their complexity level (i.e. low, medium, high I, high II). Respondents were asked to verify whether they agreed with the EPA's complexity level designation for each technology. The majority of respondents agreed with them.

4.7.3.3 Learning factors

- A majority of respondents preferred the FEV approach for learning (FEV, 2013a), which assumes that the level of cost reductions depends on where on the learning curve a particular technology's learning progression is and includes: a step-wise learning curve to approximate volume-based logarithmic learning; so-called learning 'schedules' that define the steps in the curve that are varied in order to reflect that different technologies follow different learning due to their different levels of maturity; the net incremental technology costs are estimated for a technology based on its mass-production level, and costs are therefore "reverse-learned" to account for higher costs in earlier periods. (The alternative would have been an approach adopted in an earlier study by the European Commission (European Commission, 2009)).
- The majority of respondents suggested a learning rate (the rate that defines the percentage of cost reduction once the cumulative production volume has doubled) of 0.8 or 0.9 (0.8 being the rate that also underlies the EPA/FEV analysis.
- A majority of experts believed that although the trajectories were broadly correct, the learning factors should be set based on a continuous rather than a step-wise function. *[Note: in our study analysis this would only have an impact if it affected the net resulting cost reductions in a significant way at the 2015, 2020, 2025 and 2030 points of interest, which seems unlikely.]*
- A majority of experts believed that additional curves to the ones proposed in the EPA/FEV analysis would be a valuable addition to better reflect the learning of some technologies.
- Respondents were asked to place the different technologies on the different pre-defined learning curves (while being confronted with the suggestion of the study team). The majority of experts agreed with all proposed learning curve assignments. However, the assignments for the technologies stated in Table 4.23 are most contested: one third or more of the respondents (but less than half) propose the same alternative assignment. [NB: A higher-numbered learning curve number indicates a steeper learning up until 2030 – see Appendix 3 for the shape of the different pre-defined learning curves.]

Table 4.23: Technologies with the most contested learning curve assignment

Technology	Assignment proposed by study team	Alternative assignment proposed by respondents
Lubricant improvements	0	1
Friction Reduction Engine	0	1
Mass Reduction >10-20%	1	2
12 volt start-stop systems (and starter-generators)	2	1
Fuel cell electric vehicles (non-battery/fuel cell)	2	3
Battery electric vehicles (battery)	4	3

- A majority of respondents agreed with the application of steeper learning curves for electric drivetrain technologies (including additional systems for fuel cell electric vehicles).
- A majority of respondents preferred that steeper learning curves be applied to the various sub-components of the electric drivetrain instead of only to the battery pack or fuel cell technologies.
- A majority of respondents believe that alternative high/low learning rates should be applied to adjust for the impacts of different possible deployment scenarios of xEV[25] technologies and that these different deployment rates should be reflected via shorter/longer periods for achieving high market penetration.
- A majority of respondents believed that the learning for BEVs will be similar to the learning for PHEVs and REEVs (assuming a similar rate of deployment into the fleet).
- Only a minority of respondents would divide up different electric drivetrain components to apply different learning scenarios to these components.

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[25] xEV = PHEV, REEV, BEV and FCEV

- A majority of respondents believed that battery vehicle technologies will be mass produced before 2025 (of these, a majority said that they were already being mass produced, the minority said that they will be mass produced in the period to 2020).

4.7.3.4 Other issues of debate

- A majority of respondents believed that some additional factoring should be introduced to reflect OEM and supplier strategies to reduce costs. The values proposed for such a factor range from 3-25%. [NB: Respondents' answers however suggest that this question was misinterpreted as several of these respondents referred to manufacturers' *pricing* strategies instead of cost reduction strategies.]
- A majority of respondents believed that some factoring should be introduced that accounts for possible discrepancies between ex-ante technology cost estimates and ex-post technology cost out-turns. The valued proposed for such a factor range from 3-50%.
- A majority of respondents believed that it would be preferable to look at costs of whole technology packages instead of at costs of single technologies. The majority of these did not believe that such developments could be adequately reflected by applying a %-correction factor that is progressively applied to technology costs to account for the difference between individual costs and technology packages but rather suggested that such factors/overlaps of defined technology packages have to be simulated.
- The current methodology applies a correction to CO_2 reductions in order to account for overlaps in CO_2 reductions stemming from different technical measures. A majority of respondents did not believe that the 'overlap' correction functions for CO_2 reductions used in the cost-curve approach should be further extended (i.e. beyond 15% for petrol and 5% for diesel) given that the study explores an increasing number of technologies compared to previous studies. A majority of experts instead suggested that technology packages be simulated in order to revise the overlap correction functions.

4.7.3.5 General observations

Respondents largely agreed with the important main methodological approaches proposed in this study. For example, there was general agreement concerning:

- The information sources used for the scaling approach (EU-tailored and industry–derived data);
- The ICM approach used for accounting for indirect manufacturing costs and the preferred use of EU-tailored ICMs over EPA ICMs; and
- The preference of the EPA/FEV learning approach over the previous EC approach to predict technology costs developments.

However, on some of the lower-level details of the methodology experts in some cases had somewhat more diverging views [NB: The 'majorities presented in the previous section were sometimes only 'slight majorities' and in all cases based on only those respondents that did not state to either have 'No opinion' or 'Don't know'.] Issues on which views were slightly more divergent included:

- xEV penetration rates (i.e. the specific impacts on costs for different component types);
- The full extent of the different factors to be included in indirect costs: The opinions diverged on whether pension costs, health care costs, transportation costs, dealer net profit allowance, dealer selling costs and manufacturer's profit allowance should or should not be included;
- Specific aspects of the cost curve methodology (e.g. which learning rate to use);
- How (/whether it was possible) to account for manufacturers' strategies to reduce costs;
- Handling overlaps/synergies between technologies; and
- Handling the impacts of integrated packages vs stand-alone technology costs

Further, it is interesting to note that the most recurring additional comment given at the very end of the questionnaire was that experts advocate a **'useable/practical' model/methodology that avoids unfounded complexity** and that can be broadly applied.

Also, interestingly very few experts reconsidered their opinion after having received feedback from the first stage questionnaire answers of other experts.

4.8 Stakeholder dataset validation and interviews

Besides the Delphi Survey on the cost methodology, the feedback provided by stakeholders on the draft technology cost and CO_2 reduction dataset and general questionnaire formed part of the core stakeholder consultation activity. The process, which started in late October 2014, involved both more specific/detailed feedback on specific dataset assumptions, as well as discussion of stakeholder views on a series of general questions/topic areas. The following Table 4.23 provides a summary of the types of organisations responding to these two threads of the validation process.

The following sections provide a summary of the process and results from these two streams of feedback from stakeholder experts.

Table 4.24: Summary of the types of stakeholders responding to the data validation and interviews

Organisation Type	Total Validation	Comments on Draft Dataset	General Interview /Questionnaire
Engineering Consultancy	2	2	1
Automotive supplier	8	5	5
Industry Association	1	1	(1)
NGO	2	1	2
OEM	3	1	2
Research/Academia	1	1	1
Policy maker			1
Sum	**17**	**11**	**11**

4.8.1 Dataset validation

It was decided in the early stages of the project that it would be a more effective strategy to provide industry experts that agreed to participate in the consultation with a complete draft dataset for comment, rather than simply send out a blank template asking for data. The rationale being that this would be more likely to prompt specific responses that would help refine this data. It was also judged that it would be easier for commercial organisations to comment on costs for particular options (e.g. being high/low/about right) rather than starting from scratch and providing specific, potentially commercially sensitive data. More significant efforts were therefore made up-front in the literature review and gap-filling exercise to ensure that the draft dataset distributed was as complete as possible.

The draft validation dataset was circulated to stakeholder in mid-November 2014 as an Excel worksheet; feedback on the dataset was followed up in many cases by interviews with participating experts to ensure correct interpretation of any comments/proposed revisions and to also gather additional general information (e.g. see section 4.8.2). As well as general explanations as to the definitions of terms used in the work sheet, the following information was provided:

- A summary of the assumed technology baseline and segmentation to be used by the project;
- Technology CO_2 reductions (trajectories from 2015 to 2030) on an NEDC basis;
- Technology costs on a 2020 direct manufacturing cost basis (to facilitate comparison with other sources), and indicative assumptions for the indirect cost multiplier (ICM) and anticipated year of mass-manufacture;

- Compatibility matrix for technologies with each other, and applicability to different vehicle segments and powertrain types;
- Key assumptions used in the estimation of baseline xEV costs, weight and efficiencies.

Since there were a significant number of technologies identified, it was decided to limit the data provided in the validation dataset to values representative for lower medium cars, and for medium (for SI engine) or large (for CI engine) light commercial vehicles. Even so, the volume of information presented was very large, which posed significant challenges for review by expert stakeholders. As a result, in most cases stakeholder experts focused their reviews and comments on particular areas where they had greatest knowledge. Overall the result was a comprehensive coverage of feedback across all areas of the validation dataset, with Table 4.24 providing a summary of the types of organisation that responded to the exercise. The quantitative and qualitative feedback provided in the validation process was used to refine the draft estimates that were initially presented. Sections 6.3 and 7.4 provide a summary of the process used to define the final CO_2 and Cost datasets, respectively.

4.8.2 Feedback from Interviews

There were two main aims of the interviews: i) to complement the validation of the dataset; and ii) to cover issues that have not been covered elsewhere in the project. While the **validation of the dataset**, which was discussed in Section 4.8.1, focused on the numbers in the dataset, the interviews contained more general questions on the dataset in order to give interviewees the opportunity to talk more broadly about it. This included questions about the segmentation used, any gaps in the dataset and their general views about the assumptions with respect to electric vehicles (such as how costs and ranges might develop). The **other issues** covered in the interviews explored issues that were of interest to the project, but which were considered not to be appropriate for the Delphi survey (see Section 4.7). A long-list of potential issues that might have benefited from further exploration was identified through an internal review of all of the tasks within the project, and was refined on the basis of an internal iteration and confirmed with the Commission. Consequently, these questions do not form an internally-coherent set of questions; rather they cover a wide range of different topics, including sensitivities around future costs, examples of variations between ex-post and ex-ante costs and views on the powertrain deployment scenarios that were developed within the project. A full set of questions can be found in Appendix 3. The number of interviewees by type is summarised in Table 4.25. The following text is a high level summary of the issues that were raised.

Table 4.25: Interviewees by number and type

Type of interviewee	Number interviewed /who submitted answers*	Approached, but who were not willing to be interviewed
Manufacturers	2	12
Suppliers	5	22
Trade associations	0	7
Experts from outside of industry	3	6
Total	**10**	**47**

Note: * Not all respondents were actually interviewed; some responded to the questions in written format.

Additionally, ACEA provided a written response to the work that is being undertaken in the study, some of which related to issues covered in the interviews, and so are covered below, while other comments were more general and so are mentioned here. It was argued that more time should be given to the study in order to improve data quality in particular, as it was challenging for industry to comment on the wide range of data provided within the timescales given. They also argued against the use of WLTP figures in the study, as the work on the Protocol had not yet been concluded, either at the UNECE level or within the Commission. Additionally, ACEA underlined that the CO_2 reduction potential of technologies cannot simply be aggregated, that the application of some technologies influences the performance of others, that technologies are generally implemented in packages of technologies not as a single technology and that while CO_2 reduction potential could be taken to be independent of the segment, the same cannot be said for the costs. These issues have been recognised by the study team and are being taken into account – as far as is possible – within the project. It was also noted that it is important to make clear whether the costs presented for an additional technology are in relation to the first technology or the base technology. This has been addressed within the presentation of the numbers in the compatibility matrix. It was also noted that care should be taken not to make assumptions at too much of an aggregate level, as factors such as technology penetration rates will vary between manufacturers, segments and models, and also that case should be taken in deriving factors and information from studies undertaken in the US.

In relation to their **general views on the dataset**, interviewees were asked for the views on the ***proposed segmentation*** for cars and LCVs. Those interviewees who commented on the proposed segmentation believed that it was generally appropriate, although some had some minor comments. One manufacturer commented that there was no difference between the brands that were mass-produced and the premium brands, while another argued that MPVs and cross-over vehicles should be considered separately from other car segments, as their masses are higher than other cars, which would affect the CO_2 reduction potential of different technologies. Comments from suppliers questioned where sports cars were covered and noted that two- and three-cylinder vehicles did not seem to be reflected in any segment. An expert from outside of industry also noted that it would be useful to capture the MPV/cross-over segment (if the data allowed for this) and to separate out the largest LCVs to make these segments more even. Another expert suggested splitting out the lightest LCVs and considering these alongside passenger cars. One interviewee noted that a segment that was developing was that of cheaper, lower performance vehicles, which could be considered to be a new sub-segment, the further development of which might be tested in a separate scenario.

The majority of interviewees believed that the ***list of technologies*** was largely comprehensive, although some suggested some technologies that have subsequently been considered for inclusion in the list. ACEA argued that the selection of a class II LCV as the base vehicle for the petrol technologies and a class III LCV as the base vehicle for the diesel technologies was not appropriate, as there are vehicles in all three classes for both fuels. Hence, they stated that it was not possible to derive estimates for reduction potential and costs across the fleet taking this approach. Generally, ACEA also felt that the CO_2 reduction potentials provided for petrol technologies were always at the upper range of what was possible, whereas for some technologies the stated potential was too positive, e.g. for homogeneous direct injection, thermodynamic cycle improvements, VVL and transmission. Similarly the reduction potential for some diesel technologies were considered to be too high, including for downsizing, transmission and reduced driveline fraction (level 1), while the costs for downweighting for cars were underestimated. ACEA also noted that while some of the reduction potential for petrol technologies were theoretically possible, e.g. for stratified direct injection and cooled EGR, they were not achievable in the real world. The latter will be taken into account in the project in the course of the simulation of packages that is being undertaken.

In addition to specific comments on gaps, some stakeholders also had more general comments on some of the other technologies included in the dataset. A supplier was not convinced about the inclusion of split cycle PCCI/HCCI/RCCI CAI, particularly at the reduction potential indicated (which was 25%). These options are currently mainly developed to reduce engine-out emissions rather than to improve efficiency for which you would need much better control. However, if you allowed for extended expansion, savings in the region of 20% to 25% might be reasonable. In relation to air/hydraulic and flywheel hybrids, the same supplier noted that the claimed 35% savings were very high, as it might be expected that all hybrid systems have a rather similar performance, i.e. 17-25%, as it is unclear how the recuperation/reuse was likely to be significantly better with hydraulic or flywheel than with a conventional hybrid system (where the total energy storage is much higher). Another supplier noted that a manufacturer has put the development of an air hybrid system on hold, which they would not have done at the costs originally set out in the spreadsheet. The costs are probably significantly more – perhaps five times as much – as we had originally stated. The same supplier noted that if the variable compression ratio (VCR) system was cheaper than variable valve actuation (VVT), as was originally suggested, manufacturers would be implementing this first, but they are not. A VCR system is very complex and will first be considered only for premium engines, and hence its cost will be more than that of a VVT. They also noted that the stated CO_2 benefits for cylinder deactivation are possible, but only if the cylinder is kept closed and a clutch system is introduced to reduce friction (which increases costs), otherwise there would be pumping losses and a lower CO_2 reduction. Additionally the supplier noted that for downsizing, a whole new engine was needed, which would increase costs, e.g. reducing the number of cylinders requires more investment in the boost system for example. Finally, for cooled EGR, in order to achieve the stated 5% reduction, they noted that coolers and extra pipes would be needed, so the costs would be higher than originally assumed.

In relation to the ***potential evolution of the characteristics of electric vehicles***, the general view was also that the assumptions made sense, although again some comments were made, which have been considered. A manufacturer noted that there is a high level of uncertainty with respect to future market share, as the investment costs are high and revenues uncertain. This comment was echoed by ACEA, which also noted that the CO_2 reduction potential for both mild and pure hybrids was lower than suggested, while the lithium-ion battery costs were higher than presented. A supplier suggested power density was a more critical issue for advanced batteries than energy density. An expert from outside of industry suggested that manufacturers will probably leave improving range to the next generation of batteries, as increasing range would increase costs, whereas in the short-term the focus is more likely to be on reducing the costs. More generally, another expert from outside of industry suggested that what matters for electric vehicles is not the situation in Europe, but the global perspective.

Three questions were asked about the **potential sensitivities around future costs**. The first of these explored how the project could take account of the fact that ***various countries around the world are introducing similar CO_2 related legislation***. The manufacturers that were interviewed suggested, respectively, that this could be achieved by considering both direct and indirect costs as function of sales volumes, while the other argued that this factor was already taken account by manufacturers, as technology is seldom adopted for a single reason. The views of suppliers differed, with one arguing that development costs have to be covered within the first two years of implementing it on the European market, so that developments in other jurisdictions are irrelevant. Another argued that as EU standards led the world, then it was not appropriate to apply any discount factor on technology costs for the EU market. A third noted that it was probably only an issue for less well developed technologies, e.g. batteries, and suggested that if a certain percentage of Asian-made batteries, for example, were used to supply the EU, it would make sense to attribute a similar proportion of development costs for the purpose of EU legislation. A fourth concluded that the technologies being developed, for example in the US and EU, were different, and so that there was little in the way of cost advantages from being able to build on technological developments elsewhere.

Experts from outside of industry also had differing views. One echoed a supplier by arguing that in spite of the fact that many different countries have introduced legislation to reduce the CO_2 emissions of new LDVs, the impact of the respective legislation is different, e.g. some are driving the uptake of petrol technology. Hence, legislation around the world is not driving technology in the same way, so there is no reason to assume that such changes will materially change the rate of cost reduction of options for Europe. Another argued that the fact that vehicle CO_2 regulations are being implemented around the world means that development costs for technologies will be spread much more widely, meaning that technologies reach ‘at scale’ production faster, thus bringing down costs further. This should be accounted for as it affects volume, so learning happens much faster, perhaps through the application of a ‘discount factor’. Finally, a third expert from outside of industry suggested that the impact of other countries’ legislation on costs in the EU was probably dependent on the extent to which Europe continues to rely on diesel or whether alternative technologies, such as petrol direct injection and hybrids, decreased diesel’s market share in Europe. If diesel continued to dominate the European market, the impact of other countries’ legislation was likely to be less; however, if diesel has peaked in Europe and if the proportion of these other technologies increases, legislative action elsewhere will have more impact on the costs of CO_2 reduction in Europe. In the latter case, it will become increasingly important to look at the technologies being used in the global market to identify what is driving costs in Europe, as these technologies dominate in other markets, e.g. in the US and Japan.

In order to complement the Delphi survey, interviewees were asked to provide examples of where the ***deployment of an integrated package of CO_2 reduction technologies led to reduced costs*** (compared to introducing them individually). Various examples were given in this respect, but a number of interviewees noted that manufacturers often do group technologies as packages, which could reduce costs, but also ‘total’ CO_2 reduction, e.g. neither costs nor CO_2 reduction potential is necessarily additive. Some suggested examples included:

- The cost of smart alternator charging alone is four to five times greater than the cost when it is added to a Start-Stop system;
- Component optimisation associated with the introduction of 48V battery technology, as LED lighting, air conditioning compressor and windscreen wiper powering all benefit from the 48V technology; and
- The introduction of lightweighting technologies can be taken advantage of to use smaller components, e.g. engines.
- The electrification of a vehicle, as this enables the car to be fitted with 48V technology, which in turn makes it easier to, for example, implement electric boosting for which the additional costs will then be small.

However, one interviewee offered a word of caution, recognising that such benefits are often spoken of in theory, but not delivered in practice. An example of this is the electrification of the powertrain combined with downsizing, which has theoretical potential, but is not delivered in practice as increased electrification increases risk of running out of battery, so back-up technology is still put into the vehicle.

The final question about potential sensitivities around future costs asked whether ***a minimum rate of 2% per annum was reasonable for the rate of cost reduction for CO_2-reducing technologies*** (based on supplier contracts). A manufacturer noted that this was strongly dependent on the technology, so it was not possible to make a general assumption. Experts from outside of industry were aware of the fact that this figure has been quoted elsewhere, but were not able to confirm it or otherwise, while another (and a supplier) suggested that it might be appropriate in the short-term, but was not sustainable in the long-term. Suppliers confirmed that they were subject to such pressures, with one suggesting a figure of 1.5% and another 3%.

Interviewees were also asked for examples where the **ex-post costs associated with the implementation of a CO_2 reduction technology were proven to be either higher or lower than originally anticipated**. Both manufacturers noted that it was often the case that technologies proved to be more expensive than had originally been anticipated, as it was difficult to estimate ex-ante the costs associated with impacts on other vehicle systems and components. While it was difficult to provide a percentage, increased costs can vary by between 10% and 20%. It was also suggested that the costs estimated by the US EPA were generally lower than what was experienced in practice. From the side of the suppliers, it was suggested that it was a very difficult issue, as often comparable ex-ante and ex-post cost assessments are not made and are difficult to do. It was suggested that ex-post costs are usually larger, as ex-ante the costs of properly integrating the technology into the vehicle are ignored or underestimated, although no specific example was provided. A concrete example from another supplier was the change in the refrigerant used in air conditioning systems, which resulted in an efficiency loss that was compensated for by the integration of an internal heat exchanger.

ICCT noted that they had compared ex-post costs to those in the 2002 National Academy of Sciences study in the US and found that the estimated ex-post costs were always similar to or lower than those estimated ex-ante. An example of lower ex-post costs was provided by a manufacturer; for smart alternator charging, as synergies that were derived from common components shared with the start-stop system were neglected in the preliminary cost estimation. A supplier suggested one of the main reasons for lower ex-post costs was due to the exploitation of the test cycle, as observed by the increasing divergence between real world and test cycle emissions, while volume effects, i.e. different levels of demand for certain technologies, might also have had an impact. An expert from outside of industry suggested that meeting the 130g gCO_2/km target, has generally cost manufacturers less than anticipated. However, another expert from outside of industry noted a final word of caution that it was very difficult to make general conclusions in this respect, as many factors influence ex-post costs including competitive pressures.

Within the project, **alternative powertrain deployment scenarios** have been developed covering various xEV powertrains, i.e. PHEV, REEV, BEV and FCEV. The aim of the development of these scenarios is to enable the investigation of cost uncertainties through possible reasonable or conceivable extremes and to identify the impacts on cost learning rates, rather than to present a view on what ‘will most likely’ happen. Interviewees were asked, in general, ***whether they agreed with the scenarios***. Of the interviewees who had an opinion, most supported the approach and considered the scenarios to be reasonable. However, views were expressed on some of the details of some of the scenarios. Four interviewees – a manufacturer and three suppliers – believed that the ultra-efficient ICEV Scenario was the most likely, with one commenting that this was because it was based on proven technologies. A supplier that thought this scenario most likely believed that the rate of hybridisation in this scenario might be too high as a result of the high costs of such vehicles. The rate of hybridisation was also considered to be high in this scenario by an expert from outside of industry, who believed that premium manufacturers will enable plug-in hybrids rather than focusing on pure hybrids as a result of the additional performance that would be gained. The same interviewee considered that by 2030, even in this scenario, the rate of BEVs would be higher.

One supplier considered the Mixed EV Scenario to be the most plausible, particularly the 10% combined market share for BEVs and FCEVs, while others also considered this scenario to be plausible. However, a supplier thought that the figures here for FCEVs and BEVs were probably too high, as the 2% market share of the former should be added instead to the PHEV market share. Another supplier was also critical of this scenario, as they did not believe that there would be a large fleet of EVs with stored electricity any time soon as a result of the high costs. On the other hand, an expert from outside of industry thought that the figures for 2020 in the Mixed EV scenario were about right, although the market share of BEVs could be slightly higher, while for 2030 the same interviewee considered that the market share of PHEVs and BEVs was too low. An expert from outside of industry considered the various Extreme Scenarios to be plausible, whereas two suppliers felt that they were not. It was suggested that an alternative approach to identifying Extreme Scenarios might be to vary the market shares in the Mixed EV Scenario by +/- 5%. Other comments considered that it was unlikely for FCEVs to develop a noticeable market share by 2030 even to the extent implied under the FCEV Extreme Scenario, that the market share of FCEVs should be reduced even further in the PHEV/REEV extreme scenario to 0.1% and that the share of BEVs in the Extreme FCEV Scenario should be reduced to 2% (from 4%) while the share of PHEVs should be increased to 9% to compensate (although it was noted that there would probably be no needed for REEVs in this case).

Interviewees were asked for their views on the ***impact of low (and high) deployment of EVs on the costs of components specific to EVs and on the costs of CO_2 reduction technologies for ICEs and Hybrid ICEVs****.* Many interviewees suggested that the costs of components specific to EVs would come down more with higher rates of penetration. A couple of interviewees – a manufacturer and an expert from outside of industry – also suggested that if EV deployment rates were low, the costs of (at least some) CO_2 reduction technologies for ICEs and Hybrid ICEVs would come down faster than if EV deployment rates were high. A supplier, however, thought that the costs of CO_2 reduction technologies for ICEs and hybrid ICEVs would be unaffected by high deployment rates for EVs, as these other technologies were already standard. Two suppliers, however, noted potential complexities in that the impact on costs was likely to vary by vehicle class and that there would also be interaction across different powertrain technologies, as improvement to battery technology for BEVs, for example, would benefit battery systems on ICEVs. As a result, one interviewee suggested that we should not try to take account of such issues in the study, as there was too much uncertainty involved. An expert from outside of industry argued that the deployment rate of EVs in Europe would have little effect on the costs of EV components as the price of EV components was determined by the global market, not by the European market. Currently, only one third of EVs sold worldwide are sold in Europe and any impact of a future low deployment in Europe could be mitigated by increased growth in China.

Finally for this set of questions, interviewees were asked whether they agreed with a proposed assumption ***that technologies that are common to conventional and electrified powertrain vehicles would be unaffected by different scenarios of electric vehicle deployment***. Generally, interviewees agreed with this approach, although one highlighted that care should be taken when identifying which components are in fact ‘common’.

Within the project, it needs to be ensured that any analysis that is undertaken is appropriate for the segments and manufacturers to which it is applied. Hence, any vehicle segments or manufacturers that needed to be treated differently within the analysis need to be identified, along with what this different treatment might mean in practice. Interviewees were asked for their views on **which segments and manufacturers should be treated differently within the analysis**. A manufacturer suggested that premium manufacturers should be treated differently to ‘mass market’ manufacturers, while a supplier suggested that there might be a case for treating manufacturers of sports cars differently, although neither suggested how this might be achieved in practice. Others disagreed, with a supplier warning against using extreme cost/price scenarios proposed by manufacturers that do not reflect the general market or are a result of marketing strategies. A supplier noted that the issue was linked more to the range of vehicles that a manufacturer offered, as those with a narrower range of vehicles are being challenged more by the targets. A supplier and an expert from outside of industry suggested that it would be difficult to account for differences between segments and/or manufacturers, as costs varied for a wide range of reasons. Another expert from outside of industry suggested that it was reasonable to analyse segments differently, but that adjusting costs for different manufacturers was not appropriate as the costs associated with a technology are independent of the manufacturer. Another expert from outside of industry suggested that while there might be a case for treating specialist sports car manufacturers differently, if these manufacturers did not already benefit from special arrangements under the existing Regulation. Similarly, as niche manufacturers also benefit from special arrangements under the Regulation, there was no case for these to be treated differently in the cost assessment.

The final set of questions explored interviewees thoughts on suggestions that some technologies may be employed for reasons other than simply improving CO_2 emissions, for example to improve overall vehicle performance as is the case for some of the recent plug-in hybrid models, and so might be treated differently in the cost analysis. Interviewees gave a number of examples of ***technologies that brought additional saleable value to buyers beyond CO_2 reductions and fuel efficiency***. The most common technology mentioned in this respect was all types of EV, as a result of their improved driveability. A couple of interviewees also mentioned turbocharging of downsized engines in this respect, while LED headlights, improvements in glazing technology, GDI engines, variable valve timing and 48V electrical system technology were also mentioned. Of those who had an opinion, a majority believed that it was not possible or appropriate to take account of any subsequent additional saleable value in any analysis. Those who disagreed – both experts from outside of the industry – highlighted the case of plug-in hybrids in particular. Both argued that all of the additional costs of these technologies should not be fully attributed to CO_2 reduction efforts, as manufacturers are increasingly advertising their benefits with respect to driveability.

A couple of interviewees had some made some additional **concluding remarks.** A manufacturer made a series of comments about learning rates, which have been taken into account in the relevant part of the projects. A supplier noted that it was important in a study such as this one to take account of wider considerations, such as the need to ensure mobility, as well as developments in terms of different models of ownership, such as car sharing, and the implications of these on manufacturers. Another supplier noted that neither the NEDC nor the WLTP take account of CO_2 reductions delivered as a result of improvements to air conditioning, which means that there is no incentive for manufacturers to invest in and deploy CO_2-saving air conditioning systems. They also noted that in a study such as this one, it was necessary to make a number of assumptions and so the degree of accuracy was limited and would not necessarily be improved by making more assumptions.

As noted above (see Section 4.7), evidence from the approaches applied in the US for their respective LDV CO_2 regulations was used to inform our thinking as to what approaches to take within this study. In this respect, it was considered to be important to understand whether any changes to the methodologies in the US were planned. For the US LDV regulations for 2017-2025, a mid-term review is planned, which will effectively confirm or amend the regulations for the period 2022-2025. However, discussions with the relevant US EPA officials indicated that it is not anticipated that there will be any major change to the methodology used for determining the costs and CO_2 reductions. The methodology has evolved over time by making refinements rather than making major changes, and it is anticipated that such a gradual evolution will continue into the future. This conclusion applies to such details as the ICMs and learning curves used. Additionally, no major changes are anticipated to the technologies that will be covered.

4.8.3 High-level summary of key actions taken as a result of stakeholder feedback

It is not possible to go into detail on all the specific actions and decisions made in response to the stakeholder feedback. Certainly, weighing and deciding on how to action sometimes conflicting feedback or general feedback that was in some cases unsupported by factual evidence was a real challenge for this study. In addition, some of the material and evidence provided was commercially sensitive and so provided under strict confidentiality agreements. However, the following list provides a general summary of some of the key actions taken as a result of this consultation process. In addition, the feedback received has also been factored into the more qualitative discussions provided in various sections across this report:

- Amendments to assumptions on the CO_2 benefits of technologies to reflect lower than optimal initial market average performance and improvements over time;
- Amendments to the initially proposed cost-curves in terms of their assignment to different technologies and moving to continuous, rather than stepped cost-curves;
- Amendments to the assumed costs of individual technologies based on feedback;
- Revisions to some of the key technology component costs and learning rates used in the advanced xEV analysis; and
- Influencing decision-making on the exclusion/inclusion and setting of a range of other cost elements / considerations in the overall analysis.

5 Exploration of factors influencing future technology costs

5.1 Overview of the exploration of factors influencing future technology costs

This report chapter provides a summary of the work carried out to explore the various factors that have an influence on the future costs of CO_2 reducing technologies from LDVs. This work covered three different aspects, as follows:

i. Development of an evidence base on measures that OEMs and suppliers take to mitigate the costs associated with CO_2 reduction technologies (*Section 5.2*);
ii. Explore variation between cost estimates (*Section 5.3)*;
iii. Exploration of the potential impacts of alternative powertrain deployment scenarios (*Section 5.4)*.

The following report sections provide a summary of the results of the analysis completed in each of these areas.

5.2 Measures that vehicle manufacturers and suppliers take to mitigate costs

Over the past decade, prices for new cars in Europe have generally been stagnant, or have even decreased in real terms (at least from the perspective of base vehicle price excluding optional extras), despite increasing amounts of fuel saving technology such as downsized engines and start-stop systems. As Wells et al. (2013) show, there has been no evidence for car price increases from fuel saving technology. This does not mean that these technologies do not incur costs. IW Köln (2013) claim that due to competitive pressures manufacturers are only passing through costs to a limited extent and expect that given the low profit margins of volume manufacturers, greater pass-through of costs to the consumer can be expected in future. A literature review found little information on cost mitigation strategies for CO_2 reduction technologies in particular, other than the discussions on this subject in previous work for the Commission informing the setting of 2020 targets (e.g. (TNO et al., 2011)). However, manufacturers continue to pursue various strategies to further reduce costs in vehicle production. The overall cost savings targeted by manufacturers over the coming years are generally in a similar range to the estimated cost increases for CO_2 saving technologies, around a few hundred and in some cases several thousand Euros per vehicle produced.

However, for most European manufacturers, the full development cycle is closer to six to eight years, with one major facelift over that period. For example, VW generally operates a policy of carrying out a major facelift on a model around four or five years after its first introduction – but in general no changes are made to the body structure and only more subtle changes are made to exterior skin panels. Hence retooling costs are more limited at this point, with the major change then coming three or four years later.

5.2.1 Strategies for increasing economies of scale

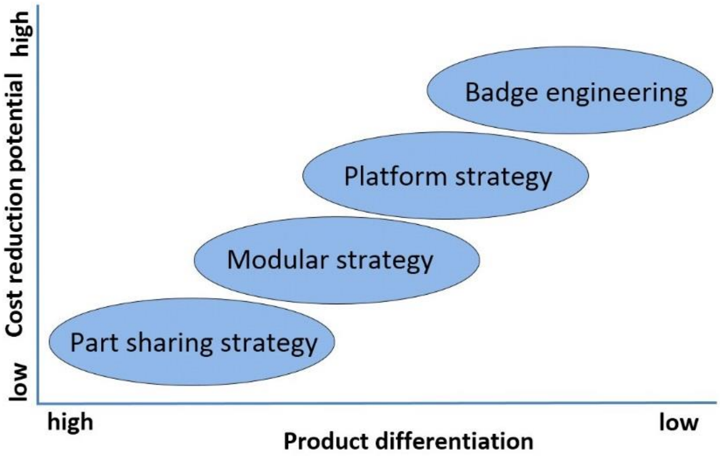
As an overall trend over the past 20 years, manufacturers with a high variety of models and model variants have increased their market shares relative to traditional volume manufacturers with few differentiation options (Waltl & Wildemann, 2014). At the same time, manufacturers face rising research and development cost pressures as typical model cycles have decreased from eight to four years since the beginning of the current century (Ibid.). A particular challenge for manufacturers is therefore to manage the substantial fixed costs of R&D and factory retooling associated with launches of new models and variants. Various strategies are used to increase economies of scale by reducing these fixed costs (Section 5.2.1.1 below), while manufacturer cooperation is a strategy for increasing scale economies by spreading fixed cost over a larger volume of cars (Section 5.2.1.2).

5.2.1.1 Consolidation of platforms and parts

In their product strategies, manufacturers face trade-offs between product differentiation and variety on the one hand and economies of scale on the other: Greater customisation will mean fewer identical models are produced. Increasing volumes by selling two or more almost identical models under different brand names, a practice known as badge engineering, means limited product differentiation which can potentially decrease consumer interest or willingness to pay for the product. For example, Aston Martin's Cygnet, a Toyota iQ-based city car with a strong visible resemblance to the Toyota model but priced more than twice as high as competitors, was withdrawn from the market after selling only 150 units between 2011 and 2013 (Reuters, 2013). However, it should be noted that there are also many examples where this approach has been more successful, for example the Toyota Aygo/Citroen C1 / Peugeot 107/108, and the VW Up / Seat Mii / Skoda Citigo, etc. This approach has also been adopted in the introduction of electric vehicles (e.g. the Mitsubishi i-MiEV / Peugeot iOn / Citroen C-Zero).

In order to provide high levels of product differentiation and customisation while increasing economies of scale manufacturers have generally concentrated on combinations of part-sharing, modular and platform strategies, as illustrated in Figure 5.1.

Figure 5.1: Manufacturer cost reduction strategies, adapted from Diez (2014)



Platform and modularisation strategies offer the potential to reduce R&D costs and increase economies of scale in production while maintaining product variety. The aim is to limit differences between model generations over time as well as within the model range at a given point in time to customer-relevant aspects (Waltl & Wildemann, 2014).

Practically all manufacturers are pursuing these strategies (Waltl & Wildemann, 2014). A platform, or vehicle architecture, describes a common vehicle design structure shared between different models. Typically, a platform consists of a floorpan with a number of shared fixation points so the same components such as suspension, engine, gearbox, steering, and more, can be used across models of different shapes and sizes (Volkswagen, 2012). Information on the degree to which different structures and components between vehicle models described as sharing a platform are standardised or model-specific tends to be very limited. However, a current trend amongst manufacturers towards platform consolidation, i.e. producing a larger number of models based on the same platform, can be identified. This requires increasing the flexibility of platforms in terms of allowing variability in wheelbase, track width, load carrying capability, ground clearance, etc. While some manufacturers such as Volkswagen, Renault Nissan and GM intend to base a large variety of models on a small number of 'mega-platforms' others, such as Ford or Fiat Chrysler have followed alternative approaches[26] (WardsAuto, 2013) (see further discussion below). Determining the extent of platform flexibility '*without negatively impacting products at either end of the range*' is a key challenge of platform design (Fiat Chrysler Automobiles, 2014).

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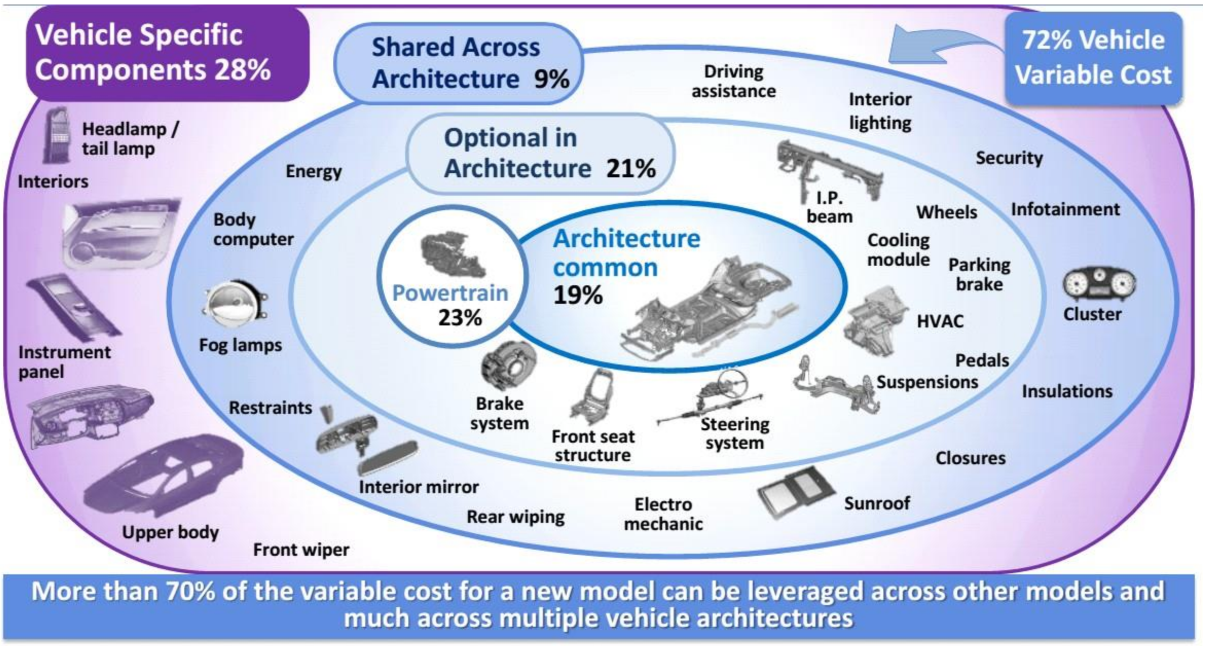
[26] Ford have tended to follow a slightly different approach of producing the same model for all world markets which brings major cost savings but in a different way to platform sharing. In contrast, VW's approach has been to differentiate some of their products for different markets (e.g. VW Passat in the US is a very different vehicle to the one sold in Europe).

Within a platform and across platforms, manufacturers also seek to use a high number of shared parts. For example, by 2016, Honda seeks to more-than-double shared parts in value terms to 40-50% between the Civic, Accord and CR-V with the introduction of a new common platform. Currently, around 20% of parts by value are shared between the Civic and the CR-V (which already share a platform) (Automotive Logistics, 2013). With the new common platform purchasing costs are expected to fall by 30% (Ibid.). Related to part-sharing is the concept of modularisation: Parts are structured in modules (e.g. engine module, HVAC module, etc.) which can be used within and across platforms. Several variants will be available for many modules to accommodate different consumer tastes and budgets (e.g. range of different petrol and diesel engines). A limited range of modules can be drawn upon to form a large number of final products, thus ensuring high volumes in module production and limiting logistical challenges. Modularisation also helps manage complexity in product development, where different engineering teams work on different modules meeting pre-defined parameters.

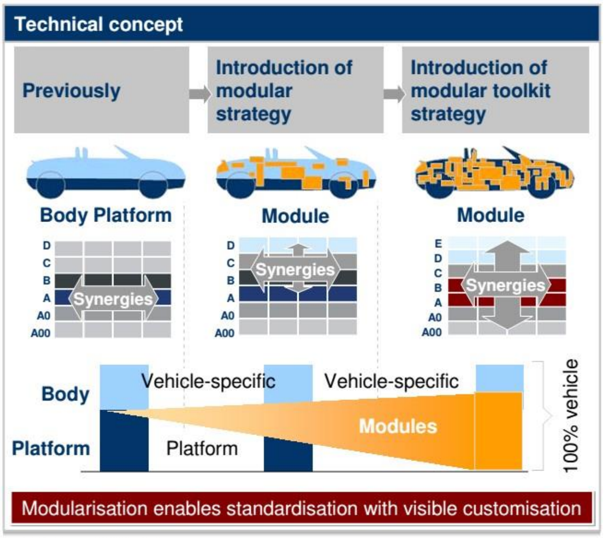
Figure 5.2 illustrates how 70% of variable costs in vehicle production can be shared between different models of the same platform. Many individual components can also be used across different vehicle platforms.

Figure 5.2: Illustration of shared and model-specific parts in a vehicle platform (Fiat Chrysler Automobiles, 2014)



Volkswagen Group's modular toolkit strategy is a widely publicised example of a platform consolidation strategy. Its aim is a modularisation of the platform (Figure 5.3). The platform, now referred to as toolkit, consists of a set of modules which can be combined in different ways to allow for a flexible layout of the car's underbody. This enables greater variety of models in terms of segment and size compared to a standard platform. For example, Volkswagen's fifth and sixth generation Golf shared their PQ35/PQ36 platforms with cars of similar wheelbase and comfort class (Caddy, Touran, Jetta, Audi A3, Q3, Skoda Superb, Seat Leon, etc. (Diez, 2014)). The current seventh generation Golf is based on the modular transversal MQB toolkit which is also used for the new 2014 Passat (D-segment), and will also be used for forthcoming generations of the Polo and Audi A1 (B-segment). The other two Volkswagen modular toolkits MLB and MSB cover larger segment vehicles. Their development is led by Audi and Porsche, respectively.

Figure 5.3: Increasing modularisation as a strategy at Volkswagen Group (Volkswagen, 2011)



[1] MQB: Modularer Querbaukasten

[2] Reduction targets illustrate benefits from MQB implementation

Source: Volkswagen Group

Figure 5.4: Illustration of the dimensional variability in Volkswagen's MQB platform

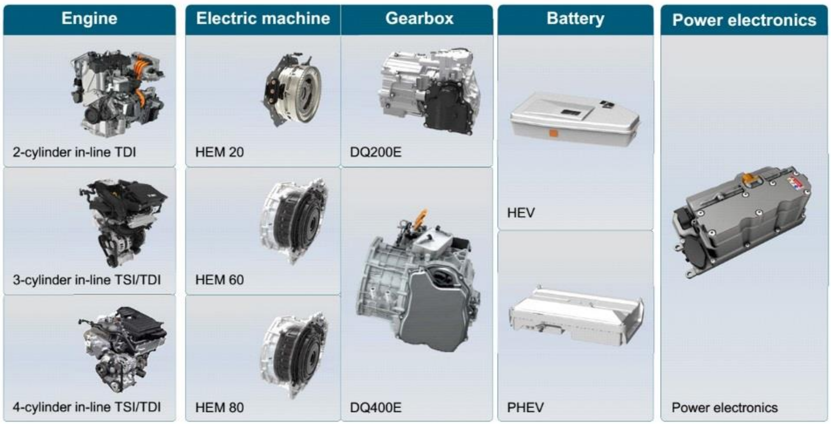
Volkswagen Group’s modular strategy also entails modularisation of the production process. Production modularisation allows for the accommodation of varying production volumes along with high product variety (Waltl & Wildemann, 2014). It entails standardisation of production practices across plants and assembly lines. Production tools are designed to be capable of producing a range of different parts. In addition, fixtures on all production lines become standardised. These measures make alterations for new models be less costly and make it possible to produce several models on the same production line; Volkswagen claims it will be possible to produce Golf, Tiguan and Passat on a single line (Volkswagen, 2012).

The investment bank, Morgan Stanley, has found the resulting increased flexibility ‘to switch between products and powertrains to meet peaks and troughs in demand, and flexibility to enter market segments with a lower break-even volume’ to be the greatest benefit of Volkswagen’s modular toolkit strategy (Automotive News, 2014).

The MQB also makes it possible for Golfs with petrol, diesel, CNG, plug-in hybrid and battery electric drivetrains to be built on the same production line. According to Volkswagen’s head of development, the costs of the (plug-in) hybrid powertrain are set to fall to a quarter of the current costs by 2020 (Auto Motor und Sport, 2014). Thanks to the modularised structure the same system can be fitted to many of the group’s vehicles. In future, Volkswagen’s head of development therefore expects the price premium for a plug-in hybrid to be approximately equal to that of a ‘modern diesel engine’ (Ibid.).

Figure 5.5 illustrates the modular structure of Volkswagen’s hybrid drive system elements.

Figure 5.5: Assembly kit for hybrid drive systems (VAG, 2014)



All-in-all, in the transition to the MQB platform toolkit (entailing increased modularisation in both production and products), Volkswagen aims to achieve cost savings of 20%, both in unit costs and in one-off expenditures for the introduction of new models. Morgan Stanley has estimated that the modular toolkit strategy costs around $70 bn to implement but could result in annual costs savings of $19 bn by 2019 which given Volkswagen Group's current production volume of some 10 million vehicles per year would mean savings of close to $2,000 per vehicle (Reuters, 2013a). Macquarie, another investment bank, expects annual gross savings to be around half, at $9 bn, assuming the modular strategy allows the company to double the volume of each individual component (Automotive News, 2014). Other commentators appear more pessimistic about cost savings potentials. An industry analyst from Bernstein Research states that *"Either VW can engineer a Polo with Passat-level weight, rigidity and specifications, or a Passat with Polo-grade components. Most industry experts think VW will end up with a much too expensive small car platform."* (WardsAuto, 2013). Commentators who see limited cost saving potential in mega-platforms argue that it is difficult to obtain economies of scale beyond certain volumes as suppliers already operate at full capacity and would be required to invest in new plants to increase output further (ParisTech Review, 2014). One study suggests that doubling production volumes within a single platform can reduce one-off costs by 10-20% and recurring costs by 4-8% (WardsAuto, 2013).

Whether cost savings have been achieved yet is not clear as the strategy is facing difficulties in its implementation on the production line, leading to Volkswagen's production chief being dismissed in July 2014 (Handelsblatt, 2014). Moreover, despite Volkswagen's moves towards the modular toolkit strategy, Volkswagen Group chairman Martin Winterkorn has recently announced plans to reduce both the number of models on offer and the options available for each model. He suggested that if an option is selected by less than 5% of buyers it should be discontinued (Der Spiegel, 2014).

Several other manufacturers are also investing in flexible mega-platforms. By 2020, Renault-Nissan aims to produce 70 % of its vehicles based on three modular platforms (Automotive News, 2014). In October 2014, GM announced plans to build all of its models based on four 'Vehicle Set Strategy' platforms by 2025. Currently, GM produces vehicles based on 14 global and 12 regional platforms (General Motors, 2014). PSA seeks to reduce the number of its platforms from seven to two between 2014 and 2022 and the number of 'programs' from 18 to five. PSA 'programs' can be understood as sub-platforms for vehicle segments. Ultimately, the number of vehicle models will be reduced from 45 to 26. By doing so, PSA plans to save €300m in costs per year (PSA, 2014).

Figure 5.6: PSA platform and model variety plans (PSA, 2014)

As part of the One Ford strategy, Ford has already reduced its number of model platforms from 27 in 2007 to 15 in 2014. By 2016 it plans to produce 99% of vehicles on the basis of nine platforms (Ford, 2014). Ford's platform consolidation strategy does not appear to aim for to produce a large variety of vehicle segments based on a single flexible mega platform. The focus appears to be more on reducing regional differences in models by developing single global platforms which replace several regional platforms. For example, the Ford Transit has now become Ford's global van and Ford's E-series van platform for the US market will be discontinued in 2015 (Automotive News, 2014). The 2014 fourth generation Ford Mondeo now shares a platform with the US Ford Fusion (Automotive News Europe, 2014) while its predecessor was based on a platform shared with several Volvo and Land Rover models (Automotive Engineer, 2011).

Fiat Chrysler plans to reduce its number of platforms from 18 in 2013 to 15 in 2018 and increase the share of vehicles produced on its four core platforms (Fiat Chrysler Automobiles, 2014). However, no radical transition to flexible mega-platforms is planned. The alliance's cost reduction strategy focuses strongly on part-sharing and modularisation as it seeks to reduce the number of part families from 1,200 in 2013 to 550 in 2018, resulting in cost savings of 2% per year within the targeted families (Ibid).

5.2.1.2 Manufacturer cooperation

There is a myriad of manufacturer co-operations within various fields, with varying levels of intensity over varying periods of time. All of the 24 largest car manufacturers pursue some form of cooperation with their competitors; some cooperate with up to 10 other large manufacturers (Financial Times, 2013). Cooperation occurs in the forms of joint development of a car platform or an engine or the purchase of a product from a partner, joint purchasing agreements with suppliers, or even the merging of organisational structures to varying degrees (Renault-Nissan Alliance or Fiat-Chrysler merger). There is a long history of cooperation in the industry. However, according to industry experts, cooperation between manufacturers is expected to intensify in future as investment requirements in the industry increase (Ibid.). As with platform and modularisation strategies, cooperation between manufacturers can help realise economies of scale in the development of a vehicle, as well as in its production or the purchasing of parts by spreading fixed costs over a larger volume of products. According to a senior automotive manager, "[b]efore, there was a fear that it would make brands seem weak. Now alliances are seen as a necessary evil" (Ibid.). Within the Renault-Nissan alliance which was founded in 1999 with Renault and Nissan swapping shares, cooperation drastically intensified after the financial crisis which threatened the existence of both manufacturers. According to the Financial Times (2013), cost savings from the alliance tripled to €1.5 bn in 2009 and reached €2.7 bn in 2012, which equates to around €340 per vehicle sold.

Co-operations are often between manufacturers who are not immediate competitors, although this is certainly not always the case (e.g. the badge-engineering discussed earlier). Carlos Ghosn who heads Renault-Nissan has stated that 'the main reason' why their cooperation with Daimler works well is that the two 'are not competing with each other' (BBC News, 2012). Cooperation has been ongoing since 2010 and expanded to an increased number of projects. For example, Renault provides low-displacement diesel engines for Mercedes-Benz models and petrol engines for the Smart. The new Renault Twingo and Smart models were jointly developed from scratch while the Mercedes Citan van is derived from the second generation Renault Kangoo via badge engineering. In October 2014 Ghosn claimed that the cooperation projects with Daimler were already saving over €2 bn (Reuters, 2014). PSA has claimed that joint programmes with GM, Toyota and Fiat for 1.25 million cars per year, as well as Ford for 2.3m diesel engines per year will yield savings of €100 million annually. Some cooperation has not been successful, for example the DaimlerChrysler merger or the Volkswagen-Suzuki alliance. One of the reasons is that cooperation at the level of engineering teams is not always successful and they might be reluctant to share ideas with each other. For example, in the case of the failed Volkswagen-Suzuki cooperation Suzuki accused Volkswagen of not being treated like a partner and of refusing to share hybrid technology on which collaboration had been agreed (Reuters, 2014a). Carlos Ghosn also views the issue of making cooperation work at the level of engineering teams as one of the main challenges and suggests it can be managed by slow, gradual intensification of cooperation over time (Economist, 2010).

Cooperation is often temporary, being formed and broken up as strategic considerations change. Recent examples in the field of engine development and production cooperation include the Global Engine Alliance, a joint venture between Chrysler, Mitsubishi and Hyundai founded in 2002 which was discontinued in 2009 with Mitsubishi and Hyundai selling their shares to Chrysler as the latter formed its alliance with Fiat (Car and Driver Blog, 2009). BMW and Ford ending the procurement of jointly developed engines from PSA is attributed to an alliance between PSA and GM in 2012 (Automotive News Europe, 2014a).

5.2.2 Building simpler, lighter cars

An approach of offering low-cost, no-frills cars based on established platforms and technologies has been pursued by some manufacturers, most notably Renault’s Dacia range. While these cars have not stood out as particularly lightweight or fuel efficient, there may be potential for combining established platforms and powertrains with weight-saving designs and materials as a low-cost strategy for improving fuel efficiency. This strategy has been pursued with the Citroen C4 Cactus, a crossover C-segment car launched on the European market in mid-2014. The C4 Cactus has been conceived as a no-frills car for which light weight was a key objective. Its project manager stated that ‘what we don’t include also won’t add weight’ (Der Spiegel, 2014). It is based on PSA’s established B-segment platform FP1 rather than the new flexible EMP2 platform for C and D-segment vehicles or the FP2 platform on which the current standard C-segment model, the C4, is based. The B-segment platform has been increased in length; the wheelbase of the Cactus is only 13mm shorter than that of the C4. However, its body is 17cm shorter and Citroen advertises it as being almost 200 kg lighter than the C4. Despite its shorter length, the boot volume is approximately comparable. In its PureTech 110 Start&Stop variant, the C4 Cactus has an unladen mass as measured by ADAC of 1130 kg which is 130 kg less than that of the 5-door Golf VII with comparable engine (1.2 TSI BMT). Judging by the difference in kerb mass, as provided by the manufacturer, the unladen mass of the basic variant with naturally aspirated engine and without start-stop would be 1075 kg.

The bonnet and the front and rear bumper mounts are made of aluminium (Citroen, 2014). Other weight-saving and price-reducing features include pop-out rear windows instead of sliding windows (saving 8 kg), a darkened polycarbonate sun roof without separate blinds (saving 5 kg) and a non-split rear-bench (saving 11 kg) (Auto Motor Sport, 2014) (Automotive Manufacturing Solutions, 2014). However, it is claimed that the greatest reductions in mass come from the choice of platform and engines (Automotive Engineer, 2014). With a prices from around €14,000 in Germany it is priced between a typical B-segment and a typical C-segment car.

5.3 Exploration of the variation between cost estimates

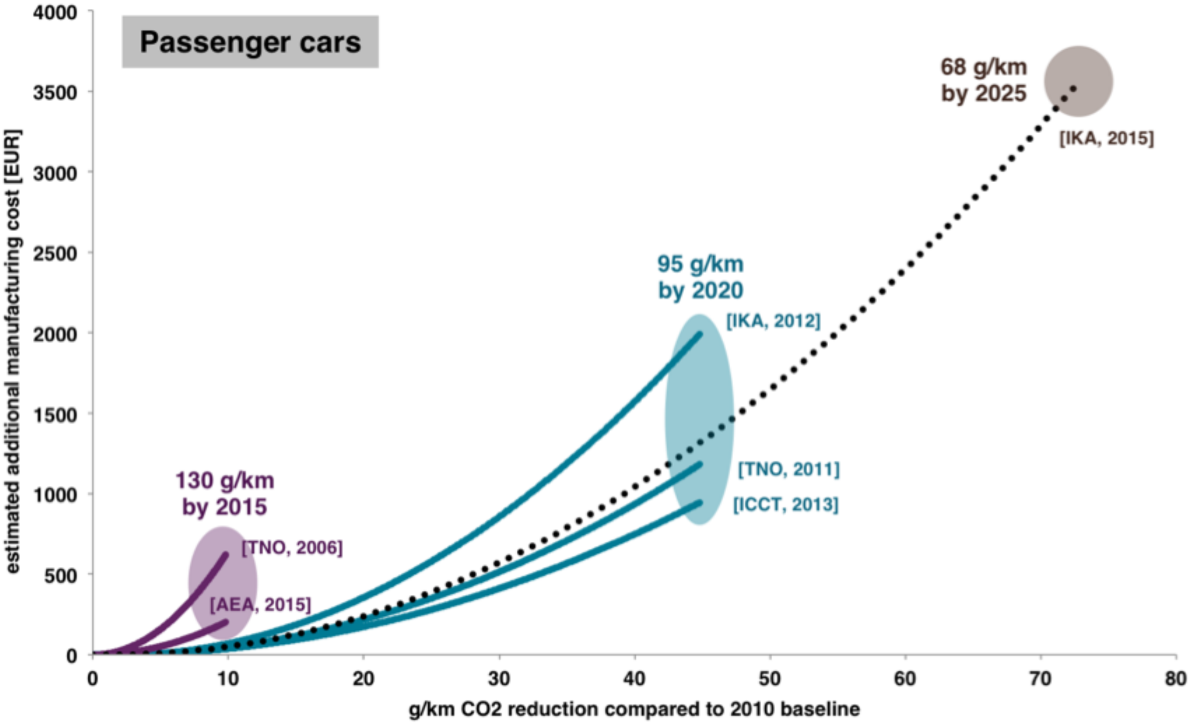
5.3.1 Background

Since before the introduction of the CO_2 Regulations for cars and LCVs, the costs of CO_2 reduction technologies has become of major interest to both industry stakeholders and policy makers alike. Emission standards have to be set in such a way that they can be met by the means of solutions that are both technically feasible and economically viable for the vehicle manufacturer. While the purpose of emission standards is to increase the environmental performance of vehicles, the sustainability of the car manufacturing industry should not be jeopardized, and the affordability of vehicle ownership should not be put at risk. Projections of technology costs have hence become of increasing importance to all stakeholder groups involved and have been the subject of numerous studies around the globe, whether conducted 'in-house' by industry stakeholders for their own purposes, or commissioned by public authorities, NGOs or other stakeholder groups for the purpose of policy making or knowledge sharing.

In Europe, such studies have been conducted in order to inform the costs of setting emissions standards in the time horizon to 2020. Cost projections for meeting the 2015 emission standard of 130 g/km CO_2 have been carried out in the years up to 2010. (Other analysis has also been conducted previously looking at the costs for going from 140g/km to 120 g/km by 2012, e.g. (ADL, 2003), which suggested costs in the region of €4000). Since 2010, the focus shifted to delivering cost projections that inform the setting of 2020 emission standards. So far 2015 has been marked by an increasing number of studies that explore the costs of forthcoming emission standards up to 2030 (including this one). While such forward-looking studies are an essential basis for decision making, a look back in time should not be neglected. Looking back at the cost projections developed in previous studies and comparing them with observed cost outturns can give an indication of the reliability of forecasts and their potential discrepancies with reality. The findings of such comparisons can serve as valuable input for forthcoming studies, in order to make their projections more realistic.

(ICCT, 2015) has conducted such a comparison. Figure 5.7 shows ICCT's comparison of different studies' estimates of costs that manufacturers were predicted to face in order to meet the EU's CO_2 emission standards in the years 2015, 2020 and potentially 2025. Comparing the cost estimates for the 130 g/km CO_2 target in 2015 is particularly interesting: While (TNO et al., 2006) was a forward-looking study, hence providing cost projections, (Ricardo-AEA, 2015) is a backward-looking study, which relies on available 'real-world' information of technology penetration for the year 2014, from which cost outturns for an average vehicle can be inferred. The comparison shows that TNO's ex-ante cost estimate of additional manufacturing costs (€620) are significantly (3 times) higher than Ricardo Energy & Environment's estimates of cost outturns (€202). When looking forward, to the year 2020 and the 95g/km target, only forward-looking studies can be compared with each other. Also among these, significant differences can be observed. (IKA, 2012) estimates additional manufacturing costs to be two times higher than (ICCT, 2013a), although the latter appeared only one year later. This shows that discrepancies of cost forecasts certainly do not only rely on the information available at a certain point in time, but moreover also on many underlying assumptions and applied cost projections methodologies.

Figure 5.7: Cost estimates for passenger cars in the EU up to 2025 (ICCT, 2015)



The former comparison between TNO's and Ricardo Energy & Environment's study suggests that there might be a categorical overestimation of costs in forward-looking studies. The comparison made here is however carried out on a vehicle basis. Neither the comparison done here, nor the information in the source documents, which is in case of Ricardo Energy & Environment not broken down into the costs of single technologies, allows for the exploration of the reasons for this discrepancy. This comparison at vehicle level also means that CO_2 emissions reductions and consequently cost savings thanks to exploiting **test cycle flexibilities** (as, for example, described in (TNO, 2012b))[27] cannot be separated out from CO_2 reductions and costs that can actually be directly linked to CO_2 reduction technologies. In forward-looking studies that provide cost estimates for CO_2 emissions reductions at the vehicle level such flexibilities will typically not have been considered and hence cause a discrepancy to estimates of cost outturns at the vehicle level. Disaggregated costs forecasts that are carried out at the technology-level will be less affected by the effects of the exploitation of test flexibilities (which can mostly not be linked to specific emission reduction technologies).

The work under this study task is an attempt to explore such discrepancies on a technology level, in order to derive conclusions on discrepancies of costs on the technology level.

5.3.2 Overview of the methodology for exploring the variation in cost estimates

The methodological approach to this task appears to be straight-forward: After ruling out 'obvious' discrepancies between different study findings, the comparison of ex-ante cost estimates with ex-post out-turns for different vehicle technologies should allow the estimation of the magnitude of discrepancies that are due to less tangible and quantifiable issues, such as potential biases in source data, unexpected technological developments, unpredicted innovations in production processes or unforeseen manufacturer strategies. This analysis could assist with the development of a correction factor that can serve to account for such potential 'intangible' residual discrepancies between findings of this (future-looking) study and real world cost observations.

Carrying out this analysis thoroughly entails looking at the level of single technologies rather than a whole vehicle. On this technology level, the main sources of cost discrepancies between projections

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[27] According to TNO's study type-approval authorities and test houses have made clear that flexibilities have increasingly been used to lower CO2 emissions of new vehicles on the type-approval test. For passenger cars it was estimated that the potential CO2 reduction in 2010 due to additional use of flexibilities since 2002 was around 11% (bandwidth 6 - 16%). For LCV a value of around 7% (bandwidth 3.5 - 10.5%) was estimated.

and real-world outturns are likely to be identifiable and distinguishable by their different natures (which are defined in the following). A technology-level analysis comes with certain methodological difficulties though, which we will (where applicable) also address in our following discussion over the next four sections.

First, Section 5.3.3 gives an overview of potential sources of discrepancies when comparing the findings of different studies. These sources of discrepancies are then illustrated by the comparison of technology cost estimates that stem from different sources (in section 5.3.4). Section 5.3.5 shows the results of six case study technologies that were explored in terms of their remaining ex-ante vs. ex-post technology cost discrepancies, after ruling out, as far as possible, all identifiable and quantifiable sources of discrepancies. Section 5.3.6 then discusses the development and usefulness of a potential correction factor that could be applied in this and future studies, in order to render cost projections as realistic and reliable as possible.

5.3.3 Identification of sources of discrepancies

The first part of this section gives an overview of potential sources of discrepancies in cost estimates of technologies across different studies. We categorise these sources into two broad groups, being sources due to *comparability issues* and *systematic issues*. Also the impact of exploiting test cycle flexibilities is discussed at the end of this section. The next section then provides some illustrations of the sources of these discrepancies.

Comparability issues are the more straight-forward sources of discrepancies, in the sense that they are generally easier to identify and quantify and as a consequence it is possible to account for and/or rule out these when attempting a comparison. They arise due to differences in the fundamental comparability of given estimates and refer to specific assumptions that are made and more or less precisely described/ highlighted in the studies. They comprise discrepancies due to

- Differences in the **understanding/scope of the technology** (or in related assumptions made).
- Differences in the **performance of the technology** (i.e. concerning CO_2 reduction potential; or any assumptions made in this respect).
- Differences in the **type of costs** that are being estimated: the type of costs being estimated can be very different across different studies, each type bringing about its additional sources of potential discrepancies:
    - ***Manufacturing costs***: Manufacturing costs can be estimated from either the suppliers' or the car manufacturers' view (depending on whether the technology is built in-house or bought-in there might be an additional mark-up factor charged by the supplier). Further, these costs can either include or exclude costs for the integration of the technology into the vehicle.
    - ***Additional* manufacturing costs** compared to baseline technology costs: These costs represent a cost difference to a baseline technology scenario, which potentially causes an additional source of discrepancy in the case where the assumed baseline varies across different studies. (The same sources of discrepancies as for manufacturing costs apply here as well.)
    - ***Direct manufacturing costs***: These costs (whether from the suppliers' or manufacturers' view; being *additional* or not) do not take account of overhead costs (of the supplier/ manufacturer) but 'only' include costs that arise due to the manufacture of the technology and its integration into the vehicle.
    - ***Total manufacturing costs***: These costs comprise direct costs (see above) *and* indirect costs. The latter ones account for overhead costs of the OEM (and/or supplier). Different assumptions can be taken regarding the comprehensiveness of these costs and the exact costs items that should be included (see Section 4.7 of this report, where different opinions of stakeholders in this respect were gauged in the frame of the Delphi survey).
    - ***Consumer costs/Retail price***: This type of cost estimate might be provided in studies that explore the effect of emission standards on the end customer (the buyer of the vehicle). In this case, different assumptions concerning the OEM (and dealer) mark-up factors as well as transportation costs become very important and are likely sources of discrepancies (NB: such costs might also already be included in total manufacturing

costs, depending on their exact definition). Cost estimates might also include value added tax (VAT) for specific countries or might consider an average VAT rate that is applied across all EU Member States.

- Differences in **projection timeframes**: cost estimates might not be comparable across different sources since they refer to different years.
- Differences in **drivetrain and vehicle segment** assumptions: cost estimates of different studies might not be available for both diesel/petrol drivetrains and/or all vehicle segments. Furthermore, definitions regarding vehicle segments, might be different across different studies.

The above stated comparability issues of cost estimates are relatively easy to control by assuring that technologies are compared on a like-for-like basis, as long as this is feasible according to the extensiveness of available cost estimates (e.g. cost estimates are available for a range of years, vehicle segments, and cost types).

Systematic issues are, compared to most comparability issues, less straight-forward to identify and quantify and hence difficult to rule out when making comparisons. They predominantly refer to the underlying method and underlying methodological assumptions of the studies to be compared. The following systematic issues can be differentiated:

1) Differences in underlying **framework conditions**: studies estimating (future) technology costs are usually based on a multitude of assumptions concerning the development of framework conditions that allow the estimation of the demand for a certain technology/vehicle type, and hence manufacturers' production volumes, their economies of scale in production processes and potentially additional learning effects. For example, these framework conditions might refer to *policy developments* (such as purchase subsidies and taxation policies), *developments of energy and resource prices*, *developments in consumer behaviour*, *demographic developments*, etc. All these framework conditions are typically related to each other. While certain studies will make explicit assumptions on each (or some) of them, and analyse the impact of different assumptions in sensitivity analysis, others might simply work with set penetration rates of different (drivetrain) technologies, to then build a scenario analysis around these. Framework conditions can also be defined to apply to a specific geographic context only. For example, not all assumptions valid for the European market would be valid similarly to the North American or Asian market.
2) Differences in the **underlying cost estimation methodology**: such differences can be manifold. Examples include:
    - Differences in the ***comprehensiveness of the projection method***: While some studies might take account of learning effects on a time-basis, others might base learning effects more directly on penetration rates (and hence production volumes). Other studies might neglect such learning aspects completely and base technology cost forecasts only on expected differences in resource prices.
    - Differences in ***sources for costs and related information***: some studies might rely on a more or less exhaustive (industry) stakeholder input, while other studies might rely on their own fundamental or academic research. Each of these sources is likely to be subject to certain biases, depending on the frame and the purpose of the specific consultation/research.

Items 1 and 2 are mostly very difficult to control when making comparisons, since:

- Methodologies are not varied within one study; cost estimates are hence built on 'only' one underlying methodology and unlikely to be available for more than three scenarios that reflect different framework conditions, and
- Insightful information on underlying assumptions for these items are not always available to the reader.

3) Differences in the **date/time of the preparation of the study**: such differences will arise when comparing studies that were undertaken at different points in time ('earlier' studies are compared with 'later' studies). They represent the sources of discrepancy that are most complex to gauge, as these cannot be identified when comparing single technologies with each other, but rather depend on 'external' factors to the study (i.e. they are not related with the study's methodology or underlying assumptions). Such external factors were not known

(could not be foreseen) when preparing an earlier study, but were already evident in a 'later' study. They typically make studies incomparable and can be expected to explain the major residual differences once comparability issues (as described above) have been controlled/ruled out. Examples of such factors include:

- ***Unexpected technological developments*** leading to new or significantly advanced technologies that were previously unpredicted/unknown and might be preferred over 'old' technologies, due to cost benefits or their better performance (i.e. regarding CO_2 emission reductions);
- ***Unpredicted innovations*** in production processes;
- ***Unpredicted manufacturer design/marketing strategies*** (see Section 5.2);
- ***Unexpected spill-over effects of technologies*** that lead to additional cost benefits in the production/design/integration of other technologies;
- ***Unpredicted developments of framework conditions*** (as described in item 2 above).

4) Differences in the assumption of the **use of test cycle flexibilities**: such differences will arise when cost comparisons are carried out at the vehicle level between forward-looking studies that did not account for such flexibilities and backward-looking studies that where carried out at a point of time where the impacts of the test cycle flexibilities have become apparent. Disaggregate costs forecasts that are carried out at the technology level will be less affected by the effects of the exploitation of test flexibilities (which can mostly not be linked to specific emission reduction technologies).

5.3.4 Illustration of sources of discrepancies

This section illustrates sources of discrepancies between cost forecasts at the technology level as described above by the means of a few case study examples.

Disregarding any potential comparability or systematic issues that might make a comparison invalid, Table 5.1 gives an overview of cost estimates that can be found in literature for four different technologies. It can be seen that cost estimates vary quite widely, e.g. from €50 to €142 for advanced engine friction reduction or from €64 to €118 for electrical assisted steering. Given the discussion above, it becomes apparent that these values (although all presented as EUR 2014 values) are not comparable with each other without having a closer look at possible sources of discrepancies.

Table 5.1: Comparison of technology cost estimates across different studies disregarding potential sources of discrepancies (EUR 2014 values)

Technology	(TNO et al., 2006)	(Infineon, 2008)	(AEA, 2009)	(ICF, 2011)	(TNO et al., 2011)	(NHTSA, 2012)	(Roland Berger, 2014)	(ICCT, 2014)
Advanced engine friction reduction	€142	-	€118	-	-	€100	-	€50
Electrical assisted steering	€118	€64	€118	-	-	€89	-	-
Aerodynamic improvements 1	€89	-	€89	-	€52	€40	€40	-
Low rolling resistance tyres 1	€41	-	€47	€67	€37	€20	€75	€50

In the following discussion we take a closer look at one technology where we explore such sources of discrepancies. We choose the example of low rolling resistance tyres 1, for which Table 5.1 shows that various different sources provide cost estimates. Furthermore, low resistance tyres are a technology that can be expected to have similar costs for different vehicle segments and drivetrain technologies. A difference with regards to these items across the different studies should hence not lead to remarkable differences in cost estimates. Furthermore, low resistance tyres are a relatively simple technology, systematic issues of discrepancies can hence be expected to be few.

Table 5.2: Cost estimates for low-resistance tyres and underlying potential sources of discrepancies

	(TNO et al., 2006)	(AEA, 2009)	(ICF, 2011)	(TNO et al., 2011)	(NHTSA, 2012)	(Roland Berger, 2014)	(ICCT, 2014)
Technology costs	*€41*	*€47*	*€67*	*€37*	*€25*	*€75*	*€50*
Indexed technology costs *(TNO, 2006 = 100)*	**100**	115	163	90	61	183	122
Sources of discrepancies concerning “comparability issues”							
Technology performance (CO_2 reduction)	2%	2%	1.5%	**3%**	1.9%	2%	**3%**
Type of costs	Total manuf.	Total manuf.	Retail price	**Total manuf.**	Total manuf.	Direct w/o integration	**Direct**
Projection timeframe (cost year)	2015	2015	2016	**2020**	2017	2013	**2020**
Drivetrain	Diesel	Petrol	D+P	D+P	D+P	Petrol	Diesel
Vehicle segment	Upper medium	Upper medium	Upper medium	Lower Medium	Lower medium	Small car	Large car
Sources of discrepancies concerning “systematic issues”							
Technology penetration	Mass	Mass	Mass	Mass	Mass	Mass	Mass
Study year	2006	2009	2011	2011	2012	2014	2014

Rows one and two of Table 5.2 highlight that there are discrepancies for the cost estimates for low resistance tyres. If indexing the cost at 100 for (TNO et al., 2006), then the cost estimates of subsequent studies (carried out up until the year 2014) vary between 61 and 183. Looking at the potential sources of discrepancies of items that can conveniently be compared (since required information is readily available in the study’s reports) is not revealing though: An obvious reason why there are differences in cost estimates cannot be identified. For example, both (TNO et al., 2011) and (ICCT, 2014) give cost estimates for the year 2020 for tyres that can improve the CO_2 performance of the vehicle by 3%. While (ICCT, 2014) looks at direct costs only, their cost estimates are still significantly higher than the estimates of (TNO et al., 2011). It is questionable whether this difference is fully attributable to the different vehicle segments the respective studies look at. It is more likely that there are residual discrepancies which are not uncovered by this table. These might refer to systematic issues that are inherently difficult to assess (as described above) or to other comparability issues that are difficult to assess due to the lack of detailed information (such as information on the exact definition of cost items, or information on the specifications of the reference vehicle to which the 3% emission reduction refers to).

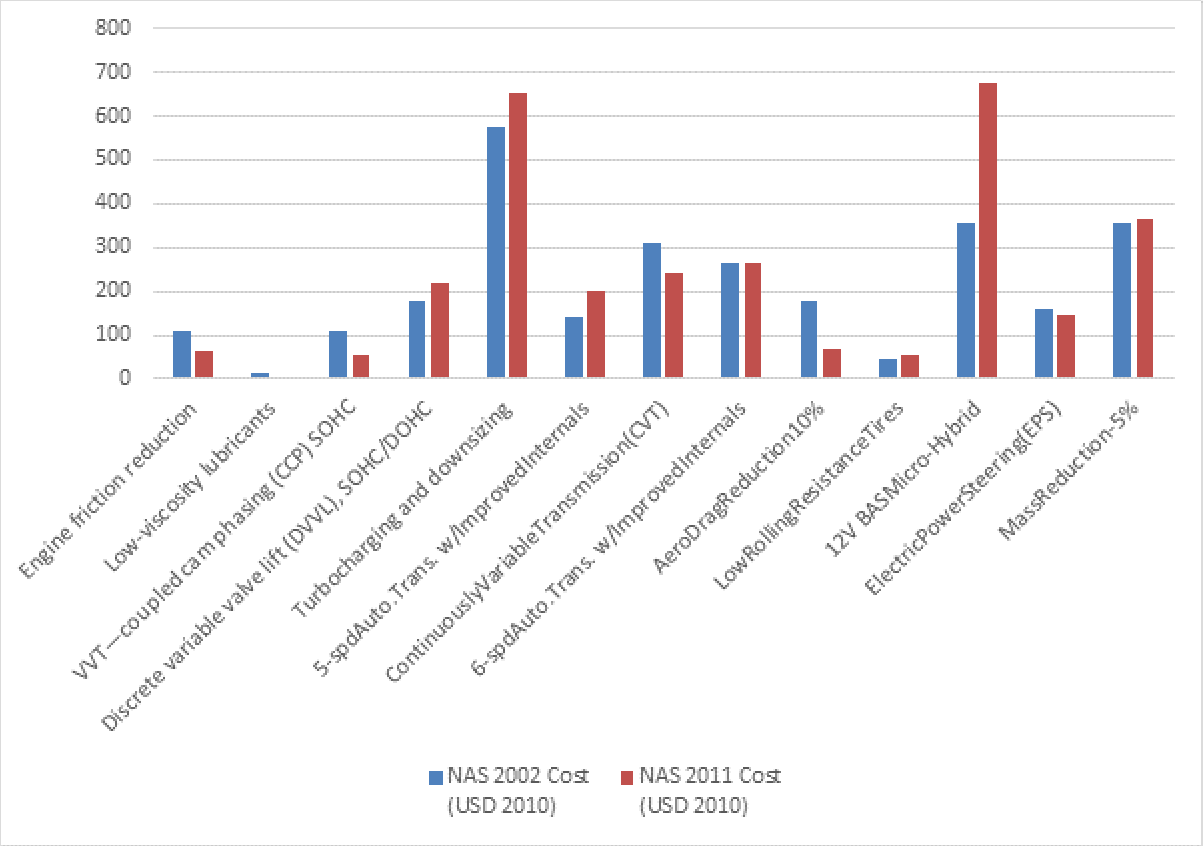
The table also shows that defining the magnitude of solely systematic issues is difficult. Almost none of the comparisons that can be made across the listed cost estimates rules out all sources of discrepancies regarding comparability issues. The most like-for-like comparison is the one between (TNO et al., 2006) and (AEA, 2009), where the more recent, 2009, reference predicts a higher technology cost than the 2006 reference for the same year. Whether this is a general pattern for cost estimates for low resistance tyres can however not be evaluated given the available data.

Figure 5.8 shows the comparison of technology cost estimates of (NAS, 2002) and (NAS, 2011). Out of the 24 technology cost estimates provided in (NAS, 2002) and the 43 technology cost estimates provided in (NAS, 2011), 13 technologies featuring in both datasets have been identified. Comparability issues have been ruled out as much as possible: cost estimates were taken for similar vehicle segments, the same drivetrain technologies, and the type of costs (retail price equivalent). Also, the underlying methodologies are fairly similar, in the sense that both rely for a large part on stakeholder input and expert judgement. The more recent study has a higher reliance on literature sources though, and also cites teardown studies among its references. Therefore, variations in estimates may be partly attributable to improved data availability in the more recent study. The main apparent difference is the year for which cost estimates are provided: both studies provide *current* technology cost estimates, hence for the years 2002 and 2011 respectively. This comparison does therefore NOT represent an example of differences in technology cost estimates between forward and backward looking studies (which will be provided in the following section), but rather shows that a comparison for which many comparability and other systematic sources of discrepancies can be ruled out are still subject to a discrepancy. We expect that this discrepancy can be mainly assigned to:

- Effects that arise due to the time difference of the preparation of the study (2002 vs 2011): During these eight years, technological developments, innovations, design/marketing strategies, spill-over effects of other technologies or other framework conditions might have contributed to cost changes in the considered technologies, and/or
- Learning effects in the production process.

The comparison shows a mixed picture. Technology costs have fallen for around half of the technologies. However, some technologies (such as 12V micro hybrid as well as turbo charging and downsizing) have experienced a significant technology cost increase. This may be due to increasing technology specifications (i.e. leading to more complex but also higher performing technologies). Energy and resource prices might also have been an influencing factor.

Figure 5.8: Comparison of total technology cost estimates for comparable technologies over time ((NAS, 2002) vs (NAS, 2011), in 2010 US$)



5.3.5 Investigation of ex-post costs for specific technologies

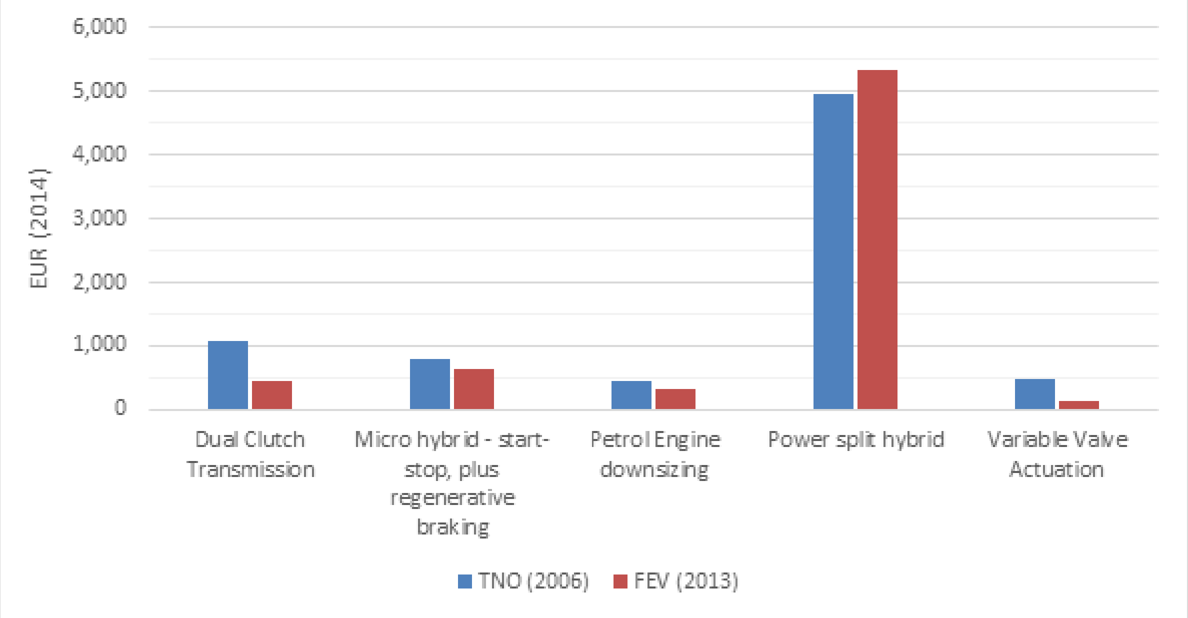
The above analysis has not yet allowed the comparison of ex-ante with ex-post technology cost estimates. For this purpose, technology costs estimates *stemming* from different years but *referring* to the same estimation year have to be compared with each other. Ex-post cost estimates or “outturns” are however very difficult to obtain: also stakeholder engagement as carried out in the frame of this study (i.e. via the Delphi survey and data verification interviews, see Sections 4.7 and 4.8 of this report) has shown that even industry stakeholders typically do not have such information and/or do not want to disclose it (multiple stakeholders did note though that such comparisons would also be extremely helpful in practice). As shown in the introduction of this section, the only ex-post estimates that typically exist, exist for whole vehicles, thanks to ex-post evaluation studies. On a technology basis, such comparisons have however not been carried out.

We circumvent this lack of available ex-post data on cost outturns by using cost estimates stemming from (FEV, 2013a) as proxies. The FEV analysis is based on tear-down analyses and is a reliable source that has been built on detailed, thorough analysis. It provides cost data for the year 2012. Taking these values as ex-post values and comparing them with projected 2012 cost estimates that were developed in earlier studies, allows for an ex-ante/ex-post cost comparison. (TNO et al., 2006) provides such ex-ante cost estimates for the year 2012.

Figure 5.9 features five technologies for which an ex-ante/ex-post comparison on the basis of these two studies is possible (as cost estimates for these technologies are available in both studies; and comparability issues, such as discrepancies due to differences in vehicle type and segment as well as type of costs (as these are all total manufacturing costs) are possibly best ruled out).

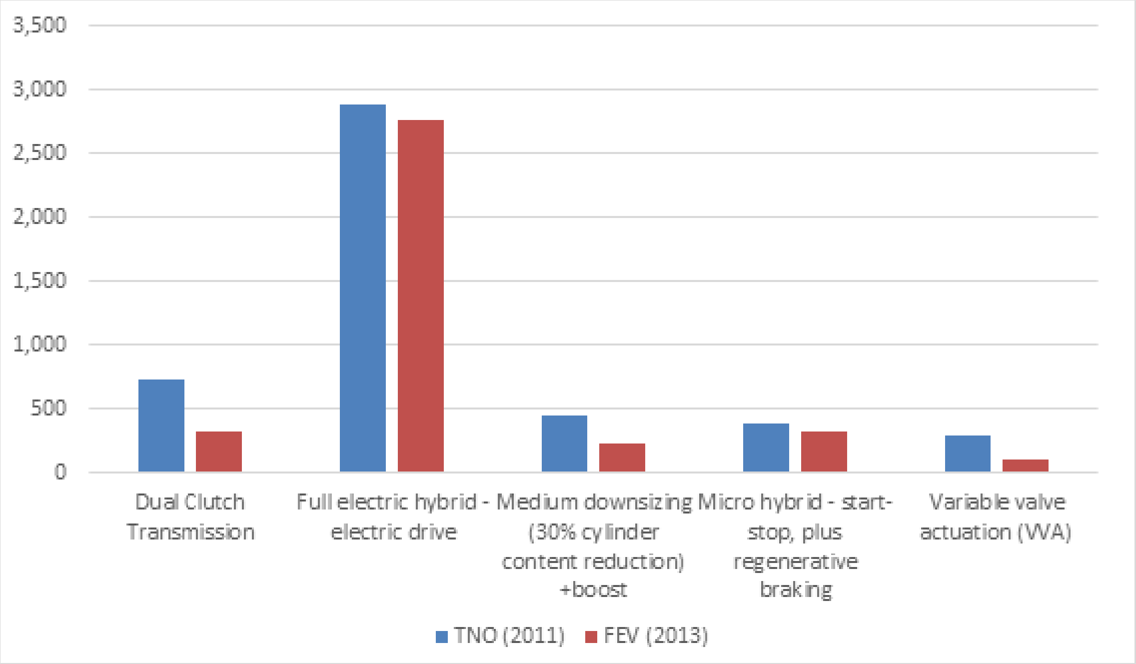
With the only exception of the power split hybrid, ex-post cost estimates appear to be lower than ex-ante cost estimates. On average, ex-post estimates amount to 70% of the magnitude of ex-ante estimates. However, this value varies across these five examples from 30 to 110%. Expressed differently, **ex-ante estimates appear to be on average 80% higher than ex-post estimates**. This value varies from -10% to 215% across the five different technologies shown here. **If not considering the power split hybrid technology, ex-ante estimates are on average 100% higher than ex-post estimates**. Excluding the power split hybrid can be considered as justified since this technology might be an outlier due to a differing underlying assumption on the technology’s performance (i.e. CO_2 reduction potential, which cannot be verified for the two data sources). Such a discrepancy in performance and also costs is especially likely for such a “young” technology - a technology that has not reached the same maturity level as the other technologies.

Figure 5.9: Comparison of ex-ante/ex-post technology cost estimates for the year 2012 (in EUR 2014)



A very similar analysis can be made with values stemming from (TNO et al., 2011) and (FEV, 2013a) for the year 2020. Given that both studies provide cost forecasts for a future year, such a comparison CANNOT be considered to be an ex-ante/ex-post comparison. Instead, it is a 'classic' comparison of two different cost estimates for the same year (while again all controllable discrepancies have been ruled out). However, it is insightful in the sense that cost differences appear to remain on a similar basis as in the previous comparison: FEV cost estimates for 2020 are on average 65% of the TNO (2011) estimates. Or, expressed differently, TNO (2011) estimates are on average 70% higher than FEV estimates (this value varies from 0 to 120% across the five given examples).

Figure 5.10: Ex-ante cost estimates for the year 2020 (in EUR 2014)



The above identified 'residual' discrepancies cannot be explained by any evident comparability factors. They are hence likely to be due to factors that we categorised as "systematic" issues. They refer to differences in underlying cost estimation methodologies as well as to potentially diverging assumptions regarding framework conditions. From the information available, we can identify the following substantial methodological difference between the two studies:

- The type of information source that was used for establishing baseline costs: while TNO's study relies heavily on stakeholder input, FEV's study is based on analytical tear down analyses; this leads to the additional discrepancy of
- The resulting type of costs that were estimated: While the FEV study provides a clear-cut definition of direct and indirect manufacturing costs and hence detailed information on what their total manufacturing costs entail, TNO's study 'only' provides total manufacturing costs based on stakeholder input. It is hence less clear which explicit cost items were included in the latter.

To which extent each of these or other related discrepancies have contributed to the total cost difference cannot be estimated though.

5.3.5.1 Exploring battery cost estimates

This subsection analyses and compares battery cost estimates. Battery cost estimates are manifold in the literature since they are seen to be one of the major cost drivers for electric vehicles. Even more so, they are frequently cited as one of the main barriers to successful electric vehicle uptake. Their price and cost developments will hence influence uptake rates to a large extent in the upcoming decade(s). Furthermore, battery cost estimates are quite practical to compare, since the delimitation of the battery is relatively clearly defined.

Figure 5.3 gives a comparison of battery cost estimates per kWh (on the battery pack level, adjusted to EUR2014 values) stemming from various different sources. Since the objective is to carry out a comparison of ex-ante and ex-post estimates, a focus has been put on studies that were carried out in the past and projected costs for the year 2015 (or 2012, 2017 and 2020 alternatively). Identified *projected* cost estimates can then be used for comparisons with *current* cost estimates of the underlying study, and in this way for an ex-ante/ex-post cost comparison. Again, all sources of discrepancies caused by comparability issues were ruled out as much as possible: all cost estimates are stated per kWh, on the battery pack level, and are valid for lithium ion batteries (unless stated differently). More detailed information on technological specifications are typically not detailed in the sources, however information on many further specifications would be necessary in order to assure comparability (such as information on the exact shape of the cells; the assumed battery size (influencing costs per kWh); exact battery performance indications concerning power, mass, energy density, safety etc.). Likely remaining comparability issues can hence not be ruled out in the following comparison.

Table 5.3: Comparison of ex-ante EV battery cost forecasts up to 2020

Source, Year of publication	Year of cost forecast	Cost per kWh (battery pack level; EUR2014)	Battery technology
Forecasts for BEVs			
(EC, 2004)	2012	**€431**	Lithium Ion
(NHTSA, 2010)	2015	€221	Lithium Ion
(Anderman, 2010)	2015	€436	Lithium Ion
(CCC, 2012)	2015	€250	Lithium Ion
(Roland Berger, 2011)	2015	€314	Lithium Ion
(IEA, 2011)	2015	€393	Lithium Ion
(ZEV, 2011)	2015	**€462**	n/a*
(NHTSA, 2012)	2017	€296	n/a*
(ZEV, 2011)	2020	€303	n/a*
Forecasts for PHEVs			
(JRC, 2009)	2012	€1139	Lithium Ion
(Anderman, 2010)	2015	€785	Lithium Ion
(CCC, 2012)	2015	€300	Lithium Ion
(Roland Berger, 2011)	2015	€440	Lithium Ion
(IEA, 2011)	2015	€590	Lithium Ion
Forecast for unknown vehicle type			
(Roland Berger, 2009)	2012	€481	Lithium Ion
(Deutsche Bank, 2009)	2015	€370	Lithium Ion
(Frost & Sullivan, 2009)	2015	€372	Lithium Ion
(BCG, 2009)	2020	€455	Lithium Ion
(Argonne National Laboratory, 2012)	2020	€211	Lithium Ion

* Information not available in source

Looking at the forecasts for BEV batteries only, two observations are remarkable:

- **Cost estimates have not significantly changed over time**, which is illustrated by the following example:
    i. (EC, 2004) forecasted costs of BEV battery costs to be €431 in 2012, while
    ii. seven years later, (ZEV, 2011) forecasted the same costs to be €462 in 2015.
- **Cost forecasts carried out at a similar point in time and for the same year, are still subject to a high discrepancy**, highlighting the level of uncertainty involved in these forecasts (and potentially comparability issues that could not be ruled out). As an example, taking all BEV battery cost estimates stemming from the years 2010 or 2011 that were carried out for the year 2015, a quite broad range of estimates, from €221 to €462 can be found.

The following table provides an ex-ante/ex-post comparison of cost estimates. The ex-ante cost estimates are derived from Table 5.3 (they are the average values of 2012 and 2015 estimates, brought to the year 2013 by assuming a linear decline between 2012 and 2015). The ex-post cost estimate is the (preliminary) current cost estimate used for the baseline (2013) in this study, which is derived from (ACEA et al, 2014), and is based on the costs of actually deployed vehicles in the marketplace.

Table 5.4: Comparison of ex-ante/ex-post BEV battery cost estimates for the year 2013 (in EUR2014)

Vehicle Type	Ex-ante cost estimate (average of previous studies, extrapolated to 2013)	Ex-post cost estimate (this study, baseline 2013 estimate)
BEV	€409[28]	€383

The comparison in Table 5.4 shows that ex-ante and ex-post cost estimates are quite well aligned. **Ex-ante cost estimates are 7% higher than the ex-post estimate** – a discrepancy which is significantly less than what was found for the previous ex-ante/ex-post comparison based on 5 technologies (where the average value amounted to 80% (with a value range of -10% to 215%).

There are several possible reasons for the lower identified ‘residual’, systematic cost discrepancy in battery ex-ante/ex-post comparisons compared to the previous comparison based on five technologies:

- First, the battery analysis is based on a multiple data points, whereas the previous analysis was based on two data sources only, and deriving an average of comparisons carried out for five different technologies. The analysis based on multiple data points might be more reliable.
- Second, comparability issues might not have been similarly supressed in both comparisons. Whereas the battery analysis refers to various different studies where comparability issues might arise for the same technology, the previous analysis is only concerned with comparability across two different studies, but across five different technologies.
- Finally, the case of batteries might be ‘special’: Most of the battery forecasts in previous years were generally perceived as being ‘very optimistic’, ‘ambitious’ or even ‘too optimistic’. Such projections that were back then thought to ‘push’ the boundaries, now turn out to be the best aligned with reality. Batteries might be a unique example in this respect. However, it is possible that if similarly ‘ambitious’ forecasts had been made for other technologies, that also for these fewer discrepancies between ex-ante/ex-post comparisons would have been found.

5.3.6 Development of a correction factor

The results of the above analysis could theoretically be used to develop a correction factor that accounts for systematic discrepancies between cost estimates and hence also for discrepancies between ex-ante and ex-post estimates. However, the above findings are quite diverse as the following factors were identified:

- **A factor of 3.0**: The introductory comparison of studies that showed ex-ante cost estimates and ex-post cost outturns on a *vehicle level*. It finds that TNO’s (TNO et al., 2006) ex-ante cost estimate of additional manufacturing costs, necessary for achieving Europe’s 2015 emission standard targets (€620/vehicle), need to be divided by a factor of 3 in order to be in line with Ricardo Energy & Environment’s (Ricardo-AEA and TEPR, 2015) estimate of the respective cost outturns (€202/vehicle). Given the identified major methodological difference (stakeholder consultation vs. analysis of technology penetration), this factor could be interpreted as giving an indication of the potential size of the discrepancy in cost estimates provided by industry stakeholders and actual cost outturns. However, there are clearly a range of complex factors involved.

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[28] Based on (EC, 2004), (NHTSA, 2010), (Anderman, 2010), (Roland Berger, 2011), (IEA, 2011), (ZEV, 2011) – the studies that provide ex- ante cost estimates for BEVs for the year 2012 or 2015.

- **A factor of 1. 8 (or 2)**: The comparison carried out on a technology level, on the basis of TNO's (TNO et al., 2006) ex-ante estimates and FEV's ex-post estimates of five different technologies (or 4 in case the less mature split-hybrid technology is excluded from the comparison), suggests that ex-ante estimates need to be divided by a factor of 1.8 (or 2) in order to arrive at FEV's (FEV, 2013a) ex-post estimates. Looking at each single technology, this factor varies from -1.1 to 3.2. Also here, given the identified major methodological difference (stakeholder consultation vs. tear-down analysis), this factor could also be interpreted as giving an indication of the potential size of discrepancy in cost estimates provided by industry stakeholders and actual cost outturns.
- **A factor of 1.1**: The comparison carried out for battery cost estimates based on multiple sources and using this study's baseline estimates as ex-post values, suggests that ex-ante cost estimates need to be divided by a factor of 1.1 in order to be in line with ex-post technology cost estimates.

Overall, this variance of factors developed on the basis of various different types of comparisons clearly shows the danger of assuming a blanket cost reduction factor to all technologies. This small selection of comparisons delivers very different results. Identified discrepancies are shown to vary a lot with single technologies and the exact sources of these discrepancies cannot be identified. The general application of a single reduction factor to all technologies is hence not advisable, would very likely lead to significant distortions in all estimations made, and compromise the validity of the study including all stakeholder consultation inputs. Applying a general factor would likely lead to increasing difficulties and biases when carrying out stakeholder consultations for any future studies.

Concerning the impact of the use of test flexibilities (as described in section 5.2.1 and 5.2.3), it is to be mentioned that this study takes account of the potential use of such test flexibilities in its cost estimates and technology cost curve development.

5.4 Exploration of the potential impacts of alternative powertrain deployment scenarios

5.4.1 Overview of the methodology for the alternative powertrain scenarios analysis

This task was concerned with identifying new powertrain deployment scenarios that take into account the likelihood that, (natural or bio-) gas-fuelled vehicles, BEVs, PHEVs/REEVs and FCEVs will all be deployed to some extent in the light duty vehicle fleet between now and 2030. The level of deployment for each of these technologies over the next 15 years will have significant implications for the costs of vehicles equipped with these technologies due to learning rate effects. The task therefore provides additional sensitivity analysis on the technology cost trajectories and learning rates developed in earlier tasks/report chapters to provide the Commission with information on how they might be affected under the different scenarios. The outputs of this task subsequently defined the uncertainty ranges for powertrain technologies as inputs to cost-curve analysis (Section 8).

This task was split into the following two stages:

i. Development of deployment scenarios for alternative powertrain technologies;
ii. Estimate the potential impacts of different scenarios on costs.

The following subsections provide a summary of the results of the analysis for this task.

5.4.2 Development of alternative powertrain scenarios and estimation of impacts

As part of the study, we needed to develop and explore the implications on technology costs of alternative scenarios for the deployment of alternative xEV powertrains (i.e. PHEV, REEV, BEV and FCEV). We have developed some different deployment scenarios – see Figure 5.11, which have also been tested with stakeholders as part of the general consultation/interview process. The objective of the task was to investigate cost uncertainties through the possible reasonable/conceivable extremes and their impacts on cost learning rates, rather than a view on actually what *'will most likely'* happen.

The percentage shares presented in Figure 5.11 for the different scenarios are for registrations / sales for relevant year and are NOT the share in the total fleet. The developed scenarios sit within the low-mid range of scenarios, forecasts and projections in the literature – see Figure 5.12.

It was agreed with the Commission early in the project that there was not a strong case for separating out cars and vans (since volumes are so much bigger for passenger cars, deployment in this sector will likely dominate effects on technology costs.). The consulted stakeholders also broadly agreed with the assumption that the future costs of technologies for application to ICEVs were unlikely to be significantly impacted by the alternative scenarios for xEV deployment (see earlier section 4.8.2).

In setting up the sensitivity analysis it was assumed that the costs for key components reduced from the estimated 2013 levels based on the estimated current levels and the cumulative percentage deployment according to the relevant powertrain scenario. Cumulative deployment was calculated based on the matrix presented in Table 5.5 below – i.e. certain components are included in only some xEV types. The contribution to learning for batteries was weighted according to their estimated relative kWh size compared to BEVs, so deployment of PHEVs/REEVs required almost three times higher deployment (in percentage terms) in the new fleet to achieve the same contribution to learning as BEVs. Since some groupings of components are common and have similar anticipated learning factors (i.e. percentage change in cost per percentage change in deployment) they can be grouped for the purposes of the analysis, and have therefore been assigned a ‘Learning Rate Category’ in the table.

Table 5.5: xEV system components assumed present in different powertrain types

Component	ICEV	Hybrid ICEV	PHEV /REEV	BEV	FCEV /REEV	Learning Rate Category
Wiring Harness		X	X	X	X	General xEV
Regenerative Braking System		X	X	X	X	General xEV
HVAC Standard Electric		X	X	X	X	General xEV
Motor		X	X	X	X	General xEV
Inverter		X	X	X	X	General xEV
Boost converter		X	X	X	X	General xEV
Control unit		X	X	X	X	General xEV
Wiring Harness		X	X	X	X	General xEV
HVAC Heat Pump			50%	100%	50%	Heat Pump
Single-speed gearbox				X	X	EV Gearbox
Battery*		2%	36%	100%	24%	Battery
On-board charger			X	X	X	xEV Charger
Fuel cell stack					X	Fuel Cell
FC Peripherals					X	Fuel Cell
H2 Storage					X	H2 Storage

Notes: * The contribution to learning for batteries was weighted according to their estimated relative kWh size compared to BEVs.

The key assumptions on learning factors are also presented in Table 5.6; these have been also informed by the feedback from the stakeholder consultation. The results of the learning assumptions for different scenarios are presented in Figure 5.13. Overall, the highest levels of cost reduction were found for PHEVs, REEVs and BEVs under the ‘BEV Extreme’ scenario, and under the ‘FCEV Extreme’ scenario for FCEVs. The highest costs for all xEV powertrain types was found under the ‘Ultra Efficient ICEV’ scenario. This is illustrated in Figure 5.14, also with comparisons with the original static estimates for cost reduction of xEV components. For the final cost-curve analysis, the Mixed xEV scenario was used to define the ‘TYPICAL’ baseline xEV powertrain costs, with upper and lower bounds from the xEV powertrain analysis being used to define the LOW and HIGH baseline xEV estimates.

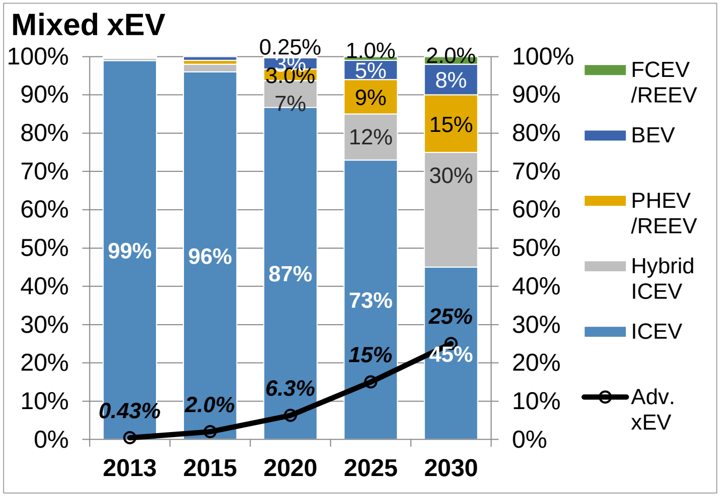
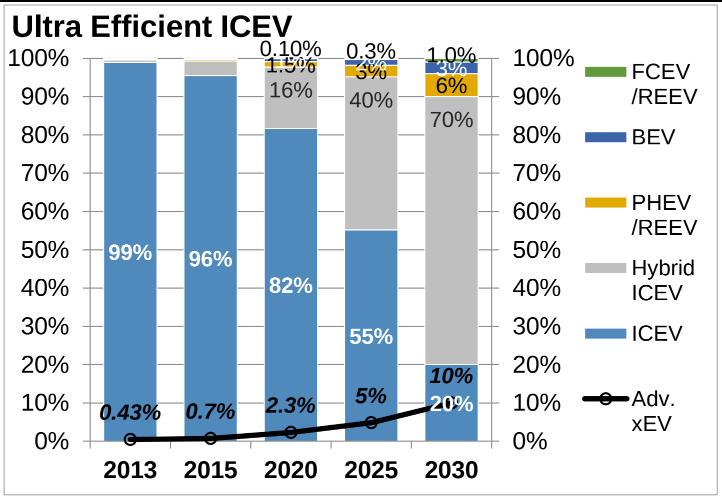
Table 5.6: Assumptions on learning factors for powertrain scenario calculations

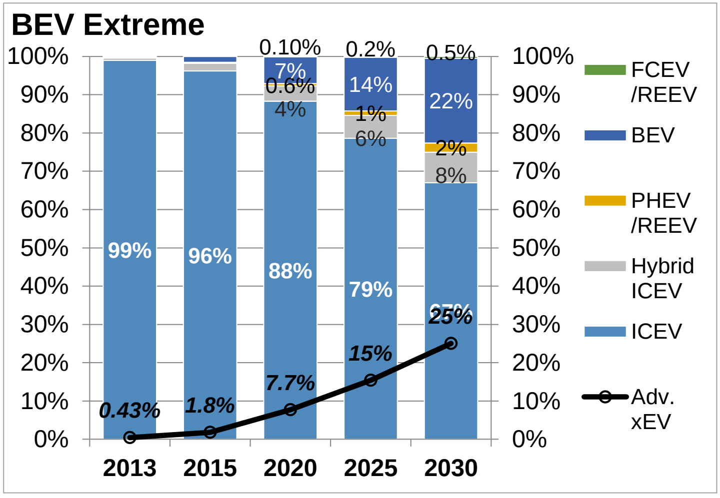
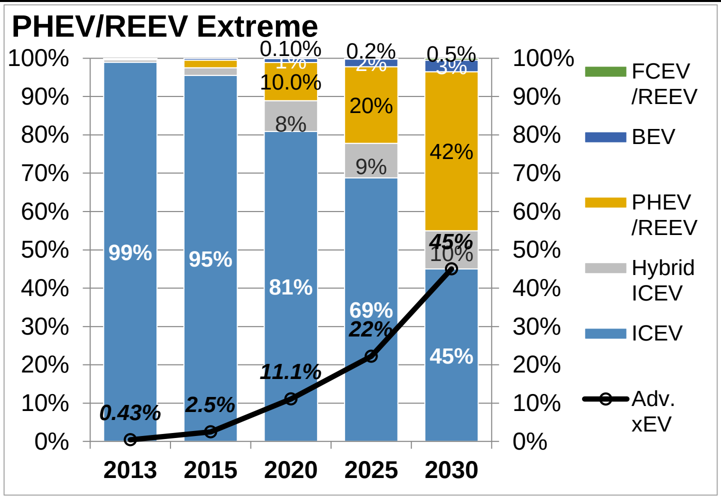
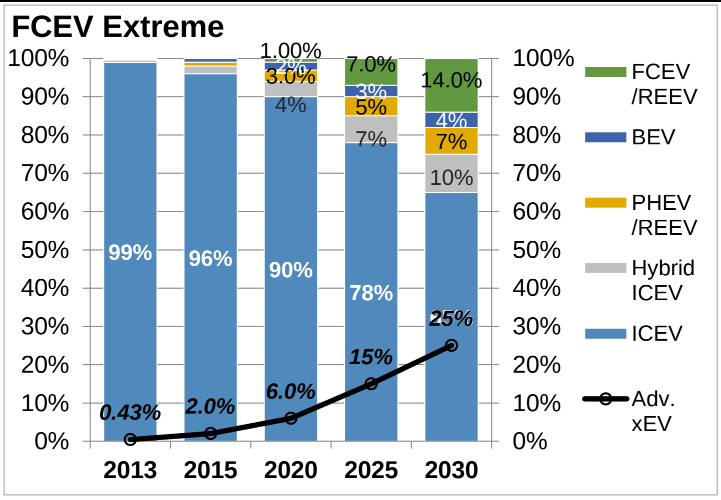
	High Learning Rate	Medium Learning Rate	Low Learning Rate
Battery*	12.5%	11.0%	8.5%

Fuel cell system	15%	15.0%	15.0%
H2 Storage	10.0%	10%	10%
Other xEV components	5%	5%	5%

Notes: The high learning rate was applied only in the BEV extreme scenario and the lower learning rate only in the ultra-efficient ICEV scenario. In all other scenarios the medium learning rate was applied.

Figure 5.11: Summary of the alternative powertrain deployment scenarios developed

Scenario breakdown by powertrain type	Summary description/basis
	Assumes xEVs are deployed at a rate consistent with the lower-middle range of estimates from the literature (see Figure 5.12), and the current central estimates for xEV technology cost reduction and performance improvement (see data validation Excel file). Assumes ongoing support by Member States to early market development for vehicle sales and the provision of supporting infrastructure. Also assumes future regulatory CO_2 targets for LDVs are introduced.
	Assumes low-cost and ultra-efficient ICEV hybrids are deployed, with minimal xEV uptake, e.g. future cost and performance improvements for batteries (fuel cells) in particular and other xEV components take longer to realise than currently anticipated, and improvements to ICEV and hybrid technologies make these relatively more attractive, and/or there is greater resistance to uptake of xEV from the mass market consumer, etc. Influenced also by lower conventional fuel prices, and less than ideal development of supporting xEV infrastructure.
ICEV = Conventional petrol, diesel and natural gas powertrain vehicles; **Hybrid ICEV** = Mild or full hybrid (electric /air / flywheel, etc.) vehicles**; PHEV/REEV** = plug-in hybrid or range extended electric vehicles; **BEV** = battery electric vehicles; **FCEV/REEV** = Hydrogen fuel cell electric, or range extended electric vehicles.	

Scenario breakdown by powertrain type	Summary description/basis
	Variant on the optimistic scenario, where uptake of BEVs is more rapid than other xEV types. Recent announcements by major OEMs [29,30,31,32] on their expectations for range and cost reduction of BEVs for 2017-2020 models are fully realised and the continued development of rapid charging networks leads to more rapid than anticipated uptake of BEVs by mass market (and in particular business) customers.
	Variant on the optimistic scenario, where uptake of PHEV/REEVs is more rapid than other xEV types. Improvements in battery performance and costs leads, and the introduction of a wide variety of PHEV/REEV models with improved dynamics and equivalent range to conventional vehicles leads to their relatively rapid uptake; mass-market customers still remain more sceptical of BEVs and FCEVs due to perceived (or real) range /infrastructure /up-front costs concerns in comparison.
	Variant on the optimistic scenario, where uptake of FCEVs is more rapid than other xEV types. Assumes costs for FCEVs reduce at the maximum forecast rate, potentially reaching parity with HEVs by 2025 (i.e. as targeted by some manufacturers[33,34]) and rapid development of H2 infrastructure. Rate of penetration of FCEVs is still more limited than other xEVs due to their later market entry, and the time needed to establish sufficient H2 production, distribution and refuelling infrastructure.
ICEV = Conventional petrol, diesel and natural gas powertrain vehicles; **Hybrid ICEV** = Mild or full hybrid (electric /air / flywheel, etc.) vehicles**; PHEV/REEV** = plug-in hybrid or range extended electric vehicles; **BEV** = battery electric vehicles; **FCEV/REEV** = Hydrogen fuel cell electric, or range extended electric vehicles.	

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[29] http://www.motoring.com.au/news/2014/volkswagen/volkswagen-expects-500km-battery-range-by-2020-46561

[30] http://www.autocar.co.uk/car-news/new-cars/mercedes-benz-lays-out-its-vision-powertrains-future

[31] http://www.autoexpress.co.uk/audi/89535/audi-to-develop-all-electric-family-car

[32] http://www.hybridcars.com/ceo-ghosn-nissan-has-affordable-250-mile-range-ev-battery/

[33] http://www.autonews.com/article/20141124/OEM06/311249976/toyotas-fuel-cell-goal-big-cost-cutting

[34] https://www.iea.org/media/workshops/2013/hydrogenroadmap/Session1.1WindDaimlerProgressonFCEVdevelopment.pdf

Figure 5.12: Project xEV deployment scenarios in comparison with a range of scenarios, forecasts and projections from the literature

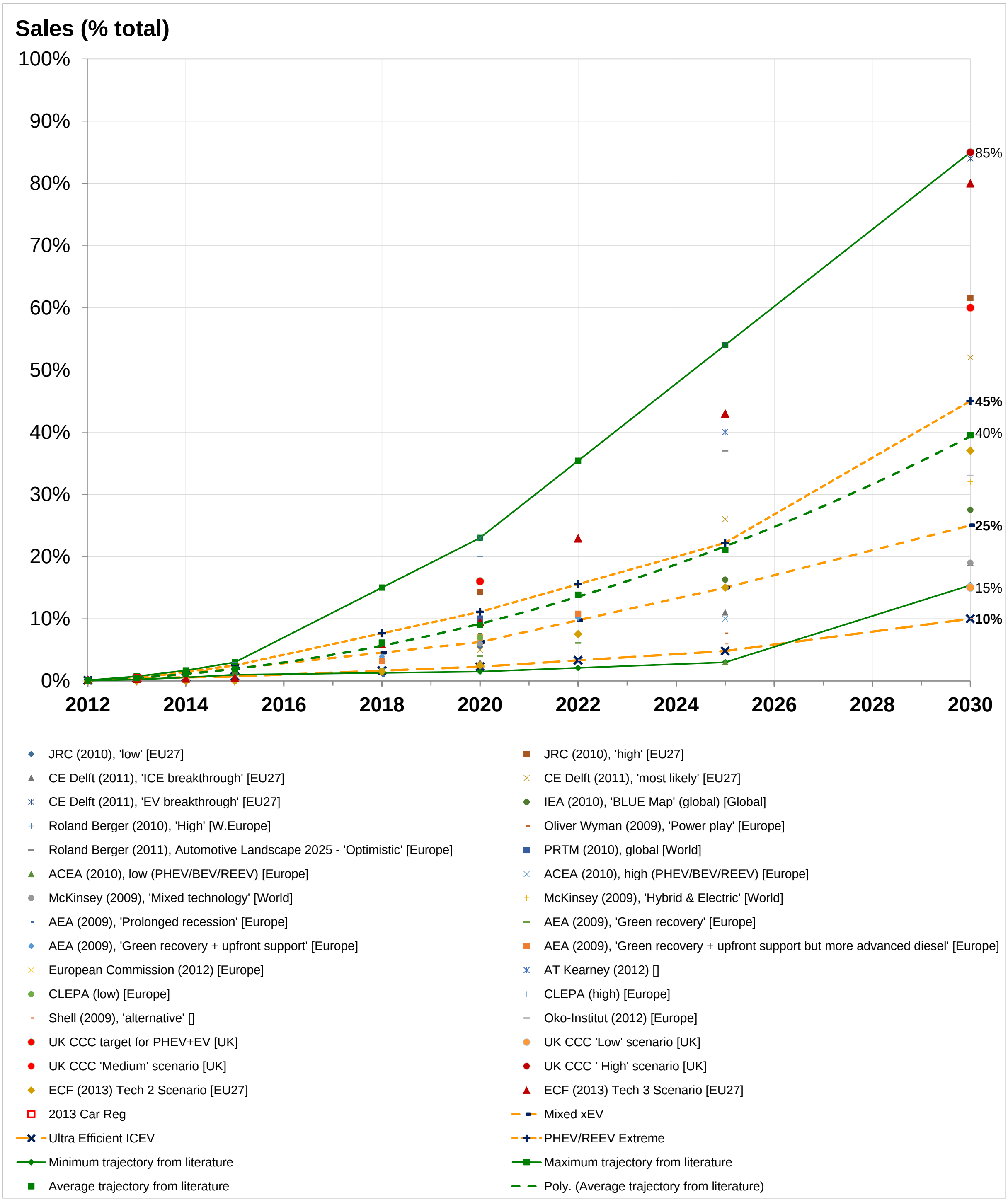
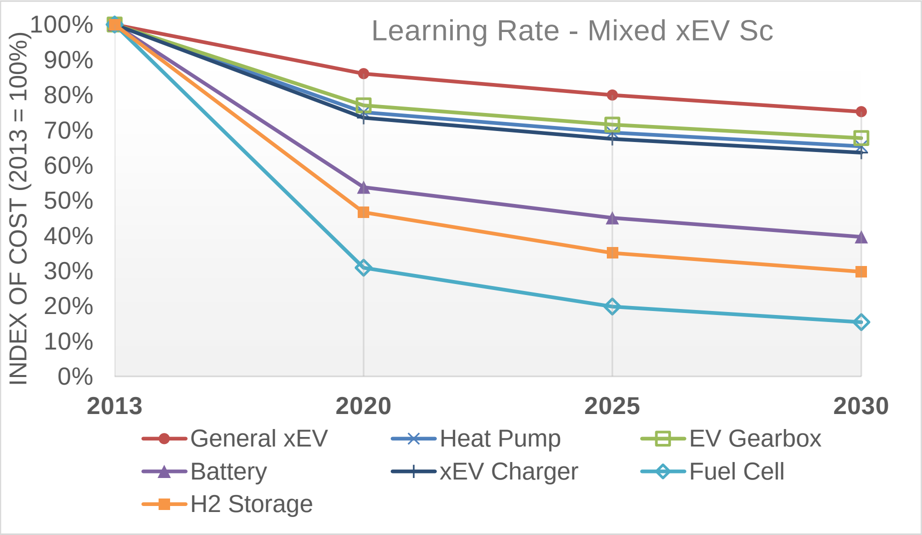
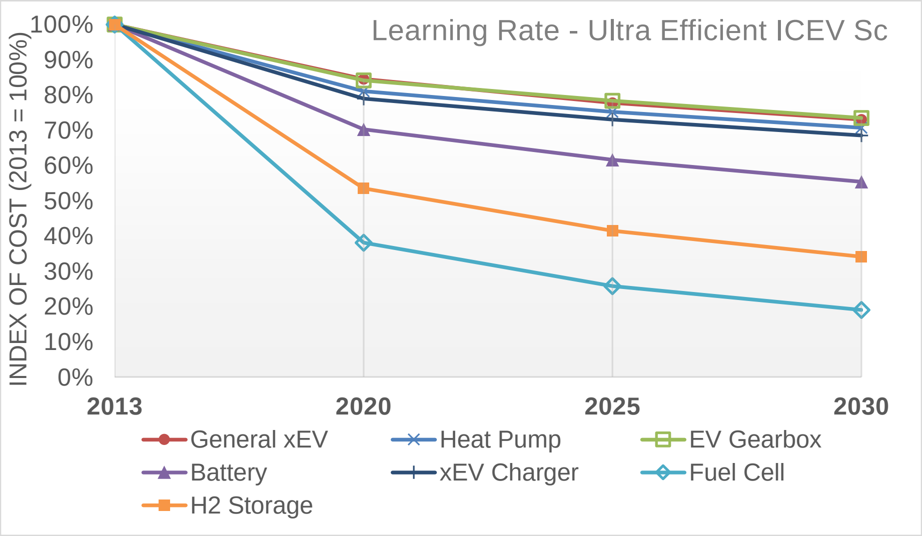
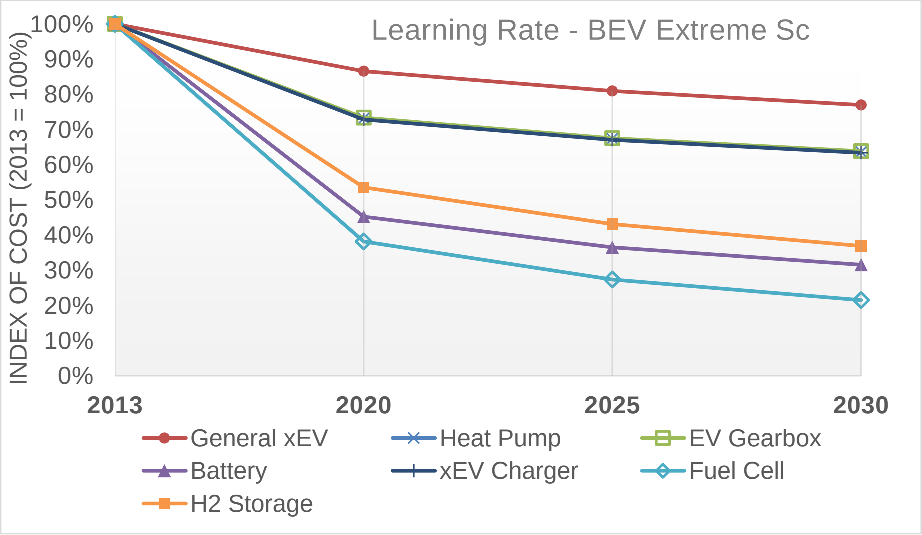


Figure 5.13: Impacts of the different powertrain deployment scenarios on the rate of cost reduction of different xEV technology types

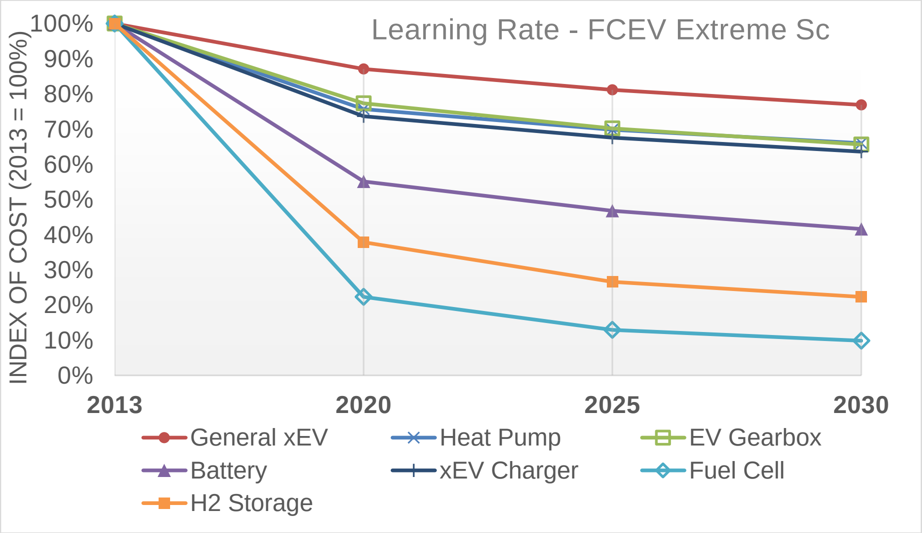


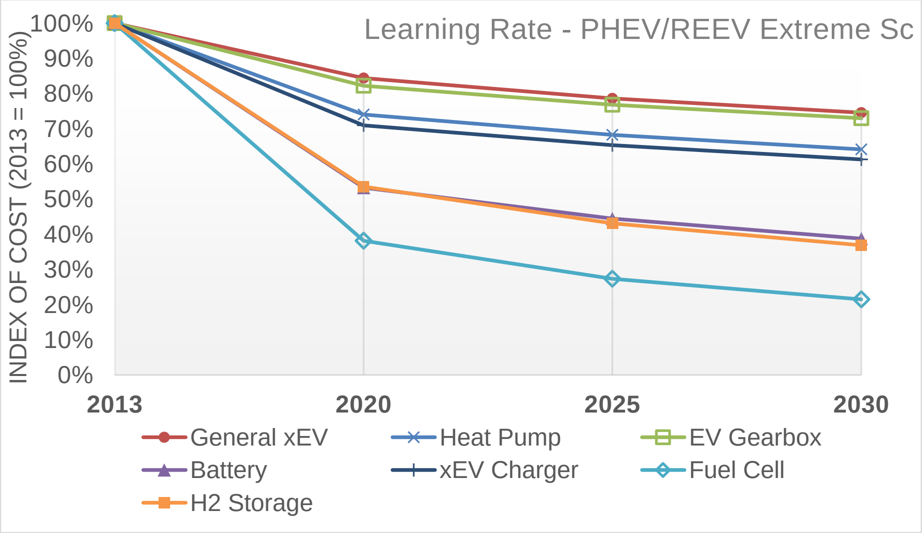




Notes: The presented trajectories for batteries, fuel cells and H2 storage are presented on a per kWh (batteries, H2 storage) or kW (fuel cells) basis. The anticipated move to higher capacity battery packs for BEVs to improved electric range would counteract to a degree the cost reductions illustrated here.

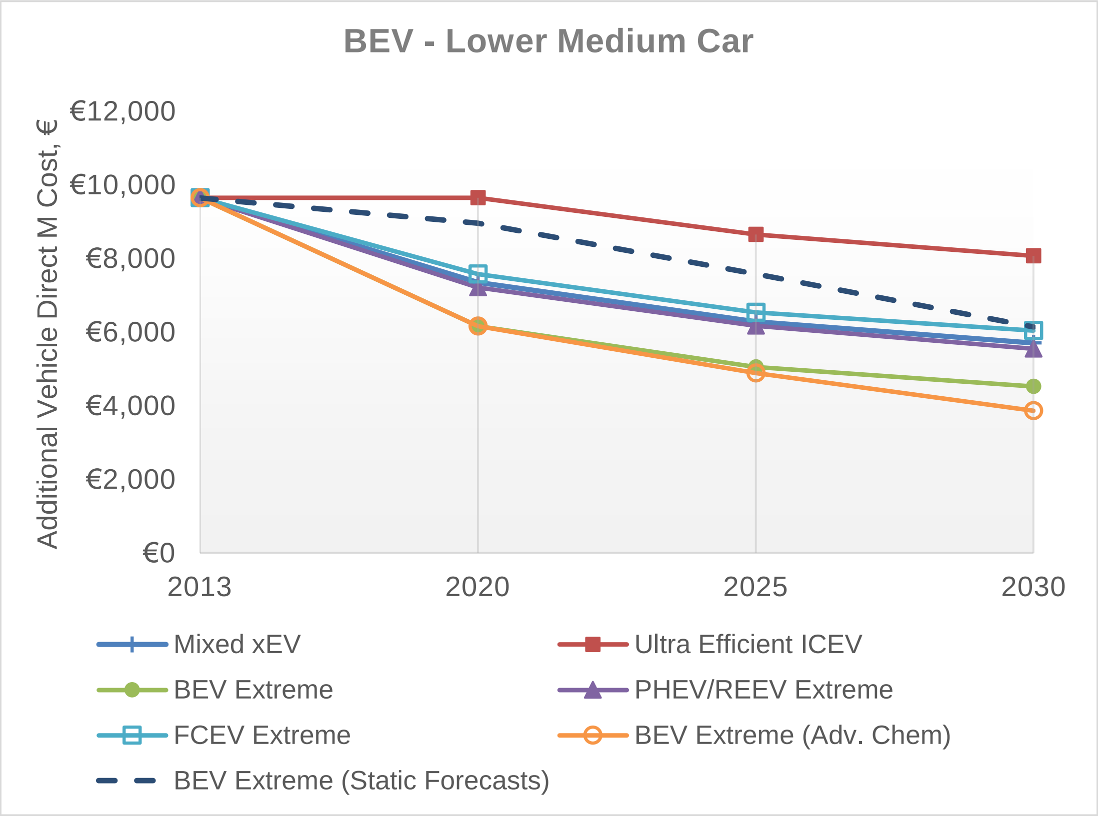
Figure 5.13: Impacts of the different powertrain deployment scenarios on the rate of cost reduction of different xEV technology types (continued)

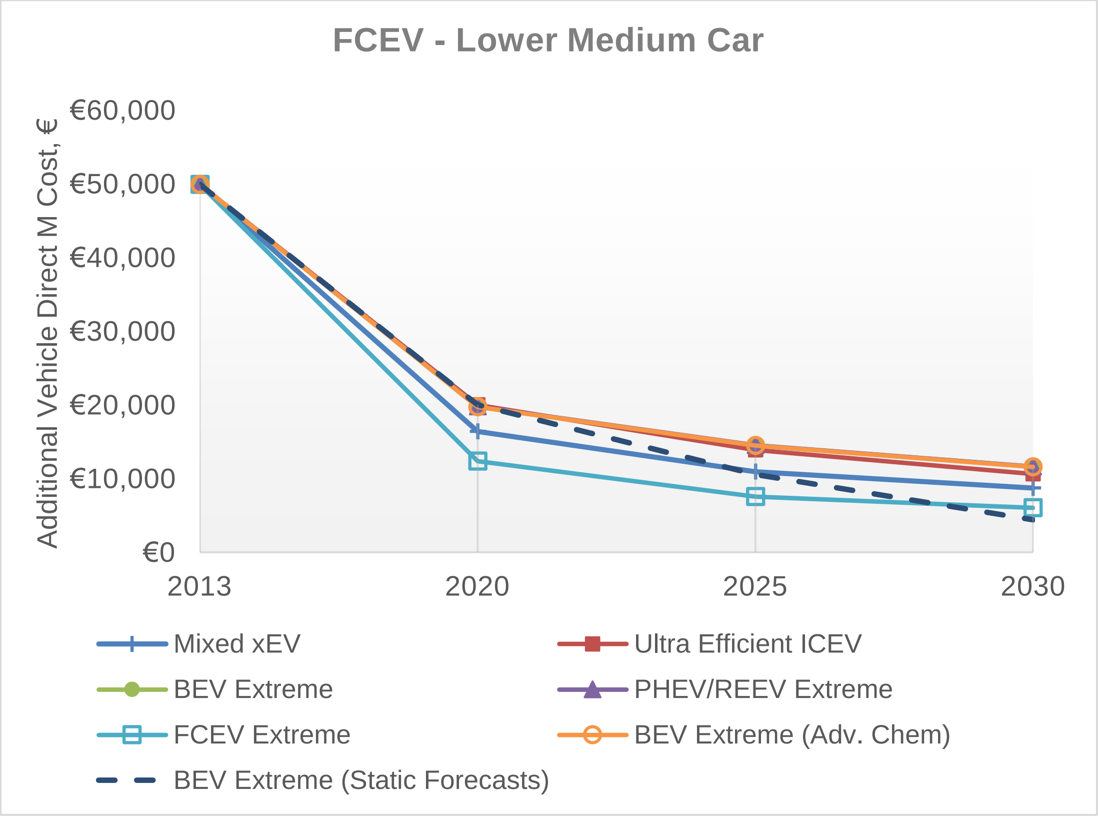




Notes: The presented trajectories for batteries, fuel cells and H2 storage are presented on a per kWh (batteries, H2 storage) or kW (fuel cells) basis. The anticipated move to higher capacity battery packs for BEVs to improved electric range would counteract to a degree the cost reductions illustrated here.

Figure 5.14: Summary of the powertrain scenario cost extremes for Lower Medium Car BEVs and FCEVs





Notes: The results above factor in both cost reductions in individual components, as well as anticipated increases in battery capacity / electric range for BEVs in future years that reduce the impact of reductions in cost per kWh on the overall additional costs of these powertrains.

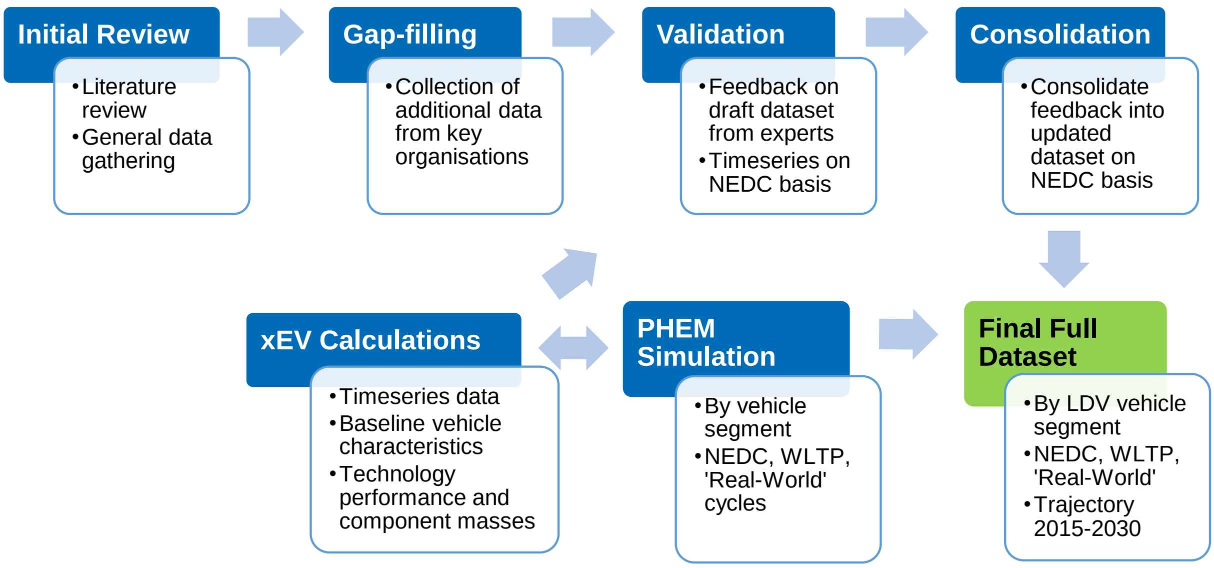
6 Analysis of the CO_2 benefits associated with each technology

6.1 CO_2 benefits of technologies that reduce test cycle emissions

In addition to cost data, an important element of this study was gathering data on the CO_2 abatement performance of each technology of interest. Figure 6.1 below provides a summary of the overall methodological approach and process used to develop the estimates of the CO_2 benefits associated with different technologies. A summary of the process used to identify, review and seek stakeholder feedback on draft estimates for CO_2 reductions for the identified technologies has already been provided in Chapter 4 of this report.

This work also included gathering and assessing information on the potential improvements in the average CO_2 abatement performance of technologies adopted. As pointed out by some stakeholders in feedback gathered during this study, an important consideration here is that technologies introduced into the marketplace rarely fulfil their expected full potential, and this performance often varies between the systems developed by different suppliers and OEMs (and also depending on which other technologies the system has been packaged with). Over time it is to be expected that the market average performance of technologies will improve towards their overall technical potential as they are optimised; in some cases future evolutions of the technology into more sophisticated systems may also take performance beyond initial expectations. Therefore, such considerations also had to be factored into the development of the final consolidated dataset.

Figure 6.1: Summary of the methodology to estimating the CO_2 benefits of technologies



The Commission's specification also indicated that such data will be required in a format that is in line with the WLTP test procedure, as this is expected to be the basis for testing in the 2025-2030 time horizon. However, given that at the time of writing (May 2015), the WLTP has not been finalised yet, such data is only available for a small minority of technologies, with the vast majority of data being based on the current official test cycles (i.e. the NEDC for Europe). Some of the technologies of interest are being examined under the Commission's ongoing NEDC-WLTP correlation test programme, with which we have had some involvement. However, results from this programme have still not yet become available, and it has been necessary to adopt a different approach to develop the final estimates in the required WLTP format. The approach adopted for this aspect was to simulate the CO_2 reductions by different technologies for different vehicle segments and test cycles using PHEM modelling by TU Graz. A summary of this work is provided in section 6.2 of this report.

The summary of the processes and assumptions for estimating the CO_2 performance of xEV powertrains has been provided earlier (in Section 4.5); the assumptions for the final consolidation of the data into the Technology Results Data Fiche is discussed further in later section 6.3.

Later, in Section 8.2 of this report, we present the results of analysis that investigated how multiple technologies applied in combination should be treated from the perspective of calculating CO_2. In doing so we considered the key areas of efficiency losses that a particular technology is addressing. In some cases technologies will be addressing the same areas of energy consumption so the overall benefits might be less. This work has informed the review and adjustments to the previous ‘safety margin’ approach applied to cost-curves in earlier studies to reduce benefits due to technology overlaps (and other factors which might limit achievement of overall efficiency improvements). The results of this analysis and its application to correct the raw data generated from the cost-curve model are discussed further in Section 8.1.

6.2 Simulation of CO_2 abatement performance using PHEM modelling

The main task of this chapter is the assessment of the CO_2 reduction potential of the relevant technologies in different vehicle segments over different driving cycles:

- NEDC: most data available in literature is based on this test cycle.
- WLTP: will most likely be the relevant test procedure for the CO_2 type approval after 2020;
- Real world cycles (here the Common ARTEMIS Driving Cycle (CADC) and a real driving emissions (RDE) cycle are simulated): the inclusion of these will help to give an impression of whether real world reduction rates are expected to be different to the type approval reduction rate for some technologies.

The different test procedures have different vehicle speed trajectories and also use quite different test masses and driving resistances. WLTP values are closer to real-world operational conditions than NEDC values in this respect. However, additional auxiliary energy consumption (e.g. for HVAC) and non-perfect vehicle and boundary conditions (tyre pressure, side wind, etc.) lead to typically higher driving resistances in real world conditions than in the WLTP.

Since the assessments shall be made for a huge number of vehicle and technology combinations, an approach based on physical relations was established to define vehicle-specific input data for the different test procedures in a consistent way (see chapter 6.2.3).

In total the following base vehicle classes were considered (to be consistent with the overall approach taken in the project):

- Small Car
- Lower Medium Car (= C-Segment)
- Upper Medium Car
- Large Car
- Small Van
- Medium Van
- Large Van

The assessments include:

- Petrol engines (SI) for base 2002 technology and for advanced technologies;
- Diesel engines (CI) for base 2002 technology and for advanced technologies;
- Alternative propulsion systems (Hybrid (HEV), PHEV, BEV, FCEV, REEV);
- Improved vehicle technologies;
- Improved engine technologies;

  - Improved transmission systems;
  - Waste energy recovery systems.

The technologies simulated cover more than 2500 vehicle/technology combinations.

Some of the technologies can be calculated with the PHEM simulation tool easily (e.g. reduction of aerodynamic drag), some need more effort (e.g. adjusting engine rated power and transmission system to account for mass reductions) and some technologies needed a high level of effort.

The most demanding technologies for simulation are those which need to be adjusted to each vehicle configuration to achieve low fuel consumption values. These are, for example:

- *Hybrid vehicles*: adjustments in the hardware (engine and battery dimensions) and also in the control strategy (engagement of the electric motor for generation or for driving as a function of actual vehicle status and of the driver demands for acceleration or deceleration) have to be made separately for each vehicle to achieve best fuel efficiency.
- *Transmission systems*: transmission ratios and for automatic and automated manual transmission, as well as the gear shift control strategy, have to be adjusted to the vehicle configuration.

For these complex technologies, we attempted to elaborate general valid, generic control algorithms which were implemented in the simulation tool PHEM. This means that in several cases the results do not reflect completely optimised hardware and software structures[35]. Since in reality several constraints typically also do not allow the entire theoretical reduction potential of a technology to be achieved, the effects of a non perfect-optimisation in the simulation are not seen as being critical for the assessment of CO_2 reduction levels. Since the level of optimisation achieved with the generic strategies may differ between vehicle segments and cycles, a proportion of the differences in the reduction potentials calculated may be related to this effect. Due to this uncertainty, all results were checked for the plausibility of the differences per segment and cycle and seemed to be within the correct ranges. All results from PHEM simulations were stored in a database together with data gained from other sources to allow for a structured analysis.

It was assumed at the beginning of the project that some important model input data would be gained from the study on WLTP-NEDC correlation which was running in parallel for DG CLIMA and is performed by LAT, JRC and ACEA. JRC has supported the actual PHEM simulations with a tool to calculate generic gearbox transmission ratios and with their assessments of cycle-specific differences in test masses and resistances[36]. Unfortunately no data on advanced vehicle and engine technology has yet been made available from the WLTP-NEDC correlation study. This therefore significantly increased the effort for elaborating PHEM model input data compared to the effort that was originally planned.

In the report sections below the methods implemented are described and the general trends and findings from the simulations are explained. An extended discussion with specific information with regards to the simulation of the different types of technologies is also provided in Appendix 5.

6.2.1 Method description

The methods used to compute the CO_2 reduction potentials for fuel consumption on NEDC, WLTC, CADC and on a Real World Cycle (RWC) are based on vehicle longitudinal dynamics that are used to calculate the engine power demand and the engine speed in 1 Hz increments over the test cycles and on engine fuel flow maps to interpolate the fuel consumption over the cycle. The PHEM tool was used for these calculations, and an overview of the simulation tool is provided in Box 2 below, with a discussion of the different cycles provided in the following section 6.2.2.

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[35] An accurate optimisation of a complex technology combination for one single vehicle would already need the resources available for the simulation of all 2500 vehicle technology combinations performed here. Thus generic strategies seemed to be the only viable way.

[36] We want to acknowledge especially the support provided by Mr. Giorgos Fontaras from the JRC in this context.

Box 2: Overview of the PHEM simulation tool

Overview pf the PHEM simulation tool

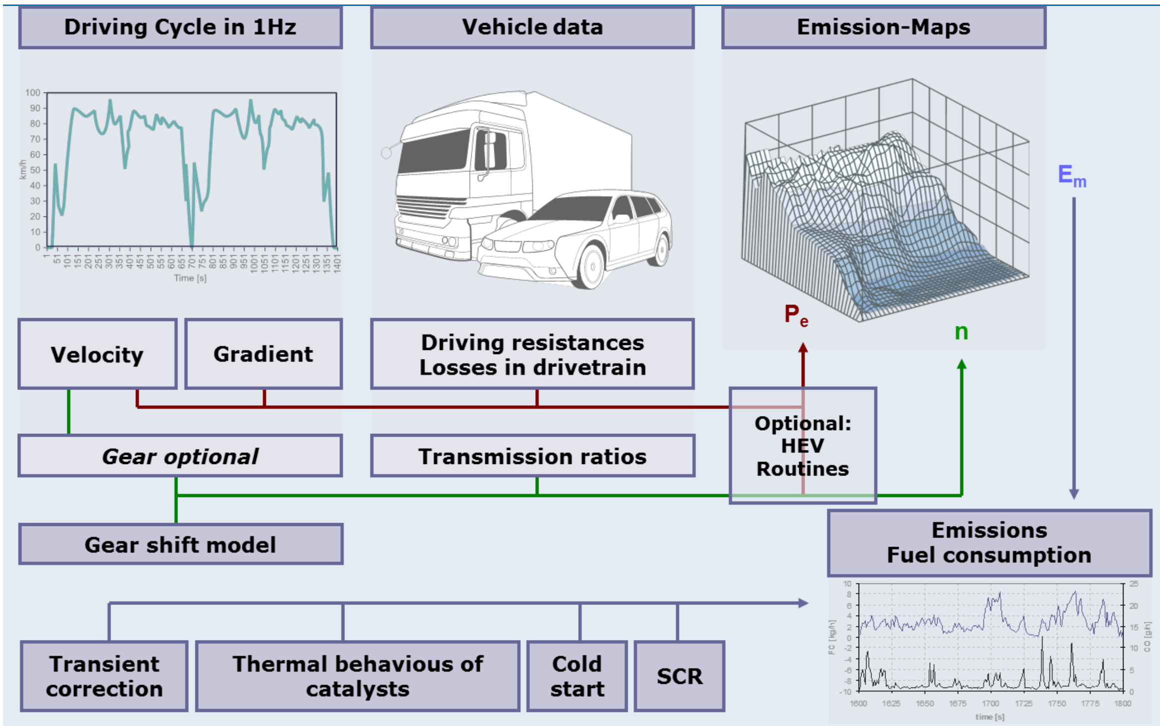
PHEM (Passenger car and Heavy duty Emission Model) has been developed at IVT from TU Graz since late 1990s. Development is continuously ongoing to include new technologies where relevant and to improve its accuracy and user friendliness. A short description is given below. More details can also be found e.g. in (Luz & Hausberger, 2013), (Hausberger S. , New Emission Factors for EURO 5 & 6 Vehicles, 2012), (Hausberger S. , 2011), (Zallinger, 2010), (Rexeis, 2009), (Hausberger S. , 2003).

Fields of application: Simulation of fuel consumption and exhaust gas emissions for light duty vehicles, heavy duty vehicles and for two-wheelers from vehicle velocity trajectories (velocity and road gradient over time or over distance). Simulation can be carried out for single vehicles or for vehicle fleets and for conventional propulsion systems as well as for alternatives (HEV, BEV, etc). Interface with micro-scale traffic models and with air quality models is also possible. PHEM provides inter alia the emission factors for all traffic situations in the Handbook Emission Factors (HBEFA, www.hbefa.net) which are also used in the COPERT model coordinated by the European Environment Agency (EEA), e.g. (http://emisia.com/copert).

Short description: PHEM is an emission map-based instantaneous emission model. It calculates the fuel consumption and emissions of vehicles in 1 Hz increments for a given driving cycle based on the vehicle longitudinal dynamics and emission maps (Figure 6.2). The engine power demand is calculated in 1 Hz increments for the cycles from the driving resistances and losses in the transmission line. The engine speed is simulated by the tyre diameter, final drive and gearbox transmission ratio as well as a driver gear shift model. Exhaust emissions and fuel consumption are then interpolated from engine maps. To increase the accuracy of the simulated emissions, transient correction functions are applied to consider different emission behaviours under transient engine loads. Furthermore, the temperature of catalytic converters is simulated by a zero-dimensional heat balance and from the heat transfer between exhaust gas and the catalyst material and from the exhaust line to the ambient environment. This routine is especially important in simulating SCR systems (cool down at low engine loads) and in simulating cold start effects. In this report exhaust gas temperatures are relevant for the efficiency of waste heat recovery systems. A driver model is implemented to provide representative gear shift manoeuvres.

Since the vehicle longitudinal dynamics model calculates the engine power output and speed from physical interrelationships, any imaginable driving condition can be illustrated by this approach. The simulation of different masses and payloads of vehicles in combination with road longitudinal gradients and variable speeds and accelerations can thus be illustrated by the model just like the effects of different gear shifting behaviour of drivers or of test procedures. In vehicle development, the model can illustrate different combinations of engine, power train and vehicle, including hybrid-electric power trains.

Figure 6.2: Scheme of the PHEM model



The actual version of PHEM offers a predefined database for cars, LCVs and HDVs from Euro 0 to Euro 6/VI and for diesel and petrol to allow user friendly calculation of average emission values from the vehicle fleet. A first data set for simulating two-wheelers in PHEM is under preparation. The interface to micro scale traffic models as an alternative source for providing vehicle speed patterns to the model PHEM allows purely simulation-based analysis and optimisation of traffic control systems to minimise emissions and energy consumption. The standardised output files also include total emission quantities allocated to the single segments of the road network under consideration to directly feed air quality models.

The Hybrid tool of PHEM includes the relevant electric components (battery and motor). The losses in the battery are simulated based on the internal resistances while the electric motor simulation uses efficiency maps. A generic hybrid controller is implemented in PHEM which decides each second which mode is expected to provide overall best efficiency. The background of this decision is the rule that electric driving shall save more fuel per kWh propulsion work than is necessary to generate the electric energy necessary to run the electric motor. From this assumption a characteristic line is produced, which defines the limits for electric driving and power generation as $\mathrm{kWh}_{\mathrm{fuel}}/\mathrm{kWh}_{\mathrm{electric\ energy}}$ as function of the actual SOC level (Luz, 2011). The characteristic line can be adjusted to the relevant vehicle and test cycle combination but usually leads to reasonable results for most combinations in the standard settings.

6.2.2 Test cycles used

The following test cycles are applied in the simulation:

- *NEDC*: actual type approval test cycle in Europe, cold start with 25°C
- *WLTC*: future test cycle according to the WLTP, cold start with 23°C
- *CADC* (André, 2002): a cycle compiled from several representative real world short trips. The CADC is a frequently used cycle to measure real world behaviour of cars on the chassis dyno and thus allows comparisons with data existing from the ERMES data collection (http://ermes-group.eu/). Consequently the CADC is applied as a hot start in the simulation
- *RWC*: a test cycle measured in the RDE test procedure development including urban, road and motorway phases with corresponding road gradients. To reflect average European conditions, the RWC is simulated with cold start extra fuel consumption for 14°C ambient conditions assuming an average trip length between cold starts of 20 km .

The test cycles are shown in Figure 6.3 and Figure 6.4. It has to be noted, that so far no test cycle has been developed in Europe which is verified to be representative of the real driving situation. The WLTC is certainly missing road gradients and the gear shift strategy of the WLTP seems to lead to rather low engine speeds compared to average real world situations. In addition the cold start temperature is above EU average ambient conditions. The CADC seems to represent rather high shares of very dynamic driving conditions. Further adjustments of the RWC used here to develop this in the direction of a validated representative cycle are possible but are not part of this project.

Figure 6.3: NEDC and WLTC test cycles

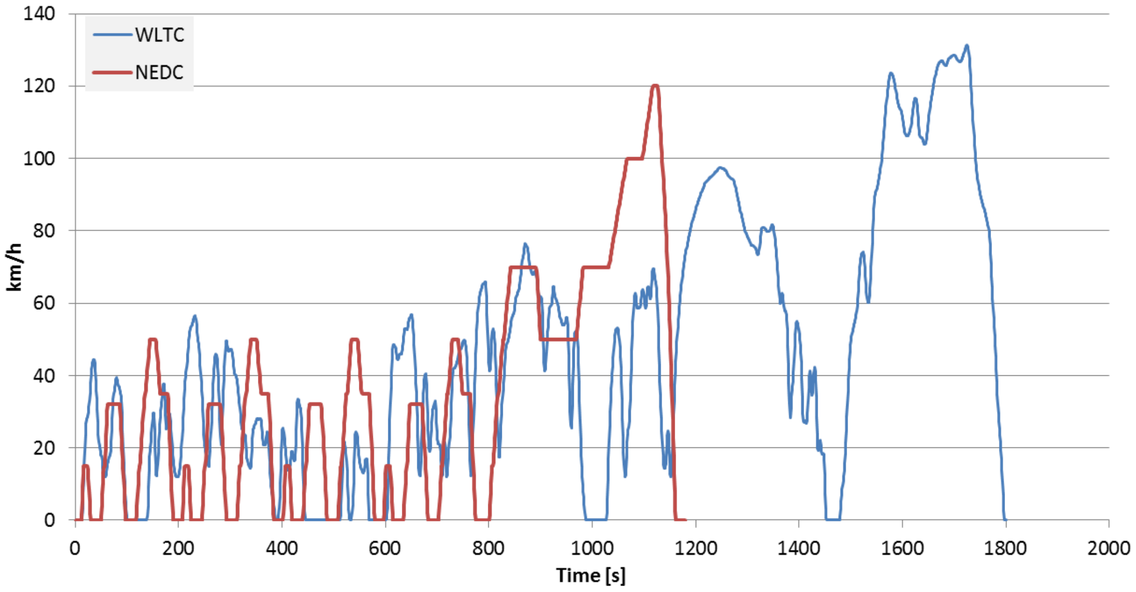
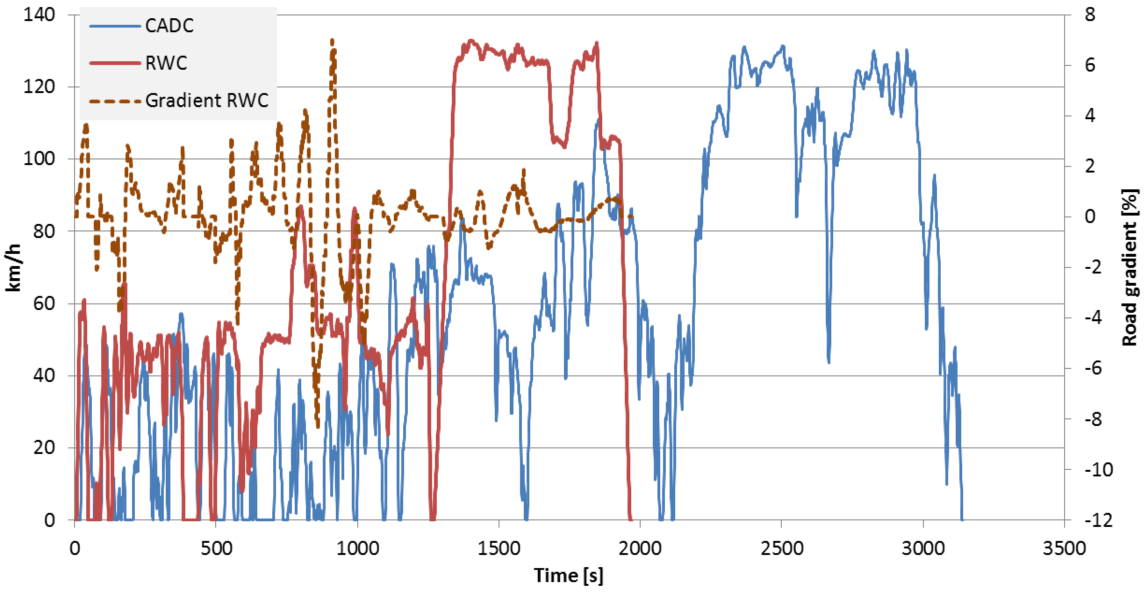


Figure 6.4: CADC and RWC test cycles



The different cycles have quite different levels of velocity and of acceleration and in the case of the RWC also different road gradients. Thus the engine load distribution for a vehicle is also quite different in these cycles. The differences in the engine load distribution between the cycles are not constant but depend on the vehicle specifications (e.g. ratios between mass, C_d x A, the rolling resistance coefficient and engine rated power, etc.).

Figure 6.5 and Figure 6.6 show the distribution of engine loads in the engine map in 1Hz for the cycles.

Figure 6.5: Engine loads simulated for the C-segment petrol base vehicle in the NEDC and WLTP (each dot represents one second in the cycle, Power normalised between zero and rated engine power, rpm normalised between idling speed and rated speed)

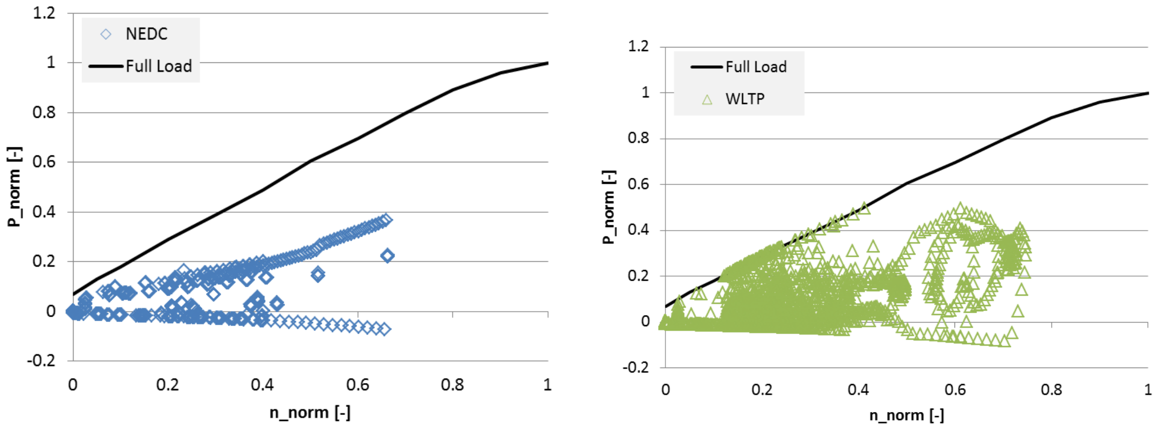


Figure 6.6: Engine loads simulated for the C-segment petrol base vehicle in the CADC and RWC (each dot represents one second in the cycle, Power normalised between zero and rated engine power, rpm normalised between idling speed and rated speed)

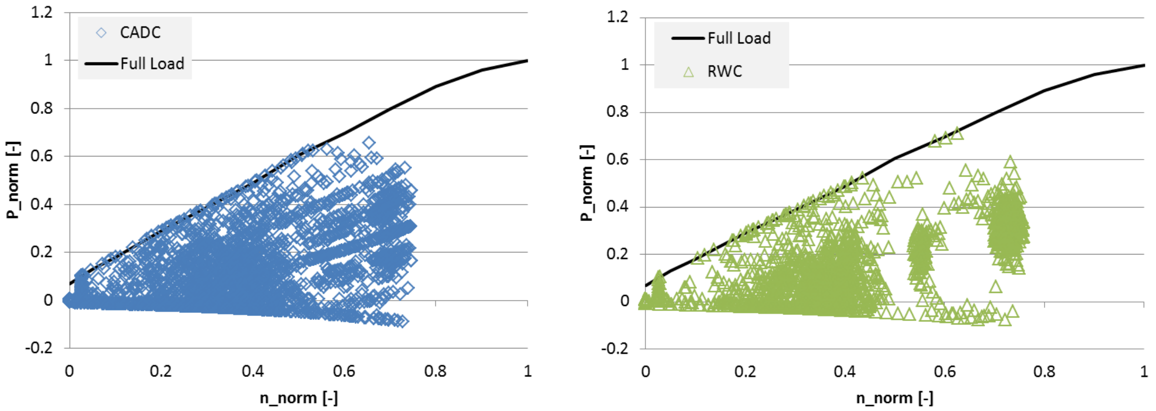


Table 6.1 to Table 6.3 summarise the main cycle parameters. Load and engine speed related values are shown for the petrol base car from segment C. No cycle seems to reflect European mileage shares according to road categories. The real world cycles used obviously have too high a share of motorway driving. This results from the demand to have minimum durations per sub-cycle for chassis dynamometer tests to obtain representative results. Due to the high velocity, the highway distance is then long compared to the urban and road parts of the cycle.

Table 6.1: road category shares of the cycles

	Share in mileage		
	Urban	Rural	Motorway
NEDC	37%	34%	29%
WLTC	34%	31%	36%
CADC	11%	33%	56%
RWC	20%	21%	59%
EU 28(1)	28%	40%	32%

Notes: (1) Different sources (TREMOVE, HBEFA, FLEETS) give very different results for same countries, thus mileage shares seem to have high uncertainties (Hausberger, 2015).

The average vehicle speeds increase progressively from the NEDC to WLTC, CADC and RWC. Consequently the engine speed levels also increase since the high speed phases are generally driven in the highest gear in all cycles. The average power demand is for the C-segment car is only 4% of the rated power in the NEDC, while in WLTP it is 8%, and in the real world cycles it is 11 to 14%.

Table 6.2: parameters from the test cycles simulated (engine speed and power shown for the base petrol lower medium car)

	dist	velocity	pos. acc	$v*a_{neg}$	relat. pos. acc.	pos grad	n_{norm}	Pe_{norm}
	[km]	[km/h]	[m/s^2]	[m²/s³]	[m/s²]	[%]	[-]	[-]
NEDC	3.69	33.65	0.53	-4.48	0.107	0.00	0.22	0.043
WLTC	8.15	46.53	0.45	-5.16	0.147	0.00	0.24	0.081
CADC	17.48	58.29	0.55	-7.15	0.150	0.00	0.35	0.114
RWC	13.41	66.77	0.34	-4.68	0.094	1.04	0.41	0.138

Notes:

pos grad… average positive road gradient

$v*a_{neg}$….average product of velocity (m/s) and acceleration [m/s²]. Only counted if a<0.…

n_{norm}….engine speed normalised between idling and rated engine speed

P_{norm}….engine power normalised between idling and rated engine power

The share of auxiliary power demand is highest in the RWC, where "average engagement of all auxiliaries" was assumed and thus not only alternator and steering pump but also blower and compressor for HVAC are running (see Section 6.2.3 for details). In the WLTC and in the CADC no HVAC and no extra electricity consumers are engaged but the electric energy balance of the battery needs to be zero over the cycle. In the NEDC the test procedure allows for the inclusion of electric consumers in principle from the battery over the entire test, leading to low effective auxiliary power demand. The share of air resistance is highest in the cycles with the higher velocities. Rolling resistance changes in the opposite direction since air resistance increases are more pronounced over speed than is rolling resistance. The "brake power P_{brake}" summarises the energy lost over the cycle from the mechanical brakes. This energy is the part lost from the energy provided from the engine during the acceleration phases.

Table 6.3: Share of total power demand in the test cycles simulated (engine speed and power shown for the base petrol C-segment car)

	$P_{auxiliaries}$	P_{transm}	P_{roll}	P_{air}	P_{grad}	P_{brake}
	[% from avg. engine power demand]					
NEDC	1%	8%	30%	34%	0%	26%
WLTC	5%	6%	30%	38%	0%	22%
CADC	4%	6%	26%	44%	0%	20%
RWC	10%	6%	28%	46%	1%	10%

General effects of the cycles on the CO$_2$ reduction potentials for different technologies

- Lower average engine power favours engine technologies that aim at low torque improvements (downsizing, cylinder deactivation, lean burn SI, HCCI, VVT and others). Consequently we have to expect the highest potential for these technologies in the NEDC and the lowest effect in real world cycles.
- Low average power also favours load shifting by hybrid power trains (electric driving in very low load and power generation in low load) since the ICE engine loads can be shifted towards more efficient torque values. This effect is more pronounced in vehicle segments with high

rated engine power relative to mass and driving resistances since these cars drive in the lowest torque ranges.

- Also the "brake power P_{brake}" value is important for hybrid systems using brake energy recuperation, i.e. all HEV, PHEV and BEV systems. The RWC has rather low shares of energy lost in braking due to less dynamic driving at higher speeds. Consequently the energy recuperated by the electric system has a lower share of the total energy provided by the ICE. If the cycle in addition has a high "$v*a_{neg}$" value this means that there are high average kinetic energy levels to be recuperated which leads to higher current and higher losses in the electric system.
- Higher velocities result in higher effects from aerodynamic improvements but slightly reduce the effect of improved tyre technologies. The latter however is uncertain, since the tyre drum test procedure for the label value does not provide information as to whether the rolling resistance changes similarly over the entire speed range[37].
- Higher engine loads produce typically higher exhaust gas temperatures which make waste heat recovery systems more efficient.
- High mileage shares in high velocities reduce the effect of automated transmission systems since the highest gear is used in these phases by all systems over long periods.
- Transmission systems without torque interruption interestingly showed increased fuel consumption values in the cycles with more gear shifts since they lead to higher average velocities (no torque interruption during gear shifts) and thus higher energy demand per km. Only in combination with downsizing of the engine and/or longer transmissions and/or earlier gear shifts did such systems show a fuel saving potential. Thus for these technologies the gear shift points for the AT and AMT simulations have been adjusted towards lower engine speeds.

6.2.3 Vehicle classes simulated

In order to simulate the fuel consumption on NEDC, WLTC, CADC and RWC of vehicles in PHEM, various input data are necessary. Table 6.4 gives an overview of the most important data, e.g. vehicle test mass, unladen mass (EU), maximum unladen mass and the maximum permissible mass.

To be able to run PHEM simulations for hundreds of combinations of vehicle classes and technologies it was important to parametrise all vehicle classes based on the same physical relations (e.g. dependency of test masses in the different cycles on vehicle empty weight, tyres with similar rolling resistance coefficient in all vehicles, same base engine efficiency etc.). The vehicle classes and the relations applied are described below.

The maximum unladen mass of the vehicle is needed to simulate the best and worst case of WLTC (in NEDC there is not a comparable worst case, instead the use of inertia classes) and is composed by the unladen mass and the mass of the optional equipment. In Table 6.4 the maximum unladen mass is assumed to be 10 % higher for all vehicles than the respective unladen mass. So far no statistical data on typical ratios of WLTC-mass values compared to NEDC mass values of vehicles are available, neither are detailed data regarding optional equipment per vehicle segment. The consideration of optional equipment reduces the effective payload of the vehicle.

Engine and transmission inertia of petrol and diesel vehicles are adjusted in proportion to the engine power of each vehicle, based on the absolute values for the lower medium car for the respective petrol and diesel vehicles (these values correspond to data for the respective VW Golf cars).

The gear ratios for each vehicle are calculated with the gearbox calculation tool provided by JRC (version from 4th December 2014). In some cases the ratios needed to be revised to achieve reasonable fuel consumption values. In these cases typically data from a serial production vehicle in the corresponding vehicle segment was used.

The inertia of wheels is converted in PHEM to a "reduced mass of the wheels" which is 1.5% of unladen mass (EU) + 25 kg in the case of the NEDC and for a single axle simulation and 3% of unladen mass (EU) + 25 kg in the case of WLTC, CADC and RWC according to the WLTP draft.

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[37] In the actual calculations always a similar reduction of rolling resistance coefficients in all speed ranges was assumed.

For the simulation of fuel consumption in the NEDC, fixed gear shift points related to the number of manual gears (5 or 6) are defined in the legislation. For the WLTC the gear shift points depend on the transmission ratios and on several vehicle parameters (engine power, mass etc.). For this analysis the gear shift points for each vehicle are calculated according to the WLTP draft (Version 20th December 2013). This calculation was implemented in the PHEM simulation tool to be able to also run WLTP simulations in batch mode. For CADC and RWC the basic gear shift algorithm from the driver model in PHEM was chosen. Furthermore, the traction interruption for manual transmission is set to 1 second.

Table 6.4: Main vehicle data for the vehicle classes with ICE and electric motor simulated (data for HEVs, BEVs, etc. are derived from these base cases)

Vehicle	Power ICE (E-Motor) [kW]	Unladen mass (EU) [kg]	Unladen mass (DIN) [kg]	Max. unladen mass [kg]	Max. permissible mass [kg]	Max. payload [kg]
Petrol small car	61	1091	1016	1118	1526	510
Petrol lower medium car	92	1380	1305	1436	1835	530
Petrol upper medium car	120	1523	1448	1593	2018	570
Petrol large car	156	1648	1573	1730	2193	620
Petrol small van	56	1091	1016	1118	1526	510
Petrol medium van	72	1374	1299	1429	2039	740
Petrol large van	95	1863	1788	1967	2848	1060
Diesel small car	66	1244	1169	1286	1679	510
Diesel lower medium car	91	1510	1435	1579	1965	530
Diesel upper medium car	113	1659	1584	1742	2154	570
Diesel large car	143	1926	1851	2036	2561	710
Diesel small van	57	1191	1116	1228	1626	510
Diesel medium van	68	1450	1375	1513	2115	740
Diesel large van	95	2023	1948	2143	3008	1060
BEV small car	41	1152	1077	1185	1587	510
BEV lower medium car	80	1510	1435	1579	1965	530
BEV upper medium car	53	1682	1607	1768	2177	570
BEV large car	50	1970	1895	2085	2560	665
BEV small van	35	1186	1111	1222	1621	510
BEV medium van	44	1521	1446	1591	2186	740
BEV large van	109	2171	2096	2306	3156	1060
Petrol REEV small car	34 (55)	1194	1119	1231	1629	510
Petrol REEV lower medium car	50 (80)	1483	1408	1549	1938	530
Petrol REEV upper medium car	63 (101)	1625	1550	1705	2120	570
Petrol REEV large car	83 (133)	1754	1679	1847	2344	665

Vehicle	Power ICE (E-Motor) [kW]	Unladen mass (EU) [kg]	Unladen mass (DIN) [kg]	Max. unladen mass [kg]	Max. permissible mass [kg]	Max. payload [kg]
Petrol REEV small van	31 (50)	1177	1102	1213	1612	510
Petrol REEV medium van	37 (60)	1470	1395	1535	2135	740
Petrol REEV large van	52 (84)	1983	1908	2099	2968	1060
Diesel REEV small car	34 (55)	1362	1287	1415	1797	510
Diesel REEV lower medium car	50 (80)	1629	1554	1710	2084	530
Diesel REEV upper medium car	63 (101)	1779	1704	1874	2274	570
Diesel REEV large car	83 (133)	2052	1977	2175	2642	665
Diesel REEV small van	31 (50)	1291	1216	1338	1726	510
Diesel REEV medium van	37 (60)	1561	1486	1634	2226	740
Diesel REEV large van	52 (84)	2159	2084	2293	3144	1060
Petrol HEV small car	51 (28)	1147	1072	1179	1582	510
Petrol HEV lower medium car	75 (41)	1432	1357	1493	1887	530
Petrol HEV upper medium car	94 (51)	1572	1497	1647	2067	570
Petrol HEV large car	124 (67)	1691	1616	1778	2281	665
Petrol HEV small van	47 (25)	1133	1058	1164	1568	510
Petrol HEV medium van	56 (30)	1415	1340	1474	2080	740
Petrol HEV large van	78 (42)	1899	1824	2006	2884	1060
Diesel HEV small car	51 (28)	1322	1247	1372	1757	510
Diesel HEV lower medium car	75 (41)	1589	1514	1665	2044	530
Diesel HEV upper medium car	94 (51)	1739	1664	1830	2234	570
Diesel HEV large car	124 (67)	2007	1932	2125	2597	665
Diesel HEV small van	47 (25)	1254	1179	1297	1689	510
Diesel HEV medium van	56 (30)	1513	1438	1582	2178	740
Diesel HEV large van	78 (42)	2087	2012	2213	3072	1060
Petrol PHEV small car	51 (28)	1144	1069	1176	1579	510
Petrol PHEV lower medium car	75 (41)	1416	1341	1475	1871	530
Petrol PHEV upper medium car	94 (51)	1544	1469	1616	2039	570

Vehicle	Power ICE (E-Motor) [kW]	Unladen mass (EU) [kg]	Unladen mass (DIN) [kg]	Max. unladen mass [kg]	Max. permissible mass [kg]	Max. payload [kg]
Petrol PHEV large car	124 (67)	1650	1575	1733	2240	665
Petrol PHEV small van	47 (25)	1131	1056	1162	1566	510
Petrol PHEV medium van	56 (30)	1414	1339	1473	2079	740
Petrol PHEV large van	78 (42)	1902	1827	2010	2887	1060
Diesel PHEV small car	51 (28)	1319	1244	1368	1754	510
Diesel PHEV lower medium car	75 (41)	1573	1498	1648	2028	530
Diesel PHEV upper medium car	94 (51)	1712	1637	1800	2207	570
Diesel PHEV large car	124 (67)	1967	1892	2081	2557	665
Diesel PHEV small van	47 (25)	1252	1177	1294	1687	510
Diesel PHEV medium van	56 (30)	1513	1438	1581	2178	740
Diesel PHEV large van	78 (42)	2090	2015	2216	3075	1060
FCEV small car	51	1224	1149	1264	1659	510
FCEV lower medium car	75	1561	1486	1635	2016	530
FCEV upper medium car	94	1740	1665	1831	2235	570
FCEV large car	124	1974	1899	2089	2564	665
FCEV small van	47	1257	1182	1300	1692	510
FCEV medium van	56	1531	1456	1601	2196	740
FCEV large van	78	2110	2035	2238	3095	1060

The test mass for each car in the NEDC is calculated using the equation:

$$m_{NEDC} = m_{unloaden}\ (DIN) + 100\ kg$$

Eq. 6.1

Since the NEDC test mass is incorporated in equivalent inertia classes to test the vehicle on the dynamometer (in accordance with the NEDC regulation), the inertia classes are used for the simulation.

For the WLTC and CADC test mass (weighted average from best and worst case), the following equations are valid:

$$m_{WLTC\_best\_case} = m_{unloaden} + 100\ kg + 0.15 * (m_{permissible\_max} - m_{unloaden\_max} - 100\ kg)$$

Eq. 6.2

$$m_{WLTC\_worst\_case} = m_{unloaden\_max} + 100\ kg + 0.15 * (m_{permissible\_max} - m_{unloaden\_max} - 100\ kg)$$

Eq. 6.3

For vans the factor 0.15 in Eq. 6.2 and Eq. 6.3 is replaced by 0.28 according to the WLTP draft to consider higher loadings. The equation for the consideration of optional vehicle equipment with additional 10% vehicle mass is:

$$m_{unloaden\_max} = m_{unloaden\ (DIN)} * 1.10$$

Eq. 6.4

To take account of the fact that vehicles in the lower segments have rather less optional equipment than the upper segments, weighting factors to calculate the test mass were used. Since no statistical data on the proportional distribution of optional equipment for each segment are available, estimates have been made. The weighting factors used in the simulation are shown in Table 6.5.

$$m_{CADC} = m_{WLTC} = a * m_{WLTC\_best\_case} + b * m_{WLTC\_worst\_case}$$

Eq. 6.5

Table 6.5: Weighting factors per segment for test mass calculation

Weighting factors	a [-]	b [-]
Small car	2/3	1/3
Lower medium car	1/2	1/2
Upper medium car	1/2	1/2
Large car	1/3	2/3
Small van	1/2	1/2
Medium van	1/2	1/2
Large van	1/2	1/2

The RWC test mass is calculated in the same way as the WLTC test mass, but instead of a factor of 0.15 in Eq. 6.2 and Eq. 6.3, a factor 0.25 is used. This reflects the assumption that in real world driving the average vehicle load is a little bit higher than defined in the WLTC. For the CADC the same weighting factors as for the WLTP are applied.

The rolling resistance coefficient (RRC) consists of fr0 and fr1:

RRC = fr0 + fr1 x v

In this equation fr0 represents the speed independent part of the RRC (~75%) and fr1 consists of the RRC proportional to the velocity (~25%). The speed dependent part is related typically to losses in bearings and in the transmission where rotating parts are engaged in the coast down tests.

The RRC for the NEDC was set to 9.44 kg/ton for all investigated vehicles (which corresponds to the E-rating on the tyre label) and was also the basis for the RRC calculations of WLTC, CADC and RWC. The RRC for the WLTC best and worst case is calculated with the Audi-tool (version from 10th February 2014, provided by Ms. Feucht from Audi within the WLTP-NEDC correlation group) and is higher than the RRC for NEDC due to different regulations on which tyre has to be used in coast down tests and due to the higher profile depth required. The RRC values applied for CADC and WLTC simulation are given by weighting the best and worst case values with the factors in Table 6.5. The same method is applied for the RWC.

The aerodynamic drag for NEDC (given by C_d x A) is based on a literature study for cross sectional areas and drag coefficients for each segment. The conversion to WLTC, CADC and RWC was performed with the Audi-tool mentioned before.

The power demand from auxiliaries for diesel vehicles are adjusted in proportion to the engine power. The absolute values are based on a diesel lower medium car (C-segment). For the petrol vehicles the same auxiliary power demand per segment is adopted as for diesel cars. For the NEDC, only the mechanical power demand from the alternator in idling condition is applied in the simulation since the whole electrical energy could be provided by the battery during the cycle. For the WLTC the possible CO_2 savings due to using only electrical energy from the battery were corrected for a balanced SOC according to the WLTP draft. This implies for the simulation that the alternator has to provide the energy for all consumers activated in the WLTC (i.e. all systems needed to run the vehicle such as controllers, fuel injection system, etc). For the CADC the same power for the auxiliaries is used as for the WLTC. For real world driving additional energy consuming systems (e.g. radio, light, air conditioning, etc) are also used, based on a literature study for typical energy consumption values for these systems and on the share of time each system is active under average real world conditions. For example, the share of driving time with the air conditioning active at different ambient conditions and corresponding electrical and mechanical power demand is taken from (TU Graz/TNO/LAT, 2013).

6.2.3.1 Cold start model

The NEDC, WLTC and RWC are simulated with cold start, which means that the oil and coolant temperature from the simulated vehicle is identical with the ambient temperature (in the case of the NEDC this is 25°C, for the WLTC it is 23 °C and for the RWC it is 14°C). The CADC is not affected because by definition the CADC is measured and simulated with a hot start.

In the case of cold starts the engine needs extra energy to warm up and to overcome the higher friction under ambient conditions. Since the actual PHEM version supports only the hot start for the batch mode calculations applied here a special cold start model was developed for this project. For this aspect, Euro 5 vehicles measured and simulated on the NEDC and WLTC under cold start and hot start conditions were analysed. The data were taken from the study on WLTP-NEDC correlation which was running in parallel for DG CLIMA. As a result, the following average factors were found (**Eq. 6.6** and **Eq. 6.7**). The cold start effect per km in the WLTC is lower than in the NEDC due to the longer distance driven.

NEDC cold [g/km] = NEDC hot [g/km] * 1.08 **Eq. 6.6**

WLTC cold [g/km] = WLTC hot [g/km] * 1.03 **Eq. 6.7**

For the RWC estimates of the extra fuel consumption associated with cold starts were obtained from the fuel used for cold starts in the WLTP. The weight of the extra fuel used was divided by the average trip length of the RWC (20km). With a cold start correction from 14 °C to 23 °C as described in the WLTP correction functions report (Hausberger, 2015) the g/km are known and were consequently added to the fuel consumption of the RWC with hot start.

This approach was used for all baseline vehicles. For most of the technologies that were not affected by the cold start due to their engine size and/or friction reduction, the extra mass of fuel consumed per cold start from the baseline vehicles were applied. The following simulated technologies are exceptions and use the cold start model as mentioned before (% increase due to cold start):

- Mild, medium and strong downsizing
- Engine friction reduction
- HEVs
- PHEVs
- REEVs

For BEVs and FCEVs no cold start effects are taken into account since this effect could be neglected for these vehicles.

6.2.4 Overview on CO_2 reductions simulated

The results from the simulation are provided for each combination of vehicle class and technology (“segment”) in an Excel file. For each segment one line is provided per cycle which contains 50 data sets (average cycle duration, average power and engine speed, work to overcome the single driving resistances, fuel consumption hot and cold, etc.). As indicated earlier, specific information with regards to the simulation of the different types of technologies is provided in Appendix 5.

For this report, information for nearly 2500 simulations in total has been calculated. Showing all of the individual results is not feasible in this report, thus an overview on the data is given here. All details can be checked in the Excel file that has been provided alongside this report.

Figure 6.7 and Figure 6.8 show the simulation results for the SI base technologies which represent 2002 model years, as far as possible, in comparison to the NEDC target values from the monitoring data base, corrected for the estimated CO_2 savings from technology that has already been deployed (i.e. based on the analysis from the earlier Section 2.4.1.2). The base vehicles’ model input data was calibrated with the values from the monitoring data base and meets these targets accurately.

The results for the WLTP are higher than those for the NEDC for all base vehicles. Under the WLTP, the cars with SI engines have between 4 and 10% higher CO_2 emissions (on average +6%), and the diesel cars have 5% to 12% higher CO_2 emissions in the WLTP (8% on average). The LCVs on average have 8% higher CO_2 emissions in the WLTP compared to the NEDC. In older studies a less pronounced increase in the WLTP was found, e.g. (ICCT, 2014). The higher results for the WLTP in this study result from additional know-how gained on the effects of the changes in test flexibilities and test procedures which add extra load to the vehicles in the WLTP as described in Section 6.2.3.

The base cars on average have 23% higher CO_2 values in the RWC compared to the NEDC. For the vans the average ratio is +27% mainly caused by the high ratios for the large vans (>+30%). The latter is a result of the high aerodynamic resistance of these vehicles.

In principle this ratio from RWC to NEDC seems to be in the right order of magnitude, compared to other studies, e.g. (ICCT, 2013) since the actual simulation combines the usage of cycle flexibilities to get low NEDC values and uses older engine technologies. As discussed in Section 6.2.2 several engine technologies tend to have a higher reduction potential in the NEDC than in the RWC. Thus the ratio RWC/NEDC increases for several of the more recent technologies. This increasing deviation over time between real world CO_2 and type approval CO_2 values is known from several studies, e.g. (ICCT, 2013).

Figure 6.7: Simulation results for the SI base technologies (approx. 2002 model years) and NEDC target values from the monitoring data base

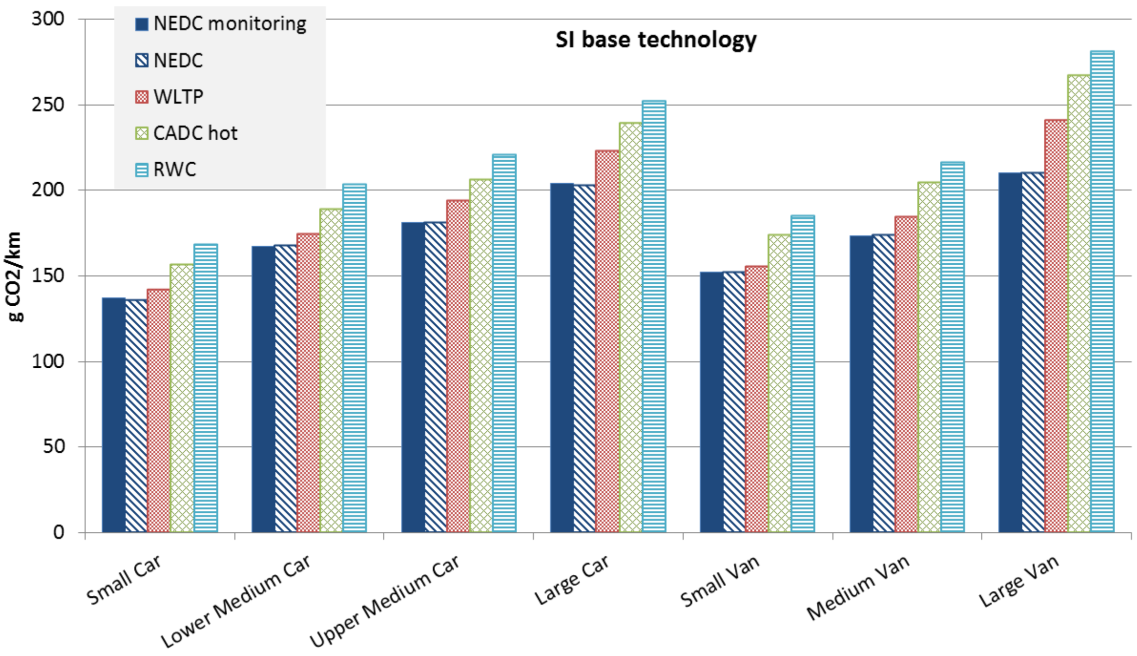
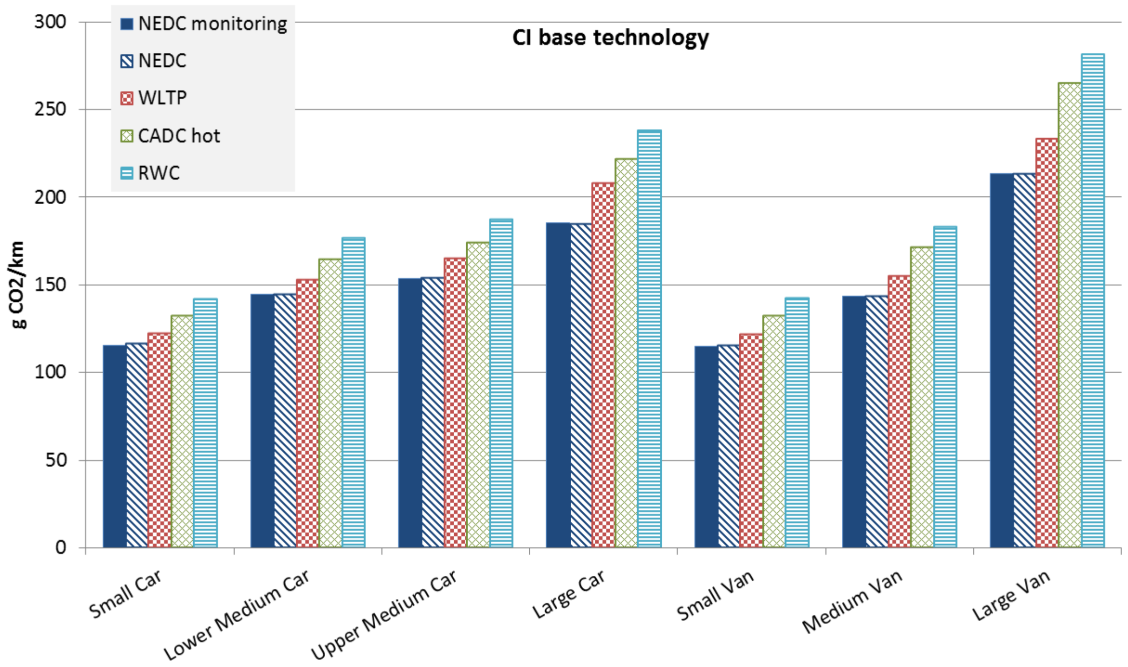


Figure 6.8: Simulation results for the CI base technologies (approx. 2002 model years) and NEDC target values from the monitoring data base



In the following examples, the calculated CO_2 reduction from different technologies compared to the base vehicles are shown.

The simulation first used a measured CNG engine map which has not delivered reasonable reduction rates for all vehicle classes. Obviously the CNG engine and the base SI engine had differences in construction and control details which influence the results. To overcome the problem the base SI engine map was also used as basis for the CNG map. The conversion to the CNG engine was carried out with the knowledge of lower carbon content per heating value (giving fixed reduction of gCO_2/kWh compared to petrol) and a higher octane number which was used for the slightly increased compression ratio and corresponding efficiency improvements.

Figure 6.9: Simulation results for the CNG engine technology compared to the base SI vehicles

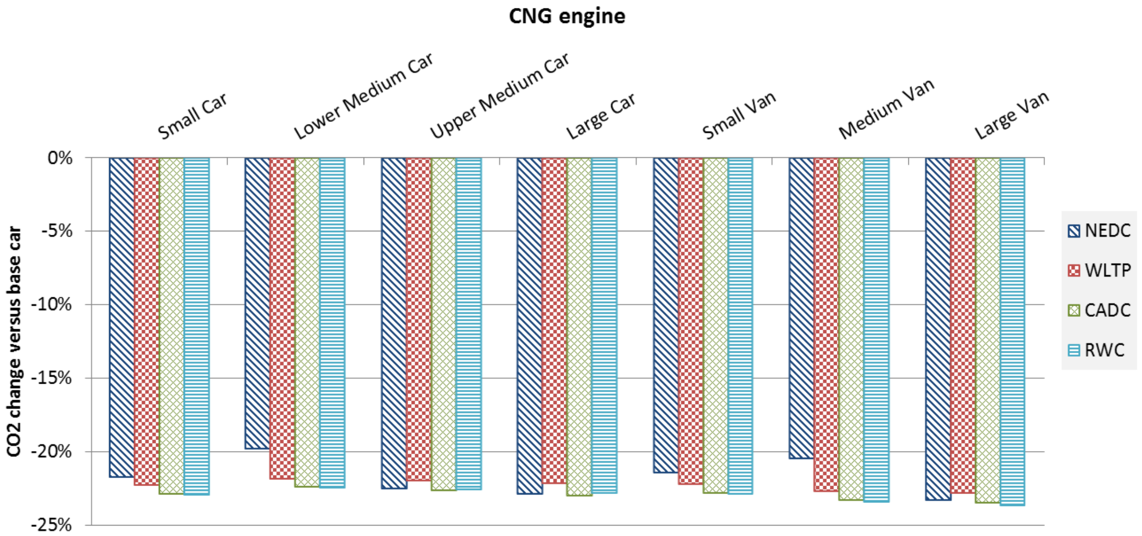
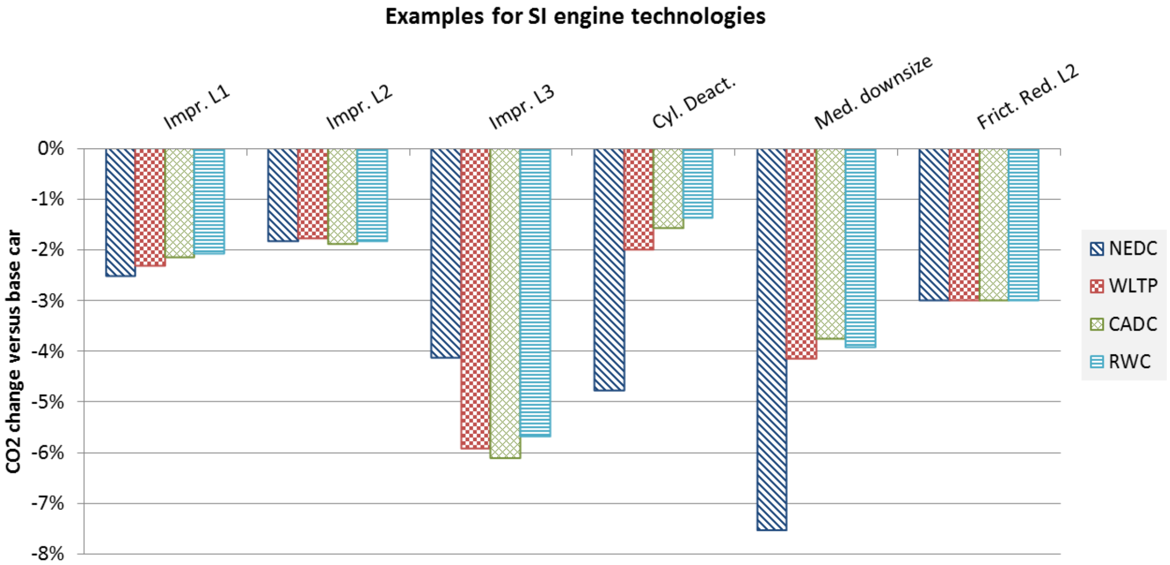


Figure 6.10 shows results for some engine technologies simulated. Most of the technologies improve the part load efficiency of the SI engine and thus show more efficiency in the NEDC than in WLTP and real world cycles. Variable compression ratio (VCR) with a mechanical system (crank mechanism) on the contrary has higher potential at higher loads since at low loads the extended expansion ratio does not deliver useful work at the end of the expansion any more (see Appendix 5, Section A5.1.6).

Figure 6.10: Simulation results for some SI engine technologies compared to the base SI vehicles (average reduction values over all vehicle segments)



With:

Impr. L1	Combustion improvements level 1: Gas-wall heat transfer reduction
Impr. L2	Combustion improvements level 2: 1 point increase in compression ratio
Impr. L3	Combustion improvements level 3: Variable compression ratio (VCR) with mechanical system

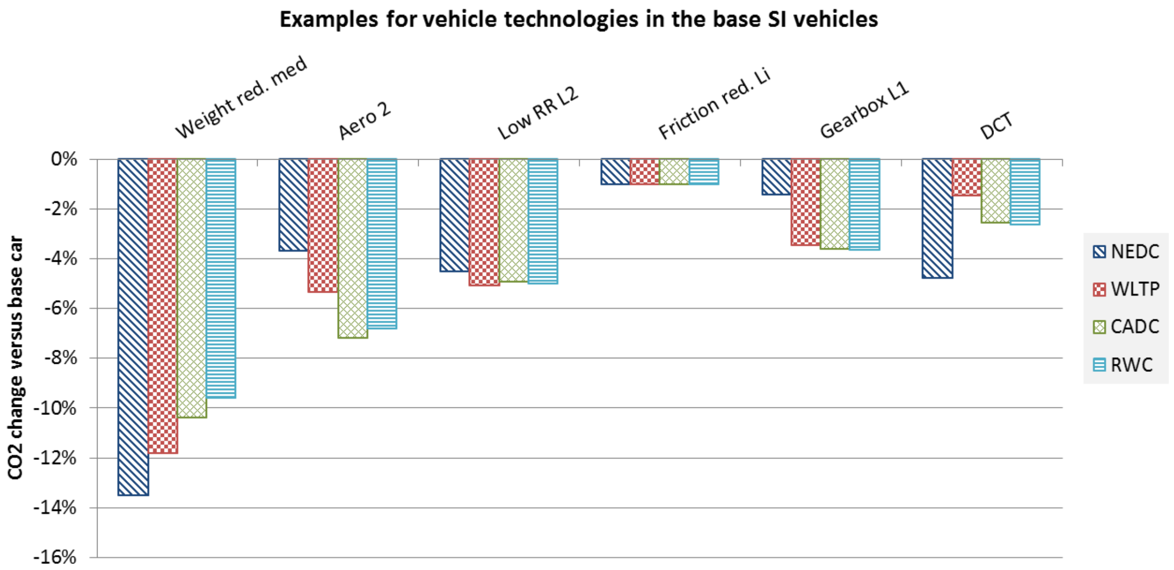
Cyl. Deact...................Cylinder deactivation

Med. Downsize...........medium downsize (30% cylinder volume reduction)

Frict.red L2 ....Friction reduction in the engine level 2

Figure 6.11 shows some of the simulated vehicle technologies. The highest potential is seen here for the medium mass reduction which means a 20% reduction of the entire vehicle mass including a reduction of the engine size to maintain constant maximum acceleration levels. Due to a decreasing share of rolling resistance and/or of the acceleration energy lost by mechanical braking from the NEDC compared to the RWC the CO_2 reduction due to mass reduction also decreases (the mass influences rolling resistance and acceleration work). For the aerodynamic improvements the trend is in the opposite direction. The overdrive gear shows on average more advantages in cycles with higher high speed shares since this gear is used only in such phases. For the DCT gear box systems simulated it is questionable how well the optimisation was done in the simulation and if the optimisation is balanced between the different test cycles. However, it seems to be clear that the WLTP has lower potential for fuel/CO_2 savings with automatic gear boxes than the NEDC, CADC and RWC as the very low engine speed levels of the WLTP gear shift rules provide for manual transmission already.

Figure 6.11: Simulation results for some vehicle technologies implemented in the base SI vehicles compared to the base SI vehicles (average reduction values over all vehicle segments)



With:

Weight red.med..........Medium weight reduction (-20%)

Aero 2.........................Aerodynamic improvement level 2 (-20% in Cd value)

Low RR L2..................Low rolling resistance tires level 2

Friction red. L1 ....Friction reduction in the drive line level 1

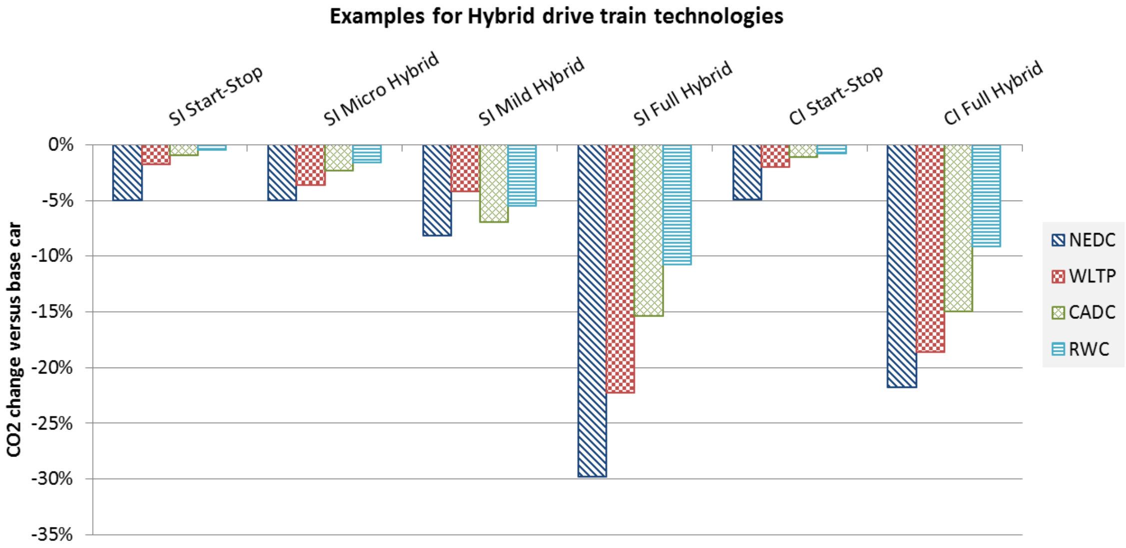
Gearbox L1.................Improved gear box system level 1 (6 instead of 5 gears with the 6th gear simply as additional overdrive to the base gear box transmission)

DCT ....Dual clutch gear box with 5 gears

Figure 6.12 gives an overview of the simulation results for hybrid drivetrain technologies (SI or CI engine with battery and electric motor or starter/alternator). The start-stop function for the engine has the highest potential in the NEDC due to the high share of idling time in this cycle. As you move to the

RWC the idling shares drop and consequently also the CO_2 reduction due to engine stops at idling. It has to be noted that the shares of idling times in CADC and RWC may not be representative for EU average driving. No data on the idling shares in real driving has yet been found. The results for the SI mild and full hybrid show lower reduction potentials in the WLTP than in the NEDC. This is due to the high shares of idling and low load driving in the NEDC where the engines have a low efficiency and thus a replacement by electric driving or and torque increase for power generation has the highest energy saving effects.

Figure 6.12: Simulation results for hybrid drivetrain technologies implemented in the base vehicles compared to the base vehicles (average reduction values over all vehicle segments)



With:

SI start-stop	**Engine Start Stop system in SI engine equipped vehicles**
SI Micro Hybrid	Engine Start Stop system and recuperative operation of the 12V alternator in SI engine equipped vehicles
SI Mild Hybrid	As Micro-Hybrid but with boost and recuperation function of the electric motor in SI engine equipped vehicles
SI Full Hybrid	Hybrid system with sufficient electric power to drive at low loads with electric motor in SI engine equipped vehicles
CI start-stop	Engine Start Stop system in CI engine equipped vehicles
CI Full Hybrid	Hybrid system with sufficient electric power to drive at low loads with electric motor in CI engine equipped vehicles

6.3 Combination of material from the literature review, consultation, analysis and simulations

Earlier Figure 6.1 has already provided an overview of the process of developing the final dataset on CO_2 reductions by technology, vehicle segment, (test) cycle and time period. Essentially the final stage of the process in arriving at the data presented in the Technology Results Data Fiche was a 3 step in process:

1) **Collation of stakeholder feedback:** The feedback from the validation exercise with stakeholders (discussed in Section 4.8) was used to develop final assumptions on the average CO_2 reduction performance of technologies under the NEDC for lower medium cars, and how this might evolve between 2015 and 2030 as technologies in the marketplace are further developed and optimised (the final values by technology are provided also in the daft Technology Results Data Fiche). This information is important since the TUG simulation work was only able to calculate optimal savings potentials for specific technology configurations, and not the market average situation.
2) **Scaling to different segments and cycles using the simulation results:** The second step was to use the results of the PHEM simulations to scale the validated CO_2 savings for lower medium cars to different vehicle segments and to the different cycles (i.e. WLTP and real-world, taken to be based on the RDE results).
3) **Gap-filling where no simulation data is available:** The final step was to fill gaps in the simulation results dataset to cover technologies not (or not yet) simulated. This was done by either (a) extrapolating from the results for technologies that had been simulated, where trends might be expected to be similar, or (b) assuming broadly similar savings across different vehicle segments or cycles where no suitable comparable technology types are available.

The final results of this process are provided in the accompanying Technology Results Data Fiche, and are further discussed in the next chapter (see Section 7.5).

7 Final methodological development and technology analysis results

7.1 Overview of the development of the final technology analysis results

This task draws together the findings from earlier work to provide the Commission with detailed information on how the costs and the CO_2 abatement performance of each technology are likely to change over time. The work included the use of statistical techniques to generate more accurate representations of the uncertainty associated with technology cost estimates. The end objective was to provide final information on costs and CO_2 abatement for all of the test-cycle and off-cycle technologies identified in Section 3 of this report, to feed into the final cost curve development (Section 8).

This task represents the culmination of the work carried out in the previous tasks, as described in the earlier report sections. The information has also been pulled together in the form of final technology fiches for each of the technologies of interest. The results consist of:

- The study report providing an overview of the methods used. This includes a narrative explaining the rationale for the final assumptions used to generate the cost projections;
- A Microsoft Excel file that includes (for each technology) data sheets providing the following information as separate worksheets within a single workbook:
  - A summary description of each technology, its deployment status in the marketplace/anticipated launch;
  - Summary sheets showing the baseline and segmentation results, and also the compatibility of different technologies with each other and with different LDV segments and powertrain types;
  - Input sheets showing the final assumed values for the modelling parameters for learning rates, segment scaling factors and indirect cost multipliers (ICMs);
  - Output summary tables for each technology showing a range of estimates for the costs and CO_2 performance of each technology and how these values vary from 2015 to 2030.
  - Summary tables providing the post-processing correction factors applied to the raw data outputs from the cost-curve model (discussed further in Section 8.1 of this report).

The aim here was to produce reference documents for each technology that could be used to support not only this project, but future work in the area of developing post-2020 legislative measures for controlling CO_2 emissions from cars and LCVs.

The following report sub-sections provide a summary of:

i. The final methodological approach (Section 7.2);
ii. The developed learning and scaling factors applied in the analysis (Section 7.3);
iii. The uncertainty analysis used to develop estimates for future technology costs (Section 7.4);
iv. The overall outputs from the CO_2 and cost analysis (Section 7.5).

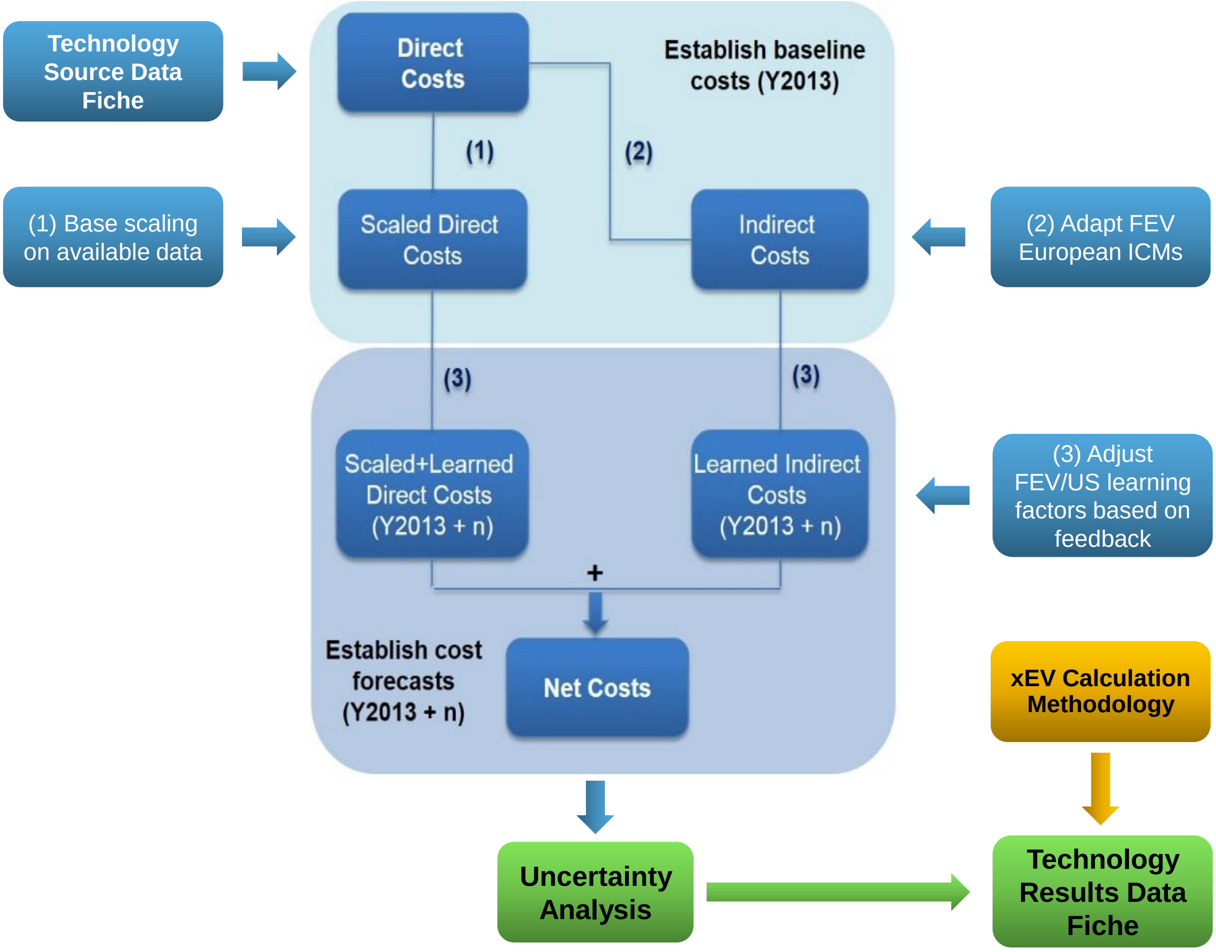
7.2 Summary of the final methodological approach

7.2.1 Overview of methodology

A summary of the final methodological approach for estimating the CO_2 performance of different technologies has already been presented earlier in Figure 6.1 (Section 6.2.1).

The following schematic presents a summary of the final methodological approach developed for estimating the future costs of different technologies, based on the feedback from the stakeholder consultation, summarised in Sections 4.6 to 4.8. The following subsections provide a summary of the development of the final datasets for the vehicle segment scaling factors, ICMs and learning factors, as well as a summary of the uncertainty analysis approach used to generate estimates for the Typical, Low and High technology costs presented in the Technology Results Data Fiche submitted alongside this report.

Figure 7.1: Schematic of the final technology cost calculation methodology



7.3 Development of learning and scaling factors

7.3.1 Learning factors for different technologies

7.3.1.1 Learning factors for direct manufacturing costs

Figure 7.2 below summarises the base learning curves adopted for the analysis, which are based on those used in previous US and European tear-down analysis (and converted into continuous functions in response to stakeholder feedback). The presented cost curves are based on the assumption of a certain year for mass-manufacture (defined as ~450,000 units/year), as also presented in the footnotes to Figure 7.2. The basis of the learning curves was also sense-checked through discussions with expert stakeholders during the overall engagement process. A summary of the relationship of these cost curves to the original FEV cost curve designations is presented below:

Table 7.1: Summary of the relationship between the learning curves used in this study to the original versions used by FEV

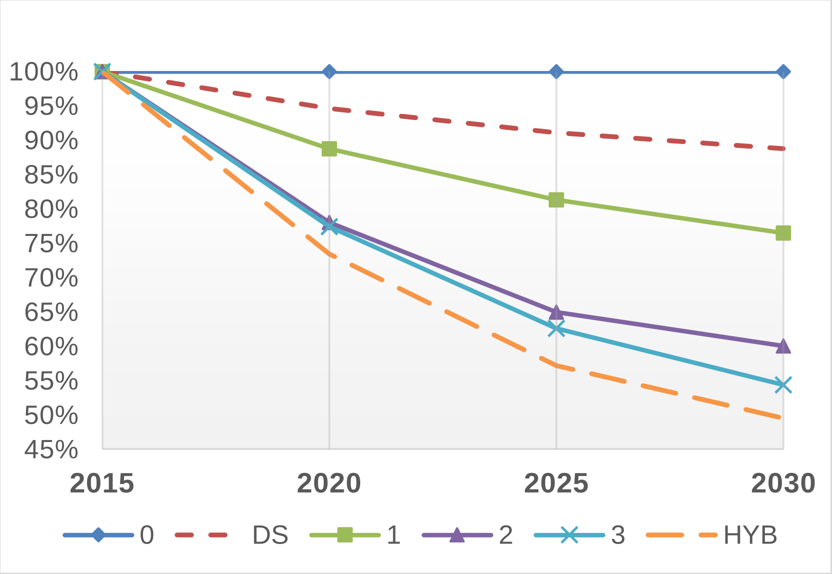
Learning curve	Relation to original cost curves used by FEV	Base year
0	Original learning curve schedule #6 (zero learning/cost reduction)	2012
DS	Average of learning curve schedule #6 and #12 (elements of the downsizing+boost technology are judged to be on different curves)	2012
1	Learning curve schedule #12	2015
2	Learning curve schedule #16	2015
3	Average of learning curve schedule #16 and #19 (assessed in the Delphi Survey for new high complexity technologies)	2020
HEV	Average of PS HEV and P2 HEV learning curves	2020
4	Learning curve schedule #19	2025

Notes: DS = the net learning curve for medium downsizing from the FEV analysis for ICCT (FEV, 2013a);

Sources: The original cost curves used by FEV in (FEV, 2012), (FEV, 2013a), are based on those originally presented in (EPA & NHTSA, 2012)

In particular, one OEM indicated in their comments that a 2-3% time-based learning assumption was reasonable for technologies of low to medium complexity (consistent with the utilised cost curves) – see Figure 7.3. This was based on internal analysis on the cost reduction seen on some of their deployed technologies, as shared with the project team in December 2014. However, they also believe the underlying assumption of 20% reduction in costs for each doubling in volume was over-ambitious and a maximum of 15% was appropriate for highly complex technologies, and 10% for others (which has been factored into the approach used for the xEV calculations, see section 4.5). This OEM also noted that a “time-based” learning factor (of 3% annually) was equivalent to a doubling in mass production volume at a 10% learning rate.

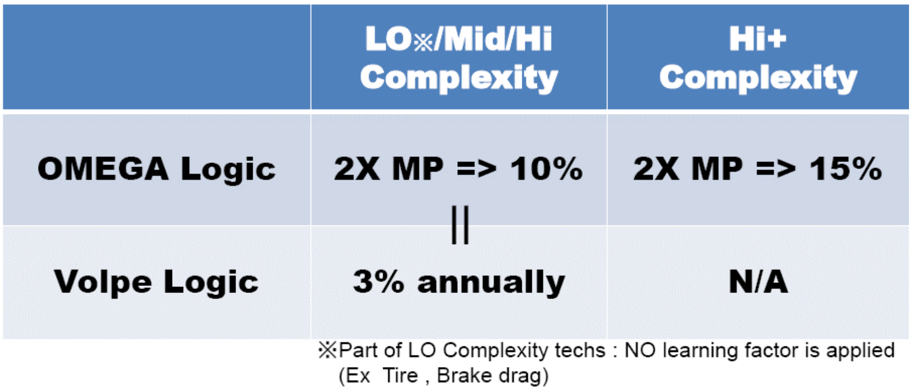
Figure 7.2: Final base learning curves utilised in the cost projection estimates (typical cost case)



Notes: The ‘0’, ‘DS’, ‘1’, ‘2’, ‘3’ and ‘HYB’ labels denote the different learning curves used in this study, based on those initially developed by FEV. DS = the net learning curve for medium downsizing from the FEV analysis for ICCT (FEV, 2013a); HYB = the net learning curve for full hybrid systems based on the FEV analysis for ICCT. The learning curves presented are also based upon the assumption of the following mass-manufacturing years:

0 = 2012 DS =2012 1 = 2015 2 = 2015 3 = 2020 HYB = 2020

Figure 7.3: Summary of the view of one OEM on the appropriate cost learning rates to assume for different technology complexities



	LO※/Mid/Hi Complexity	**Hi+ Complexity**
OMEGA Logic	**2X MP => 10%** ||	**2X MP => 15%**
Volpe Logic	**3% annually**	**N/A**

※Part of LO Complexity techs : NO learning factor is applied
(Ex Tire , Brake drag)

Source: OEM data, December 2014.

Notes: "Volpe Logic" = time-based learning; "OMEGA Logic" covers the volume based learning approach developed by/for the US EPA (EPA & NHTSA, 2012)

The allocation of different technologies to different curves was informed by the final results of the Delphi survey. The final learning factors used in the uncertainty analysis were also adjusted for certain technologies to reflect later market introduction and anticipated mass manufacture points. This was achieved via a horizontal shift of the base learning curves, which had been defined with a specific mass-manufacture point associated with them.

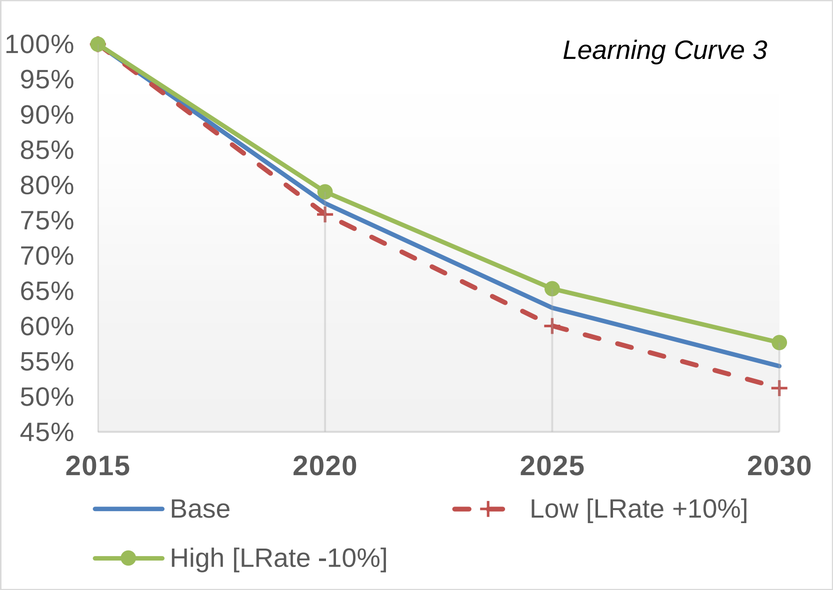
The level of uncertainty in the learning curves used in the uncertainty analysis was defined in a two-stage process:

1. *Uncertainty in the overall rate of learning:* This element affects the rate of cost reduction per doubling of production. This was approximated via an increase or decrease in the annual rate of cost reduction in the learning curves.
2. *Uncertainty in the rate of deployment of technologies:* The effect of this uncertainty was estimated by compressing or stretching the learning curves in the x-axis (i.e. taking less or more time to achieve the same level of deployment).

Stage 1

In the first stage, a degree of uncertainty in the overall rate of learning (i.e. cost reduction) through deployment was estimated via an increase (low cost scenario) or decrease (high cost scenario) in the annual rate of cost reduction for the learning curves. This was set at +/-10% for cost curves 3 and HYB, and at +/-5% for the other learning curves. An illustration of impact of this effect for Learning Curve #3 is presented in Figure 7.4.

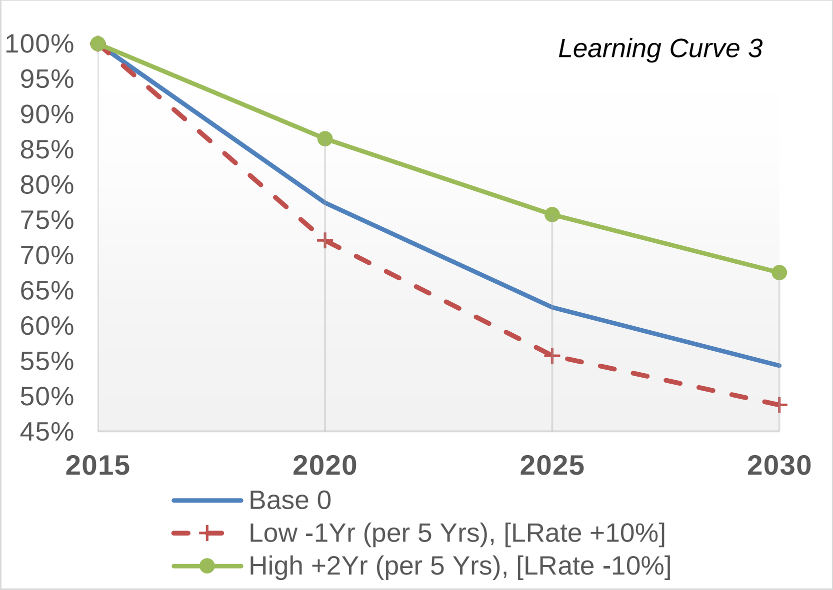
Figure 7.4: Impact of uncertainty on the learning rate on the rate of technology cost reduction for learning curve #3



Stage 2

In the second stage, uncertainty in the rate of deployment was introduced by introducing either a one year advance (lower future cost/higher time-based learning rate) or up to a two year delay (higher future cost/lower time-based learning rate) per 5 year period in the default trajectory towards the point of mass-manufacture of a technology. An illustration of impact of the combined effects for both stage 1 and stage 2 for Learning Curve #3 is presented in Figure 7.5.

Figure 7.5: Impact of uncertainty in the rate of learning *and* in earlier or later mass manufacture points in the rate of technology cost reduction for learning curve #3



Notes: Base = no shift in the cost curve, Low = 1 year advance to the mass manufacture point assumed by the cost curve, and -10% uncertainty in learning rate. High = 2 year delay to the mass manufacture point assumed by the cost curve and +10% uncertainty in learning rate.

The final set of learning factors by technology have been presented in the Technology Results Data Fiche submitted alongside this report, and are also included in Appendix 4. The learning approach described in this section applies only to technologies applied to baseline conventional and xEV powertrains. A different approach (also using different xEV deployment scenarios) was taken to estimate the uncertainty in the rates of cost reduction for the baseline xEV powertrains themselves – this has been discussed in earlier Section 5.4.

7.3.1.2 ICMs and learning trajectories

The final developed set of ICMs were put together to be consistent with the findings from the Delphi survey (discussed in Section 4.7). The ICM time series utilised in the analysis were therefore based on those developed for the European situation by FEV for ICCT (FEV, 2013a) (FEV, 2013b), and were adjusted to include an additional 3% factor for average manufacturer profit margins, based on analysis of information from (VVA et al, 2015) and due to stakeholders' opinions expressed in the Delphi survey that was carried out for this study (see section 4.7). Since technology-specific ICMs only existed for a subset of technologies, it was necessary to make assumptions about how to adapt those available. Where additional ICMs were available from previous analysis to inform the US CAFE regulations final rulemaking (EPA & NHTSA, 2012), these were adapted / scaled to the European ICM set. Where none were available, average ICMs were estimated for the four different complexity levels based on those that were available (see Table 7.2), and technologies were combined with the appropriate ICM in accordance with the final feedback/results of the Delphi survey.

Table 7.2: Calculated average ICMs for different technology complexity levels, fed into in the analysis

Technology	Average Indirect Cost Multipliers (ICMs)				
Complexity	2015	2016	2020	2025	2030
Low	0.127	0.080	0.065	0.057	0.057
Medium	0.266	0.227	0.178	0.054	0.054
High1	0.423	0.369	0.300	0.069	0.069
High2	0.574	0.527	0.379	0.114	0.114

Notes: The average ICMs presented here exclude the additional 3% mark-up for OEM profit that was subsequently added for the final analysis, based on analysis of information from (VVA et al, 2015) and given stakeholders' views as expressed in the Delphi survey carried out for this study (see section 4.7).

As for the final learning rates, a level of uncertainty in the ICMs was introduced on the basis of a similar two-stage process: (i) a one year advance (low cost) or up to a two year delay (high cost) for each 5 year period in the default trajectory towards the mass-manufacture of a technology, (ii) the application of a -/+10% change in the absolute uncertainty of the ICM value (for the low/high cost case respectively). The results of these assumptions were then fed into the uncertainty analysis.

The final set of ICMs by technology have been presented in the Technology Results Data Fiche submitted alongside this report, and are also included in Appendix 4.

7.3.2 'Segment Multiplier' scaling factors for different vehicle segments

For some technologies there are significant deviations in the costs associated with the implementation in different vehicle segments; this is particularly significant for advanced xEV powertrains. However, for some technical options (e.g. sensors or software-based improvements) the costs are expected to be broadly the same, irrespective of vehicle size.

A set of segment scaling factors were therefore developed based on information in the available literature where comparable costs for different vehicle sizes has been previously presented (e.g. principally previous studies for the Commission, for the US EPA and for ICCT), as well as additional information (often only qualitative) provided as part of the gap-filling and validation exercises with stakeholder experts (discussed in Chapter 4). Since this information did not cover all the technologies identified, it was necessary to assume the missing scaling factors were similar to comparable types of technologies.

Since the majority of the data available relate most directly to the lower medium car segment, and this is also the largest segment in terms of European registrations, these scaling factors - 'Segment Multipliers (SM) - were defined relative to this segment.

In addition, the absence of sufficient data to make technology-specific assumptions on the uncertainty around the scaling factors means that only a single set of uncertainties were applied across all technologies, based on an analysis of the overall variation in costs between different segments – see Table 7.3. Overall, the available information was rather limited in this area and this is reflected in these uncertainties.

Table 7.3: Assumed uncertainty in the cost Segment Multipliers (SM), by LDV segment

Estimated Uncertainty in the Cost Segment Multipliers						
Small Car	Lower Medium Car	Upper Medium Car	Large Car	Small Van	Medium Van	Large Van
2.5%	0.0%	8.0%	14.0%	13.0%	20.0%	20.0%

Notes: The uncertainty in the lower medium car scaling factor/segment multiplier is necessarily zero, since the costs for other segments are scaled relative to this one.

The final set of scaling factors by technology have been presented in the Technology Results Data Fiche submitted alongside this report, and are also included in Appendix 4.

7.4 Simulation of technology costs using uncertainty analysis

7.4.1 Overview

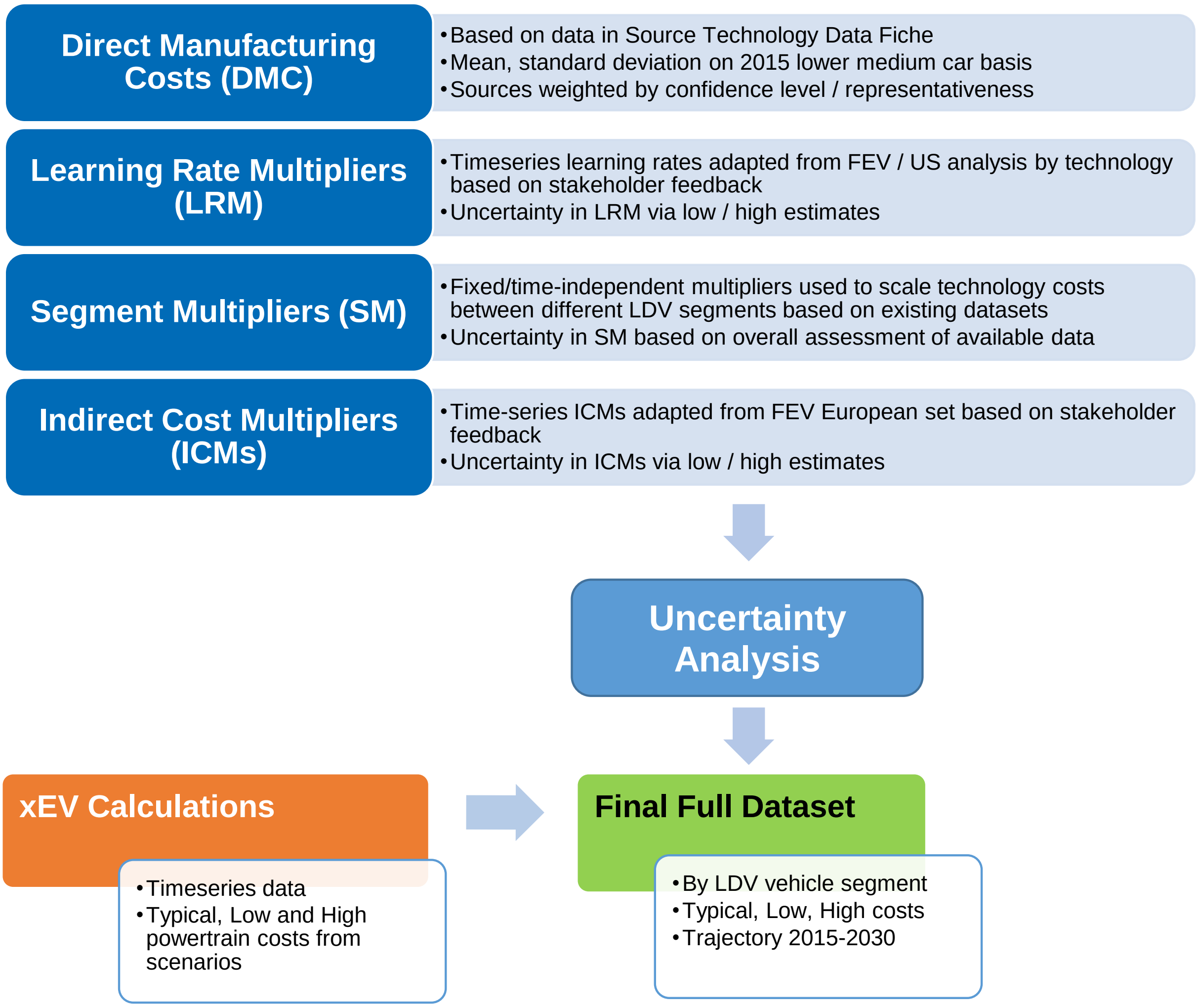
Figure 7.6 provides an overview of the overall approach taken to estimating the future technology costs using an uncertainty analysis approach. Section 7.3 has already provided a summary of the development of the learning, segment scaling and indirect cost factors taken as inputs to the uncertainty analysis, with the following Sections 7.4.2 and 7.4.3 providing more details on the remaining aspects of the analysis.

As outlined earlier, the final total cost of manufacturing values used in the cost-curve derivation (see later Section 8.1) are calculated from the output direct manufacturing costs (DMC) and ICM from the uncertainty analysis according to the formula below (i.e. consistent with that outlined in (FEV, 2013b)):

$$\textbf{Total Cost of Manufacturing, } TCM_{[20xx]} = DMC_{[20xx]} + ICM_{[20xx]} \times DMC_{[20MM]}$$

Where, ‘20xx’ is the relevant year for the calculation and ‘20MM’ is the estimated year of mass manufacture for the technology.

Figure 7.6: Summary schematic of the uncertainty analysis used to develop the final cost dataset



7.4.2 Initial estimation of the standard deviation of the costs in the years 2025 and 2030

As illustrated in Figure 7.6 above, the initial 2015 mean and standard deviations have been calculated from the Technology Source Data Fiche containing all the gathered information and the results/feedback from the gap-filling and data validation exercise. To maximise the number of data points for this analysis, all technology costs were forward- or reverse-learned back to 2015 values, and the segment scaling factors used to base all costs on a lower medium car.

The information on mean and standard deviation values for technology costs was fed into the uncertainty analysis alongside the learning factors, segment scaling factors and ICMs (see Section 7.3); this is also discussed further in the next section (Section 7.4.3). In estimating the mean and standard deviations, a source-weighting approach has been adopted, so that higher confidence/detailed sources (such as data from tear-down studies, gap-filling and validation interviews) were weighted to reflect the greater levels of robustness associated with these figures. Even so, for some technologies there was an unrealistic spread in the derived standard deviations (which would have resulted in extremely low or negative costs in some cases where the standard deviation was greater than the mean), due to some very high estimates from certain sources (e.g. based on data from low volume premium segment vehicles). In such cases the lower boundary for the input to the uncertainty analysis was limited to a minimum of -30% (to avoid unrealistically low estimates), and the upper bound was limited to a maximum of +60% (this latter constraint impacted on only very few technologies).

A summary of the estimated mean and standard deviations in the direct manufacturing costs of individual technologies is provided in the Technology Results Data Fiche submitted alongside this report, and are also included in Appendix 6.

7.4.3 Outline of the uncertainty analysis approach developed

A Latin Hypercube Sampling (LHS) process was utilised in order to assess the combined estimated uncertainty in individual technology costs for different years and LDV segments. The following subsections provide a summary of the data and assumptions used in this analysis and a summary description of the overall process used to estimate the final set of central/typical, low and high technology cost trajectories taken forward for the cost-curve analysis (see Section 8.1).

7.4.3.1 Input data and assumptions for the uncertainty analysis

The costs of CO_2 reduction technologies have been developed taking account of the following four elements (as previously outlined in Figure 7.6):

- Direct Manufacturing Costs (DMC);
- Indirect Cost Multiplier (i.e. ICM, for calculating indirect manufacturing costs), also discussed in Section 7.3.1.2;
- Learning Rate Multiplier (LRM), also discussed in Section 7.3.1.1;
- Segment Multiplier (SM), also discussed in Section 7.3.2;

As outlined in the previous chapters of this report, DMC were identified through analysis of available data from a range of sources and input from industry representatives during the various phases of the stakeholder consultation (i.e. Delphi Survey, gap-filling, data validation and general interviews). This work is already presented elsewhere in this report, but in summary this data was further developed and used for the uncertainty analysis as follows:

- The specific data on DMCs obtained in this way have been assigned to individual market segments based on the source information.
- Where data was only available on a total cost basis, the DMC components were estimated (i.e. reverse-calculated) using the developed technology-specific ICMs.
- These DMCs were then adjusted to represent costs in 2015 by reverse- or forward-learning the original cost figures using the learning curves assigned to individual technologies.
- The primary segment for this cost analysis was selected as the lower medium car segment. The SMs then relate the technology costs in the other market segments to this one, as already discussed in Section 7.3.2.

To provide overall cost data for the cost curve analysis with low, central and high values, an analysis has been performed using the uncertainties in these individual cost elements (which have been derived as described in Section 7.3) to obtain the uncertainties in the overall costs for different segments and time periods. These uncertainties have then also been used to derive the low and high estimates from the central value.

For the direct manufacturing costs for the lower medium car segment, the central cost for each technology has been obtained by taking the average (or mean) of the different estimates for that technology as obtained from the range of sources assuming a normal distribution. The uncertainty in this central cost has been calculated as the standard deviation of those costs. When calculating those parameters, the level of confidence in the data has been taken into account through the weighting of the values (generally based on the specific source, with data from detailed tear-down analysis, gap-filling and validation feedback given higher weighting). Thus, the mean value is calculated as:

$$Mean = \sum (Weight \times Cost) / \sum (Weight)$$

Correspondingly, the standard deviation is calculated as:

$$StDev = \sqrt{\left\{ \sum (Weight \times Cost^2) / \sum (Weight) - Mean^2 \right\}}$$

The weighting factors have been applied to the cost data based on an assessment of the confidence in the source of the data. To increase the amount of data included in the analysis, cost data for the other segments have been scaled to match the lower medium car segment (using the inverses of the segment multipliers described below).

Because of the diversity of the cost data included in the calculation, some additional controls have been placed on this part of the process. For example, in cases where there is only a single data point available, the above approach results in a standard deviation of zero. In these cases, an indicative standard deviation of +/-10% of the mean has been used in the subsequent analysis.

The LRMs have been derived for each analysis year (2015, 2020, 2025 and 2030) and for each technology using an overview of the anticipated ability to reduce costs over time due to the maturity of the production process and the mass application of the technology, using the learning curves identified/developed as described in Section 7.3.1.1.

The uncertainty in the LRM has also been derived as described in Section 7.3.1.1. Unlike the uncertainty in the direct manufacturing costs (which, as it has been calculated as the standard deviation of a number of data points, is inherently symmetric, i.e. the same uncertainty on either side of the mean), this approach allows different uncertainties to be derived on the plus and minus sides of the mean.

The SMs have been derived in a similar manner to the LRMs as functions of the market segment (Small Car, Lower Medium Car, Upper Medium Car, Large Car, Small Van, Medium Van, and Large Van), as has been described in Section 7.3.2.

The final direct cost of manufacture, for each combination of technology, vehicle segment and analysis year, can then therefore be calculated as follows:

$$\mathbf{DMC_{[20xx]} = DMC_{[2015]} \ x \ LRM_{[20xx]} \ x \ SM}$$

Where, ‘20xx’ is the relevant year for the calculation.

However, because of the different manners in which the different data elements have been sourced and calculated, it is not feasible to calculate these directly, particularly as part of the aim is to ultimately calculate an overall uncertainty for the total cost. Therefore, the mean (or central/typical) costs and uncertainties, as described above, have been used as inputs to a LHS process (a summary of the LHS approach is provided in Appendix 4, together with tables including the primary individual technology input parameters). The application of the LHS analysis is summarised in the next section.

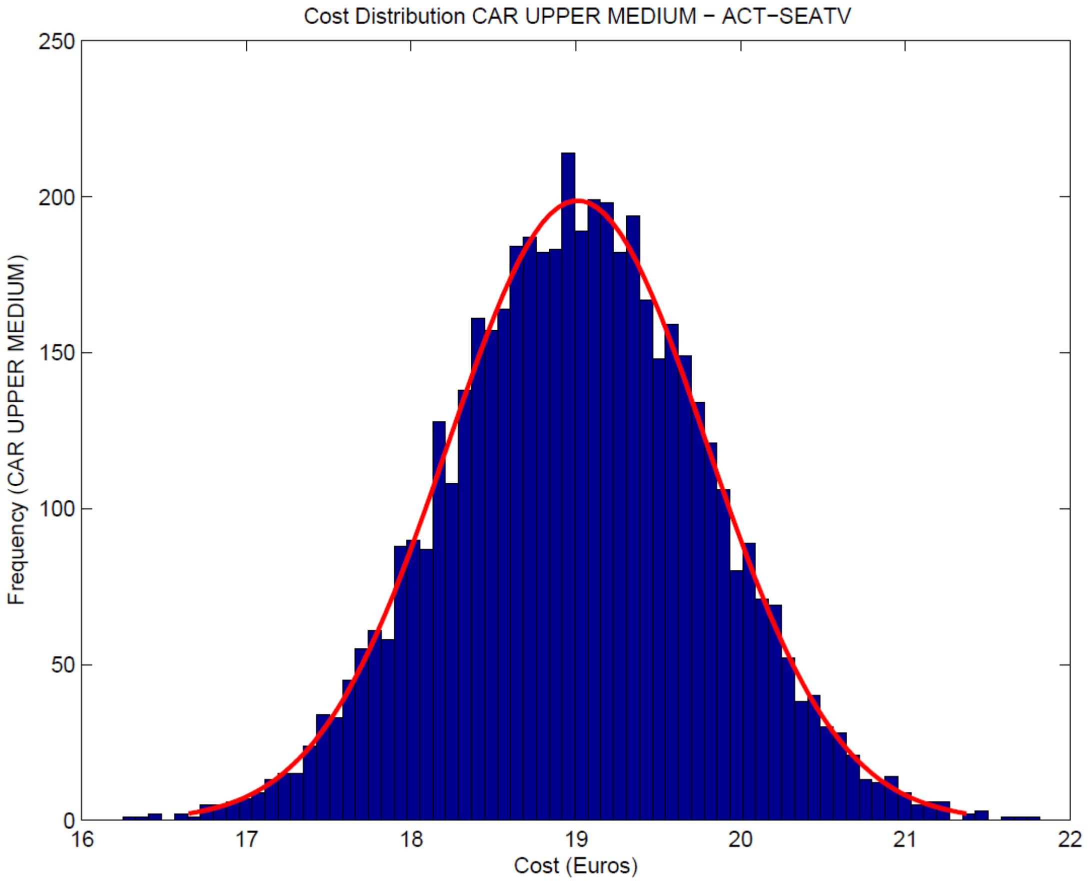
7.4.3.2 Application of the Latin Hypercube Sampling (LHS) process for uncertainty analysis

The LHS analysis was performed using the analytical software package MATLAB as a LHS routine was already available for it. The concept behind the use of the LHS approach was for it to be used to generate a large number of triples of the three cost elements (i.e. a triple is a combination of a DMC, a LRM and a SM) using their means and uncertainties (described earlier) as inputs. The LHS algorithm obtains the value of each of the three elements with an equal probability using a normal probability distribution based on the relevant mean and standard deviation values input for the cost element. The LHS approach was selected instead of the alternative Monte Carlo approach as it was considered to provide more reliable overall uncertainty values using fewer triples. The MATLAB script written took the different triples generated by the LHS routine (a total for 5,000 triples were generated for this work) and calculated the same number (i.e. 5,000) of total DMC values from them using the formulation described above. From these 5,000 cost values, a mean and standard deviation were then calculated to represent the central/typical estimate and the uncertainty (i.e. taken as low and high cost).

To manage the cases where the uncertainties in the individual cost elements were different on the two sides of the mean (i.e. plus and minus), the above analysis was performed twice, once using the “plus” uncertainties, once using the “minus” uncertainties. The “plus” uncertainty in the final DMC estimation (where the “High” cost estimate is the mean plus the “plus” uncertainty) was set to be the standard deviation obtained from the distribution of final DMCs derived using the “plus” uncertainties in the individual cost elements. Similarly, the “minus” uncertainty in the final DMC estimation (where the “Low” cost estimate is the mean minus the “minus” uncertainty) was set to be the standard deviation from the distribution of costs derived using the “minus” uncertainties in the individual cost elements.

To illustrate the above description, Figure 7.7 shows the distribution output from the MATLAB analysis for one technology (Active Seat Ventilation) in the year 2030.

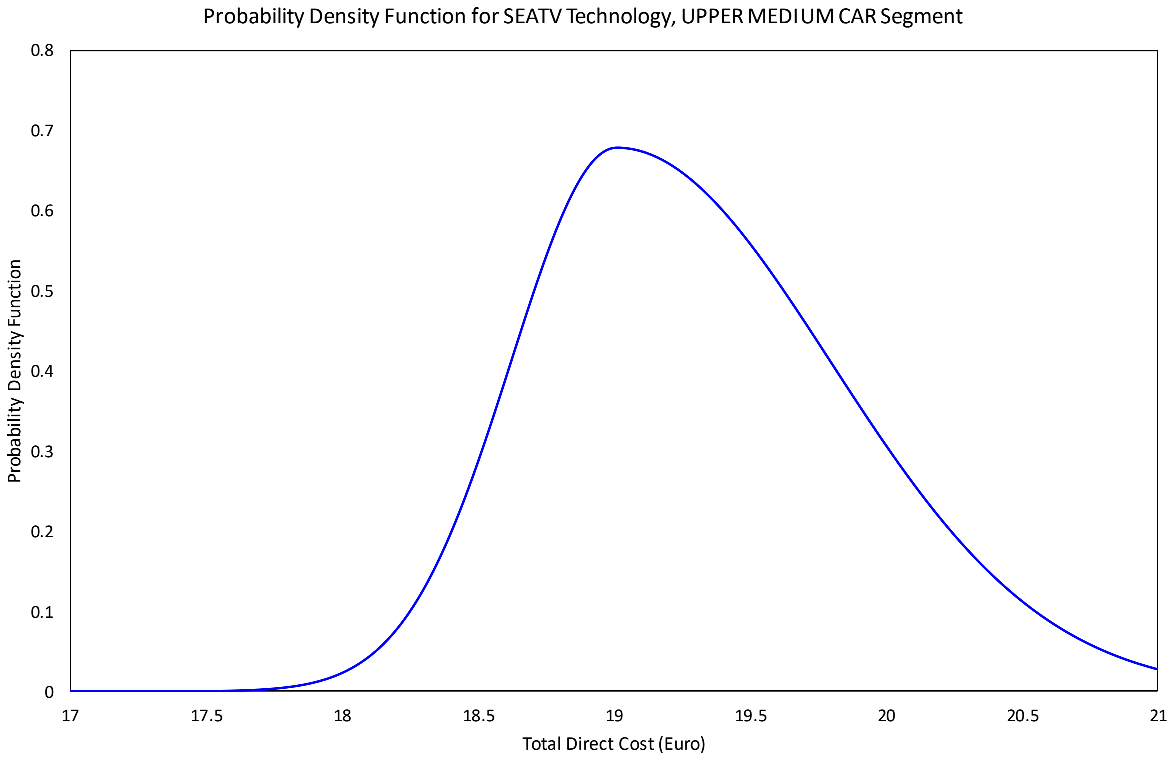
Figure 7.7: Frequency distribution for direct manufacturing costs (DMC) as calculated using LHS approach for ACT-SEATV technology, Upper Medium Car segment, "plus" uncertainties



The figure above shows the frequency distribution for the DMC obtained using the "plus" uncertainties. The standard deviation for the distribution shown is 0.79. The equivalent standard deviation for the total direct costs using the "minus" uncertainties is 0.39, approximately half the "plus" value.

From the results obtained from this analysis, using both the "minus" and "plus" frequency distributions, it is possible to obtain the complete probability distribution for the final costs as shown in Figure 7.8 below.

Figure 7.8: Probability distribution for direct manufacturing cost (DMC) for ACT-SEATV technology, Upper Medium Car segment, "plus" and "minus" uncertainties combined



The asymmetric nature of the result can be clearly seen in Figure 7.8. There is a risk in this approach of performing the LHS calculations separately using the "plus" and "minus" uncertainties that the means of the two resulting cost distributions could be different, due to the random nature of the selection of the sample points using the LHS function. To avoid this risk, it is necessary to choose an adequately high number of samples. A manual check has been made on the means calculated from the two distributions for a number of technologies and LDV segments. This has shown that the two means are always the same (within a very small tolerance), whether the "plus" and "minus" uncertainties are the same or different. Hence, it is considered that the sample size used for this analysis (the 5,000 triples described above) is sufficient.

The above description applies to the calculations of the DMCs. The same methodology has also been applied to the calculation of the ICMs. However, in this case, there is only one element in the ICM calculation (the central values for the ICM and their uncertainties as supplied), so the output from the process gives the same mean and uncertainty values as the input.

7.5 Outputs from the CO_2 and cost analysis

The full final outputs on the cost and CO_2 reduction potential of LDV technologies are presented in the accompanying Technology Data Results Fiche Excel file. Due to the sheer volume of information/data generated as a result of the combination of technologies (>80) with segments (7), time-periods (4), and cost or CO_2 reduction types (3 each) and powertrain types (8, for CO_2 reductions mainly) it is not possible to present and analyse these results within the body of this written report. An example of the output results is presented for the direct injection – stratified charge & lean burn technology for petrol engines in Table 7.4 below for lower medium cars.

Table 7.4: Example Technology Results Data Fiche Summary for the Direct Injection – Stratified Charge technology for lower-medium cars

TECHNOLOGY OVERVIEW

Technology name			**Technology applicability**	
Direct injection - stratified charge & lean burn (Study Abbrev. = DI-SC)			*Segments*	All LDV
2013 EU Market Share, %	*Cars*	*7.0%*	*Powertrains*	Spark-ignition engines (see compatibility table)
	Vans	*3.8%*		
Anticipated launch		*Current*	*Fuels*	Petrol (or ethanol), natural (or bio-) gas
Mass manufacture year		*Current*		

Technology description

A method of direct injection to achieve a very lean burn at the expense of high NO_x emissions. The cylinder is fed a stratified fuel/air mixture (layered, as opposed to homogeneous, in an area surrounding the spark plug requiring piezo-electric injectors) with excess air which reduces pumping losses. Secondly, the high pressures used then allow sufficiently late injection during the compression stroke so as to delay auto-ignition which allows very high compression ratios to be reached. These two mechanisms enable high thermal efficiencies and a better combustion.

As of 2014, a number of manufacturers have released a lean burn GDI engines in selected models (e.g. BMW, Ford, Toyota, VW, etc.), and many have development programmes for the technology. Lean-burn strategies encourage the formation of NO_x and currently require expensive after-treatment systems (NO_x-trap catalysts) to bring emissions into conformity with the Euro VI regulations. Exhaust gas recirculation (EGR) is now employed to reduce these NO_x emissions, after years of research to combat stability issues. Manufacturers are expected to utilise this technology to a greater extent in the near future due to the substantial savings offered. The EPA has estimated (1) significant CO_2 reductions as compared to port-fuelled stoichiometric engines (8-10% for cars, 10-14% for large vans); a recent European report (2) has estimated 9.3% and 9.5% efficiency improvements for cars and vans respectively. Stable combustion at air-to-fuel mixtures of 146:1 have been reported (typically 15:1), revealing the potential of this method. (3)

This technology works well with downsizing strategies and can only be applied to petrol engines.

Examples of application/technology variants

Already in the marketplace:	*Planned for introduction in the future:*
1 Mercedes' BlueDIRECT CLA250 engines (4) 2 BMW N53 and onwards (5) 3 Bosch' HDEV4 piezo injectors (6)	1 No specific examples identified.

COMPATIBILITY WITH OTHER TECHNOLOGIES

Incompatible technologies	**Most beneficial compatible technologies**
See compatibility table. Total: 4.	Cooled low-pressure EGR for SI engines; Mild downsizing (15% cylinder content reduction) + boost; Medium downsizing…, etc. Total: 7.

SUMMARY OF KEY DATA SOURCES AND ASSUMPTIONS USED TO DEFINE COST AND CO_2 SAVINGS

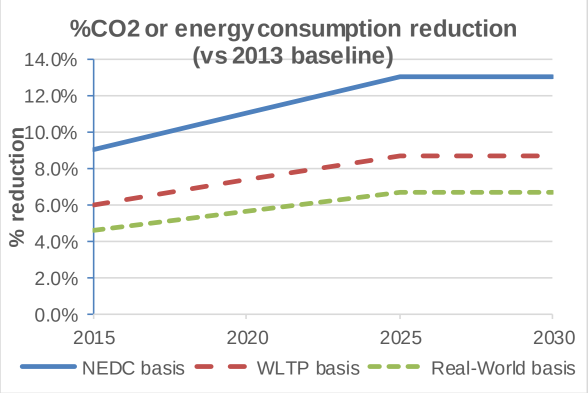
Technology CO_2 Savings Potential	**Technology costs**
NEDC savings based on a review of literature sources, with the final figure validated/adjusted based on feedback from stakeholders. Relative savings for different vehicle segments and savings on WLTP and other test cycles were based on PHEM model simulations.	Initial costs based on a review of literature sources, with the final figure validated/adjusted based on feedback from stakeholders. Low and high technology costs based on an uncertainty analysis based on the range of available cost estimates, and estimated uncertainty in the Learning Rates, Segment Scaling Factors, and ICMs.

Table 7.4: Example Technology Results Data Fiche Summary for the Direct Injection – Stratified Charge technology for lower-medium cars (continued)

TECHNOLOGY CO2 OR ENERGY CONSUMPTION REDUCTION **Final Data**

By Segment and Powertrain

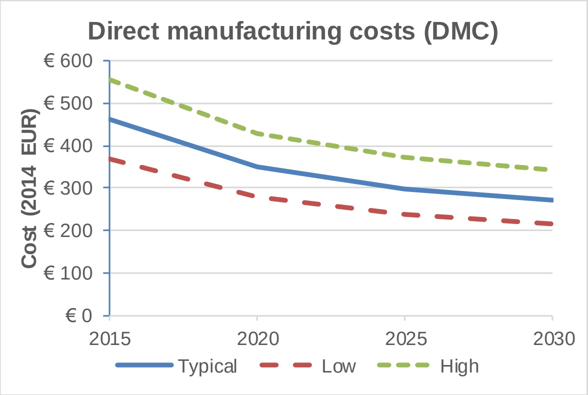
Lower Medium Car	**SI ICE+HEV**		**Petrol**	
%CO2 or energy consumption reduction (vs 2013 baselin				
Cycle	**2015**	**2020**	**2025**	**2030**
NEDC basis	9.0%	11.0%	13.0%	13.0%
WLTP basis	6.0%	7.4%	8.7%	8.7%
Real-World basis	4.6%	5.7%	6.7%	6.7%



ESTIMATED TECHNOLOGY COSTS **Final Data**

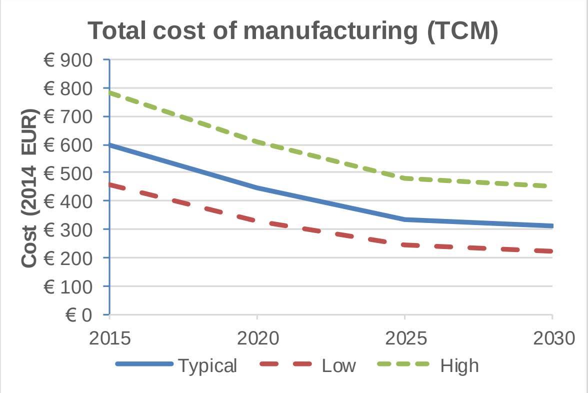
By Segment and Powertrain

Lower Medium Car	**SI ICE+HEV**		**Petrol**	
Cost (2014 EUR)	**2015**	**2020**	**2025**	**2030**
Direct manufacturing costs (DMC)				
Typical	€ 462	€ 349	€ 296	€ 272
Low	€ 370	€ 277	€ 238	€ 216
High	€ 554	€ 430	€ 373	€ 344
Indirect Cost Multiplier (ICM)				
Typical	0.296	0.208	0.084	0.084
Low	0.235	0.146	0.023	0.023
High	0.408	0.320	0.196	0.196
Total cost of manufacturing (TCM)				
Typical	€ 599	€ 445	€ 335	€ 311
Low	€ 457	€ 331	€ 246	€ 224
High	€ 780	€ 607	€ 482	€ 453



Cost percentage (%) change vs 'Typical' cost scenario

Direct manufacturing costs (DMC)				
Typical	0.0%	0.0%	0.0%	0.0%
Low	-19.9%	-20.5%	-19.8%	-20.7%
High	19.9%	23.3%	25.9%	26.6%
Total cost of manufacturing (TCM)				
Typical	0.0%	0.0%	0.0%	0.0%
Low	-23.7%	-25.5%	-26.6%	-27.9%
High	30.3%	36.5%	43.8%	45.7%



8 Development and verification of cost curves

8.1 Development of cost curves

8.1.1 Overview of methodology for the development of cost curves

The objective of this task was the development of new cost curves based on the technology fiches and uptake scenarios developed in previous tasks. Cost curves were therefore generated for each of the vehicle segments and powertrain types, using the baseline vehicles that we defined in Section 2.4 as reference points for each segment against which the marginal costs of achieving specific levels of CO_2 reduction could be quantified.

A cost-curve model developed by EC JRC was used to generate the required cost curves. At a summary level the analysis using this model included, for each **vehicle segment** identified, the following:

1. Cost curves covering all relevant test-cycle vehicle technologies for the years 2015, 2020, 2025 and 2030. As noted in the Commission's specification, this included only conventional ICE powertrain technologies for the cost curves that were developed for 2015 and 2020 previously.
2. Separate cost curves developed to include both on- and off-cycle vehicle technologies for 2025, 2030.

More details on the coverage and results of this work are provided in the following subsections.

8.1.2 General approach and coverage

This section provides a summary of the refinements to the task discussed and agreed with the Commission and the range of cost-curves developed for this project. As required, the main cost-curves developed have been calculated using estimates of WLTP-based CO_2 (or energy) technology savings[38].

Principally it was agreed there would not be a need for Ricardo Energy & Environment to provide cost-curve outputs for all possible combinations (which would have been unmanageably large), since the JRC had also been working with the previous technology cost dataset and was replicating and further developing the cost-curve/model methodology. A more restricted subset of central cost-curves was therefore produced for this report, to include a number of key sensitivities that are also discussed in later subsections of this report. The basic data needed to develop the full range of possible cost-curves has been made available, via the Technology Results Data Fiche, to the Commission.

To facilitate the development of cost-curves by the JRC using their model, Ricardo Energy & Environment has liaised closely with the JRC to ensure transparency /consistency in the approach taken (see also section 8.1.3).

Table 8.1 provides a summary of the cost-curves produced for this project report (with the full details provided in Appendix 6). The main modification to this list compared to the original intention is that individual curves have been developed for PHEVs and REEVs. To manage the number of cost-curves produced, previously it had been agreed to merge the petrol and diesel PHEV and REEV cost curves into a single curve. However, it has turned out to be simpler to provide better disaggregation by developing cost curves for each separate fuel/powertrain option individually.

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[38] A limited selection of additional NEDC-based cost curves were also generated for the purpose of making comparisons with previously developed equivalents (see Section 8.1.5.1).

Table 8.1: Number of WLTP-based cost-curve combinations produced for the project

Area	Number of elements	
	2015, 2020	2025, 2030
Years	**2**	**2**
Fuels and powertrains	**2**	**8**
Petrol/Gas ICE (plus hybrids), Diesel ICE (plus hybrids)	*2*	*2*
Petrol PHEV, Diesel PHEV		*2*
Petrol REEV, Diesel REEV		*2*
BEV		*1*
FCEV		*1*
Segments	**7**	**7**
Cars	*4*	*4*
LCVs	*3*	*3*
On/Off-Cycle techs (2)	**1**	**2**
Test cycle only	1	1
Including non-test cycle		1
Cost scenario	**1**	**1**
Central/Typical	1	1
Low, High	*JRC (1)*	*JRC (1)*
Total number of cost-curve combinations	**28**	**224**
Grand Total	**252**	

Notes: (1) *JRC* = Only a handful of examples of the cost-curves for the low and high cost scenarios have been provided for illustration purposes in the final report. However, JRC has run the other combinations using their cost-curve model. (2) Three technologies that were identified as off-cycle on NEDC, were deemed to be applicable as on-cycle under WLTP conditions due to differences in the basis of the different testing protocols.

In developing this list we agreed with the Commission a number of areas where simplifications could also be applied in developing the cost-curves without compromising the quality of the outputs, including:

- Treating variations on specific technologies together (e.g. different types of full hybrid technology).
- The number of years for which the cost curve analysis was carried out (e.g. only including off-cycle technologies for the 2025 and 2030 cost-curves).
- Treating natural gas powertrains as a simple addition in cost and CO_2 reduction to the developed petrol/spark-ignition cost-curves.

Analysis of the 2013 EEA CO_2 monitoring dataset for LCVs (EEA, 2014a), presented in Table 8.2, showed that for large LCVs at least (and possibly also for medium LCVs) there did not appear to be a compelling reason to include cost curves for spark-ignition engined vehicles (i.e. petrol or gas-fuelled) because sales of these types of vehicles are very low.

Table 8.2: Share of registrations by fuel type for LCVs from 2013 CO_2 monitoring database

LCV segment	Petrol	Diesel	Electric	Other spark-ignition ICE (E85, natural gas, biomethane or LPG)
Small [<1.8t GVW]	9.9%	86.8%	0.1%	3.3%
Medium [1.8-<2.5t GVW]	2.6%	93.9%	1.7%	1.7%
Large [2.5-3.5t GVW]	0.3%	99.4%	0.0%	0.3%

The following sections provide a summary of the methodological approach for developing the final cost curves (Section 8.1.3), and a summary of the outputs of the cost-curve development (Section 8.1.4). The complete list of formulae (and start/end points) for the developed cost curves are provided in Appendix 6 of this report, and also within an accompanying Excel summary file.

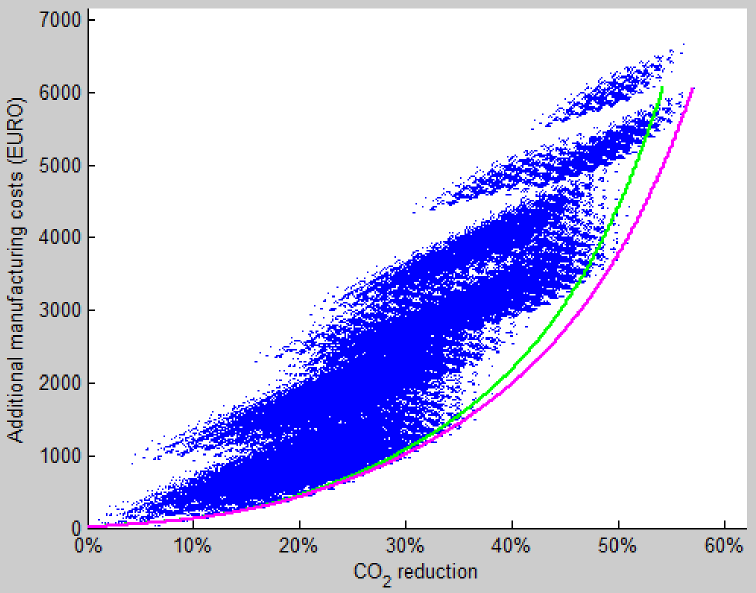
8.1.3 Methodological development of the cost-curve approach

The cost-curve approach used to date (in previous work by Ricardo Energy & Environment for the Commission, (Ricardo-AEA, 2015)) adopted a methodology whereby a cloud of data points is first created by analysing all possible compatible combinations of a long list of different CO_2 technologies. This approach is similar to the approach also adopted in the past (TNO et al., 2011) and had been demonstrated to generate highly comparable results.

Once this cloud has been obtained, the cost curve is then defined by the outer envelope of the 'cloud' (see Figure 8.1). Whilst this approach is sound, it has certain computational draw backs:

- The computational time of the above approach could still pose issues when tasked with repeating the process potentially hundreds of times and;
- The above approach only allows a maximum number of technologies of 25 to be analysed at one time before limits on computational memory are exceeded. Even if this memory issue did not exist, the computational running time for a list of over 25 technologies would be extremely unmanageable and would quickly have become impossible for the number of technologies this study analysed.

Figure 8.1: Presentation of historic cost curve approach (purely illustrative example)



Due to such considerations further work has been ongoing within Ricardo Energy & Environment and JRC to improve the current methodology with the aim to eradicate the drawbacks encountered. This work is discussed in the following sections.

8.1.3.1 Updated methodological approach

An alternative approach to the cost-curve modelling has been developed to overcome the limitations outlined above. The updated methodology that has been taken forwards was to utilise an optimisation approach whereby data points that make up the cost curve are not determined by a cloud of data points but are determined iteratively by using a set of constraints (based on incompatible technologies). Initially MATLAB's inbuilt optimisation toolbox[39] was used. An alternative approach based on Swarm Intelligence was developed at JRC at a later stage and was used to provide the raw data points to which the present cost curves were fit.

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[39] The optimisation solver used here was a genetic algorithm with integer constraints.

The optimisation problem is known to be an np-complete problem, that is, its computational difficulty grows exponentially with the number of technologies to combine. This is mainly due to the presence of constraints in combining these technologies together in a configuration.

These constraints results from incompatibilities among technologies which cannot be grouped together within a ‘technology package’ (a set of more than one technology). For example, various levels of engine downsizing technologies are being considered but there would never be a ‘package’ that contains more than one. The complete incompatibility matrix can be found in the Technology Results Data Fiche and this matrix is used to derive the full list of incompatibility pairs (pairs of incompatible technologies). In the MATLAB approach, each iteration within the optimisation process (200 was chosen as a suitable number of iterations/data points) selects a different cost value (within the range of the costs of technologies in question) and seeks to find the minimum CO_2 reduction value at each cost based on a set of incompatibility constraints[40].

The MATLAB optimisation approach was able to run 48 technologies initially (versus the limitation of 25 for the original approach). Here the model solves the problem within a few minutes. It was clear therefore that this approach is vastly more efficient and has the capacity to *at least* double the number of technologies to be analysed at any one time. It has also been estimated that this approach could potentially analyse close to 100 technologies in a relatively short period of time.

However, as the number of available technologies increases, it appeared clear that a MATLAB toolbox (which is based on a Genetic Algorithm) might very likely lead to suboptimal solutions in the computational timeframes imposed. From the technology data collected, there is the possibility of combining 83 distinct technologies, so in principle, this gives rise to a search space of 2^{83}-1 possible distinct configurations (ignoring constraints for this evaluation, just to have an idea of the size of the search space). Therefore an approach based on Swarm Intelligence, more precisely an Ant Colony Optimization (ACO), coupled with some local search (LS) technique, has been developed in Java and tested extensively at JRC. This approach proved to be able to handle the computational complexity of the problem. It has the following benefits, and a comparison of the outputs from the two approaches is presented in Figure 8.2:

1. **It is not a black box** (such as a MATLAB toolbox), and therefore for each problem, the solution (a set of optimal technology packages) is fully available in the sense that all the configurations are given in terms of technologies combined, and the resulting total CO_2 reductions and total costs of each configuration can be verified directly.
2. **It is highly efficient:** It basically provides nearly optimal solutions within few minutes of computation, and highly completed solutions within 15 minutes.
3. **It finds a rich set of pareto-optimal technology packages**, that is, a large number of points, each point being a configuration which is optimized in terms of CO_2 reduction and cost.

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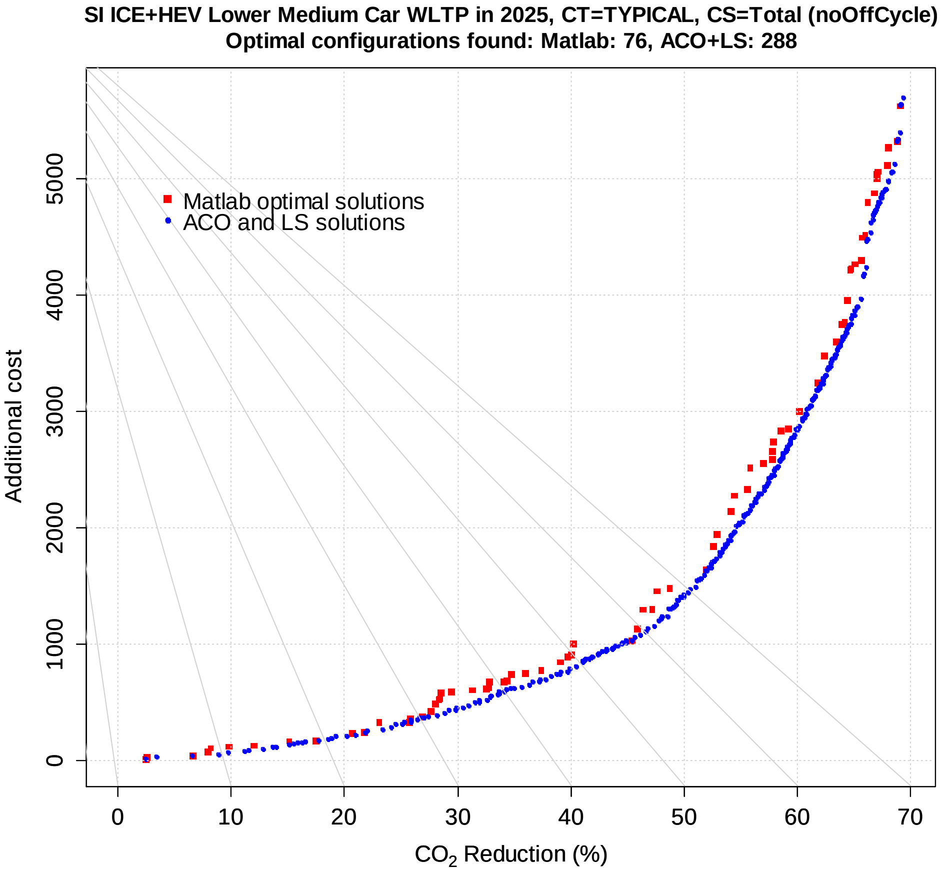
[40] Using a similar approach, the model could also have been designed to seek to find the minimum *cost* at each CO_2 reduction value based on a set of incompatibility constraints. This approach would also give the same desired results.

Figure 8.2: Presentation of two optimization approaches (purely illustrative example). Red squares: MATLAB optimal solutions, Blue dots: Ants Colony Optimisation and Local Search optimal solutions. Note that there are 76 pareto optimal MATLAB solutions, compared with 290 solutions found with ACO+LS.



Once a set of pareto-optimal technology packages has been calculated (the so called ***raw*** cost curve data) for a given configuration (year, powertrain, vehicle segment, test cycle, cost scenario, and if to include off-cycle technologies), a number of adjustments are made to each point before fitting the cost curve.

These additions/modifications have been devised by Ricardo Energy & Environment and have to be applied as post-processing steps (i.e. outside of the main cost-curve model). These include:

a. Accounting for already deployed technologies in the desired 2013 baseline:

The individual CO_2 savings potentials used in the cost-curve model are defined/based on a vehicle without any of these technologies already applied (i.e. effectively similar to the 2002 baseline used in the previous analysis). However, as discussed in Section 2, 2013 baseline vehicles already have a mix of different technologies applied. Therefore it was necessary to adjust the cost-curves to account for the already taken-up CO_2 savings potential. This was implemented by effectively moving up the raw cost-curve to the point consistent with the calculated segment average percentage savings due to technology application, calculated based on the IHS dataset on individual technology penetration in the European fleet in 2013.

b. Handling battery cost (or H_2 storage cost) savings for BEV, PHEV, REEV and FCEV:

Battery cost savings resulting from an ability to further downsize the battery (for the same range) following addition of other efficiency improvements needed to be accounted for in the final cost-curves. This was done via a powertrain-specific correction factor to the overall cost curve in € per % cumulative CO_2 / energy reduction terms. This factor is specific to the powertrain type as battery costs and share of electric driving vary. For PHEVs/REEVs this factor was scaled depending on the share of conventional fuel and electricity within each powertrain. The correction factor was also scaled linearly with the € per % improvement level to take account of the varying gradient of the cost curve.

For example, at the start of our cost-curves, the € per % improvement values are least, but as we move to the right of the curve it increases. As a result, depending on the final 'credit' for € per % compared to the early part of the initial cost curve, there may in some cases be a minimum in the total additional cost for a given xEV powertrain type at some point after the 0% CO_2 (or MJ/km) savings point, before the costs begin to go up again.

c. Handling corrections for technology overlap

Previous work using the cost cloud model assumed correction factors (15% and 5% for petrol and diesel fuel types respectively) that help to counter technology overlap that may be inherent within the model due to the first order nature of how savings from technology packages (i.e. one or more technologies) are calculated. These correction factors have been updated based on analysis of the results of TU Graz simulations of different packages (see section 8.2).

d. Handling energy savings as well as gCO_2/km savings:

BEVs and FCEVs need to be considered in terms of 'Energy/km', as these powertrains have zero tailpipe CO_2 emissions. Therefore in order to model improvements to these vehicles properly, improvements/efficiency savings must be represented in energy terms also.

The above four additions form the basis of the several post processing steps that take the raw data output from ACO (denoted by the blue data points in Figure 8.2**Error! Reference source not found.**) and transforms this into the set of points used to define the final cost curve. Further mathematical detail on these steps will be presented in Appendix 6. These steps are (in order):

Step 0. Raw data points are outputted from the AC optimization model

Step 1. 2013 Baseline adjustment: this takes into account the percentage CO_2 savings resulting from technologies that have already been applied to the 2013 baseline vehicles (specific to the relevant LDV segment). To achieve this, a horizontal translation is applied to the raw data curve (from stage 0) in the negative x-axis direction to re-baseline the CO_2, then a corresponding vertical adjustment in the negative y-direction is used to re-baseline the costs to zero in 2013. The net effect is to move the origin along the curve. The assumed % savings (based on the IHS technology penetration datasets) for different vehicle segments and powertrain types are presented in Table 10.43 in Appendix 6.

Step 2. Scaling for batteries (xEVs only): the reasoning and general methodology for step 2 is described in point b. above. This step vertically shifts the data points down (negative y-axis direction) to account for battery cost savings resulting from an ability to further downsize the battery (for the same range) following the addition of other efficiency improvements. The reduction in cost per % CO_2 improvement can be found in Table 10.44 in Appendix 6.

Step 3. Scaling for overlapping technologies: described above in point c. This adjustment is required as the technology packages are constituted of individual technologies, each with their own individual cost and CO_2 reduction potentials. The packages are derived from the sum of the individual technology costs and the product of individual CO_2 reduction values. Due to the nature of this multiplicative process, the overall CO_2 reduction potential is a first order estimation which may in fact overestimate the total reduction. Step 3 is the 'safety margin' which counteracts any overestimation that may occur and was also applied by TNO in previous cost curve work (TNO et al., 2011). Mathematically, this scaled back curve is obtained by multiplying the x-axis value (percentage CO_2 reduction) of every data point by $(1 - \gamma)$, where γ linearly scales from zero to its maximum value between the origin and the maximum reduction potential of the curve. Table 10.45 in Appendix 6 displays the maximum γ values. In Step 3, the costs remain constant.

Step 4. Rebaseline xEV relative to 2013 conventional (xEVs only): In order to present xEV cost curves as relative to conventional 2013 powertrains (i.e. including the benefits of moving from baseline ICE to xEV), xEVs have been re-baselined relative to a 2013 conventional vehicle (see Table 10.46 and Table 10.47 in Appendix 6 for the relevant values).

The effects of the above steps are illustrated below in Figure 8.3 (using an xEV powertrain type). For conventional powertrains, Step 2 and Step 4 are not relevant and so have zero impact. As indicated earlier, all relevant information to undertake these post processing steps are presented in Appendix 6.

Figure 8.3: An illustrative example of the effects of post processing steps 1 to 4 for an xEV powertrain

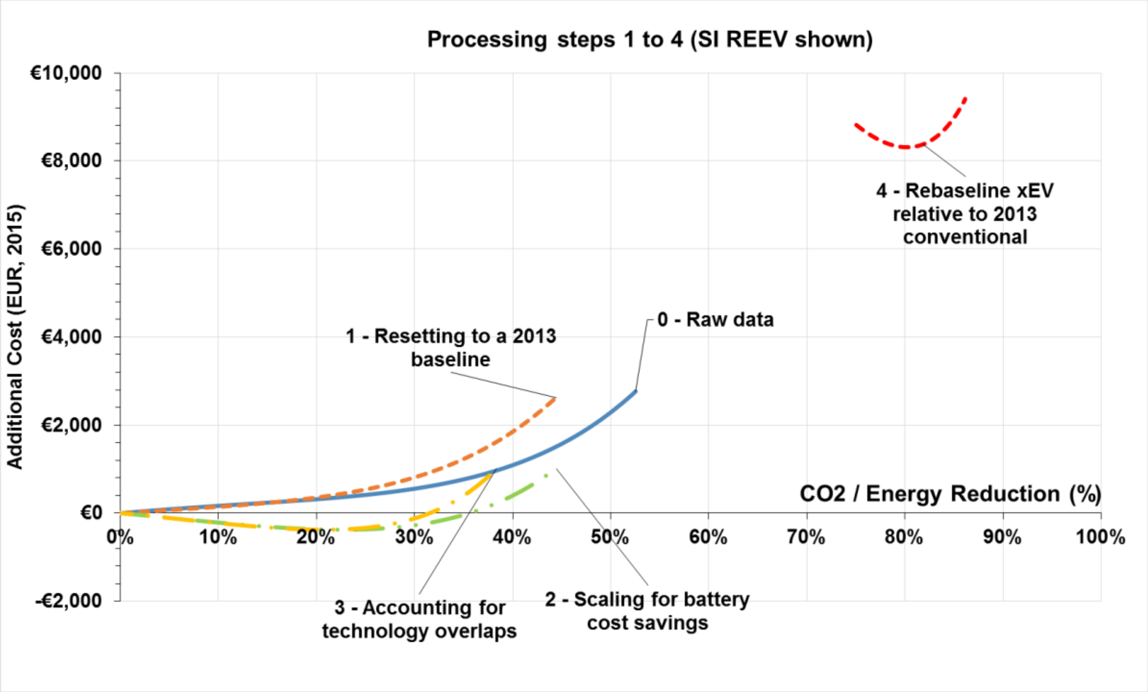


Figure 8.3 shows all four steps. As can be seen, the first step is a horizontal shift in the negative x-direction (% CO_2 savings) and a corresponding negative y-direction adjustment based on the ***raw*** data (baseline adjustment). The second step is a vertical shift in the negative y-direction only (scaling for batteries) and the third step is a further horizontal shift in the negative x-direction only (scaling for overlapping technologies). The final step (only applicable to xEVs) is the x- and y- adjustment for the baseline xEV technology performance relative to the baseline equivalent conventional vehicle (assumed to be petrol ICE for BEVs and FCEVs).

Once the above operations have been applied to the raw data, the next step is to develop the final curve fit of the points obtained by such transformations. Previous work performed by TNO (TNO et al., 2011) modelled curves using high order (sixth order to ninth order) polynomials. However, both these types of equations proved problematic with regard to the properties of the resulting cost curves. It was found that the polynomials gave rise to oscillations (or 'wiggles') at low CO_2 reduction values on the cost-curve as a result of over-fitting the data, whereas simple exponential functions tended to overestimate the CO_2 reduction values on the cost curve at low CO_2 reduction points and underestimate the fit at high CO_2 reduction values.

Several different forms of fitting functions were tested at Ricardo Energy & Environment and at the JRC in order to deal with these issues, and with the requirement for the fit to have always 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 /CI+Hybrids) and one for all xEV powertrains.

ICE powertrains

For the ICE powertrains, which comprises SI ICE+Hybrid and CI ICE+Hybrid powertrains, the form of the fitting function is the following:

[1] $$y = C + \frac{c}{x - x_0}$$

where C, c, and x_0 are the 3 parameters to be found by the fit. These coefficients were found with the Levenberg-Marquardt non-linear regression algorithm using R.

Since the density of points along the cost curve is different, highly density regions tend to "weigh" more. Therefore, to avoid divergences in lower populated regions, there is the possibility of imposing the passage of the fitting function through a determined point. To impose the passage of the fit through a given point (x_p, y_p), one of the parameters can be substituted by the expression:

[2] $$y_p = C + \frac{c}{x_p - x_0}$$

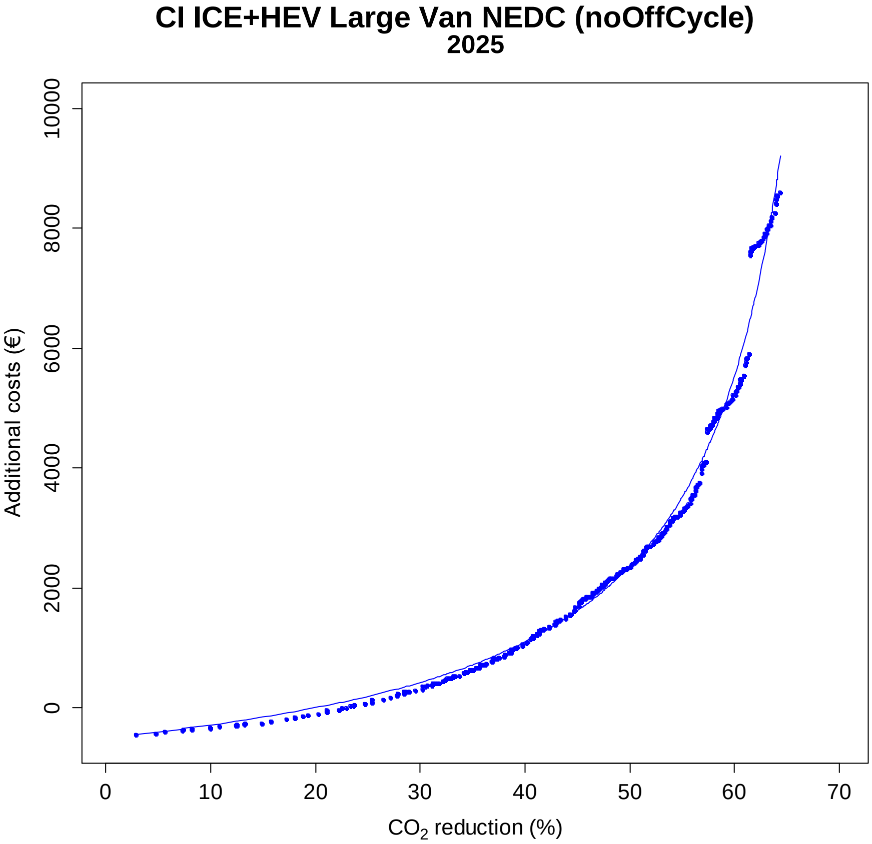
which, resolved in c, yields:

[3] $$c = (y_p - C) * (x_p - x_0)$$

This expression can be substituted in [1], thereby obtaining a regression with one less regression parameter (c, which is fixed by [2]), thus an algorithm with only the two fit parameters C and x_0. In several cases, x_p was imposed to be the abscissa value of the raw data point closest to 15%.

In some cases there are discontinuities in the right-hand side of the raw data points, visible as jumps, which tend to alter considerably the goodness of the fit. This in fact tends to interpolate the data in such a way that results overestimate costs for low x, and underestimate them for high x.

Figure 8.4: Illustration of the fitting with some discontinuities in the data points



Next, it is possible to either:

a) Request a cut-off of the fit at the discontinuity;
b) Fit distinct curves to different segments of cost curve raw data; or
c) Fit a continuous curve from minimum to maximum CO2 reduction potential and try to minimize its divergence from data.

A key requirement for the present study was to provide cost curves that cover the whole range of CO2 reduction potential, thus option a) was clearly inappropriate. Option c) was ruled out by the necessity to have continuous cost curves in order to facilitate follow-up work on optimal distribution of CO_2 reduction efforts among segments.

Thus, a single, continuous curve was fitted over the whole raw data range. To improve the fit, the fitted curve was required to pass through a second point, usually in proximity of 2/3 of the maximum x value, imposing a condition like [2]. This simple rule proved to be quite efficient. Clearly in this case one has to compute an expression similar to [2], and another fit parameter will be fixed. In this case it was decided to find the expression of C:

[4] $$C = \frac{y_s*(x_s-x_0)-y_p*(x_p-x_0)}{x_s-x_p}$$

where (x_s, y_s) are the coordinates of the second point chosen. With this expression C can be then substituted in expression [1], obtaining a fitting expression in only one fit parameter.

xEV powertrains

In the case of xEVs powertrains, it was found that the form of a 2 degree polynomial plus a hyperbolic function gave the best fitting results:

[5] $$y = a \cdot x^2 + b \cdot x + \frac{c}{x-x_0}$$

where a, b, c, x_0 are the fitting parameters and determine the shape of the fitting curve.

One of the parameters can also be expressed as a function of the other parameters, imposing the passage of the function through a predetermined point (x_p, y_p) of the data, where one can express the passage through a point in the following way:

[6] $$y_p = a \cdot {x_p}^2 + b \cdot x_p + \frac{c}{x_p-x_0}$$

The above equation can be resolved explicitly in one of the fitting parameters, the easiest being c, obtaining:

[7] $$c = \left(y_p - a \cdot {x_p}^2 - b \cdot x_p\right) \cdot \left(x_p - x_0\right)$$

which can be substituted in [5], reducing the number of fitting parameters to 3.

In a few cases, it was also necessary to impose the passage of the curve through a second point, due to the fact that the raw data consisted of rarefied configurations in some region, causing some fluctuations. Imposing a condition similar to [6], and resolving the equation in the fit parameter b, it is possible to then obtain the desired fit. With a few mathematical passages it can be proved that:

[8] $$b = \frac{(y_s - a \cdot x_s^2)\cdot(x_s-x_0) - (y_p - a \cdot x_p^2)\cdot(x_p-x_0)}{x_s\,(x_s-x_0)-x_p(x_p-x_0)}$$

where (x_s, y_s) are the coordinates of the second point chosen, and the expression of b is substituted in equation 5, leaving a fit regression problem in 2 parameters.

For both families of fit a range of values shall be specified. This is obtained by the abscissa x of the minimum and maximum CO_2 reduction among the raw data points found by the ACO algorithm for a given problem (after the appropriate post processing transformations of steps 1 to 4 described above have been applied).

Results

All of the developed final cost-curves have been characterised in terms of Cost (in Euro) per % CO_2 saving potential (or % energy saving potential for BEVs and FCEVs) relative to the equivalent 2013 conventional powertrain vehicle. These cost curves are therefore defined versus the absolute gCO_2 per km starting point for the different powertrain and segment types. Since the cost-curves have been defined on a WLTP savings basis, it is necessary to use an equivalent WLTP-basis baseline gCO_2/km figure. As part of the calibration process of the PHEM model, the baseline vehicle types were run over NEDC and WLTP cycles, enabling an estimate of the conversion of the 2013 NEDC baseline gCO_2/km performance into a WLTP equivalent. The following Table 8.3 and Figure 8.5 summarise the results of this simple correlation analysis and the 2013 baseline WLTP-basis gCO_2 values that should be used in conjunction with the WLTP cost-curves. In a similar way the 2013 SI ICE+Hybrid baseline MJ/km to be used for BEVs and FCEVs is also presented in Table 8.4.

Table 8.3: NEDC and WLTP correlation to be used for setting the gCO_2/km baselines for the developed cost-curves

Segment	SI ICE+Hybrid			CI ICE+Hybrid		
gCO_2/km	NEDC	WLTP	*% change*	NEDC	WLTP	*% change*
Small Car	118.4	123.3	*4.1%*	104.4	109.6	*5.0%*
Lower Medium Car	136.4	141.8	*4.0%*	124.0	131.2	*5.8%*
Upper Medium Car	151.3	162.3	*7.3%*	134.1	144.0	*7.4%*
Large Car	181.7	199.5	*9.8%*	162.3	182.9	*12.7%*
Small LCV	135.5	138.3	*2.1%*	105.4	111.1	*5.4%*
Medium LCV	154.8	164.2	*6.1%*	135.4	146.2	*8.0%*
Large LCV	188.4	215.7	*14.5%*	204.7	223.9	*9.4%*

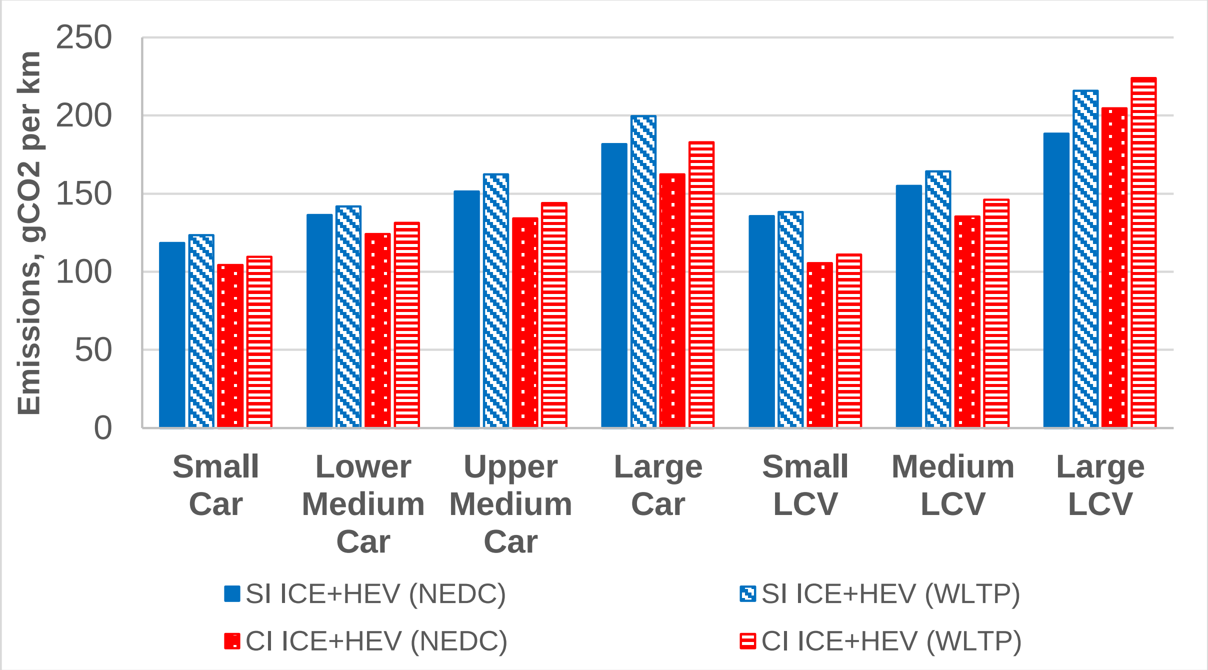
Notes: The final % energy saving cost-curves for BEVs and FCEVs are defined relative to the conventional petrol / SI ICE+Hybrid baseline. % CO_2 saving cost-curves for PHEVs and REEVs are defined relative to the relevant SI ICE+Hybrid or CI ICE+Hybrid baseline. NEDC values are the segment averages calculated from the 2013 CO_2 monitoring database (Section 2.4). WLTP values have been estimated based on PHEM modelling (Section 6.2).

Table 8.4: NEDC and WLTP correlation to be used for setting the MJ/km baselines for the developed cost-curves for BEVs and FCEVs

Segment	SI ICE+Hybrid		
MJ/km	NEDC	WLTP	*% change*
Small Car	1.637	1.704	*4.1%*
Lower Medium Car	1.886	1.961	*4.0%*
Upper Medium Car	2.092	2.244	*7.3%*
Large Car	2.512	2.759	*9.8%*
Small LCV	1.873	1.912	*2.1%*
Medium LCV	2.140	2.270	*6.1%*
Large LCV	2.605	2.983	*14.5%*

Notes: The final % energy saving cost-curves for BEVs and FCEVs are defined relative to the conventional petrol / SI ICE+Hybrid baseline. NEDC values are the segment averages calculated from the 2013 CO_2 monitoring database (Section 2.4). WLTP values have been estimated based on PHEM modelling (Section 6.2).

Figure 8.5: Graphical illustration of the comparison between calculated NEDC-basis and WLTP-basis 2013 baseline vehicle CO_2 emissions per km by conventional powertrain type



In order to estimate the additional costs of natural gas fuelled vehicles it is necessary to use the estimated additional total manufacturing cost (versus petrol equivalents) in conjunction with the developed conventional spark-ignition powertrain (i.e. SI ICE+Hybrid) cost-curves. The following Table 8.5 provides a summary of the developed estimates for CO_2 savings potential (on WLTP-basis) and costs for different periods and LDV segments. Some variation in % CO_2 savings is evident between different segments, mainly due to mass adaptation according to the natural gas system and the associated engine power correction of each segment as simulated by the PHEM modelling.

Table 8.5: Calculated direct CO_2 savings potential and additional manufacturing cost for natural gas vehicles, relative to conventional petrol spark-ignition (SI) equivalents, typical cost scenario

	% CO_2 reduction (WLTP-basis)	Total additional manufacturing cost, €			
		2015	2020	2025	2030
Small Car	23.6%	€ 2,006	€ 1,695	€ 1,388	€ 1,314
Lower Medium Car	23.2%	€ 2,111	€ 1,784	€ 1,462	€ 1,383
Upper Medium Car	23.3%	€ 2,111	€ 1,784	€ 1,462	€ 1,383
Large Car	23.5%	€ 3,272	€ 2,765	€ 2,265	€ 2,144
Small LCV	23.6%	€ 2,111	€ 1,784	€ 1,462	€ 1,383
Medium LCV	24.0%	€ 2,111	€ 1,784	€ 1,462	€ 1,383
Large LCV	24.2%	€ 3,274	€ 2,766	€ 2,266	€ 2,145

Finally, three technologies that were identified as off-cycle on NEDC, were deemed to be applicable as on-cycle under WLTP conditions due to differences in the basis of the different testing protocols. These included:

i. ENG-ENCAP: Engine compartment encapsulation;
ii. ACT-WARMUP: Active engine and transmission warm-up;
iii. ACT-AERO-1/2: Active aerodynamics.

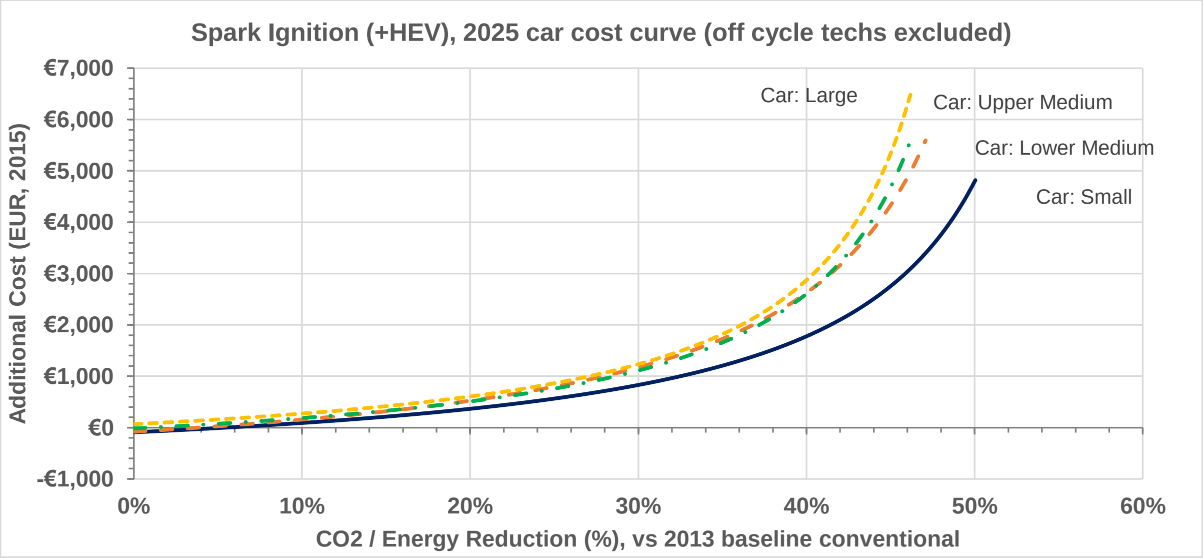
8.1.4 General cost-curve results

The following subsections provide a summary of the results for a selection of the final developed cost curves (i.e. factoring the four post-processing steps outlined in the previous section) in order to compare/illustrate the differences between segments, powertrain types, periods and the potential impact of including off-cycle technologies. Clearly it is not possible to present and compare the full range of around 250 cost-curves developed here; the equations and start/end points for all curves are presented in Appendix 6 and in the accompanying MS Excel summary file.

8.1.4.1 Comparisons of WLTP cost-curves by LDV segment

Figure 8.6 and Table 8.6 show the curves and end points (i.e. the maximum levels of potential CO_2 reduction and corresponding additional costs) respectively for the varying car SI (+Hybrid) segments in 2025 under the WLTP test cycle (off-cycle technologies excluded).

Figure 8.6: Spark Ignition (+hybrid), 2025 car cost curve (off cycle techs excluded)



Notes: The SI+Hybrid powertrain category includes technologies compatible with spark ignition engines, including HEVs and other hybrid technologies, but excluding plug-in hybrid/range-extended electric vehicle technologies, and natural gas engines, which are treated as separate powertrain types.

Table 8.6: Spark Ignition (+Hybrid), 2025 car cost curve (off cycle techs excluded)

Segment	Max CO_2 reduction potential (%)	Max additional cost (EUR, 2015)
Small car	50.0%	4,819
Lower medium car	47.1%	5,593
Upper medium car	46.2%	5,632
Large car	46.18%	6,481

The slightly counter-intuitive trend (i.e. in terms of inconsistent variation in available CO_2 reduction potential and corresponding cost) between the different passenger car segments is primarily driven by the post-processing step adjusting to the 2013 baseline, as different degrees of technology-related CO_2 reduction have been taken up in different segments. (See Appendix 6 for the specific assumptions).

The lowest reduction potential actually comes from the large car segment. Conversely the highest reduction potential is from the small car segment which is estimated to be able to achieve roughly 3% to 4% more CO_2 reduction than any other segment.

As indicated, this is driven by the baseline adjustment step. For small cars (where lower levels of CO_2 reducing technology have been deployed to date) the CO_2 reduction percentage already accounted for is significantly less than that of medium and large cars and so the small car cost curve is ‘scaled back’ much less severely.

In Figure 8.7 and Table 8.7 the curves for the varying car SI (+Hybrid) segments in 2025 are presented in absolute gCO_2/km terms.

Figure 8.7: Spark Ignition (+Hybrid), 2025 car cost curve (off cycle techs excluded) – Absolute emissions

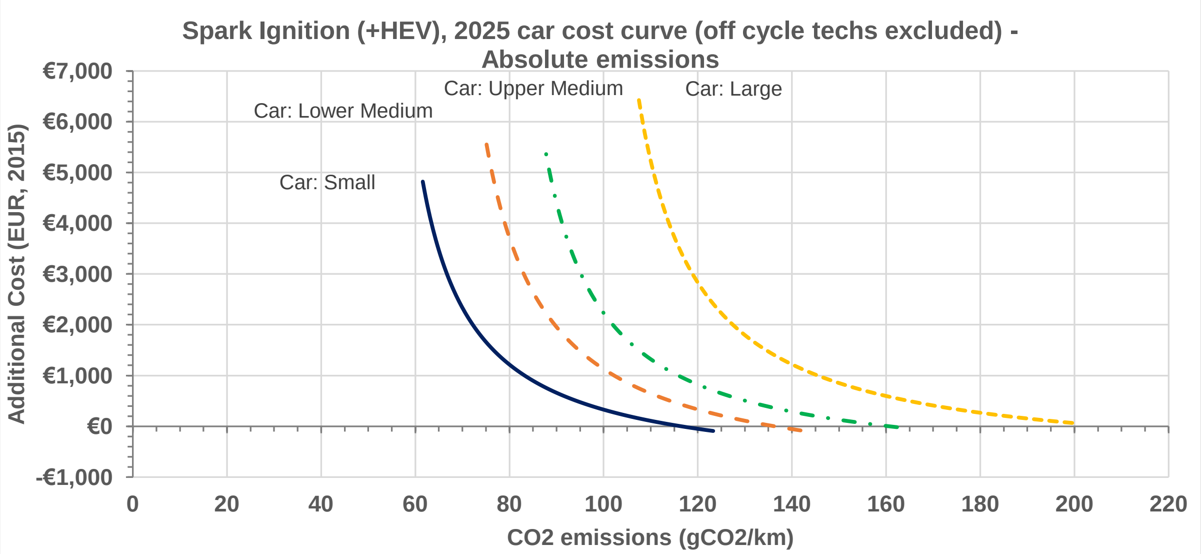
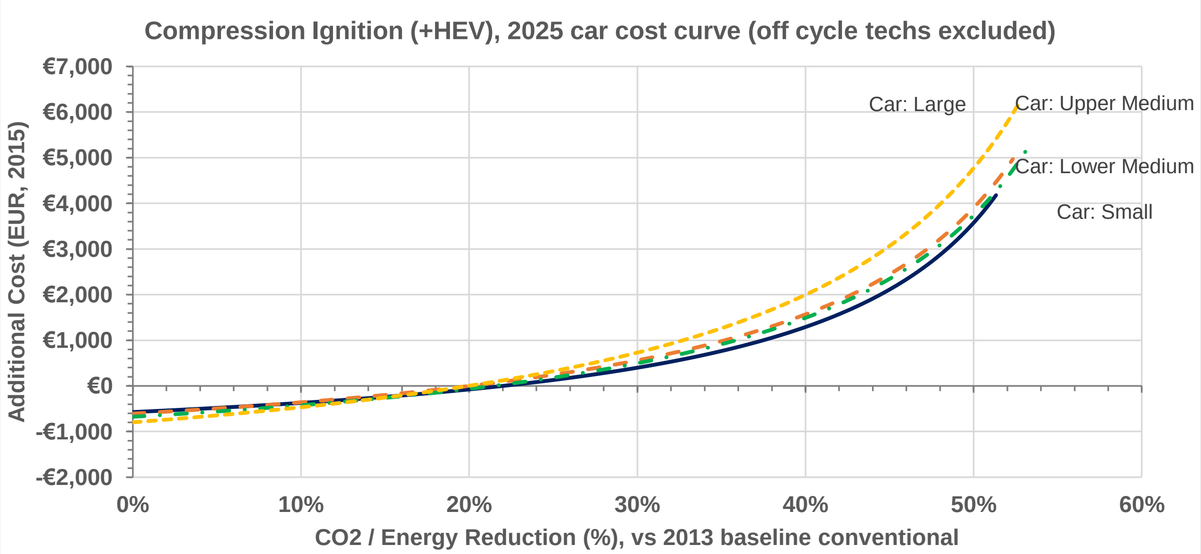


Table 8.7: Spark Ignition (+Hybrid), 2025 car cost curve (off cycle techs excluded) – Absolute emissions

Segment	Min CO_2 potential (gCO_2/km)	Max additional cost (EUR, 2015)
Small car	61.6	4,819
Lower medium car	75.0	5,593
Upper medium car	87.3	5,632
Large car	107.4	6,481

Similarly, Figure 8.8 and Table 8.8 show the curves and end points (i.e. cost at maximum CO_2 saving) respectively for the varying car CI (+hybrid) segments in 2025 under the WLTP test cycle (off-cycle technologies excluded).

Figure 8.8: Compression Ignition (+Hybrid), 2025 car cost curve (off cycle techs excluded)



Notes: The CI+Hybrid powertrain category includes technologies compatible with compression ignition engines, including HEVs and other hybrid technologies, but excluding plug-in hybrid/range-extended electric vehicle technologies, which are treated as separate powertrain types.

Table 8.8: Compression Ignition (+Hybrid), 2025 car cost curve (off cycle techs excluded)

Segment	Max CO_2 reduction potential (%)	Max additional cost (EUR, 2015)
Small car	51.3%	4,178
Lower medium car	52.3%	4,968
Upper medium car	53.5%	5,399
Large car	52.68%	6,185

The first thing to observe/note in the CI (diesel) cost curves is the relatively flat nature of the curves in the first section, and a starting point at negative costs. This is driven primarily by the inclusion of the medium diesel engine downsizing technology option which includes the removal of a cylinder, and has a negative net cost impact (i.e. as calculated by FEV tear-down analysis for ICCT, (FEV, 2012)). The implementation of this technology was close to zero in most segments (except large cars) in 2013, compared to other higher-cost options that were implemented more widely. Combination with a range of other CO_2 reducing technological options for low or zero net cost is therefore possible in the cost curve.

In terms of comparisons between different vehicle segments, here the lowest reduction potential and additional cost comes from the small car segment. Conversely the highest reduction potential is from the upper medium car segment, and the highest additional cost is from the large car segment. There is little more than 2% difference in CO_2 reduction between all four segments (and a difference of ~€2,000). The difference in CO_2 reduction between the largest and smallest car segments is therefore much more pronounced for petrol cars.

Again some counter intuitive results can be observed. The CI small car segment achieves a very similar reduction potential with a **lower** additional cost when compared to the larger segments. In the case of CI engine cars, the CO_2 savings potential already accounted for varies to a smaller degree among the segments, hence the maximum CO_2 saving end points of the curves are closer together in Figure 8.8 compared to Figure 8.6 for SI engined vehicles.

Interestingly there is little difference between a lower medium and large car in this case in relation to the CO_2 reduction potential, but the costs differ. Again this can be traced to large cars being ‘scaled back’ the most during the 2013 re-baselining step, due to greater levels of average CO_2 savings from already deployed technology.

Also presented in Figure 8.9 and Table 8.9 are the curves in absolute gCO_2/km terms.

Figure 8.9: Compression Ignition (+Hybrid), 2025 car cost curve (off cycle techs excluded) – Absolute emissions

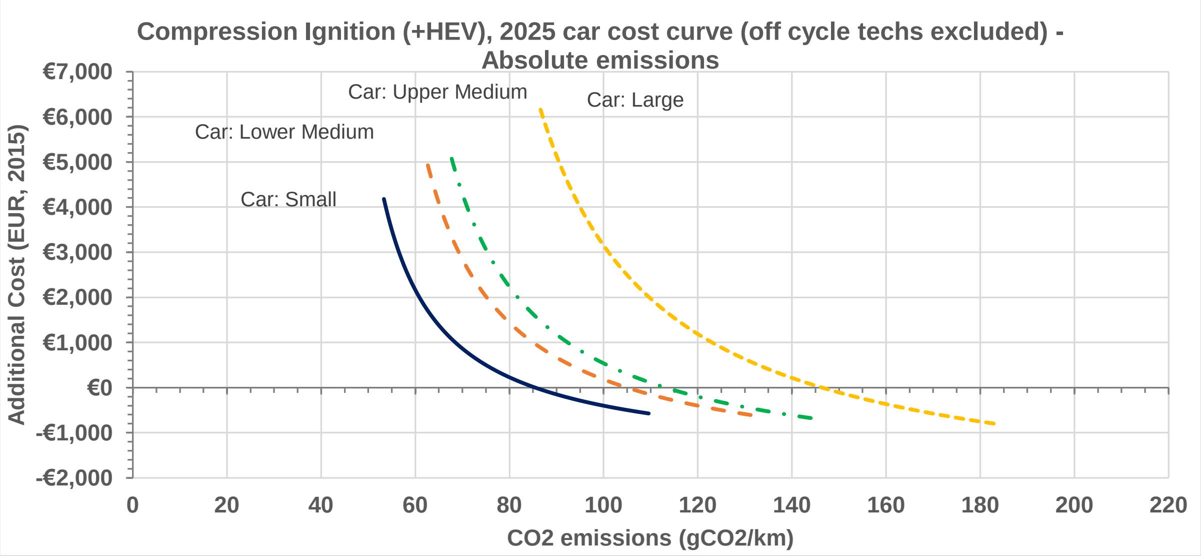


Table 8.9: Compression Ignition (+Hybrid), 2025 car cost curve (off cycle techs excluded) – Absolute emissions

Segment	Min CO_2 potential (gCO_2/km)	Max additional cost (EUR, 2015)
Small car	53.3	4,178
Lower medium car	62.6	4,968
Upper medium car	66.9	5,399
Large car	86.5	6,185

Figure 8.10 and Table 8.10 show the final cost curves and end points (i.e. cost at maximum CO_2 reduction) respectively for the varying LCV CI (+hybrid) segments in 2025 under the WLTP test cycle (off-cycle technologies excluded).

Figure 8.10: Compression Ignition (+Hybrid), 2025 LCV cost curve (off cycle techs excluded)

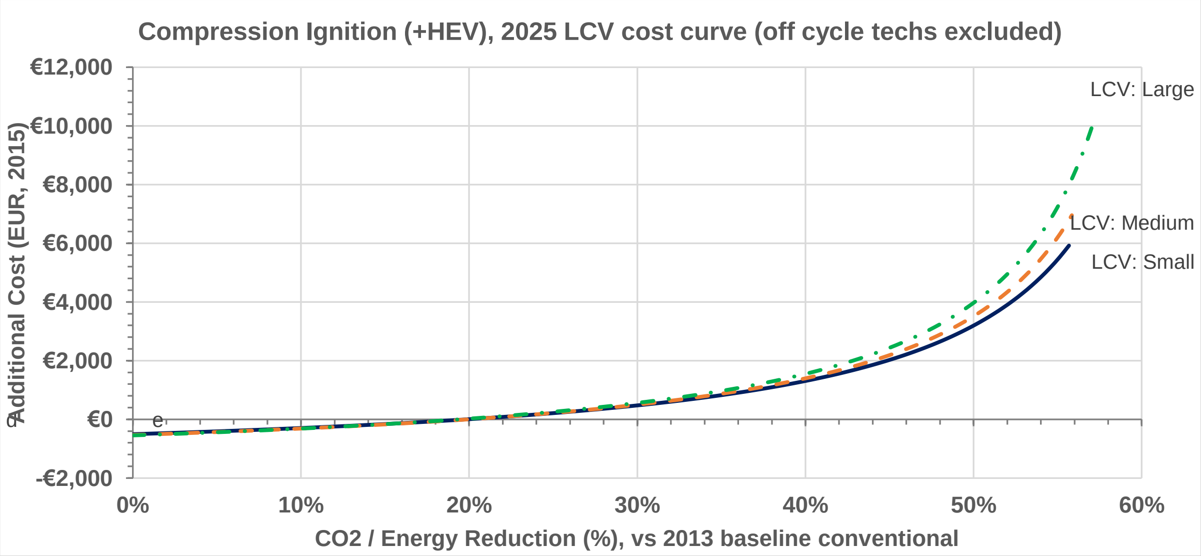


Table 8.10: Compression Ignition (+Hybrid), 2025 LCV cost curve (off cycle techs excluded)

Segment	Max CO_2 reduction potential (%)	Max additional cost (EUR, 2015)
Small LCV	55.7%	5,922
Medium LCV	55.8%	6,956
Large LCV	57.1%	10,026

The first thing that stands out from Table 8.10 is how the CO_2 reduction potential across all LCV segments is closer. Just 1.4% separates the three segments.

The lowest additional cost comes from the small LCV segment, while the highest additional cost is from the large LCV segment which can achieve a similar level of CO_2 reduction at an increased cost of around €4,100 compared to small LCV. The overall CO_2 reduction potential for the end points of the LCV cost-curves is generally slightly higher than for cars primarily because the 2013 penetration of CO_2 reducing technologies is somewhat less in LCVs compared to cars.

Also presented in Figure 8.11 and Table 8.11 are the curves in absolute gCO_2/km terms.

Figure 8.11: Compression Ignition (+hybrid), 2025 LCV cost curve (off cycle techs excluded) – Absolute emissions

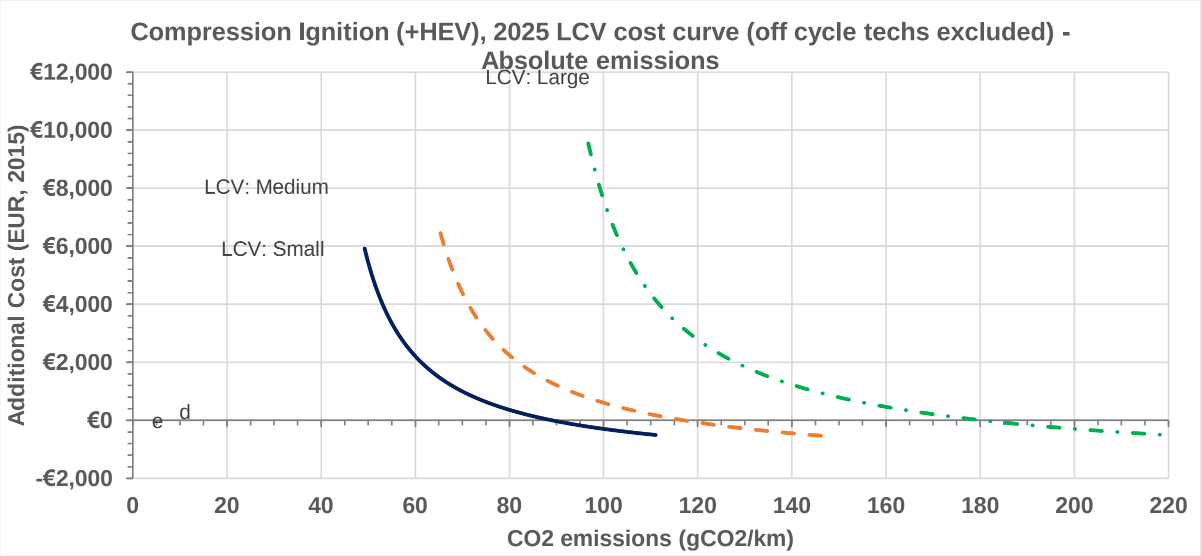


Table 8.11: Compression Ignition (+hybrid), 2025 LCV cost curve (off cycle techs excluded) – Absolute emissions

Segment	Min CO_2 potential (gCO_2/km)	Max additional cost (EUR, 2015)
Small LCV	49.2	5,922
Medium LCV	64.5	6,956
Large LCV	96.1	10,026

8.1.4.2 Comparisons of WLTP cost-curves by powertrain type

Figure 8.12 and Table 8.12 show the curves and end points (i.e. cost at maximum CO_2 reduction) respectively for the various spark-ignition powertrains in 2025 under the WLTP test cycle (off-cycle technologies excluded). All curves are presented relative to the conventional 2013 SI petrol baseline.

Figure 8.12: SI variants, 2025 lower medium car cost curves (off cycle techs excluded)

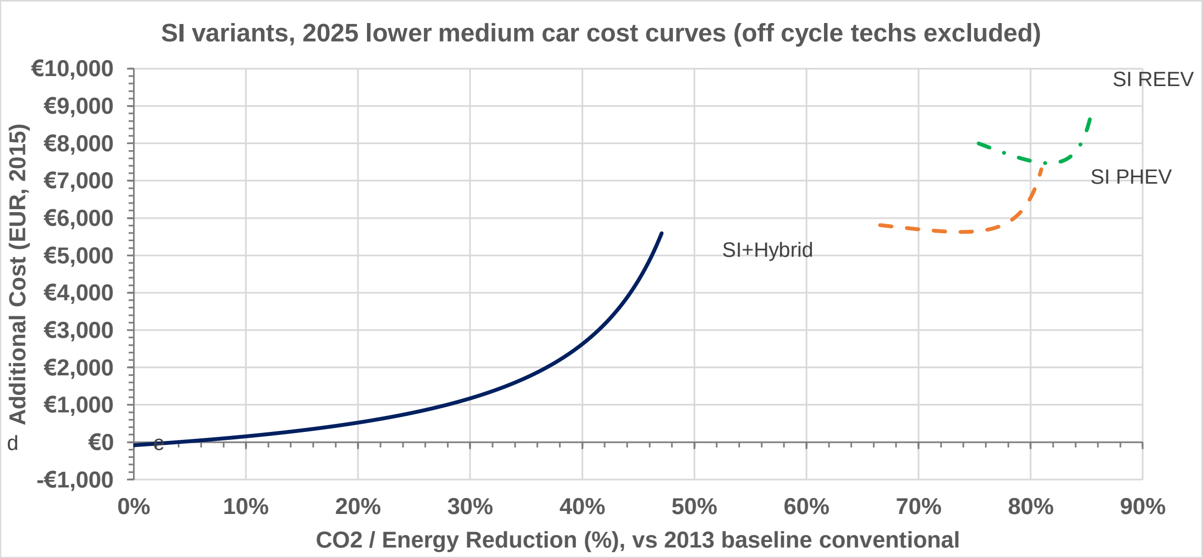


Table 8.12: SI variants, 2025 lower medium car cost curves (off cycle techs excluded)

Powertrain	Max CO_2 reduction potential (%)	Max additional cost (EUR, 2015)
SI ICE+Hybrid	47.1%	5,593
SI PHEV	81.0%	7,305
SI REEV	85.4%	8,749

For spark-ignition (SI) powertrains, it is clear from Figure 8.12 that beyond a certain point in the conventional SI+Hybrid powertrain cost-curve (somewhat above 40%% CO2 reduction), PHEVs (and, to a lesser extent, REEVs) appear to offer a more cost-effective option (in terms of CO_2 reductions per Euro cost). Whereas the maximum CO2 reduction that can be reached with SI+Hybrid powertrain technologies is around 47%, SI PHEV minimum reduction is a slightly below 70% and SI REEV reduction begins from more than 75%, with maximum reductions at 81 and roughly 85%, respectively. Thus, each of the three powertrains is the most cost-efficient one for different levels of emission reduction.

Due to the cost corrections for reducing battery size for equivalent range, the PHEV and REEV cost-curves show minima in costs somewhat beyond the baseline vehicle configuration. This shows it is more cost-effective to apply certain efficiency-improving technologies to allow for a reduction in battery size.

Figure 8.13 and Table 8.13 show the curves and end points (i.e. cost at maximum CO_2 reduction) respectively for the various compression-ignition powertrains in 2025 under the WLTP test cycle (off-cycle technologies excluded). All curves are presented relative to the conventional 2013 CI diesel baseline (i.e. if the CI PHEV and CI REEV powertrains were presented instead against the 2013 SI powertrain, the CO_2 savings and costs would both be higher).

The curves for CI-based powertrains give qualitatively similar results to the various SI powertrain curves in Figure 8.12. There are a few subtle differences to the SI variant curves, however. The main difference is that for CI powertrain there is a greater available reduction potential at equivalent cost as compared to the SI + Hybrid powertrain (since estimated CO_2 savings due to applied technologies for SI in the 2013 baseline are greater).

As indicated earlier in section 8.1.4.1, the negative costs in the first part of the CI+Hybrid cost curve are driven mainly by the negative cost medium diesel engine downsizing technology option.

Figure 8.14 and Table 8.14 below show 2025 energy-based curves and end points (i.e. cost at maximum energy consumption reduction) for BEVs and FCEVs on a WLTP basis (excluding off-cycle technologies). The costs/energy savings are presented relative to a 2013 conventional SI powertrain.

Figure 8.13: CI variants, 2025 lower medium car cost curves (off cycle techs excluded)

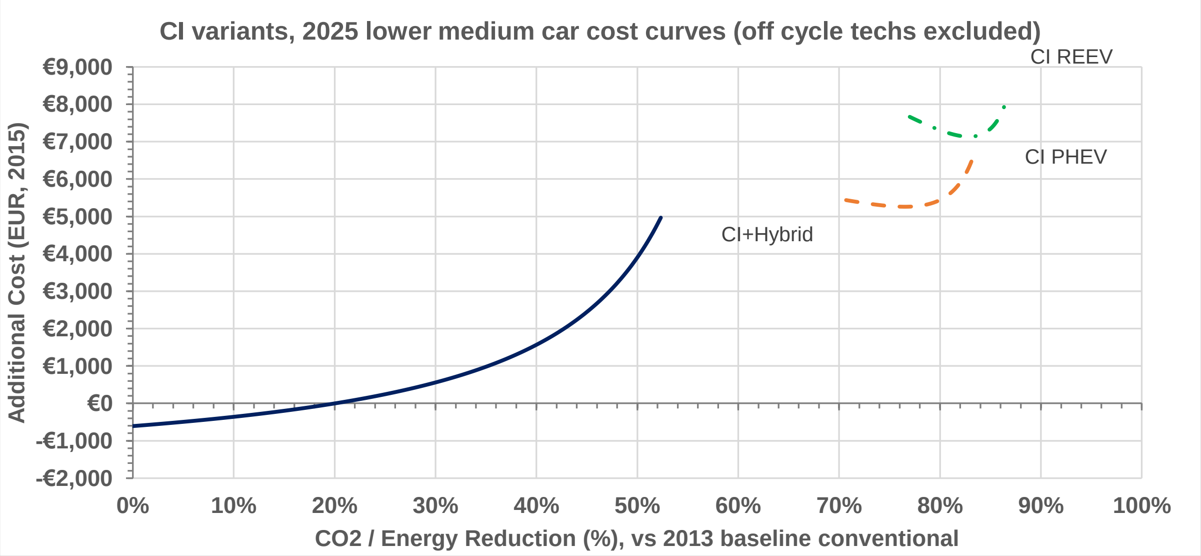


Table 8.13: CI variants, 2025 lower medium car cost curves (off cycle techs excluded)

Powertrain	Max CO_2 reduction potential (%)	Max additional cost (EUR, 2015)
CI ICE+Hybrid	52.3%	4,968
CI PHEV	83.5%	6,791
CI REEV	86.8%	8,307

Figure 8.14: EV variants, 2025 lower medium car cost curves (off cycle techs excluded)

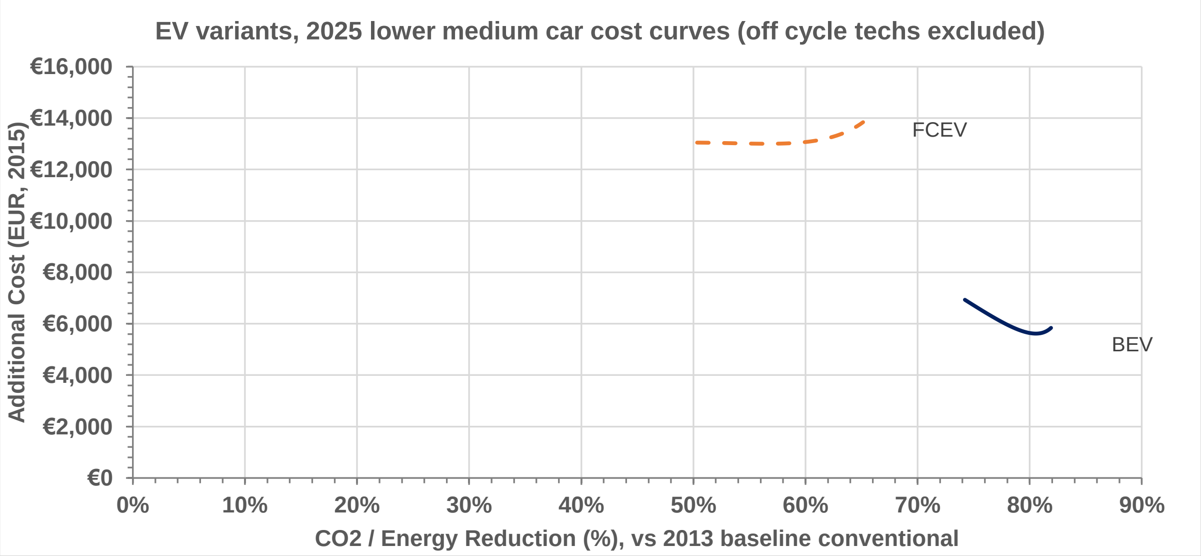


Table 8.14: EV variants, 2025 lower medium car cost curves (off cycle techs excluded)

Powertrain	Max Energy reduction potential (%)	Max additional cost (EUR, 2015)

BEV	81.9%	5,839
FCEV	65.1%	13,840

Figure 8.14 and Table 8.14 show that, largely due to the battery scaling post-processing in step 2, FCEV and BEV powertrains achieve energy consumption reductions at low or negative cost relative to their baseline powertrain cost. Improvements of 14.8% and 7.7% (vs the baseline BEV, FCEV) were considered possible for the powertrains, yielding a cost *saving* of nearly €1100 for BEVs and additional costs of just under €800 for FCEVs. The data reveals that the latter could achieve a zero-additional-cost CO_2 reduction of around 10% (vs the baseline FCEV) in 2025. Note that for PHEVs and REEVs, which use considerably smaller batteries, the data logically points to a lower cost-neutral percentage CO_2 saving potential due to the greater battery cost savings enjoyed by BEVs.

Figure 8.15 and Table 8.15 show the curves and end points respectively for the various spark-ignition powertrains in 2030 under the WLTP test cycle (off-cycle technologies excluded).

The 2030 SI curves are qualitatively similar to the 2025 curves. Reduction potentials are marginally improved in the 2030 SI powertrains, however costs to achieve the reductions are considerably reduced. The maximum reduction potentials for the SI variants in 2025 (Table 8.12) are expected to be 20%, 14% and 14% cheaper in 2030 for the SI ICE + Hybrid, SI PHEV and SI REEV powertrains respectively.

Figure 8.15: SI variants, 2030 lower medium car cost curves (off cycle techs excluded)

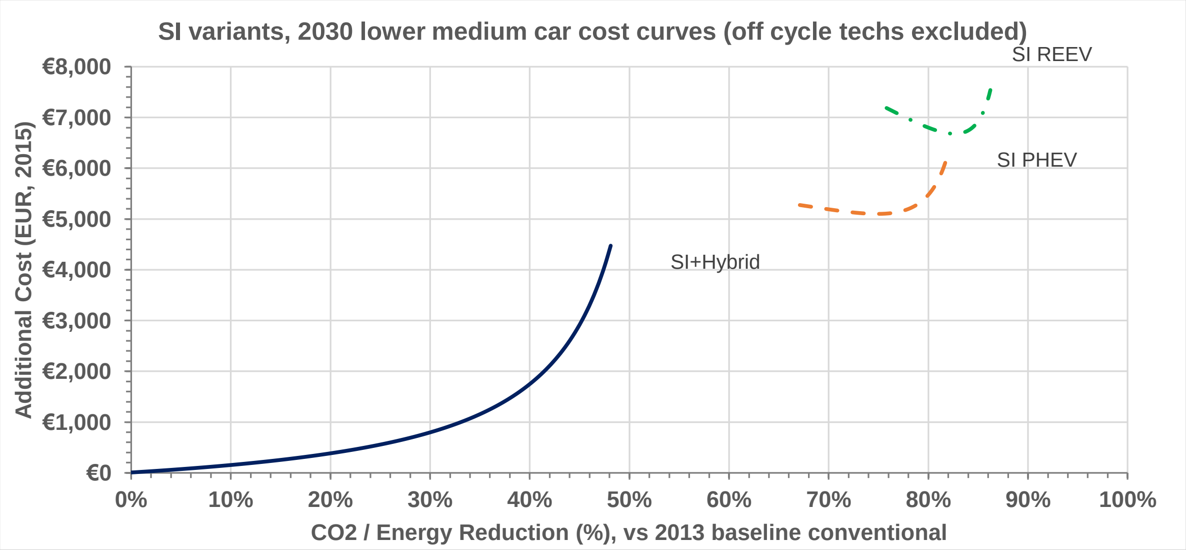


Table 8.15: SI variants, 2030 lower medium car cost curves (off cycle techs excluded)

Powertrain	Max CO_2 reduction potential (%)	Max additional cost (EUR, 2015)
SI ICE+Hybrid	48.1%	4,474
SI PHEV	82.0%	6,305
SI REEV	86.2%	7,540

Figure 8.16 and Table 8.16 below show equivalent 2030 energy-based curves and end points (i.e. cost at maximum energy consumption reduction) for BEV and FCEV lower medium cars on a WLTP basis (excluding off-cycle technologies). The costs and energy savings are again presented relative to a 2013 conventional SI powertrain.

Figure 8.16: EV variants, 2030 lower medium car cost curves (off cycle techs excluded)

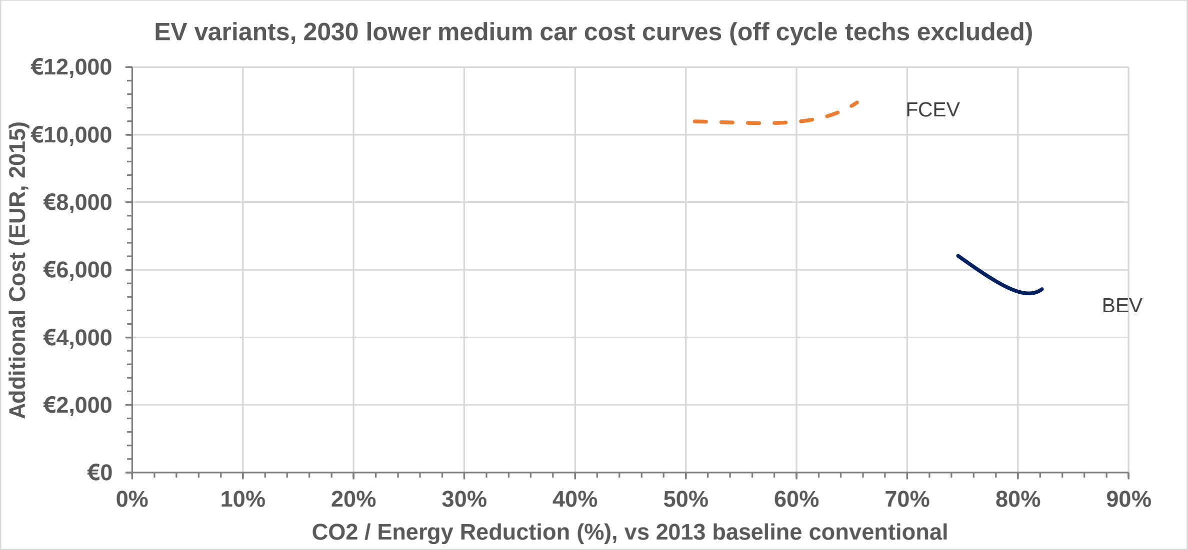


Table 8.16: EV variants, 2030 lower medium car cost curves (off cycle techs excluded)

Powertrain	Max Energy reduction potential (%)	Max additional cost (EUR, 2015)
BEV	82.2%	5,427
FCEV	65.5%	10,952

Figure 8.16 and Table 8.16 show that whilst the additional costs (relative to the 2013 SI powertrain) of BEVs and FCEVs have converged somewhat, BEVs may still be significantly lower cost (and achieve greater energy consumption reductions) versus FCEVs under the study assumptions. It is also worth noting that the battery cost scaling operation, places a slightly greater cost saving per unit energy reduction in 2025 than in 2030 due to higher battery costs.

Figure 8.17 and Table 8.17 show the curves and end points respectively for the various compression-ignition LDV powertrains in 2030 under the WLTP test cycle (off-cycle technologies excluded). Reduction potentials are similar to the 2025 case for lower medium cars for CI PHEV and REEV, while SI ICE + HEV 2030 large vans yield a greater CO2 reduction potential than 2025 lower medium cars with the same powertrain. The greatest difference to the lower medium car curves are the costs to achieve similar CO_2 reductions, which are substantially higher for 2030 large vans.

Considering near-maximum reductions, the large CI vans are comparatively very expensive: CI ICE + Hybrid LDVs require up to 65% higher expenditure to achieve the same relative (%) reduction as for the lower medium cars. Electrified large vans are less costly relative to electrified lower medium cars to reduce CO_2, in relative terms, at roughly 50% of excess expenditure.

CI REEV and CI PHEV LDVs have a larger potential for CO_2 reduction than CI+HEV large vans.

As indicated earlier in subsection 8.1.4.1, the negative costs/flat nature in the first part of the CI+Hybrid technology cost curve are driven primarily by the inclusion of the negative cost medium diesel engine downsizing technology option.

Figure 8.17: CI variants, 2030 large LCV cost curves (off cycle techs excluded)

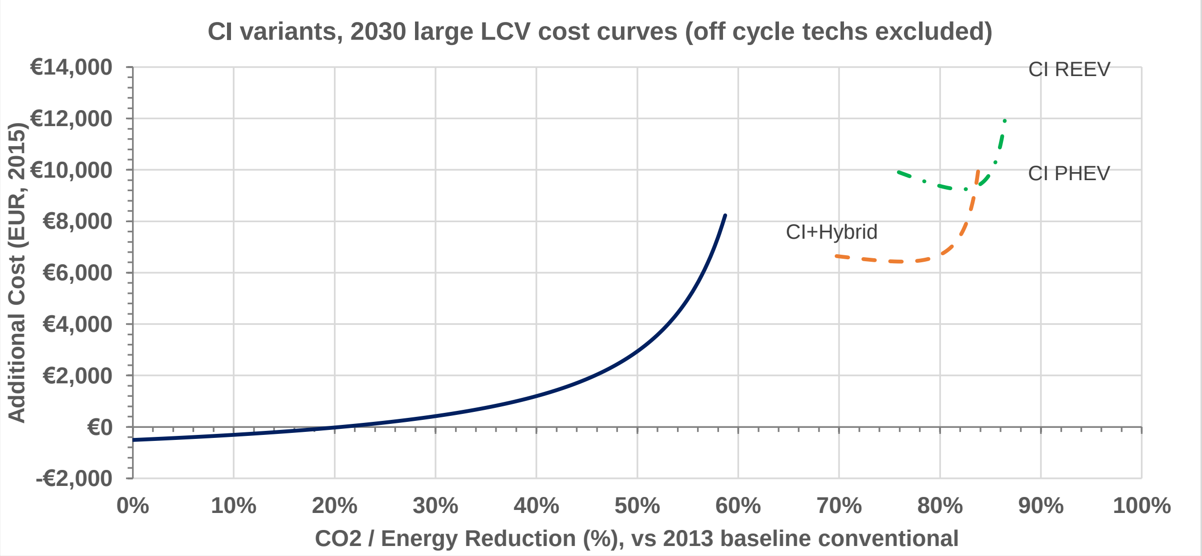


Table 8.17: CI variants, 2030 large LCV cost curves (off cycle techs excluded)

Powertrain	Max CO_2 reduction potential (%)	Max additional cost (EUR, 2015)
CI ICE+Hybrid	58.7%	8,231
CI PHEV	83.8%	10,156
CI REEV	86.6%	12,501

Figure 8.18 and Table 8.18 below show equivalent 2030 energy-based curves and end points (i.e. cost at maximum energy reduction) for BEV and FCEV large LCVs on a WLTP basis (excluding off-cycle technologies). The costs and energy savings are again presented relative to a 2013 conventional SI powertrain.

The figure and table shows that the costs of BEV and FCEV large LCVs are predicted to be much closer together than for cars, although BEVs still appear to be have lower costs and significantly higher energy savings potential under the study assumptions in the typical cost scenario.

Figure 8.18: EV variants, 20230 large LCV cost curves (off cycle techs excluded)

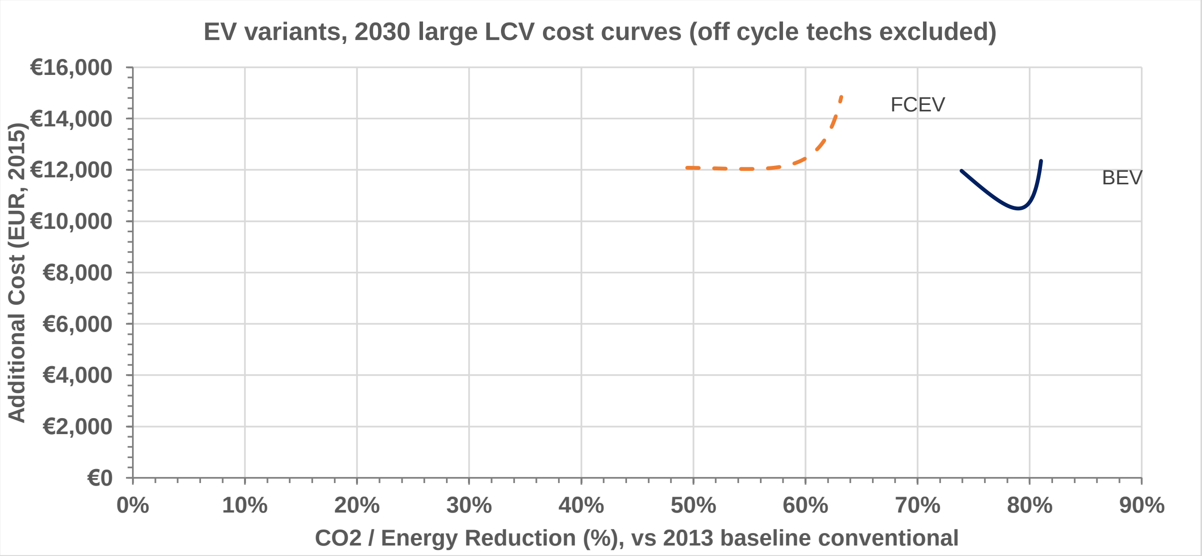


Table 8.18: EV variants, 2025 large LCV cost curves (off cycle techs excluded)

Powertrain	Max Energy reduction potential (%)	Max additional cost (EUR, 2015)
BEV	81.0%	12,351
FCEV	63.2%	14,844

8.1.4.3 Comparisons of WLTP cost-curves for different periods

Figure 8.19 and Table 8.19 show the curves and end points (cost for maximum CO_2 reduction) respectively for SI + Hybrid cars, lower medium segment from 2015 to 2030 under the WLTP test cycle (off-cycle technologies excluded). These cost-curves are all defined in relation to the 2013 baseline vehicle.

Figure 8.19: Spark Ignition (+Hybrid), lower medium car cost curve (off cycle techs excluded)

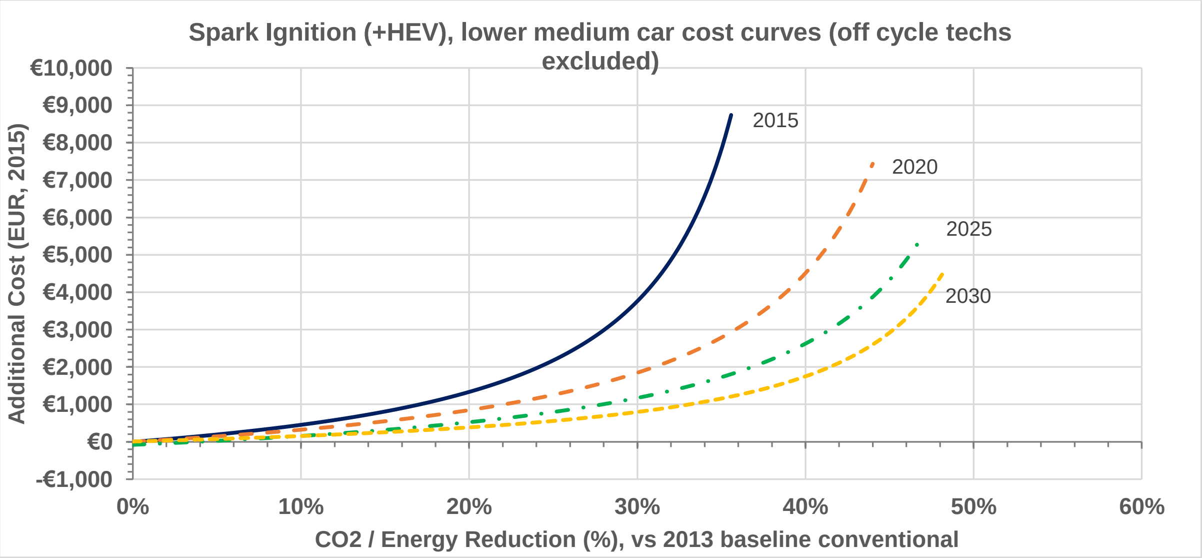


Table 8.19: Spark Ignition (+Hybrid), lower medium car cost curve (off cycle techs excluded)

Year	Max CO_2 reduction potential (%)	Max additional cost (EUR, 2015)
2015	35.6%	8,741
2020	44.0%	7,435
2025	47.1%	5,593
2030	48.12%	4,474

As expected, we see a large increase in CO_2 reduction potential from 2015 to 2020. This is due to the large amount of new technologies available post 2015. Looking past 2020, we continue to see a trend of increasing reduction potential through time (due to both improvements to deployed technologies as well as new technologies added in later periods) and with reductions in cost as a result of assumptions with respect to learning rates[41].

The effect of this is that by 2030 an additional 4.1% reduction is estimated to be achievable (versus 2020) at a cost of around €3,000 less than in 2020 with the same selection of available technologies (but potentially a different package/combination). The final cost curves for other LDV segments show similar trends over time.

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[41] These results are based on the market penetration of technologies assumed under the typical cost scenario.

Figure 8.20 and Table 8.20 show the curves and end points (cost for maximum CO_2 reduction) respectively for CI (+Hybrid) cars, lower medium segment from 2015 to 2030 under the WLTP test cycle (off-cycle technologies excluded).

Figure 8.20: Compression Ignition (+Hybrid), lower medium car cost curve (off cycle techs excluded)

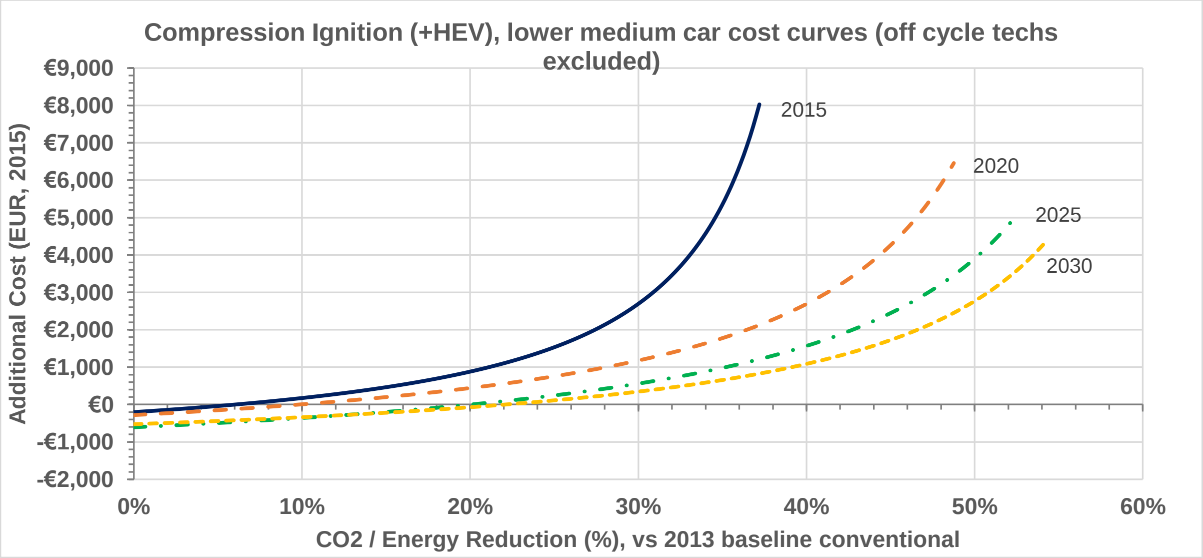


Table 8.20: Compression Ignition (+Hybrid), lower medium car cost curve (off cycle techs excluded)

Year	Max CO_2 reduction potential (%)	Max additional cost (EUR, 2015)
37.2%	8,029	6,994
48.8%	6,458	6,245
52.3%	4,968	4,926
54.07%	4,273	4,155

The pattern with respect to cars with CI engines is the same as that for cars with SI engines. As expected, there is a large increase in CO_2 reduction potential between 2015 and 2020, as a result of the large amount of new technologies available post 2015. Looking past 2020, there is still a trend of increasing CO_2 reduction potential through time and a reducing cost as due to the impact of learning rates.

The effect of this learning rate is that by 2030 an additional 5.3% reduction (versus 2020) is estimated to be achievable at a cost around €2,200 less than in 2020 the same selection of available technologies (but potentially a different package/combination). This is a greater progression through time than observed in SI (petrol) cars, at a lower price increment.

Figure 8.21 and Table 8.21 show the curves and end points (cost for maximum CO_2 reduction) respectively for CI (+Hybrid), large LCV segment from 2015 to 2030 under the WLTP test cycle (off-cycle technologies excluded).

As indicated earlier in subsection 8.1.4.1, this flat nature of the first part of the CI+Hybrid technology cost curve is driven primarily by the inclusion of the negative cost medium diesel engine downsizing technology option.

Figure 8.21: Compression Ignition (+Hybrid), large LCV cost curve (off cycle techs excluded)

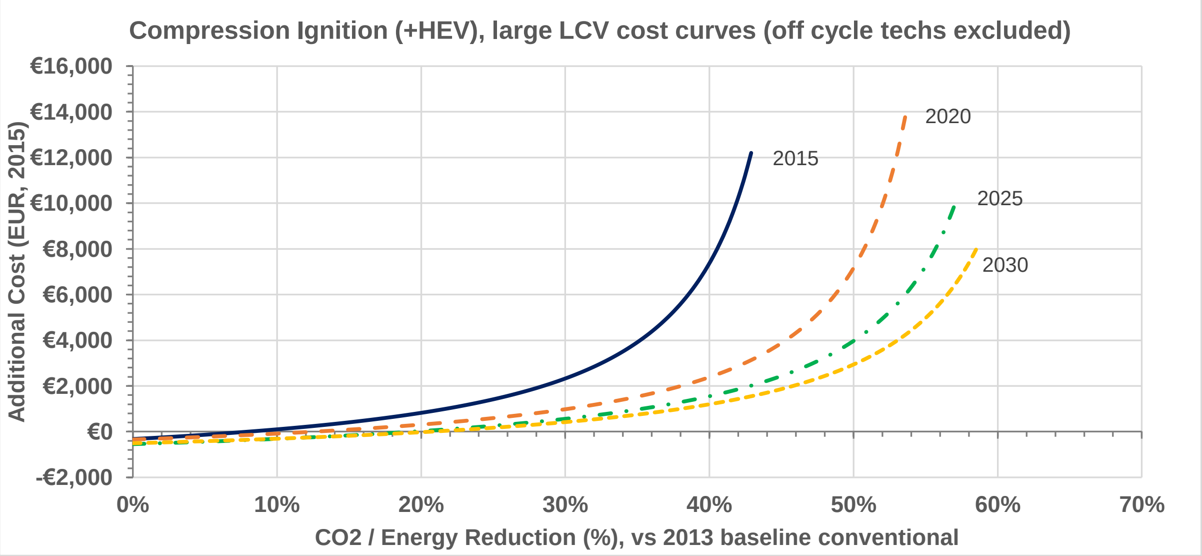


Table 8.21: Compression Ignition (+Hybrid), large LCV cost curve (off cycle techs excluded)

Year	Max CO_2 reduction potential (%)	Max additional cost (EUR, 2015)
2015	42.9%	12,200
2020	53.6%	13,926
2025	57.1%	10,026
2030	58.71%	8,231

The trends are similar to those that were seen for cars, for the same reasons, with the exception of an increase in maximum cost between 2015 and 2020 as a significant number of new technologies with higher costs becomes available.

The effect of the assumptions about learnings rate is that by 2030 an additional 5.1% reduction (versus 2020) is estimated to be achievable at a cost of €5,700 less than in 2020 the same selection of available technologies (but potentially a different package/combination).

8.1.4.4 Comparisons of WLTP cost-curves with/without off-cycle technologies

Figure 8.22 to Figure 8.25 show the 2025 cost curves for lower medium petrol, diesel and BEV cars as well as the equivalent diesel large LCV curve both with and without off-cycle technologies considered. These charts show that including off cycle technologies in the technology packages allows equivalent savings at reduced costs for conventionally fuelled vehicles. Maximum savings potentials for conventionally fuelled vehicles are roughly 8 to 12 percentage points greater when off cycle technologies are included and a bit less than 4% greater for BEV for the examples shown.

Figure 8.25 also shows that when considering both on-cycle and off-cycle technologies for lower medium BEV cars, an about 10% energy consumption improvement relative to the baseline vehicle can be achieved at negative incremental costs. This may also help explain the apparent optimism in recent announcements by vehicle manufacturers on improvements to future BEV model range and/or vehicle costs (e.g. as discussed earlier in Section 4).

As indicated earlier in subsection 8.1.4.1, the negative cost/flat nature of the first part of the CI+Hybrid technology cost curve is driven primarily by the inclusion of the negative cost medium diesel engine downsizing technology option.

Figure 8.22: Spark-ignition, 2025 lower medium car cost curves, including and excluding off cycle techs

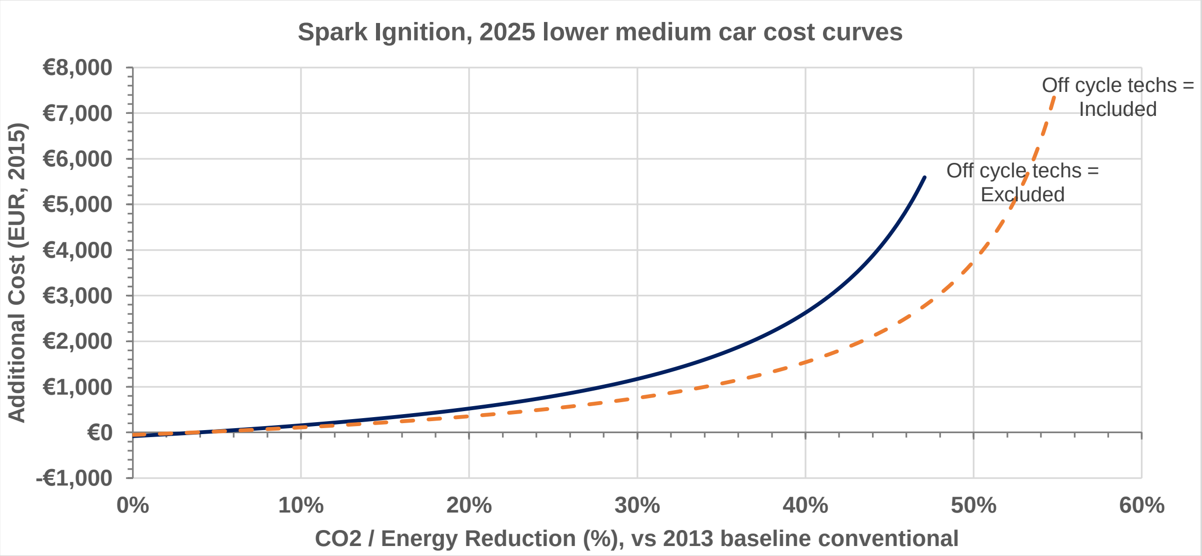


Table 8.22: Spark-ignition, 2025 lower medium car cost curves, including and excluding off cycle techs

Off Cycle Techs	Max CO_2 reduction potential (%)	Max additional cost (EUR, 2015)
Excluded	47.1%	5,593
Included	54.8%	7,420

Figure 8.23: Compression-ignition, 2025 lower medium car cost curves, including and excluding off cycle techs

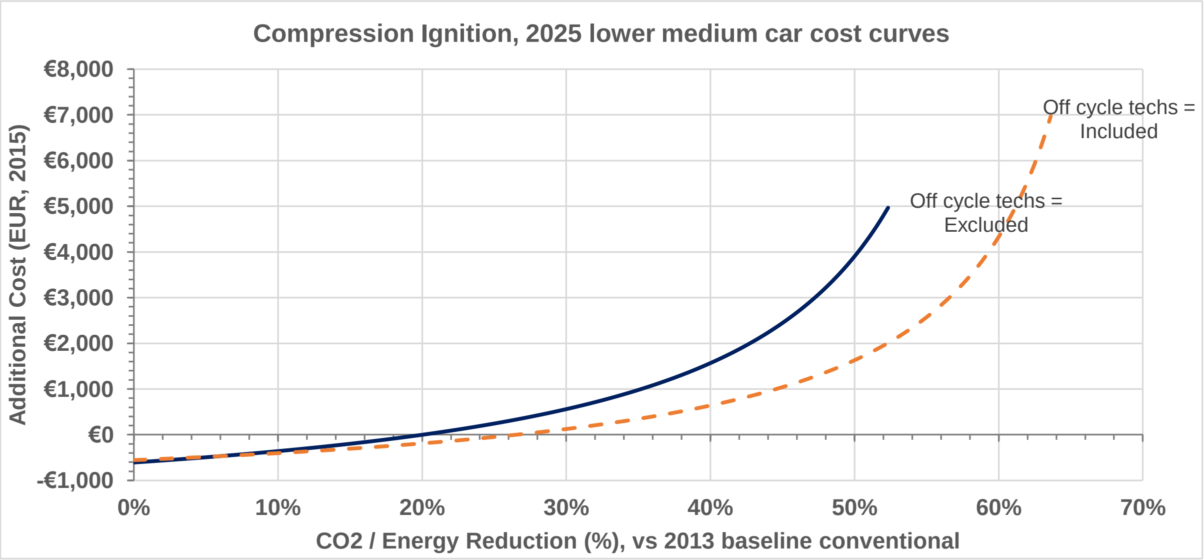


Table 8.23: Compression-ignition, 2025 lower medium car cost curves, including and excluding off cycle

Off Cycle Techs	Max CO_2 reduction potential (%)	Max additional cost (EUR, 2015)
Excluded	52.3%	4,968
Included	63.6%	6,969

Figure 8.24: Compression-ignition, 2025 large LCV cost curves, including and excluding off cycle techs

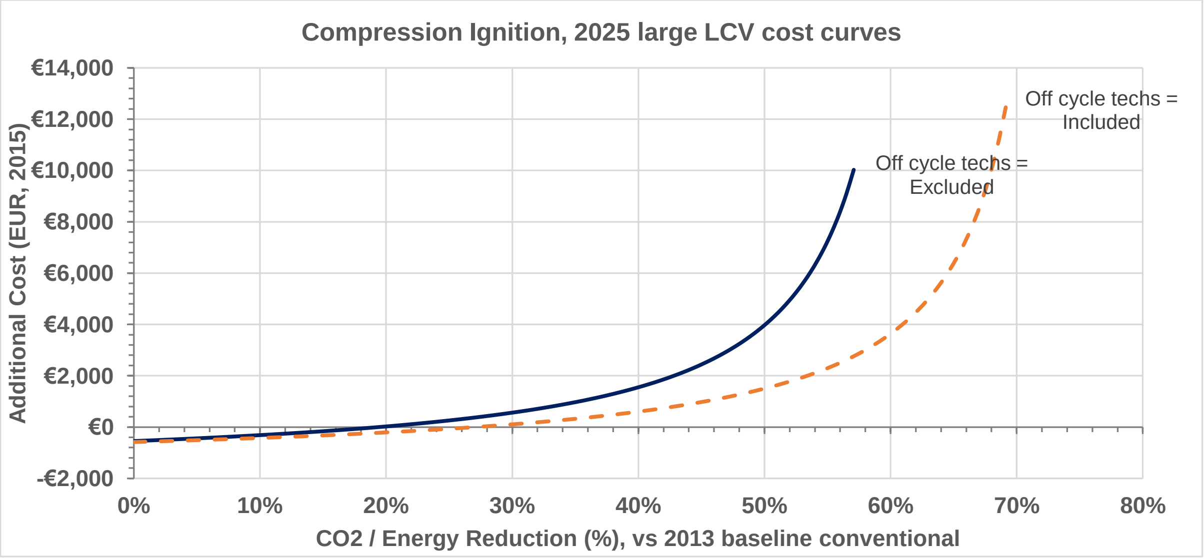


Table 8.24: Compression-ignition, 2025 large LCV cost curves, including and excluding off cycle techs

Off Cycle Techs	Max CO_2 reduction potential (%)	Max additional cost (EUR, 2015)
Excluded	57.1%	10,026
Included	69.1%	12,462

Figure 8.25: BEV, 2025 lower medium car cost curves, including and excluding off cycle techs

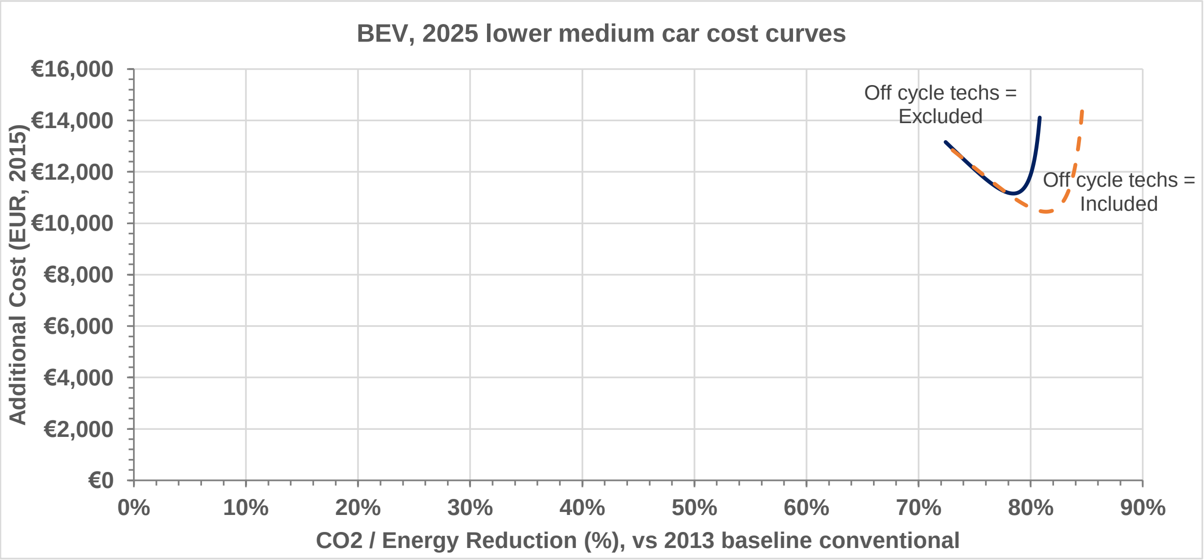


Table 8.25: BEV, 2025 lower medium car cost curves, including and excluding off cycle techs

Off Cycle Techs	Max CO_2 reduction potential (%)	Max additional cost (EUR, 2015)
Excluded	80.8%	14,113
Included	84.7%	14,901

8.1.5 Additional cost-curve sensitivities

In addition to the core WLTP cost-curves developed for the typical/central technology cost scenario, a selection of additional cost-curves were also generated to provide comparisons with those previously generated by TNO (e.g. in (TNO et al., 2006), (TNO et al., 2011)), as well as sensitivities with regards to the test cycle basis (i.e. NEDC, WLTC or RWC) and the technology cost scenario (Typical/Low/High). A summary of these comparisons is presented in the following subsections.

8.1.5.1 Comparisons of NEDC-based cost-curves with previous work

In order to get an indication on how the results of this latest updated analysis compares to previous work for the Commission, NEDC-based cost-curves were also developed for 2020 conventional petrol and diesel powertrain lower medium cars. These curves developed for this project are presented in Figure 8.26 (for SI / petrol) and Figure 8.27 (for CI / diesel) in comparison with equivalent cost curves developed by (TNO et al., 2011) and those developed for the “Downweighting” study (Ricardo-AEA, 2015). The TNO and “Downweighting” curves were originally set against a 2002 baseline vehicle with essentially none of the technologies already applied. Please note that in both Figure 8.26 and Figure 8.27, these two curves have been re-baselined to 2013 (Step 1 post-processing stage) based on the same data used in the current study to allow them to be comparable.

The charts show that the cost-curves developed for this study propose a significantly lower additional cost under nearly all CO_2 reduction magnitudes than the TNO and downweighting studies. Compared to the curves of (TNO et al., 2011), the absolute gap increases along the entirety of the spark-ignition and compression-ignition curves. Both curves from this study occupy middle-ground between the TNO and downweighting studies with regards to CO_2 reduction potential. The reasons for these differences include a number of interacting factors, such as:

a. Whilst a number of additional technologies have been added to the list for the 2020 cost-curve dataset, the CO_2 savings potentials were revised downward for a number of technologies based on more recent evidence from the literature, stakeholder feedback, and the PHEM simulations;
b. The costs for a number of technologies from this study are in some cases significantly lower than those from the previous (TNO et al., 2011) - which were also used in the downweighting study (except for weight reduction options) (Ricardo-AEA, 2015);

c. The technology overlap functions (used to scale back the overall CO_2 savings potential from the raw cost-curve outputs) have been reduced somewhat for both petrol and diesel vehicles based on the PHEM technology package simulations (see Section 8.2).

Figure 8.26: 2020, spark-ignition, lower medium car, NEDC, excluding off cycle tech cost curves from current and previous work

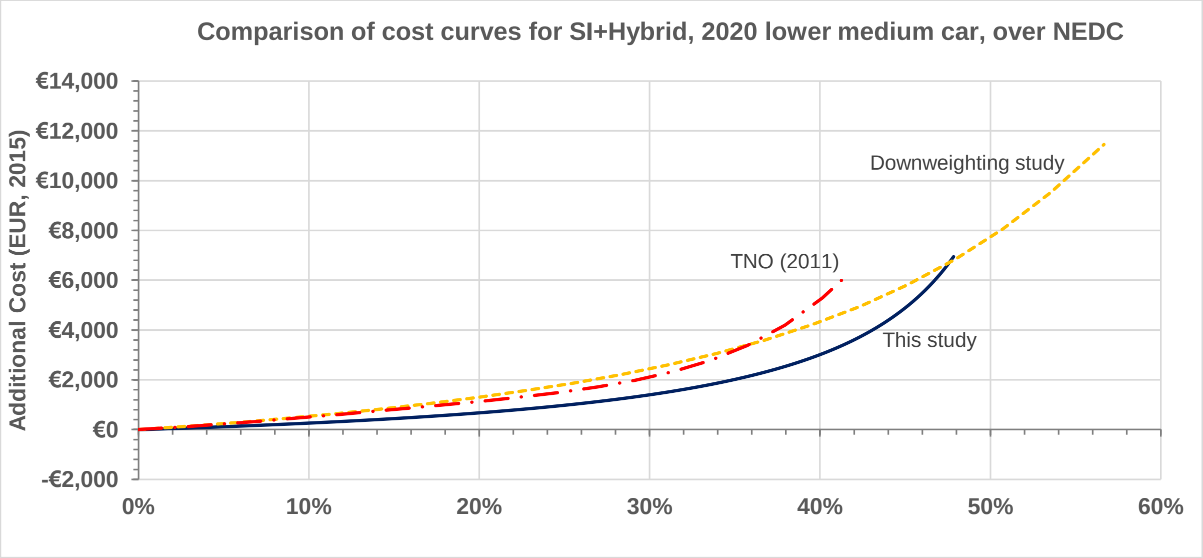
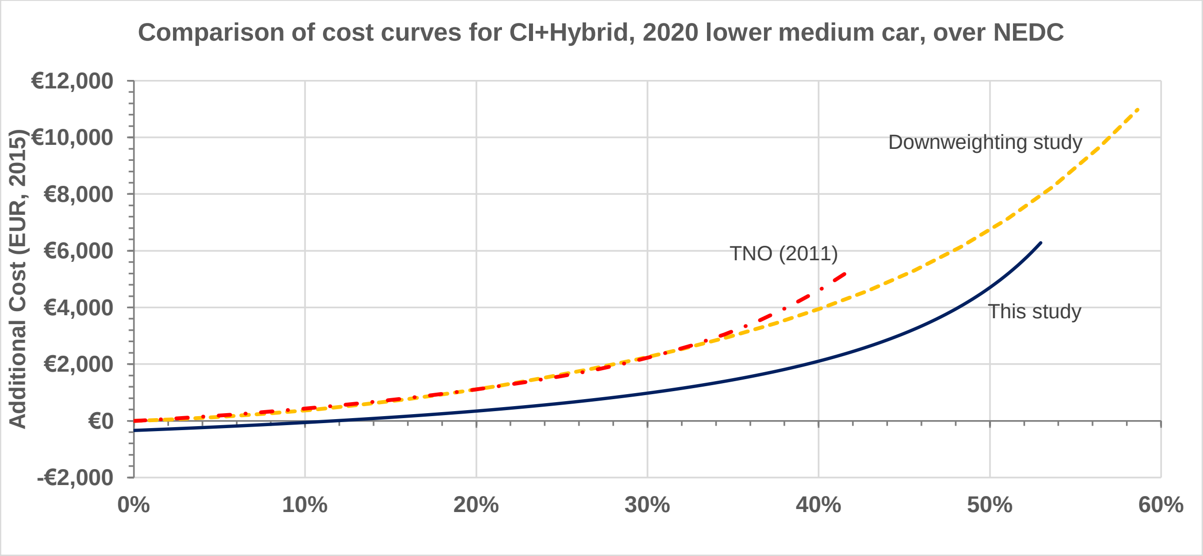


Figure 8.27: 2020, compression-ignition, lower medium car, NEDC, excluding off cycle tech cost curves from current and previous work



8.1.5.2 Comparisons of cost-curves for different cycle-types

The following Figure 8.28, Figure 8.29 and Figure 8.30 provide an illustration of the potential impact of switching the drive-cycle/test procedure basis on the derived CO_2 reduction cost-curves for conventional petrol and diesel engined vehicles. The different curves show quite different end points in terms of maximum CO_2 reduction as well as its costs. In particular, for lower medium cars, the SI+Hybrid RDC-based cost-curves appear to have a lower maximum cost as their highest CO_2 savings potentials are achieved without applying some of the more expensive technology combinations that achieve highest CO_2 savings under WLTP and NEDC. Lower medium car and large van CI+Hybrid RDC curves, in contrast, exhibit the highest maximum costs compared to WLTP and

NEDC. In general, RDC lower medium car curves reach the lowest maximum CO_2 reductions. In addition, at lower levels of % savings the costs on the RDC-based curves are closer to those on the NEDC curves, but are closer to the WLTP curves at higher % savings.

These curves illustrate the potential importance of cycle/procedure considerations on the selection of technologies to improve fuel consumption/reduce CO_2 emissions – i.e. different combinations of technologies may be prioritised for take-up based on different testing/regulation regimes. For example, for SI petrol cars, the present results seem to indicate that CO_2 reductions of up to roughly 42% compared to 2013 can be achieved at lower costs on the RDC example than an equivalent CO_2 reduction under WLTP. However, some care needs to be taken in such a comparison, as some of the specific details for WLTP are not yet finalised, and the RDC comparison is for only one of many different real-world driving cycles that are available.

As indicated earlier in section 8.1.4.1, the negative costs in the first part of the CI+Hybrid cost curve is driven mainly by the negative cost medium diesel engine downsizing technology option.

Figure 8.28: Comparison of cost curves for 2025, spark-ignition, lower medium car, on the basis of different drive-cycles

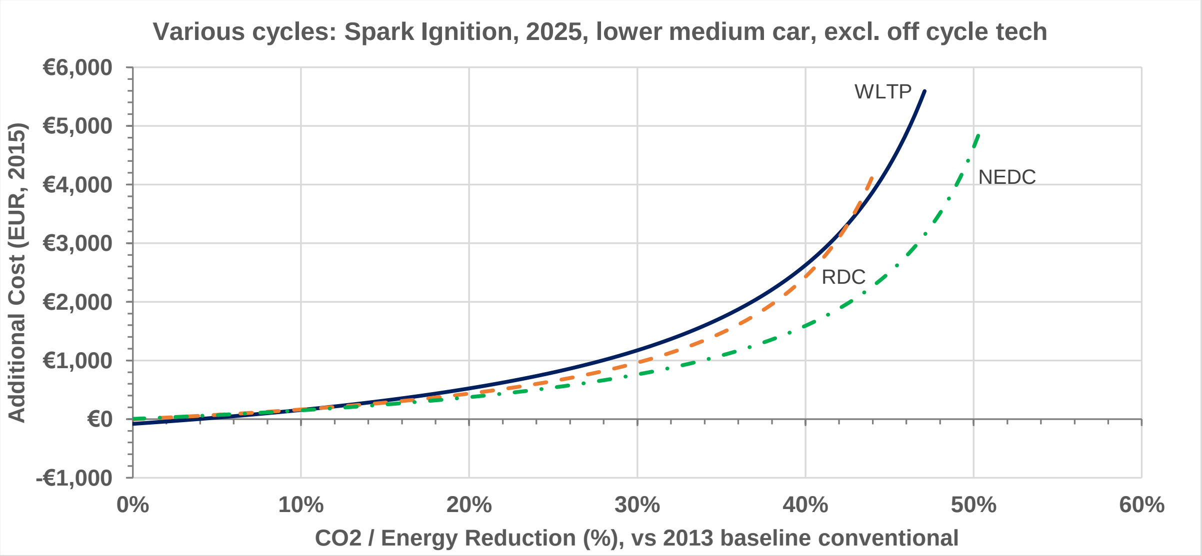


Table 8.26: Comparison of cost curves for 2025, spark-ignition, lower medium car, on the basis of different drive-cycles

Cycle	Max CO_2 reduction potential (%)	Max additional cost (EUR, 2015)
WLTP	47.1%	5,593
RDC	44.3%	4,343
NEDC	50.3%	4,874

Figure 8.29: Comparison of cost curves for 2025, compression-ignition, lower medium car, on the basis of different drive-cycles

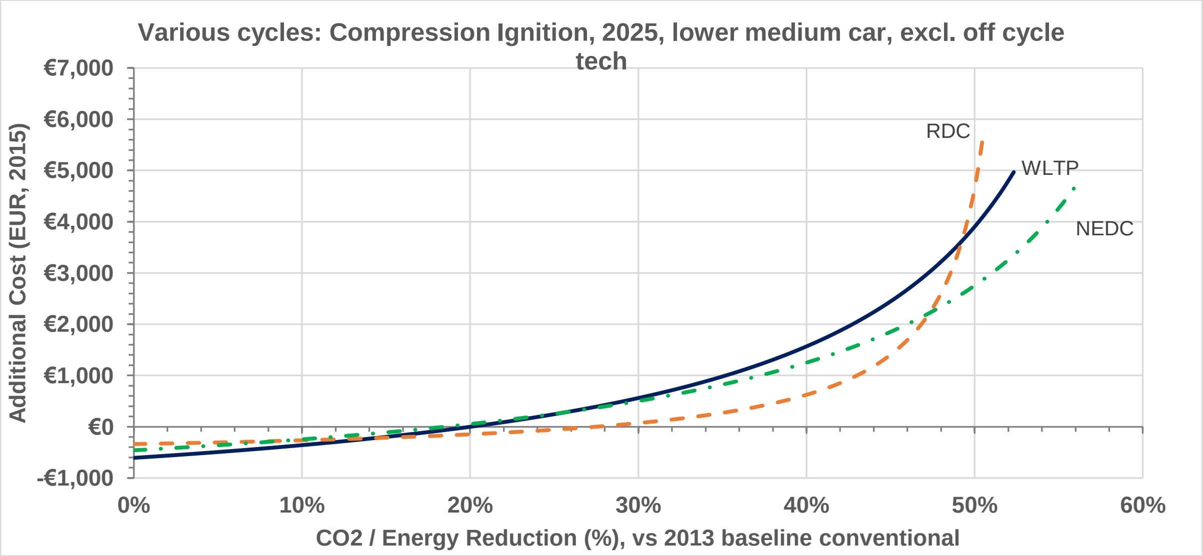


Table 8.27: Comparison of cost curves for 2025, compression-ignition, lower medium car, on the basis of different drive-cycles

Cycle	Max CO_2 reduction potential (%)	Max additional cost (EUR, 2015)
WLTP	52.3%	4,968
RDC	50.6%	5,829
NEDC	56.1%	4,729

Figure 8.30: Comparison of cost curves for 2025, compression-ignition, large LCV, on the basis of different drive-cycles

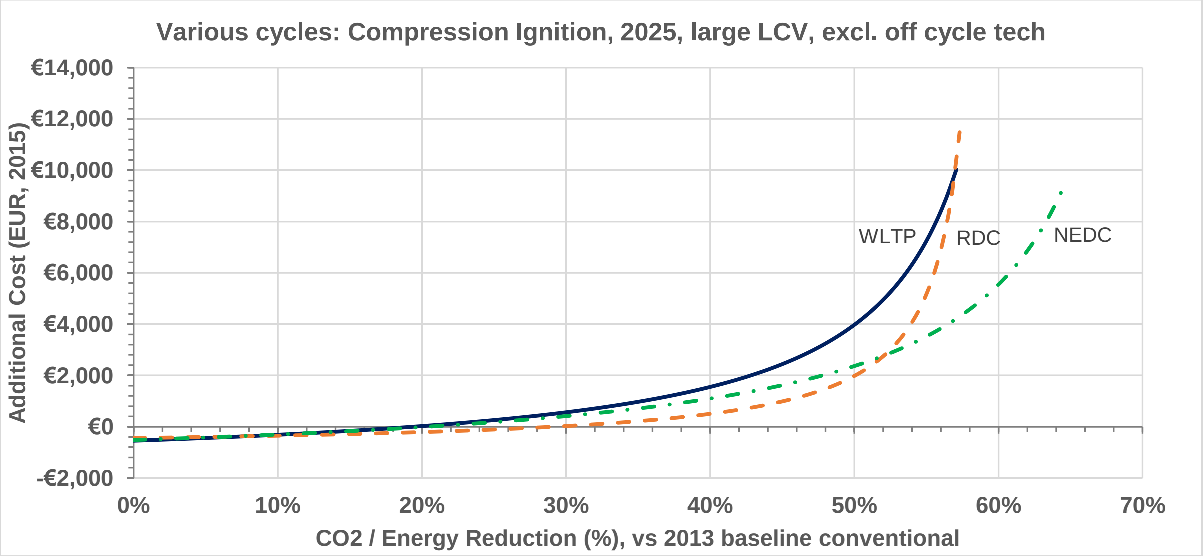


Table 8.28: Comparison of cost curves for 2025, compression-ignition, large LCV, on the basis of different drive-cycles

Cycle	Max CO_2 reduction potential (%)	Max additional cost (EUR, 2015)
WLTP	57.1%	10,026
RDC	57.3%	11,480
NEDC	64.4%	9,184

8.1.5.3 Comparisons of cost-curves for different cost scenarios

The following Figure 8.31, Figure 8.32 and Figure 8.33 provide an illustration of the differences between the developed cost-curves for 2025 lower medium passenger cars for conventional SI (petrol), CI (diesel) and BEV powertrains for the different technology cost scenarios. At their end points, the costs for equivalent CO_2 reduction are 28-29% lower under the Low cost scenario, and 44-46% higher under the High cost scenario for lower medium conventional powertrain cars. For BEVs (which combine differences in baseline powertrain costs, battery costs and costs of individual technologies) the maximum cost differentials are slightly smaller than this for the low cost scenario (~-16%), but similar for the high cost scenario (~49%).

As indicated earlier in subsection 8.1.4.1, the flat nature of the first part of the CI+Hybrid technology cost curve is driven primarily by the inclusion of the negative cost medium diesel engine downsizing technology option.

Figure 8.31: Various cost scenarios for 2025 spark-ignition, lower medium cars, excluding off cycle techs

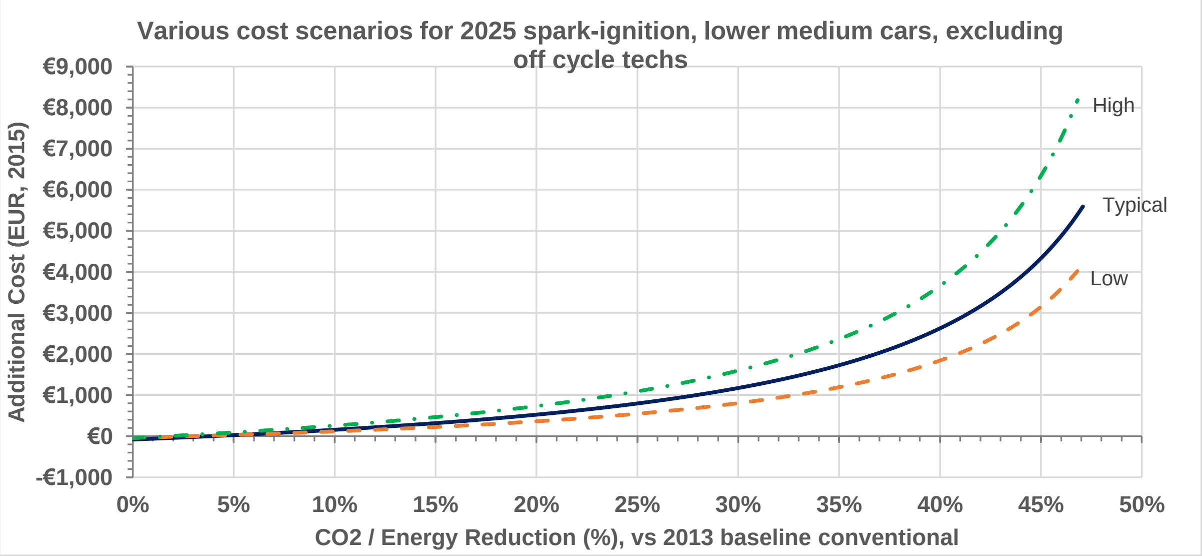


Table 8.29: Various cost scenarios for 2025 spark-ignition, lower medium cars, excluding off cycle techs

Cost scenario	Max CO_2 reduction potential (%)	Max additional cost (EUR, 2015)
Low	46.8%	4,018
Typical	47.1%	5,593
High	46.8%	8,182

Figure 8.32: Various cost scenarios for 2025 compression-ignition, lower medium cars, excluding off cycle techs

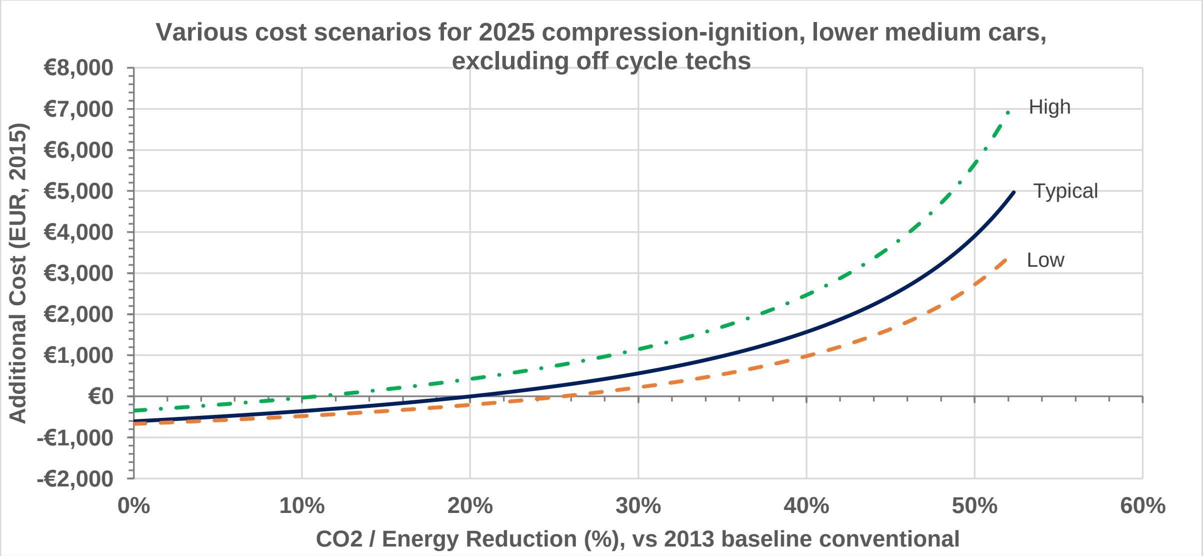


Table 8.30: Various cost scenarios for 2025 compression-ignition, lower medium cars, excluding off cycle techs

Cost scenario	Max CO_2 reduction potential (%)	Max additional cost (EUR, 2015)
Low	52.3%	3,507
Typical	52.3%	4,968
High	52.3%	7,170

Figure 8.33: Various cost scenarios for 2025 BEV, lower medium cars, excluding off cycle techs

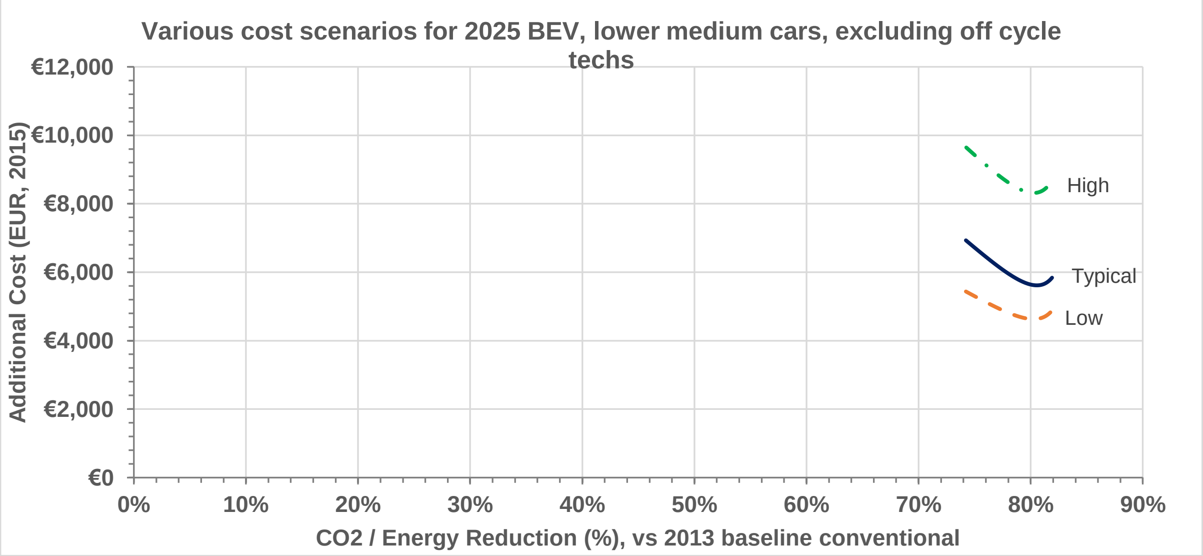


Table 8.31: Various cost scenarios for 2025 BEV, lower medium cars, excluding off cycle techs

Cost scenario	Max CO_2 reduction potential (%)	Max additional cost (EUR, 2015)
Low	81.9%	4,881
Typical	81.9%	5,839
High	81.9%	8,690

8.2 Verification of developed cost curves

8.2.1 Overview of methodology for verifying the cost curves

The cost curve approach adopted (prior to post-processing) assumes that the combined impacts of individual technologies on vehicle CO_2 emissions can be calculated via a simple multiplicative effect. To date, this approach has been appropriate (with some estimated corrections for overlap), but with ever more complex combinations of technologies now being applied to cars and LCVs to reduce vehicle emissions, it was important in this study to verify whether the outputs from the cost curves generated for this project (Section 8.1) are in line with real-world test data and with the outputs obtained from vehicle simulations. This task therefore focused on assessing the extent to which the current cost curve approach was still valid using a variety of verification techniques, and to feed into a post-processing adjustment of the developed cost curves where appropriate.

i. Verification of cost curve data and simulation results using information from currently deployed vehicle types (Section 8.2.2);
ii. Verification of cost curve data using complex vehicle modelling (Section 8.2.3);
iii. Verification of cost curve data using component testing and simulation (Section 8.2.4);
iv. Overall recommendations based on the findings of the verification work.

The results of the analysis were used to calibrate the developed cost curves through the use of a technology overlap/synergies correction post-processing step (as outlined in earlier Section 8.1.3).

8.2.2 Verification of cost curve data and simulation results using information from currently deployed vehicle types

Direct comparison with predecessor vehicles most often shows effects of combinations of technologies and includes to some extent the better use of test cycle flexibilities in testing (up to 50% of the reductions shown in type approval since 2010 seem to result from more efficient testing than from the improved technologies, e.g. (ICCT, 2013)). Thus comparison of CO_2 certification values from different model years may overestimate the reduction potential for a technology, and make it difficult (or perhaps even impossible) to draw firm conclusions in making comparisons with modelled/simulated results.

From the work undertaken for HBEFA (www.hbefa.net), test data on many conventional vehicles in the CADC cycle were already available against which test results on new technologies could be compared. By comparing the gCO_2 per kWh work delivered at the driven wheels, the drive train efficiencies could be compared in valid way and the reduction rates can be applied directly to measured CO_2 emissions on per kilometre basis. From the ERMES database all Euro 5 and Euro 6 LDVs were extracted where at least NEDC and CADC emissions had been measured. The database was analysed to identify vehicles with relevant technologies for the validation; however, unfortunately (but as expected) it showed that for many vehicles neither the driving resistances used in the tests nor the detailed model description was provided by the testing lab. However, useful data was identified and test data used within the project to inform the complex vehicle modelling elements and ensure that the developed estimates were in-line with expected performance.

This modelling work is described in more detail in earlier Section 6.2 (for individual measures), and also below (Section 8.2.3) for the technology packages.

8.2.3 Verification of cost curve data using complex vehicle modelling

The second approach for carrying out plausibility checks on / calibrations for cost-curve results is based on the simulation results for the base vehicle technologies for each segment. The main aim of the simulation work undertaken here was the calculation of fuel consumption and CO_2 emissions for vehicles with a bundle of fuel saving technologies. The results indicate how combined technology effects can be accounted for in the cost curves. The main questions that it sought to answer were:

I. **Is a simple multiplicative approach in the cost curves accurate enough?**
Example: adding 3 technologies with 4% fuel saving each shall result in 11.5% fuel saving (0.96 x 0.96 x 0.96 = 0.885). If e.g. weight reduction and better tires are combined, both measures reduce rolling resistance and thus the relevance of this driving resistance. Thus the effect of such a combination may be lower than the multiplication suggests.

II. **Are there any important synergy effects which may intensify the effects of single technologies if combined with other technologies?**
Example: if driving resistance reduction is combined with a hybrid power pack system, more kinetic energy can be used for brake energy recuperation. Thus the effect of hybrids may be larger in such combinations compared to a single technology.

III. **What should a correction function look like that takes account of the overlapping effects of technologies?**
Example: it is assumed that an OEM will introduce technologies which show synergies first and overlapping technologies last to meet CO_2 targets. Thus a simple generic correction function should have higher reduction effects on the fuel savings of combined measures the more technologies are combined. In the PHEM simulation therefore the technologies were introduced in an order where the lowest level of overlapping was assumed to check possible correction functions.

The PHEM vehicle models were consequently set up in a modular way to allow for a quick exchange of input data for each component (see also Section 6.2 for the model descriptions). For all vehicles the base technology represents 2002 technology, as far as possible, to allow for the implementation of all technologies defined in the technology list without double counting.

The main technologies expected for 2025 were introduced step by step in the conventional base vehicles and in the hybrid base vehicles. The selection of technologies was based on the demand to create high reduction potential values to analyse the questions set above. Thus the vehicles compiled demonstrated the upper limit of fuel efficiency without a consideration of cost restrictions.

The results are shown in this section below, the analysis on the effects I to III described above is summarised in later Section 8.2.5, and also discussed previously given in Section 8.1.3 with regards to the post-processing correction of the developed cost-curves.

For conventional (non-hybrid) vehicles, the following technology packages in Table 8.32 were simulated for petrol and diesel vehicles with conventional powertrains (i.e. excluding full hybrids). An additional Tech-pack 5 was originally planned as waste heat recovery but uncertainties in simulation were too high to deliver any reliable trends. From actual point of view this technology should roughly follow a multiplicative effect in combination with most technologies but show reduced effects with better engine technology due to the lower exhaust gas enthalpy with higher engine efficiencies.

Table 8.32: Overview of technology packages simulated for conventional petrol and diesel engines

	Name	
Base ICE	**Petrol**	**Diesel**
Conventional ICE basis (5 speed AT)	ICE basis G	ICE basis D
-+8 speed DCT	Tech-pack 1-0	Tech-pack 3-0
-+2025 ICE	Tech-pack 1-1	Tech-pack 3-1
+10% Weight-reduction (mild weight reduction)	Tech-pack 1-2	Tech-pack 3-2
+20% Cd-reduction (aerodynamic improvements level 2)	Tech-pack 1-3	Tech-pack 3-3
+30% RRC-reduction (LRRT level 2)	Tech-pack 1-4	Tech-pack 3-4

Similarly, Table 8.33 summarises the technology packages simulated for hybrids with petrol and diesel engines. Each technology was treated as an add-on to the technologies already included in the step before.

Table 8.33: Overview of technology packages simulated for hybrids with petrol and diesel engines

	Name	
Base ICE	**Petrol**	**Diesel**

	Name	
Base ICE	**Petrol**	**Diesel**
HEV Basis (5 speed AT)	HEV basis G	HEV basis D
+8 speed DCT	Tech-pack 2-0	Tech-pack 4-0
+2025 ICE	Tech-pack 2-1	Tech-pack 4-1
+10% Weight-reduction (mild weight reduction)	Tech-pack 2-2	Tech-pack 4-2
+20% Cd-reduction (aerodynamic improvements level 2)	Tech-pack 2-3	Tech-pack 4-3
+30% RRC-reduction (LRRT level 2)	Tech-pack 2-4	Tech-pack 4-4
30% Weight-reduction (strong weight reduction) *(replaces 10% weight reduction)*	Tech-pack 2-6	Tech-pack 4-6

Notes: Tech-pack 5 was planned as waste heat recovery but uncertainties in simulation were too high to deliver any reliable trends, so this package was not taken forwards in the final analysis.

The DCT was introduced to mimic any kind of automated transmission with highly variable transmission ratios. The settings of the DCT controller in PHEM were applied (as described in Appendix 6, Section A5.3.3). The hybrid controllers were set (as shown in Appendix 6, Section A5.6) and proved to deliver efficient operation strategies in all combinations. Nevertheless it has to be noted that for each technology package in each vehicle segment an extra optimisation of the hardware and controller software (e.g. the ratio of ICE and motor power, battery capacity, transmission ratios and controller functions) would be necessary to identify ideal vehicle configurations. Such optimisations are very time consuming and were not possible with the resources available in this project. However, since in real vehicle configurations, it is typical that not all of the theoretical potential can be achieved, omitting the specific optimisation loops may give more realistic reduction values. Since the single vehicle segments may show different optimisation potentials compared to the base settings used here, the differences found for the single segments may be partially an effect of un-optimised settings.

The engine maps for the combination of technologies were basically produced by a simple multiplicative combination of the reduction potentials identified for the single technologies. The overall reduction found for each single point in the map was applied to the engine fuel map of the base engines. For some areas this approach leads to very high efficiencies. Thus the maximum efficiency was limited to 40% (210 g/kWh) for the petrol engine and to 43% (197 g/kWh) for the diesel engine. Since the engines are medium to strong downsized (an 80/20 ratio from medium and strong downsize effects was assumed) and turbocharged and also need to fulfil future RDE emission legislation these values seem appropriate. Table 8.34 shows the shares of single technology effects combined in the engine map for the 2025 vehicle. Due to future RDE legislation it was assumed that lean burn would not be widely applied. Cylinder deactivation combined with hybridisation does not seem to be very attractive for low powered vehicles since electric driving at low loads competes with cylinder deactivation in the same areas, thus also this technology was not introduced to 100%. Where the OEM has such engines from conventional vehicles these may be used in a hybrid version as well.

Table 8.35 shows the single technologies implemented in the diesel engine map for the 2025 vehicles. Again the future RDE regulation is assumed to limit the implementation of strong downsizing especially for small engines due to limits in the EGR rates for NO_x control in transient operation. In hybrids this limitation is less pronounced since the electric motor can assist in transient accelerations when the turbo lag limits EGR levels, thus a mix of medium and strong downsizing was selected here. Again it has to be noted that this exercise aimed at combining many technologies to test the cumulative effects.

Table 8.34: Shares of single technologies assumed for the “2025 petrol engines”

% Application	Technology
100%	Combustion improvements Level 1: Gas-wall heat transfer reduction
100%	Combustion improvements Level 2: 1 point increase in compression ratio
100%	Direct injection – homogeneous
30%	Direct injection - stratified charge & lean burn
100%	Thermodynamic cycle improvements (b): Efficient cycles (e.g. Atkinson, Miller)

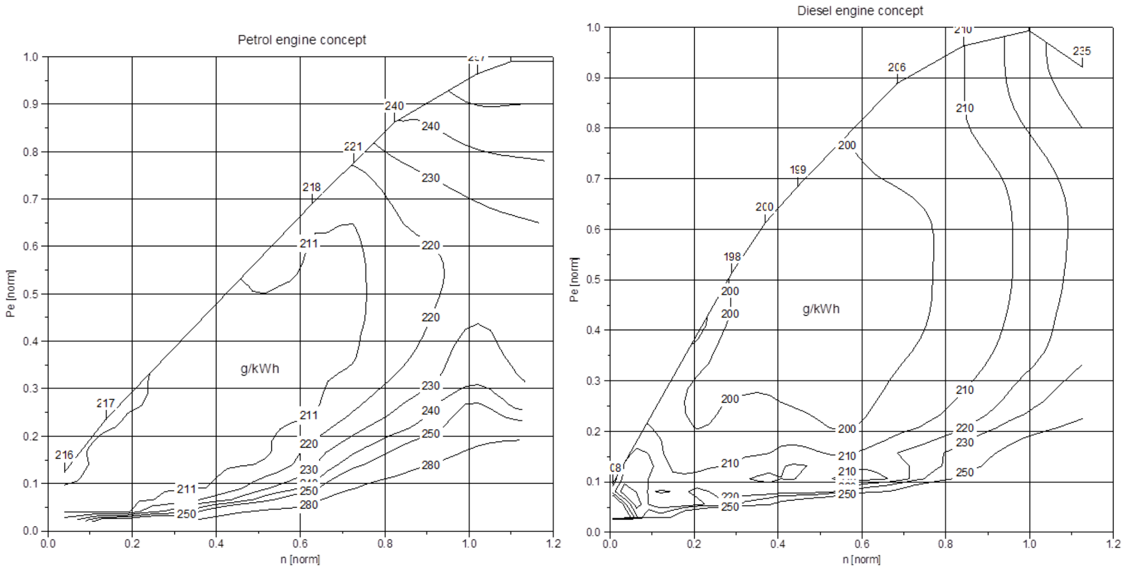
% Application	Technology
100%	Cooled EGR
100%	Variable valve actuation and lift
100%	Medium downsizing (30% cylinder content reduction) + boost
20%	Engine friction reduction for SI engines: Level 1
80%	Engine friction reduction for SI engines: Level 2
30%	Cylinder deactivation
100%	Thermal Management

Table 8.35: Shares of single technologies assumed for the “2025 diesel engines”

% Application	Technology
100%	Combustion improvements Level 1: Improvement of compression ratio, expansion ratio, etc.
100%	Combustion improvements Level 2: Increased injection pressures, individual management
100%	Low pressure cooled EGR
100%	VVT
80%	Medium downsizing (30% cylinder content reduction) + boost
20%	Strong downsizing (>=45% cylinder content reduction) + boost
100%	Engine friction reduction for CI engines: Level 2

The resulting efficiency maps for engine concepts applied for the simulation of the 2025 engined vehicles are shown in Figure 8.34. The effect of the technologies implemented is an improvement of the low load efficiency compared to the base 2002 engines, especially for an SI engine, and an enlargement of the area with optimum fuel efficiency.

Figure 8.34: Fuel maps for petrol and diesel engines applied for 2025 vehicles



With this input data PHEM was used to simulate all vehicle segments in all cycles for each single technology package.

For conventional, non-hybrid powertrains the results can be briefly summarised as follows, and illustrated for NEDC and WLTP cycles:

1. The resulting average fuel consumption savings for **Technology Package 1** are about 30% for diesel and 46% for petrol vehicles on the NEDC compared to the baseline vehicles. Due to the higher efficiency improvements for petrol engines expected by 2025 the percentage savings are

higher than for diesel cars. On the WLTC the average savings are 23% for diesel and 35% for petrol vehicles. CADC and RWC have the same trend as the WLTC.

2. The average savings for **Technology Package 2** are about 35% for diesel and 49% for petrol engines on the NEDC. The average savings on the WLTC are 27% for diesel and 38% for petrol engines.
3. **Technology Package 3** includes also the aerodynamic reduction by 20%. This results in 38.4% average fuel saving for diesel and 52% for petrol engines on the NEDC. For the WLTC the average saving potentials are 32% for diesel and 42.5% for petrol vehicles.
4. **Technology Package 4** adds 30% less rolling resistance. The average savings are 42% for diesel and 55% for petrol engines on the NEDC. On the WLTC the savings are 36% for diesel and 46% for petrol vehicles.

This information is also summarised in the following Figure 8.35 and Figure 8.36 for petrol (SI) and diesel (CI) lower medium cars (there are some small variations between different LDV segments, but the general trends are very similar).

Figure 8.35: Fuel /CO$_2$ reduction potential compared to the base vehicle for petrol ICE, PHEM analysis for a Lower Medium Car

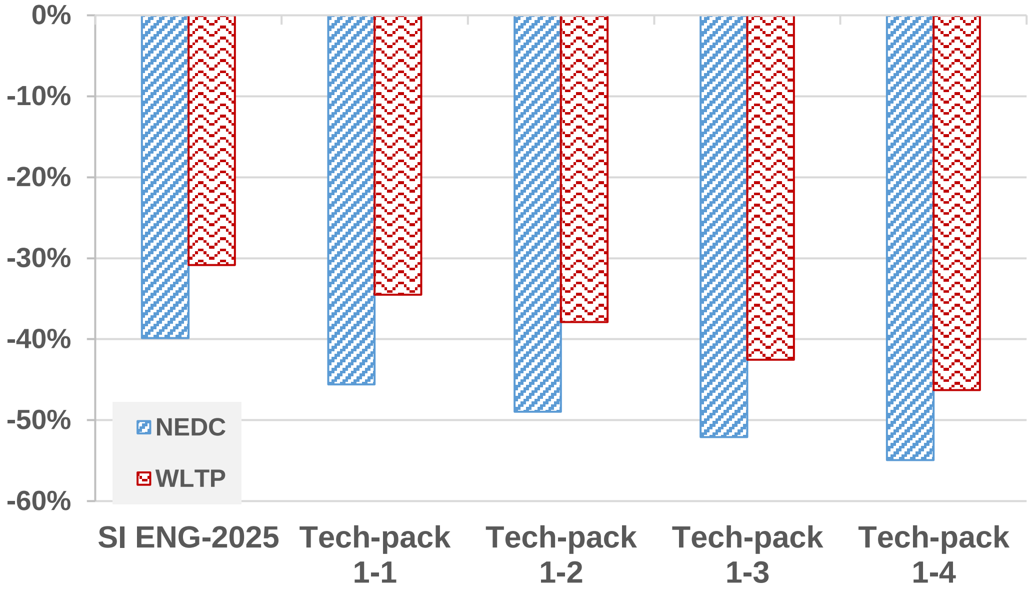
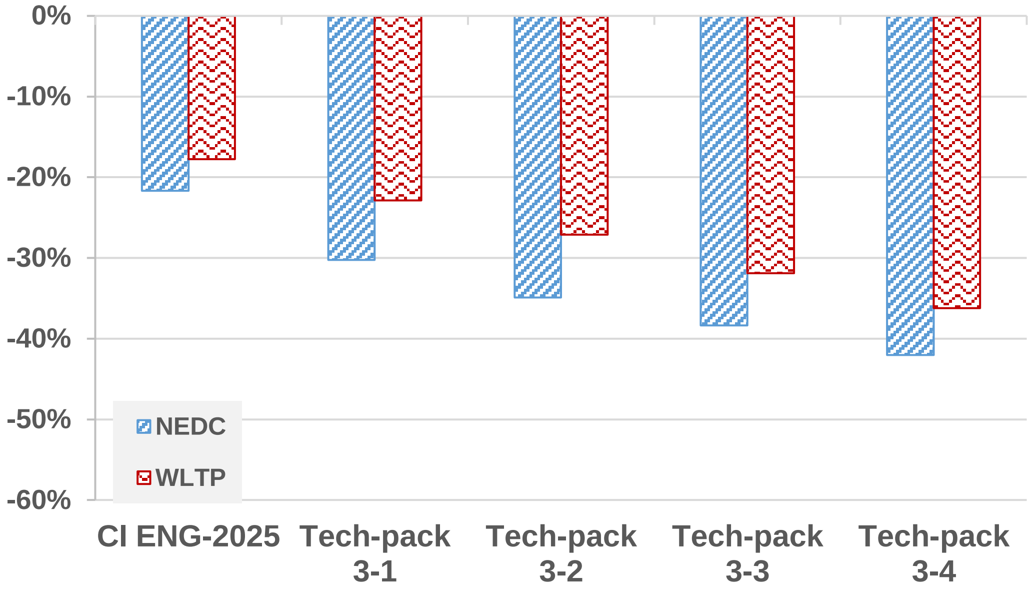


Figure 8.36: Fuel /CO_2 reduction potential compared to the base vehicle for diesel ICE, PHEM analysis for a Lower Medium Car

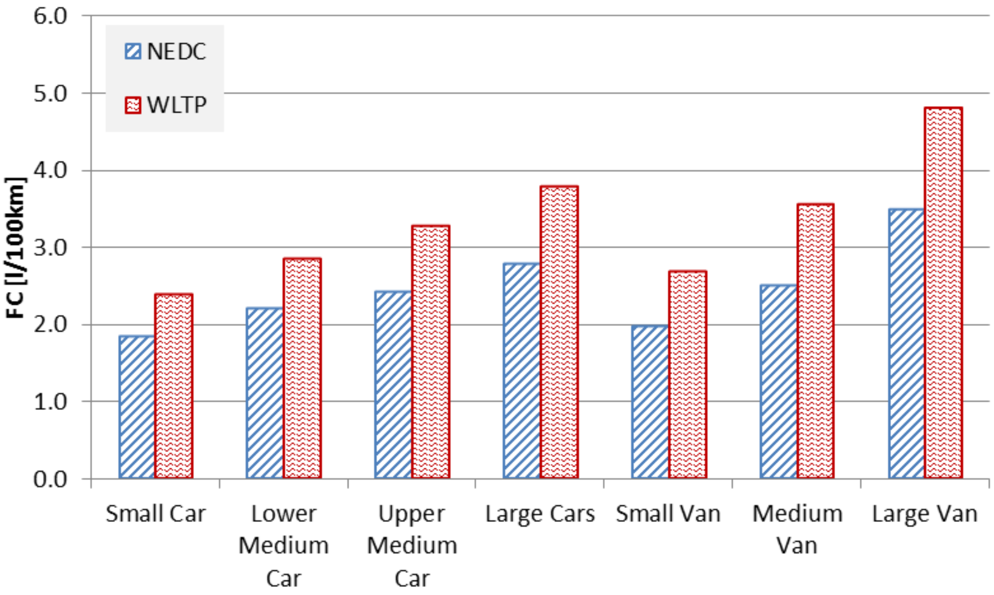


A more detailed discussion of the results of the technology package analysis for the hybridised powertrains is presented below.

Figure 8.37 shows the fuel consumption and the CO_2 reduction achieved with the technology package 6 for the HEVs with petrol engine. On average a more than 40% reduction in the CO_2 emissions compared to the base HEV vehicles resulted from the combination of technologies. The reduction potential was somewhat lower in the WLTP than in the NEDC.

Figure 8.37: Fuel consumption and reduction potential compared to the base HEV vehicle for petrol HEV

Fuel consumption



Reduction potential

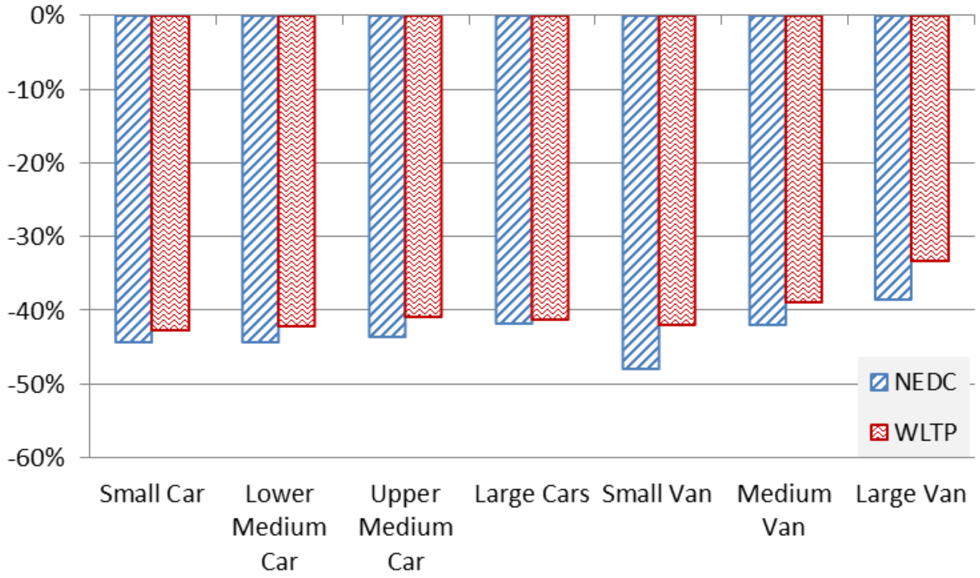
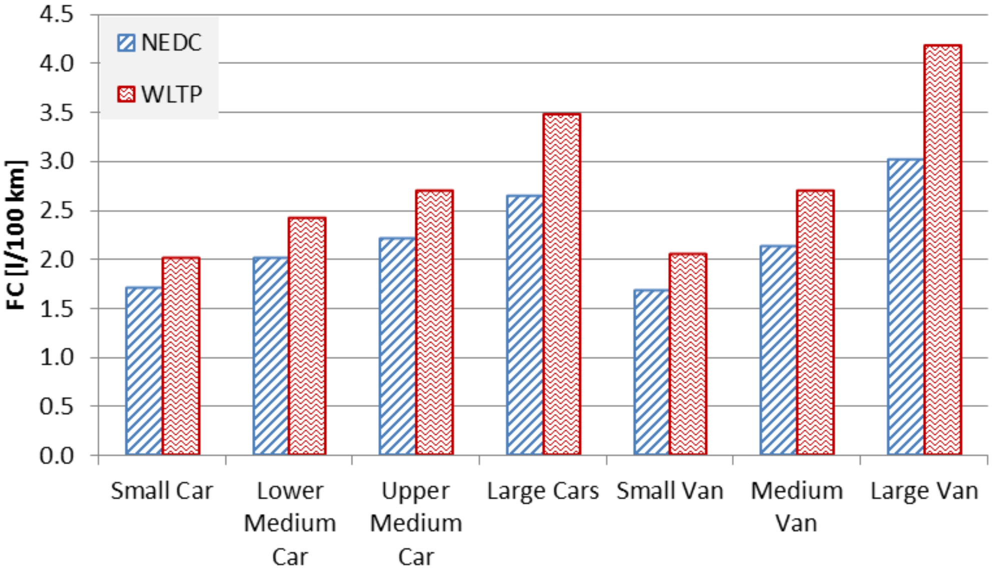


Figure 8.38 shows the fuel consumption and the CO_2 reduction achieved with the technology package 6 for the HEVs with diesel engine. A somewhat less than 40% reduction in CO_2 emissions compared to the base HEV vehicles resulted from the combination of the technologies. The reduction potential was somewhat lower in the WLTP than in the NEDC for most vehicle segments. The lower reduction for the diesel equipped HEV technology package is mainly due to the smaller improvements in engine efficiency from the CI package compared to the SI package.

Figure 8.38: Fuel consumption and reduction potential compared to the base HEV vehicle for diesel HEV

Fuel consumption



Reduction potential

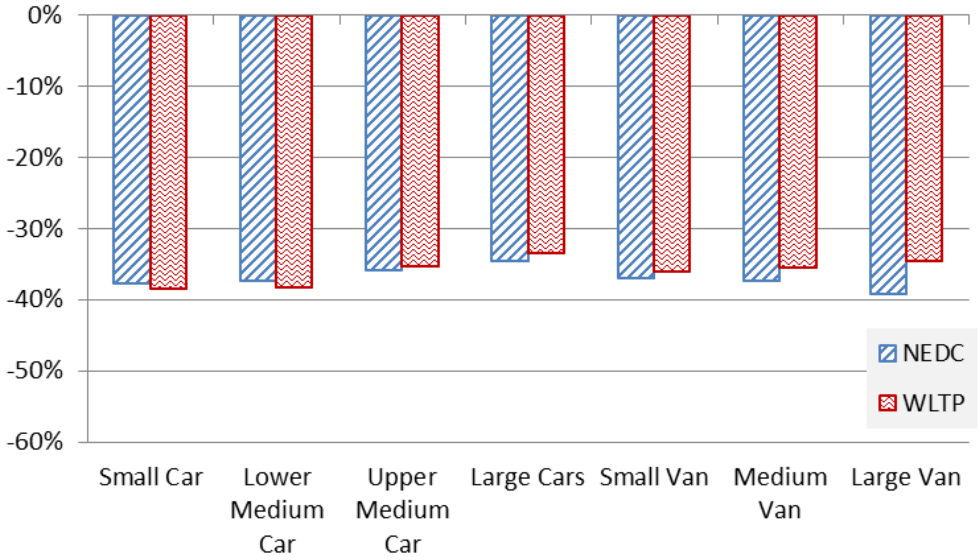


Table 8.36, Table 8.37 and Table 8.38 compare as an example the petrol and diesel lower medium car and the hybrid petrol lower medium car technology package effects. “PHEM” means the results from the simulation of the combined technologies as shown above and “multiplied” shows the simple multiplicative approach from the single technology effects. The engine technologies listed in these tables for the petrol and diesel engine in 2025 were compiled for the multiplicative approach also by a multiplication of the single, weighted effects. It can be seen that the engine efficiency improvements differ as might be expected between the two approaches for combining technologies, particular for the petrol engines. The differences may be due to higher gradients from the specific-fuel-consumption-isolines in the part load area at petrol engines which causes larger absolute differences at similar relative changes. I addition more new technologies are simulated for petrol engines than for diesel engines and thus more overlapping is expected. For the diesel engine the efficiency improvements are nearly identical between the two approaches. The accuracy of the approach to compute an engine fuel map for the technology combinations described before certainly is not very high but the simple multiplicative approach seems to be much too optimistic for a combination of so many engine technologies.

Table 8.36: Comparison of the technology package effects for conventional petrol lower medium car simulated by PHEM with the result from a simple multiplicative approach from the single technology effect (CO_2 emissions as a percentage of the base vehicle)

	Base SI	+8gear DCT	+2025 ICE	+10% Weight-reduction	+20% Cd-reduction	+30% RRC-reduction	Total
NEDC PHEM	100%	87.3%	52.9%	50.0%	47.5%	44.8%	**44.8%**
NEDC multiplied	*100%*	*87.3%*	*49.1%*	*45.8%*	*44.2%*	*41.8%*	***41.8%***
WLTP PHEM	100%	90.7%	63.5%	60.0%	56.0%	52.3%	**52.3%**
WLTP multiplied	*100%*	*90.7%*	*58.3%*	*54.7%*	*52.2%*	*49.6%*	***49.6%***
CADC PHEM	100%	89.1%	65.1%	61.8%	56.4%	52.8%	**52.8%**
CADC multiplied	*100%*	*89.1%*	*59.0%*	*55.7%*	*52.3%*	*49.8%*	***49.8%***
RWC PHEM	100%	88.0%	64.5%	61.9%	56.5%	52.6%	**52.6%**
RWC multiplied	*100%*	*88.0%*	*58.6%*	*55.5%*	*52.4%*	*49.9%*	***49.9%***

Table 8.37: Comparison of the technology package effects for conventional diesel lower medium car simulated by PHEM with the result from a simple multiplicative approach from the single technology effects (CO_2 emissions as a percentage of the base vehicle)

	Base CI	+8gear DCT	+2025 ICE	+10% Weight-reduction	+20% Cd-reduction	+30% RRC-reduction	Total
NEDC PHEM	100%	86.8%	68.8%	63.4%	60.8%	57.6%	**57.6%**
NEDC multiplied	*100%*	*86.8%*	*68.2%*	*62.4%*	*60.5%*	*58.0%*	***58.0%***
WLTP PHEM	100%	91.6%	75.3%	70.9%	66.8%	62.4%	**62.4%**
WLTP multiplied	*100%*	*91.6%*	*74.7%*	*70.0%*	*66.8%*	*63.1%*	***63.1%***
CADC PHEM	100%	90.0%	74.9%	70.9%	65.3%	61.2%	**61.2%**
CADC multiplied	*100%*	*90.0%*	*73.5%*	*69.4%*	*65.1%*	*61.7%*	***61.7%***
RWC PHEM	100%	89.7%	74.5%	71.2%	65.7%	61.3%	**61.3%**
RWC multiplied	*100%*	*89.7%*	*73.6%*	*69.8%*	*65.5%*	*61.8%*	***61.8%***

Table 8.38: Comparison of the technology package effects for petrol lower medium car HEV simulated by PHEM with the result from a simple multiplicative approach from the single technology effects (CO_2 emissions as a percentage of the base vehicle)

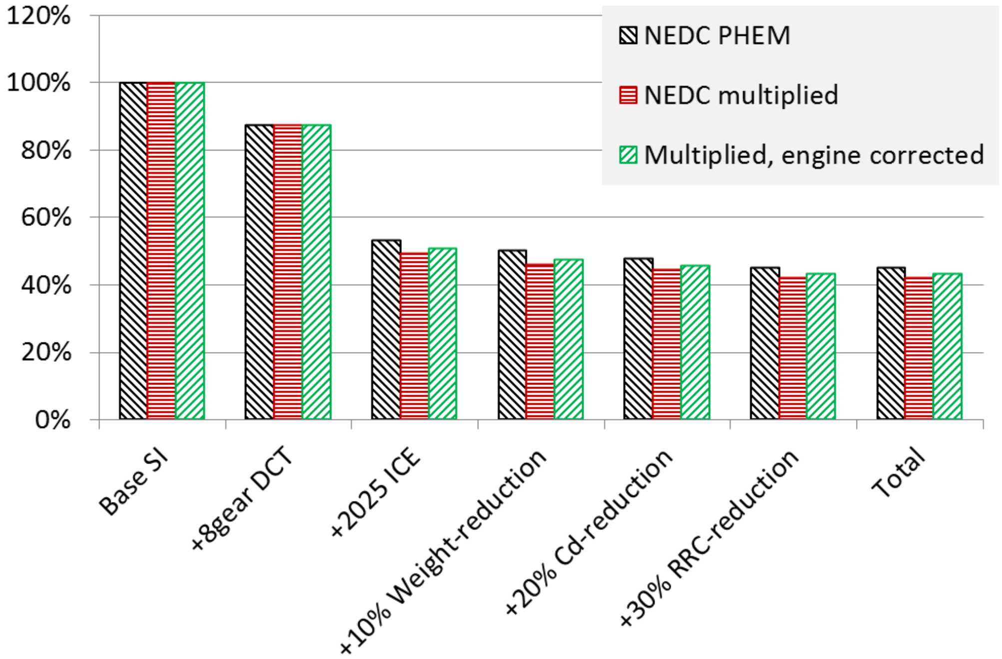
	Base SI	HEV base	+8gear DCT	+2025 ICE	+10% Weight-reduction	+20% Cd-reduction	+30% RRC-reduction	Total
NEDC PHEM	100%	70%	65.4%	53.7%	52.6%	47.6%	43.2%	**43.2%**
NEDC multiplied	*100%*	*70%*	*66.3%*	***35.9%***	*33.5%*	*32.3%*	*30.6%*	***30.6%***
WLTP PHEM	100%	77%	77.0%	65.5%	61.9%	55.5%	49.2%	**49.2%**
WLTP multiplied	*100%*	*77%*	*76.2%*	***48.5%***	*45.5%*	*43.5%*	*41.3%*	***41.3%***
CADC PHEM	100%	82%	83.9%	71.8%	67.8%	60.9%	55.3%	**55.3%**
CADC multiplied	*100%*	*82%*	*80.1%*	***52.2%***	*49.3%*	*46.3%*	*44.1%*	***44.1%***
RWC PHEM	100%	87%	86.1%	74.0%	71.5%	63.3%	56.9%	**56.9%**
RWC multiplied	*100%*	*87%*	*84.7%*	***56.3%***	*53.4%*	*50.4%*	*48.0%*	***48.0%***

Figure 8.39, Figure 8.40 and Figure 8.41 compare again the technology package effects from a petrol/diesel lower medium car and hybrid petrol lower medium car for:

a) the values simulated by PHEM
b) the result from the simple multiplicative approach from the single technology effects
c) As b) but with the PHEM results for the engine technology related reduction potential.

This exercise shows that in the case of the petrol lower medium car the multiplicative approach overestimates the engine technology effects. Furthermore, the engine technology in 2025 has the biggest CO_2 reduction potential against the other listed technologies. In total the reduction potential is up to nearly 55% on NEDC and 48% on WLTC.

Figure 8.39: Comparison of the technology package effects for conventional petrol lower medium car simulated by PHEM with the result from a simple multiplicative approach from the single technology effects once with multiplied engine effects and once with PHEM-engine effects (Example for segment C with petrol engine in NEDC and in WLTP)



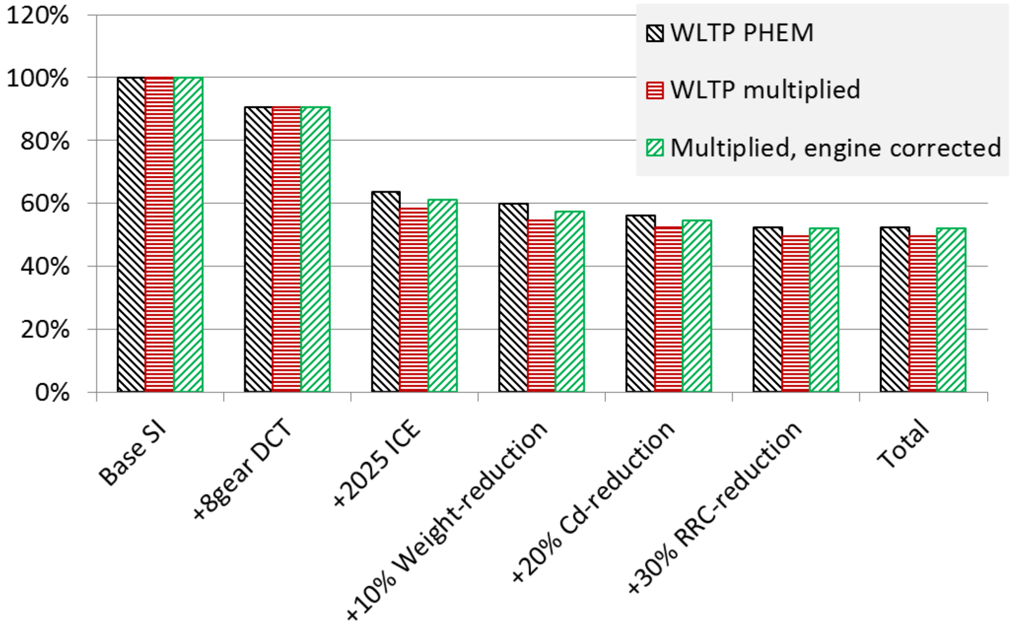
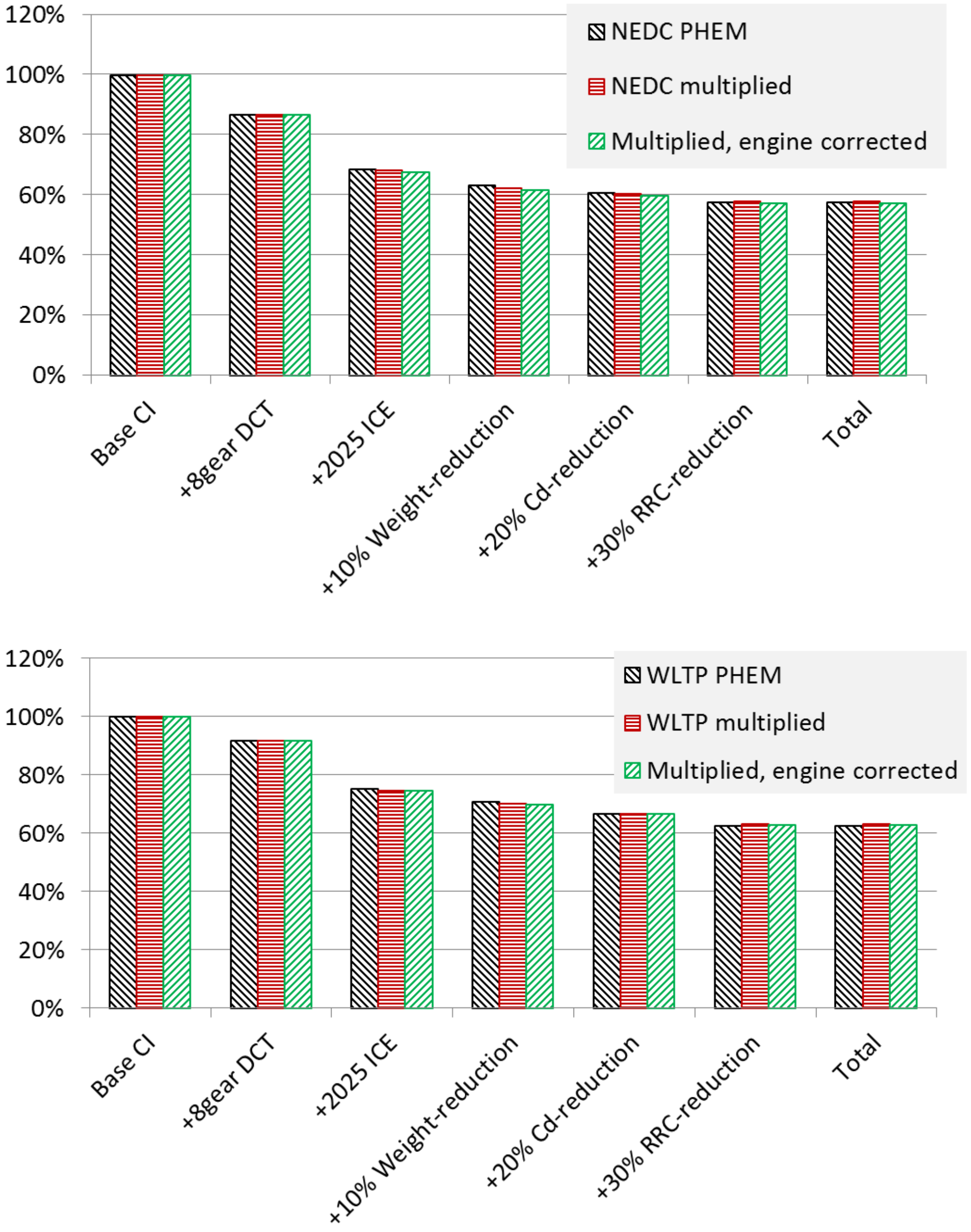


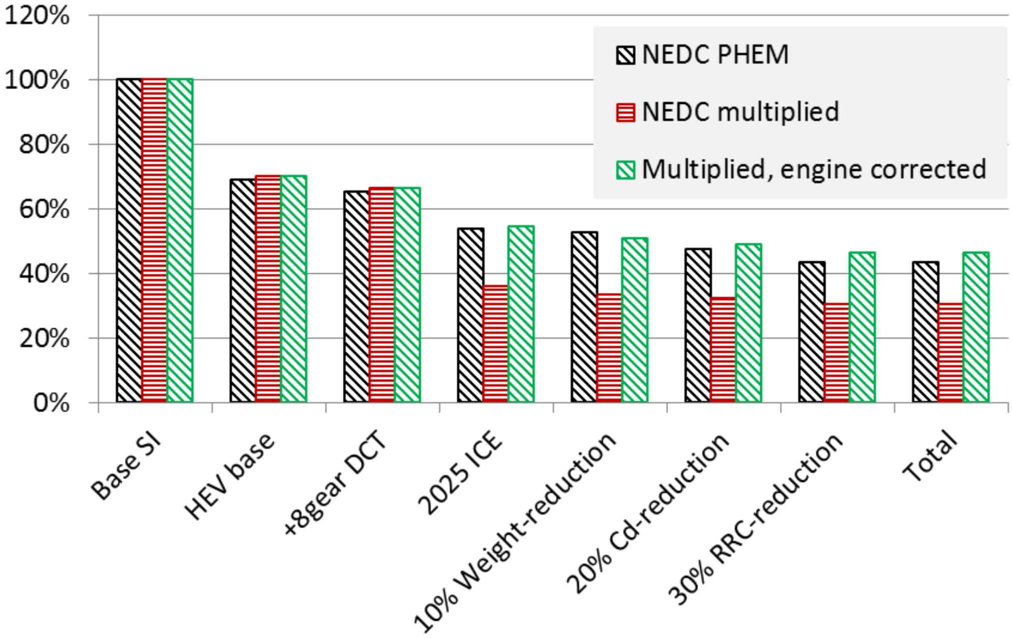
Figure 8.40 shows that in the case of the diesel lower medium car the multiplicative approach partly overestimates or underestimates the single technologies. The reason for this may be as mentioned before that the gradients from the specific-fuel-consumption-isolines in the part load area are lower than the gradients form the petrol engine map. In total the CO2 percentage savings are up to nearly 42% on NEDC and 38% on WLTC.

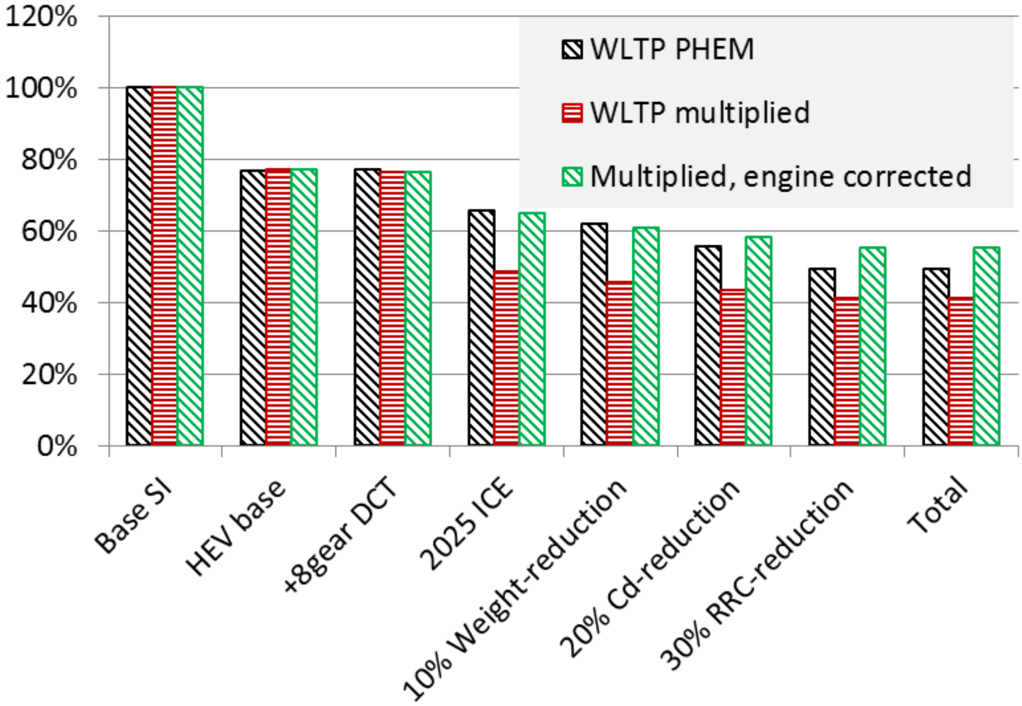
Figure 8.40: Comparison of the technology package effects for conventional diesel lower medium car simulated by PHEM with the result from a simple multiplicative approach from the single technology effects once with multiplied engine effects and once with PHEM-engine effects (Example for segment C with petrol engine in NEDC and in WLTP)



For the hybrids the multiplicative approach produces overestimations only for the engine technology effects. The effect of reductions in the rolling and air resistance show synergies with the brake energy recuperation and have higher potential in the combination than as single technology. On the other hand, weight reduction has lower potential in hybrids than in the conventional vehicle since a part of the kinetic energy is recuperated which reduces the share of work to accelerate the vehicle mass.

Figure 8.41: Comparison of the technology package effects for petrol lower medium car HEV simulated by PHEM with the result from a simple multiplicative approach from the single technology effects once with multiplied engine effects and once with PHEM-engine effects (Example for segment C with petrol engine in NEDC and in WLTP)





8.2.4 Verification of cost curve data using component testing and simulation

Tests were performed on the chassis dynamometer at TU Graz using the NEDC, the WLTP, the CADC and/or the RWC cycle for up to three vehicles. The tests covered complex technologies by testing mainly for parametrisation and for the validation of simulation results.

An analysis of the main uncertainties in the simulation of vehicle CO_2 emissions based on the earlier task work was carried out as basis for the vehicle selection and is documented in earlier Section 6.2.

It was found in this analysis that technologies with sophisticated control strategies are related to high uncertainties. Therefore it was decided to measure vehicles with corresponding technologies on the chassis dyno of TU Graz. The following vehicles thus have been measured:

- Seat Leon 81kW with manual transmission and modern petrol engine;
- Seat Leon 81kW with DCT (dual clutch automated) transmission and modern petrol engine;
- Toyota Auris hybrid 73kW with modern Atkinson cycle petrol engine, planetary gearbox and battery-powered electric motors. The results for the Toyota Auris have been presented already in the validation section of the hybrid vehicle simulation (see Appendix 5, Section A5.6.1).

The tests of the two Seats were used to calibrate and to validate the simulation of the conventional vehicles in the different cycles and especially to validate the simulation of DCT systems. The Auris was used for the same purposes for the hybrid simulation.

All tests used the masses and driving resistance values from the simulation of the corresponding technology and the test cycles (NEDC, WLTC, RWC) are measured in the corresponding settings. For the Toyota Auris the RWC was not measured due to the high effort needed as HEVs have to be measured twice for each cycle due to the delta SOC correction demanded in the CO_2 regulation. This allows for a direct comparison of the measured and the simulated CO_2 emissions and the model data can be adjusted by the measured component behaviour if necessary. Using identical vehicles with different transmission systems allowed for the isolated analysis of the influence of the gear box system.

Unfortunately, no results from either the measurements or the simulation work from the WLTP-NEDC correlation working group have been available for the project. The colleagues from DG JRC kindly supported the simulations by sharing their experience and existing (and not confidential) data[42]. As described already in Section 6, this significantly increased the effort needed for data acquisition at TUG and also reduced the data quality for several technologies where only OEMs have access to prototypes and/or to test and simulation results.

The settings for the corresponding cycles applied for the measurements of the Seat Leon with manual transmission are listed in Table 8.39.

Table 8.39: Dynamometer settings applied for the Seat Leon measurements

	Test mass [kg] $^{2)}$	R0 [N]	R1 [Ns/km]	R2 [Ns²/km²]
NEDC	1405	112	0,828	0,385
WLTC	1515	148	0,864	0,412
RWC	1545	164	0.972	0.412
NEDC optimized$^{1)}$	1275	71	0.528	0.307
WLTC optimized$^{1)}$	1378	101	0.552	0.329

Notes: $^{1)}$ Technology package: Mild weight reduction (10% reduction; without engine power adaptation) + aerodynamics improvement 2 (20% reduction) + low rolling resistance tyres 2 (30% reduction)

$^{2)}$ Adjusted masses on the dynamometer are slightly different to the listed masses in Table 8.37. Due to dynamometer structure only inertia classes with defined increments could be chosen.

It is important to note that all possible auxiliaries, such as air conditioning, radio, light, rear window heating, were switched off during the basic measurements.

Figure 8.42 shows the absolute CO_2 values from the Seat Leon with manual transmission measured and simulated with the C-Segment settings. Due to statutory regulation requiring a balanced battery State of Charge (SOC) the CO_2 values on WLTC were corrected as defined in the WLTC draft. For

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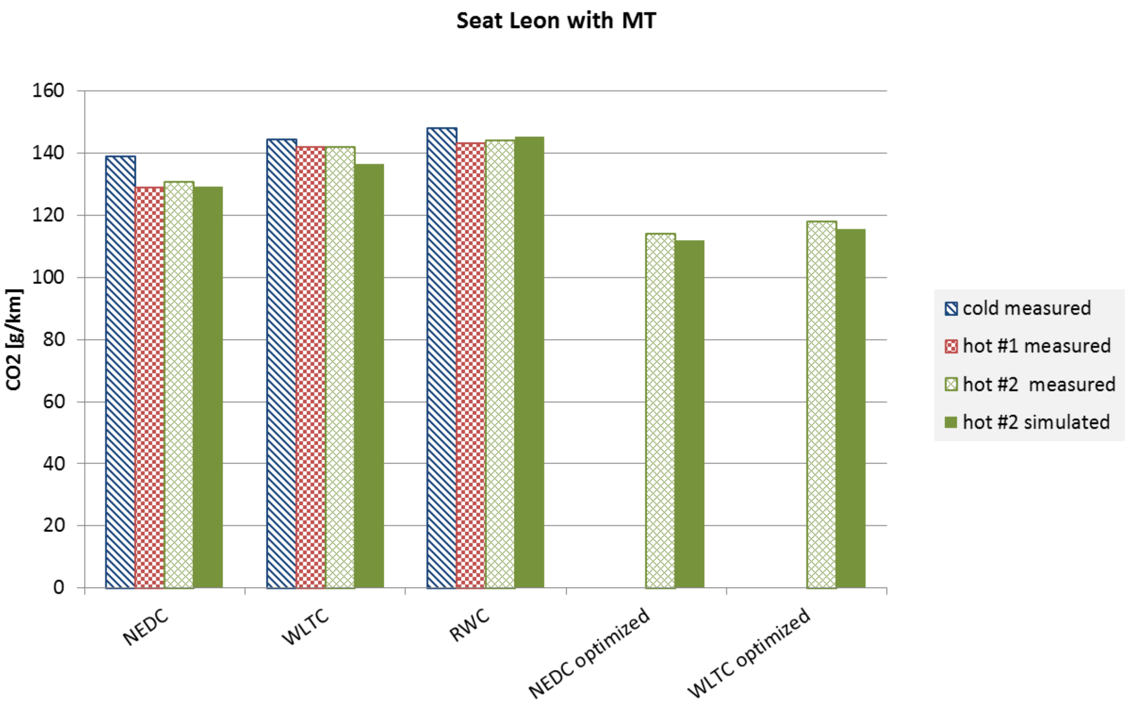
[42] Especially the support given by Giorgos Fontaras was very helpful and is acknowledged very much.

the RWC a similar procedure was chosen. In the NEDC no regulation for SOC balancing exists, therefore no CO_2 correction was made. To check for repeatability the hot cycles were measured twice for the NEDC, WLTC and RWC. In Figure 8.42 CO_2 values for the NEDC hot and WLTC hot from an optimized vehicle are also shown. An ‘optimised’ vehicle means that the vehicle mass was reduced by 10%, the aerodynamic drag coefficient by 20% and the rolling resistance by 30% as indicated in Table 8.39. The savings between the measured base and the optimised vehicle under hot start conditions are 13.4% in the NEDC and 15.4% in the WLTC. For reasons of budget and time no cold start and no second hot start were carried out with the optimised vehicle. The absolute CO_2 value for the measured NEDC with cold start amounts to 139 g/km and is 17.1% lower than the simulated CO_2 value on the NEDC with cold start for the C-Segment petrol car. The main reason for this deviation is the engine technology. For the C-Segment (lower medium) car an engine map from the year 2002 was used, whereas the Seat Leon has an engine with 2013 technology. 17% less fuel consumption from the Seat with the more fuel efficient engine and the better transmission system compared to the “2002 model year baseline vehicle” seems to be a reasonable ratio.

Figure 8.42: Measured and simulated cycles from the investigated Seat Leon with manual transmission

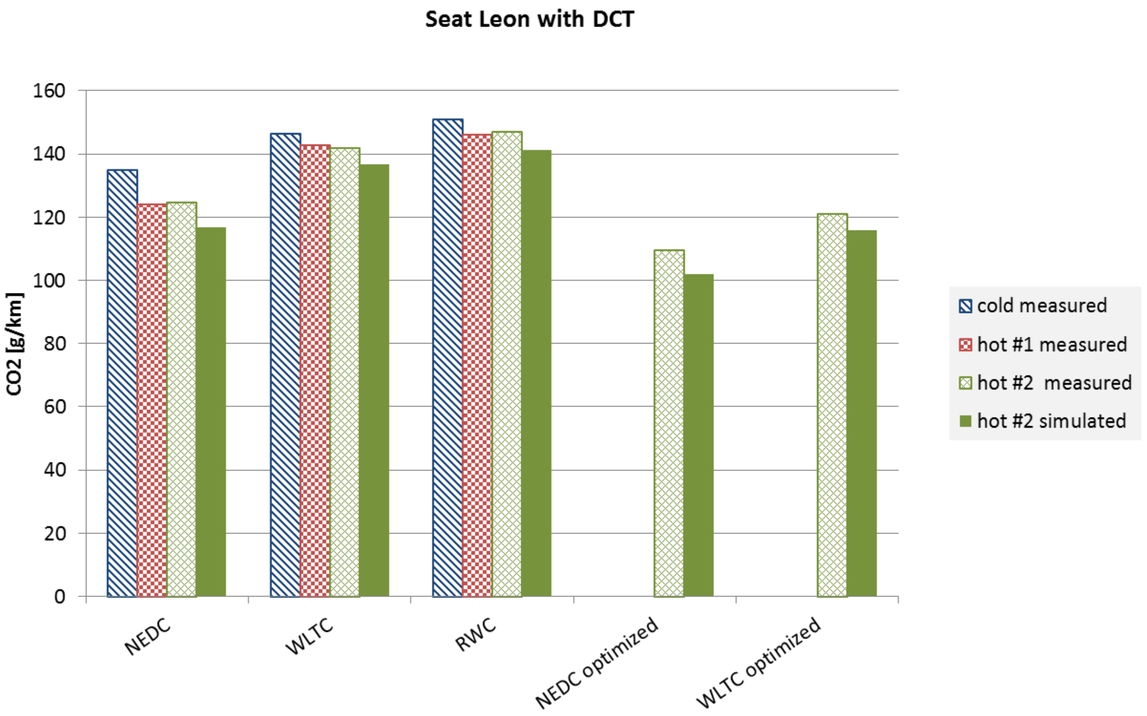


To verify the measured data some simulations were undertaken, which are also shown in Figure 8.42. For these cases the same PHEM input data (i.e. regarding test mass, driving resistances, auxiliaries, modern engine map, etc.) were chosen as adjusted on the dynamometer. The comparison between adjusted simulation and measured values showed a deviation of between 1% (i.e. the simulation overestimated the fuel consumption) and -4% (i.e. the simulation underestimated the fuel consumption) for the investigated cycles. This deviation is within the accuracy expected from the simulation using generic engine efficiency maps and also a generic model for the transmission losses. Higher accuracy would need engine maps and gear box losses from the specific vehicle make and model. Such data is not available for reasonable costs.

Thus the technologies implemented in PHEM are on a representative level in terms of absolute CO_2 emissions and also in terms of differences between the cycles.

For the measured Seat Leon with DCT, the mass and driving resistance settings were set to be identical to the Seat Leon with manual transmission.

Figure 8.43: Measured and simulated cycles from the Seat Leon with dual clutch transmission



The Seat Leon with dual clutch transmission was measured, evaluated and simulated in the same way as the Seat Leon with manual transmission. The savings between the base and the optimised vehicle under hot start condition are 12.8% on the NEDC and 15.2% on the WLTC and have the same trend as the Seat Leon with manual transmission.

The verification between measured and simulated data showed a deviation of between -4% and -7% (in all cases the simulation slightly underestimated fuel consumption).

A further task was to compare the fuel consumption and CO_2 results of a vehicle with dual clutch transmission and manual transmission. To have a useful comparison it was important to investigate the same vehicle model with the same engine technology. The measured Seat Leon fulfilled the requirements. In Figure 8.44 the percentage CO_2 changes for the different cycles and vehicle settings are presented. The vehicle with dual clutch transmission has a lower fuel consumption (about 3-4%) on the NEDC compared to the vehicle with manual transmission. For all other cycles it is reversed. Furthermore the difference on the hot WLTC is virtually zero.

These results were also reflected in the basic DCT simulations. To simulate future DCT transmissions which are assumed to be designed to gain fuel savings in the WLTP test procedure the transmission ratios and the gear shift logics have been adjusted to the WLTP conditions (see Appendix 5, Section A5.3.5 for more detail).

Figure 8.44: CO_2 changes by manual transmission versus dual clutch transmission

8.2.5 Recommendations based on the findings from the verification procedures

The key purpose of this sub-task was to analyse whether the current, relatively simple cost curve approach is still fit for purpose in terms of being able to analyse the cost effectiveness of increasingly complex vehicle technology packages. The findings from the work carried out under this task could have led to a number of different possible recommendations, including the following:

A. **The simple cost curve approach is no longer appropriate and detailed vehicle simulations and testing programmes are required.** This was a possible outcome in light of the findings from the verification programme. However, a move to a simulation-based approach would add significant cost to the ongoing development and assessment of vehicle CO_2 legislation

B. **The simple cost curve approach is broadly fit-for-purpose but adjustment factors are needed to account for complex technology packages.** It was possible that our analysis showed that there are systematic errors introduced by the basic cost curve process because of the simplified way in which this procedure deals with combinations of technologies fitted to individual vehicles. It was anticipated that in this event it might be possible to develop adjustment factors which could be used to correct the outputs from cost curve analysis with a reasonable degree of accuracy.

C. **The simple cost curve approach is fully fit-for purpose.** It was also possible to find that the outputs from the verification procedures were broadly in line with the outputs generated by the simple cost curve modelling approach, in which case, there would be no need for any modifications to the procedure.

The discussion and summary of the PHEM simulation analysis carried out for individual technologies (discussed in earlier Section 6.2) and for technology packages (above) have demonstrated the complexity in estimating both the impacts of individual technologies and combined impacts of packages of technologies on LDV fuel consumption/CO_2 reduction. Whilst the analysis has allowed for the calibration of the input assumptions for CO_2 reducing impacts of individual technologies by segment and powertrain type, the comparison of simulated package results with figures calculated from simple combinations has demonstrated significant deviations, showing that Option C above is not correct. However, the analysis has equally shown that such deviations vary considerably depending on the type of technology and its effect / interaction with other types of technologies.

Within this project it was possible to develop post-processing correction factors based on a comparison between the simulated package results and those anticipated through simple combination of individual measures. This approach, consistent with Option B above (and similar to the overlap correction previously applied in (TNO et al., 2011) and (TNO et al., 2012)), has been outlined in earlier Section 8.1.3, with the specific maximum correction factors also presented in Appendix 6 of this report.

Based on the discussion above, it is believed this (Option B) represents a good compromise between the two extremes of Options A (relatively much more expensive compared to the anticipated improved accuracy) and C (too simplistic leading to significant over-estimation of potential improvements for SI engines in particular). However, it is believed that the current approach could potentially be further enhanced by a lower level programme of selected simulations and tests to build on the work that was possible/already carried out under this project and could then better inform the adjustment for technology overlaps in the development of the final cost-curves. Especially combinations of technologies where reasonable overlapping effects are assumed could be analysed in future in packages with detailed simulation to improve the robustness of the adjustment factors.

8.3 Adjust analysis to vehicle segments or manufacturers

8.3.1 Overview of methodology for adjusting the analysis to vehicle segments or manufacturers

This task was effectively an ongoing task that aimed to identify whether there was a case for adjusting the main analysis for any particular vehicle segments or manufacturers. This might have potentially been appropriate for a number of reasons, including a narrow range of vehicles for a specific manufacturer, or the particular characteristics of a vehicle segment. If a particular segment and/or manufacturer was identified, the next stage was to identify what the implications were for the analysis. This might, for example, require sub-dividing a segment, identifying costs differently, or simply recognising that the results for a particular segment are less certain than for others.

As noted in Section 4.8.2, in the course of the project’s stakeholder engagement, those interviewed were asked for their views on whether there was a case for a particular segment or manufacturer to be treated differently within the analysis. While there was no clear conclusion from the responses, small volume manufacturers and performance vehicles were mentioned as a segment/vehicle type that might warrant further consideration in this respect. Consequently, in order to explore this issue further a direct engagement with small volume manufacturers was undertaken, along with a review of the approach taken in the US, where performance vehicles were considered to have different costs for some technologies compared to ‘non-performance’ vehicles. These two pieces of work are discussed in the two following sections.

8.3.2 Engagement with small volume vehicle manufacturers

8.3.2.1 Initial engagement

In early January 2015, the study and its methodological approach were presented to the Society of Motor Manufacturers and Traders (SMMT) in the UK. The session was attended by the European Small Volume Car Manufacturers Alliance (ESCA), as well as a number of small volume manufacturers (SVMs). After an introduction to the project, attendees were asked to suggest approaches how to adjust cost curves for non-representative segments.

The first discussion encompassed the SVM marketplace, and whether it is best represented by one or more independent segments in the analysis. It was agreed that the answer was not trivial due to mainly the following reasons:

- SVMs manufacture a diverse range of vehicles (e.g. sports cars, limousines, hearses, wheelchair accessible vehicles, taxis) with heavily divergent masses (from 500kg for the Atom to a 3 tonne Rolls Royce) and hence varying segments.
- Production volumes can vary to extremes: even if a ‘<10,000 units per annum’ approach were to be deployed, then this would also apply to manufacturers that only produce 50 units per year.
- Some SVMs produce within a single segment, while others produce segments that do not appear to be covered in the study.
- Some SVMs buy off-the-shelf engines and others develop their entire powertrain; some create new vehicles and others adapt pre-existing vehicles, which can result in SVMs working with technologies a generation behind the major manufacturers/suppliers.

The conclusion of the above considerations was that any potential adjustment factor for SVMs would necessarily have to be an ‘average’ again, covering this broad range of SVMs. Ideally an adjustment might be considered along multiple axes, i.e. (i) scale/volume and (ii) segment type.

Regarding specific *technology cost differences* between high volume (HVM) and small volume manufacturers, the following items were raised:

- **Tooling and R&D:** The amortisation of tooling and R&D is the biggest difference to HVMs which should be reflected in a change of the ICMs (i.e. in the magnitude of x 10 or even x 100). Both cost items will be amortised over much smaller vehicle numbers (hence the cost per vehicle will be much higher). Further, the metric of *€/production unit* might not be appropriate for SVMs in this respect, since significant R&D costs would have to be ‘charged’ to a very small number of vehicles.
- **Warranty costs:** SVMs have to meet a completely different level of customer satisfaction than HVMs, this cost item will hence have to be significantly higher.
- **Integration costs:** Many technologies are bought since an in-house development of the technologies would not be cost effective. However, when bought-in, adaptation costs are usually high for SVMs: given the lower volume, the integration costs per unit might be 10-100 fold higher compared to the costs of HVMs.
- **General costs for technology improvement**: SVMs are frequently already at the ‘edge of performance’, hence any further improvements will generally be much more expensive than for HVMs. Certain changes, such as changes to the floorplan, are usually avoided by all means, since this would entail the need for new crash tests, approvals etc. For an SVM such additional cost items, spread over a much smaller number of vehicles, would quickly increase the costs per vehicle immensely.

The following ‘*other’ differences* between SVMs and HVMs were discussed:

- **Learning rates**: The lifecycle of many SVM models is very different to that of HVMs. Learning rates (currently applied per technology and the same across different segments) are likely to be very different for SVMs.
- **Access to technology**: SVMs typically get access to the technologies with a 2-5 year delay. Frequently these technologies are then already more refined, however, that also signifies that SVMs do not necessarily have access to the best performing technologies that are already on the marketplace. Technologies are then generally at a better developed stage since issues (e.g. reliability) are usually resolved as they have been tried and tested already.
- **Customer demands**: Customer demands are very different in the SVM market: older technologies are frequently accepted. Usually, the customers of SVMs are not the ones asking for innovative energy saving technologies like stop start systems or low rolling resistance tyres. On the contrary, they prefer high performance and grip and appreciate sound, tone and driving experience (this is the reason why there is for example no turbo in many high performing vehicle models; and why there is little demand for EVs as these perform less well at high speeds etc.). Also fuel efficient technologies are typically ‘only’ deployed due to imposed standards, since greater fuel efficiency is not of great value-added for many customers of SVMs.

8.3.2.2 Follow-up engagement

The meeting with SVMs was followed by engagement via email with the manufacturers present at the meeting in order to enable them to contribute to the validation of the costs and CO_2 reduction dataset from the perspective of SVMs (see Section 4.8), and to give them the opportunity to comment on any other aspect of the study. A limited number manufacturers responded with comments on the dataset, all of which commented on the SI petrol technologies sheet, although not all of these gave their views on the costs of these technologies or the other worksheets in the database, i.e. on the non-powertrain technologies that have on-cycle CO_2 effects.

Of the 26 SI petrol technologies associated with the powertrain that were listed in the spreadsheet, there was agreement amongst the respondents that 10 were compatible with cars produced by SVMs and five were not; for the other eleven, the views were mixed. The following table provides a summary on the views of the consultation on the compatibility of different Si petrol technologies.

Table 8.40: Respondents' view on the compatibility of SI petrol technologies with cars produced by SVMs

Compatible technologies (respondents agreed)	Disagreement among respondents concerning the compatibility	Incompatible/irrelevant technologies (respondents agreed)
Combustion improvements for SI engines: Level 1	Natural Gas Vehicle	Combustion improvements for SI engines: Level 2
Direct injection - homogeneous	Variable valve actuation and lift	Direct injection - stratified charge & lean burn
Mild downsizing (15% cylinder content reduction) + boost	Medium downsizing (30% cylinder content reduction) + boost	Strong downsizing (>=45% cylinder content reduction) + boost
Cam-phasing	Automated manual transmission (AMT)	Continuously variable transmission (CVT)
Engine friction reduction for SI engines: Level 1	Dual clutch transmission (DCT)	Air hybrid
Engine friction reduction for SI engines: Level 2	Thermodynamic cycle improvements (a)	
Start-stop system	Thermodynamic cycle improvements (b)	
Micro hybrid - start-stop, plus regenerative braking	Cooled EGR	
Mild electric hybrid - torque boost for downsizing	Flywheel hybrid	
Full electric hybrid - with limited full electric operation	Optimising gearbox ratios / downspeeding	
	Cylinder deactivation	

Notes: Compatible = all respondents felt the technology was compatible; Not Compatible = all the respondents felt the technology was not compatible; Disagreement = mixed response / uncertainty, technology was judged to be compatible to some SVMs, but not to others.

Overall, each respondent believed that around 60% of the technologies listed were compatible with cars produced by SVMs. When asked about the potential CO_2 reductions associated with fitting the compatible technologies to their cars, in around 50% of cases the CO_2 reduction potential was considered to be lower than for the base case vehicle, i.e. a typical C-segment, by about 40% on average for 2025 (in all but four of the other cases it was considered that there would be no difference). In all but one case the associated costs were considered to be higher, with the average additional costs estimated to be between eight and 21 times higher than the respective costs associated with a typical C-segment vehicle by the different manufacturers. Similarly, the ICM was also considered to be higher than that for a C-segment vehicle by, on average, between around five to 12 times. As these manufacturers generally provide cars at the premium end of the market, it might have been expected that the costs for CO_2 reduction technology would be higher than for a C-category car, but these cost differences are probably higher than what might have been expected. One of the factors that contributes to these higher costs is that the recovery of fixed costs has to be spread over a smaller number of cars (as a result of the low production volumes) compared to larger manufacturers. Due to the lower number of vehicles sold the cost per vehicle will be much more sensitive to sales / uncertain than for larger volume manufacturers, adding to risk.

In the limited response on non-powertrain technologies, it was explicitly noted that seven of the technologies were compatible with cars manufactured by SVMs, while five were not. As with the CO_2 reduction potential and costs presented for SI petrol technologies, for the compatible technologies the CO_2 reduction potential was on average considered to be around 40% less than when compared with a C-category vehicle, while the costs and ICMs were considered to be considerably higher.

While it is possible to set out such average figures, it is more difficult to conclude that these figures should be applied. An average for CO_2 emissions reductions, costs and the ICM could be identified for each technology on the basis for the information supplied. However, the figures that were suggested for the same technology by different manufacturers were rarely the same and sometimes varied significantly. Similarly, an average figure for CO_2 emissions reduction potential, costs and ICMs, such as those mentioned above, could be applied across the board for all technologies used by SVMs. However, given that the figures that were suggested for different technologies vary considerably including such figures as average factors in the cost analysis also seems unsatisfactory, even though the numbers do suggest the potential scale of some of the differences involved. In addition, due to the low number of responses and confidential nature of the information provided, it is not possible to present details on the differences.

8.3.3 Considerations regarding premium/performance vehicle manufacturers

As noted above, the exploration of whether it was appropriate to assume different costs for certain technologies in relation to ‘performance’ cars (for larger volume manufacturers) was based on a review of the approach undertaken in the US in which such a distinction was made. The most recent equivalent legislation in the US is the CAFE LDV rule for 2017-25, which is a joint rule between the EPA and the NHTSA (US EPA and NHTSA, 2012). Together, the two agencies produce a Joint Technical Document (JTD), which includes some information on costs, but does not split these according to ‘performance’ and ‘non-performance’ cars. Supporting the JTD are two separate Regulatory Impact Assessments (RIAs), one undertaken by each agency ((US EPA, 2012) and (NHTSA, 2012)). The work presented in the respective RIAs is designed to be as consistent as practicable (NHTSA, 2012), but the two agencies use different models to support their respective analyses. It is the NHTSA’s model that makes the distinction between ‘performance’ and ‘non-performance’ vehicles[43]. Of the 67 different technologies (or technology combinations) for which incremental cost estimates are given, only for 13 is there a difference between the costs for ‘non-performance’ and ‘performance’ cars. These technologies, along with a summary of the way in which these costs are differentiated, are provided in Table 8.41. It is worth noting that no distinction is made between ‘non-performance’ and ‘performance’ cars in terms of the CO_2 reduction potential of the individual technologies in the either of the US analyses.

Table 8.41: Percentage increase in costs of ‘performance’ and ‘non-performance’ cars by NHTSA car segment compared to the costs for a ‘non-performance’ subcompact car, for the technologies for which costs for ‘performance’ and ‘non-performance’ cars differ in NHTSA (2012)

	Percentage increase in costs compared to those for ‘non-performance’ sub-compact cars							
	Non-performance cars*				Performance cars*			
Technology	**SC**	**C**	**MS**	**L**	**SC**	**C**	**MS**	**L**
Engine Friction reduction, Level 1	0%	0%	0%	0%	0%	50%	50%	100%
Low Friction Lubricants and Engine Friction Reduction, Level 2								
Discrete Variable Valve Lift (DVVL) on Single Overhead Cam (SOHC)								
DVVL on Dual Overhead Cam								
Continuously Variable Valve Lift								
Stoichiometric Gasoline Direct Injection (GDI)								
Stoichiometric GDI on Overhead Valve (OHV)								

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[43] The incremental technology cost estimates for 67 different technologies for passenger cars (for MY 2017 in 2010 dollars and taking the baseline as 2010) are provided in Tables V-121 and V-123 of NHTSA (2012) for ‘non-performance’ and ‘performance’ cars, respectively.

	Percentage increase in costs compared to those for 'non-performance' sub-compact cars							
	Non-performance cars*				Performance cars*			
Technology	**SC**	**C**	**MS**	**L**	**SC**	**C**	**MS**	**L**
Variable Valve Timing (VVT) – Coupled Cam Phasing (CCP) on SOHC	0%	0%	0%	100%	0%	100%	100%	100%
VVT – Intake Cam Phasing								
VVT – Dual Cam Phasing								
Variable Valve Actuation - CCP and DVVL on OHV								
6-speed Dual Clutch Transmission	0%	0%	-31%	-31%	-31%	-31%	-31%	-31%
Conversion from Strong Hybrid level 1 to level 2	0%	0%	0%	22%	0%	22%	22%	-41%[44]

* *Note:* 'SC' stands for 'sub-compact', 'C' for 'compact', 'MS' for 'mid-size' and 'L' for large.

Theoretically it would be possible to apply similar cost differentials in analysis similar to that undertaken within this project (although this would require rerunning the cost-curve model to estimate the potential updated impacts). However, it is not possible to assess from NHTSA (2012) whether the reasons for these differentials might be equally applicable in the EU, as there is no explanation as to why these 15 technology combinations in particular, which were less than one quarter of all of those considered, were thought to be more expensive for some categories of 'performance' car. (In the absence of this it is also not possible to reasonably extrapolate these differentials to the other technologies considered within this project). NHTSA (2012) notes that the agency consulted on the continued appropriateness of the categories of light duty vehicle that it uses, which includes the four 'performance' categories, but received no comments on this. Such a differential is clearly not considered to be fundamentally important, even in the US market, as the US EPA (2012) does not make such a distinction between 'performance' and 'non-performance' cars in its analysis. Indeed, it explicitly includes the 'performance' versions of all segments in the same category as the 'non-performance' vehicle[45].

8.3.4 Summary and concluding remarks

As indicated in the previous sections, the potential to adjust the developed generic mass-market cost curves to specific segments and manufacturers was explored.

In general terms, in the course of the engagement undertaken within the project, stakeholders were asked for their views on whether there was a case for adjusting the analysis for a particular vehicle segment or manufacturer. In addition there was also engagement with small volume manufacturers (SVMs), as these were mentioned as a set of manufacturers for which an adjustment might be appropriate. Finally, an assessment of the assumptions used in relation to premium/performance cars in the analysis undertaken in support of the 2017-2025 US CAFE regulations, as such cars were mentioned as potentially being appropriate for an adjustment in the analysis.

On the basis of the information presented above, it is not really possible or reasonable to include a correction factor in the developed average cost-curves in order to differentiate between the costs associated with CO_2 reducing technologies for SVMs nor specifically for performance vehicles. Given the relatively small numbers of vehicles involved, it is unlikely that such work would be sufficiently cost-effective and so other options, such as the derogations for some of these manufacturers in the Regulation itself, might remain more appropriate for dealing with such manufacturers. It is also worth noting that US has a special provision for SVMs as well, where they can be dealt with individually.

According to the information analysed above, costs and cost per unit reduction of CO_2 for small volume manufacturers can be substantially more for many technologies compared to those incurred by larger volume manufacturers. For performance cars, a sub-set of the equivalent analysis in the US concludes that costs for certain technologies might be twice as high as the costs associated with 'non-

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[44] This appears to be an anomaly – and might even be an error.

[45] See Table 3-42 of US EPA (2012)

performance' cars. The engagement that was undertaken in the course of this project also underlined the difficulties of simply applying a single factor to SVMs to account for potential cost differences, as a result of the lack of homogeneity in the sector. In order to arrive at more precise numbers, therefore, more work would need to be undertaken to determine what factors, if any, might be applied to different sub-categories of SVM. Given the relatively small numbers of vehicles involved, it is unlikely that such work would be sufficiently cost-effective and so other options, such as the derogations for some of these manufacturers in the Regulation itself, might remain more appropriate for dealing with such manufacturers.

A similar argument might also be made in relation to 'performance' vehicles. Indeed, in order to determine which car might be considered to be a performance car, the NHTSA (2012) simply listed the cars in each category according to their respective power-to-weight ratios and identified the transition point between a 'non-performance' and a 'performance' vehicle manually. As a result of the way in which the analysis in this report is undertaken, it is not possible to simply distinguish between 'performance' and 'non-performance' vehicles in this way. Even though the underlying peak power and vehicle mass parameters are included in the European CO_2 monitoring database, it is not within the scope of this project to undertake such time-consuming analysis (there are a very considerable number of model variants). This would also require a somewhat subjective judgement in many cases.

In summary, the data analysed suggests there is no correlation between cost analysis for larger manufacturers and SVMs. Therefore it does not appear appropriate nor possible to develop generic correction factors for the cost-curves generated in order to differentiate the CO_2 reduction costs for either small volume manufacturers or performance cars in the analysis undertaken for this study under its current constraints. SVMs should continue be treated differently as a result.

9 Summary and conclusions

The aim of this project was to develop a more detailed understanding of the technologies that are available now and that are likely to be available in the period up to 2030 for controlling passenger car and LCV CO_2 emissions for different vehicle segments. The final output from the project was to develop and present cost curves (for 2015, 2020, 2025 and 2030) by segment and powertrain type on a WLTP basis to support policy analysis on potential future regulatory targets for CO_2 emissions from LDVs post-2020.

To achieve the overall aims of the study it was necessary to gather and test available data on the cost and performance of CO_2 reducing technologies with stakeholders and develop a methodological approach for estimating their trajectories in performance and cost to 2030.

A fundamental starting point to the work involved establishing an appropriate baseline for the analysis, and confirming the appropriate LDV segmentation. This was achieved through evaluation of available literature, stakeholder views and analysis of the most recently available EEA car and van CO_2 monitoring databases to establish baseline performance and characteristics for the study analysis. The work also built upon previous analysis for the Commission for the recently completed LDV downweighting study (Ricardo-AEA, 2015). In addition, to support the setting of the baseline and later analysis, a dataset was purchased from IHS Global Insight detailing the estimated penetration levels of CO_2 reducing technologies into the marketplace by 2013. The result of this analysis was the establishment of the following segmentation for the project, including four segments for passenger cars and three for LCVs:

- Small Cars [A+B segment]
- Lower Medium Cars [C segment]
- Upper Medium Cars [D segment]
- Large Cars [Others]
- Small LCVs [<1.8t GVW]
- Medium LCVs [1.8-<2.5t GVW]
- Large LCVs [2.5-3.5t GVW]

Other early tasks for the project included the identification of a suitable list of CO_2 reducing technologies for LDVs, relevant for the period up to 2030, which was achieved via a preliminary review of available literature and initial discussions with key expert stakeholders. This list of technologies also included those expected to have beneficial impacts on fuel consumption/CO_2 emissions in the real-world, but that don't show such savings over regulatory cycles/testing protocols. Such 'off-cycle' technologies (e.g. including those qualifying as eco-innovations) have not been included in previous similar analysis for the Commission. Additional (on- and off-cycle) technologies were also added to the list as the project progressed, e.g. where they were identified in later more detailed discussions with stakeholders. The final full list included over 80 technologies taken forward for analysis in the cost-curves, plus additional information gathered on xEV powertrain components used to establish the future costs and performance of these vehicle types (i.e. including PHEVs, REEVs, BEVs and FCEVs).

The main part of the project involved the gathering, review and analysis of data (as well as more qualitative information) on CO_2 reducing technologies from the literature, and through stakeholder consultation in various forms. The stakeholder consultation activities included the following elements:

- *Gap-filling:* questionnaires and interviews used to gather specific information on technology performance and costs from key organisations.
- *Delphi Survey:* used to gather feedback and seek agreement with expert stakeholders on key aspects of the proposed methodology for developing cost estimates for technologies.
- *Validation*: obtaining feedback from key expert stakeholders on draft findings and on the initial data/assumptions for the performance and costs of technologies.
- *Interviews and ad-hoc communications*: used to gather both general feedback on a range of relevant areas, or specific information on key data, methodologies or other assumptions

This aspect of the project was particularly challenging due to sometimes conflicting views on the performance and costs of different technical options between different stakeholders, and also with information available in the literature. In such considerations, higher priority/weighting was given to data derived using more rigorous and transparent methodologies (such as the tear-down based cost estimates developed for the US EPA/NHTSA (EPA & NHTSA, 2012) and for ICCT (FEV, 2013a), (FEV, 2012)) and those given by expert industry stakeholders over less detailed information available in the wider public literature. (For many technologies the estimated manufacturing costs were significantly lower than those used in previous cost-curve analysis for the Commission.) Unfortunately, the approach adopted by the majority of OEMs, i.e. to only provide generalised feedback via their trade association, somewhat hampered the ability to explore in more detail the reasons for disagreement with some of the cost estimates (e.g. those derived by tear-down studies) for certain technologies. In contrast, a significant number of automotive suppliers provided useful feedback / key data for the project.

For technical options for reducing off-cycle CO_2 emissions, the challenge in many cases was in finding *any* relevant CO_2 reduction and cost estimates, rather than on resolving conflicting sometimes information. For these technical options the gap-filling and wider interviews with OEMs and their suppliers were critical to obtaining key data. Even so, some options could not be taken forward into the cost-curve analysis due to lack of data on their costs and/or CO_2 reducing performance. Overall, significant revisions were made to the original draft data/assumptions for all technical options following feedback from the data validation process and interviews with stakeholders in the consultation phase.

The outcomes from the data gathering, analysis and wider consultation activities from the cost perspective included a finalised set of direct manufacturing costs (DMC) and a refined methodological approach to estimate the future costs of individual technical options. This approach also included the development and refinement of learning curves and indirect cost multipliers (ICMs) assigned to different technologies, and the development of segment multipliers (SM) used to scale costs between different LDV segments. These elements, together with estimates for their respective uncertainties were utilised in a statistical uncertainty analysis using a Latin Hypercube Sampling (LHS) approach to derive estimates for the typical, low and high costs of technologies for different segments and future years.

For advanced xEVs, a slightly different approach was adopted, which involved the development of estimates for the additional costs (and CO_2 /energy reducing performance) of these powertrains for different time periods from information on individual components (i.e. batteries, motors, fuel cells, and a range of other xEV components) scaled to different LDV segments. The specific assumptions used in this analysis were gathered from existing available literature (including other recent studies by Ricardo Energy & Environment) and tested with stakeholders. In addition, a series of alternative xEV deployment scenarios were used to explore the potential range in possible future costs based on a simplified learning methodology applied to individual xEV components. The result was a set of typical, low and high estimates for the costs of different xEV powertrain types by vehicle segment and year.

Part of the overall work programme for this project also involved the simulation of the impacts of different technologies on the fuel consumption/CO_2 emissions from different LDV segments, powertrain types and test cycles (including NEDC, WLTP and real-world cycles). This work was conducted by TU Graz using the PHEM model and involved the definition, setting-up, calibrating and running of in the end around 2500 simulations of individual technologies with different LDV segments and powertrains, as well as a number of technology packages. The outputs from this analysis were critical to the project for a number of reasons, including:

e) Providing cross-corroboration of CO_2 savings from the literature or stakeholders for particular technical options;
f) Providing evidence to estimate the potential variation in specific CO_2 savings for different vehicle segments (and powertrain types) based on the different baseline characteristics;
g) Allowing the estimation of CO_2 savings potentials on a WLTP-basis for different technologies from the primarily NEDC-based CO_2 savings information available in the literature/from stakeholders;
h) Informing the development of suitable correction factors for the cost-curves to account for overlaps in the action of compatible technologies (i.e. by comparing the results of the technology package simulations with estimates of combined CO_2 reductions based on individual technology results).

During the course of the project TU Graz also performed a range of other analysis in order to provide verification checks for the developed cost-curves / the cost-curve input data assumptions, this included using information from currently deployed vehicle types, as well as a limited programme of component testing and simulation.

The final outputs from the LHS uncertainty analysis of technology costs and the combination of data from the PHEM simulations and consolidated CO_2 reductions by technology were used to generate a series of around 250 cost-curves on a WLTP basis using the cost-curve model newly developed by JRC. This included different combinations of powertrain type (conventional, PHEV, REEV, BEV, FCEV), LDV segment, and year (2015, 2020, 2025 and 2030), as well as providing separate cost-curves with/without off-cycle technologies included. As part of this process, a number of post-processing steps were also applied to the data output from the cost curve model, including:

5. Adjustment of the initial dataset to correct for already deployed technologies in the 2013 baseline;
6. Correcting for battery/H_2 storage cost savings in maintaining electric / hydrogen range (xEVs only);
7. Correcting for overlaps in technologies (based on analysis of the outputs of the PHEM simulation of technology packages by TU Graz);
8. Re-baselining xEV powertrain cost-curves relative to 2013 conventional powertrains (xEVs only).

The final set of cost-curve equations for the entire set of core WLTP-based cost-curves is being provided alongside this report in an Excel summary file to complement the Technology Results Data Fiche. This MS Excel based fiche of information provides all the key outputs/results from the project, including the final set of costs and CO_2 performance figures for individual technology options, as well as key datasets used to derive them (e.g. the DMCs, learning curves, ICMs, segment multipliers and their uncertainties input to the LHS analysis).

In addition a number of additional cost-curves were also developed to provide sensitivities/comparisons, including comparisons of NEDC-based cost curves for lower medium cars with those generated in other previous work for the Commission and cost-curves illustrating the impact of switching between the typical, low and high technology cost estimates.

Overall it is concluded that the revised cost-curve approach (supported by a detailed analysis of technology costs and vehicle simulations) provides a good compromise between the two alternative extremes, i.e.: (i) a full simulation/testing programme (relatively vastly more expensive to feed a similar number of cost-curves compared to the anticipated improved accuracy), and (ii) simple cost-curve generation without post-processing corrections (too simplistic leading to significant over-estimation of potential improvements for SI engines in particular). However, it is believed that the current approach could potentially be further enhanced by a lower level programme of additional selected simulations and tests to build on the work that was possible/already carried out under this project and could then better inform the adjustment for technology overlaps in the development of the final cost-curves.

The final task for this project involved also consideration of the need/potential to adjust the developed average (mass-market) cost-curves to other vehicle segments or manufacturers. In the course of the engagement undertaken within the project, stakeholders were asked for their views on whether there was a case for adjusting the analysis for a particular vehicle segment or manufacturer. In particular, engagement was carried with small volume manufacturers, as these were mentioned as a set of manufacturers for which an adjustment might be appropriate. In addition, an assessment of the assumptions used in relation to performance cars in the analysis undertaken in support of the 2017-2025 US CAFE regulations was carried out, as such cars were mentioned as potentially being appropriate for an adjustment in the analysis.

Overall, the analysis concluded that it was not appropriate or possible to develop a generic correction factor for either small volume manufacturers or performance cars more widely for the analysis undertaken within this study. In both cases, more work would be needed to explore whether suitable, more specific factors could be identified, but even then it is likely that subjective judgement would be required, thus questioning the added value of such additional work.

Given the relatively small numbers of vehicles involved, it is unlikely that such work would be sufficiently cost-effective and so other options, such as the derogations for some of these manufacturers in the Regulation itself, might remain more appropriate for dealing with such manufacturers / segments.

10 References

ACEA. (2015, February). *Statistics.* Retrieved from http://www.acea.be/statistics

ACEA et al. (2014). *A Review of Battery Technologies for Automotive Applications.* EUROBAT, ACEA, JAMA, KAMA and ILA. Available at: http://www.acea.be/uploads/publications/Rev_of_Battery_technology_-_full_report.pdf. Retrieved September 2014, from http://www.acea.be/uploads/publications/Rev_of_Battery_technology_-_full_report.pdf

ADL. (2003). *Investigation of the Consequences of Meeting a New Car Fleet Target of 120g/km CO2 by 2012.* Arthur D. Little.

AEA. (2009). *Assessment with respect to long term CO2 emission targets for passenger cars and vans.* EC, DG Environment; http://ec.europa.eu/clima/policies/transport/vehicles/docs/2009_co2_car_vans_en.pdf .

AEA et al. (2009). *Assessment of options for the legislation of CO2 emissions from light commercial vehicles. Updated report for the European Commission.* Retrieved from http://ec.europa.eu/clima/events/docs/0019/final_report_lcv_co2_250209_en.pdf

Anderman. (2010). *Feedback on ARB's Zero-Emission Vehicle Staff Technical Report.* http://www.arb.ca.gov/msprog/zevprog/2009zevreview/anderman_review.pdf.

Argonne National Laboratory. (2012). *Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles.* http://www.cse.anl.gov/batpac/files/BatPaC%20ANL-12_55.pdf.

Audi. (2007, März). Retrieved Mai 23, 2015, from http://origin-www.audi.com/etc/medialib/ngw/product/used_cars/a3/pdf/a38p.Par.0047.File.pdf/2007_03_a3_ab2_20tdi.pdf

Auto Motor Sport. (2014, 06 11). *Fahrbericht Citroën C4 Cactus: Genügsamer Pragmatiker unter den Crossovern*. Retrieved from http://www.auto-motor-und-sport.de/fahrberichte/citroen-c4-cactus-genuegsamer-pragmatiker-unter-den-crossovern-8376724.html

Auto Motor und Sport. (2014, 10 01). *VW-Entwicklungschef: Kein Dreizylinder im VW Passat .* Retrieved from http://www.auto-motor-und-sport.de/news/vw-entwicklungschef-kein-dreizylinder-im-vw-passat-8636638.html

Autocar. (2014, 10 24). *PSA Peugeot Citroën seeks partners for Hybrid Air tech. By Steve Cropley.* Retrieved from http://www.autocar.co.uk/car-news/industry/psa-peugeot-citroen-seeks-partners-hybrid-air-tech

Automotive Engineer. (2011, 05 11). *Range Rover Evoque. By Simon Bickerstaffe.* Retrieved from http://ae-plus.com/vehicle-development/range-rover-evoque/page:2

Automotive Engineer. (2014, 06 13). *Q&A: Anne Ruthmann. By James Allen.* Retrieved from http://ae-plus.com/qanda/qanda-anne-ruthmann

Automotive Logistics. (2013, 01 09). *Honda overhauls platform strategy.* Retrieved from http://www.automotivelogisticsmagazine.com/news/honda-overhauls-platform-strategy

Automotive Manufacturing Solutions. (2014, 10 03). *Villaverde: To blossom with Cactus? By Glenn Brooks*. Retrieved from http://www.automotivemanufacturingsolutions.com/focus/psa-villaverde-to-blossom-with-the-cactus

Automotive News. (2014, 11 03). *GM, Renault, VW, others bet on megaplatforms.* Retrieved from http://www.autonews.com/article/20141103/OEM/141039956/gm-renault-vw-others-bet-on-megaplatforms

Automotive News. (2014). *Toyota's fuel cell goal: Big cost cutting*. Retrieved from Automotive News: http://www.autonews.com/article/20141124/OEM06/311249976/toyotas-fuel-cell-goal-big-cost-cutting

Automotive News. (2014, 03 03). *Transit family will replace long-popular E-series vans. By Bradford Wernle.* Retrieved from http://www.autonews.com/article/20140303/OEM04/303039969/transit-family-will-replace-long-popular-e-series-vans

Automotive News Europe. (2014, 07 05). *Ford says Mondeo sales will be boosted by platform sharing with Lincoln. By Nick Gibbs.* Retrieved from http://europe.autonews.com/article/20140705/ANE/140709908/ford-says-mondeo-sales-will-be-boosted-by-platform-sharing-with

Automotive News Europe. (2014a). *PSA in engine supply talks as BMW, Ford end partnerships.* Retrieved from http://europe.autonews.com/article/20141002/ANE/141009923/psa-in-engine-supply-talks-as-bmw-ford-end-partnerships

BBC News. (2012, 10 03). *Will carmaker alliances result in identikit cars? By Jorn Madslien.* Retrieved from http://www.bbc.co.uk/news/business-19784691

BCG. (2009). *The comeback of the electric car? How real, how soon, and what must happen next.* http://electricdrive.org/index.php?ht=a/GetDocumentAction/id/27914.

Beene, R. (2015, April 20). *VW says it could cut battery costs with single design*. Retrieved from Automotive News: http://www.autonews.com/article/20150420/OEM06/304209953/vw-says-it-could-cut-battery-costs-with-single-design

Brogan, M. (2014, October 6). *Volkswagen expects 500km battery range by 2020*. Retrieved from Motoring.com.au: http://www.motoring.com.au/news/2014/volkswagen/volkswagen-expects-500km-battery-range-by-2020-46561

Car and Driver Blog. (2009, 10). *Chrysler Buys GEMA Stakes from Mitsubishi and Hyundai. By Jake Holmes.* Retrieved from http://blog.caranddriver.com/chrysler-buys-gema-stakes-from-mitsubishi-and-hyundai/

CCC. (2012). *Cost and performance of EV batteries.* Final report by Element Energy for the UK Committee on Climate Change. Available at: http://www.element-energy.co.uk/wordpress/wp-content/uploads/2012/06/CCC-battery-cost_-Element-Energy-report_March2012_Finalbis.pdf.

Citroen. (2014). *Citroen C4 Cactus web page*. Retrieved from http://www.citroen.de/modelle/citroen/citroen-c4-cactus.html

Clay-Wiliams, R., & Braithwaite, J. (2009). Determination of health-care teamwork training competencies: a Delphi study. *International Journal for Quality in Health Care 2009; Volume 21, Number 6*, 433-440.

Crosse, J. (2014, October 15). *Mercedes-Benz lays out its vision for the powertrains of the future*. Retrieved from Autocar: http://www.autocar.co.uk/car-news/new-cars/mercedes-benz-lays-out-its-vision-powertrains-future

Daimler AG. (2013). *Progress on FCEV development, IEA H2 Roadmap Workshop.* Retrieved from International Energy Agency: https://www.iea.org/media/workshops/2013/hydrogenroadmap/Session1.1WindDaimlerProgressonFCEVdevelopment.pdf

Der Spiegel. (2014, 06 20). *Autogramm Citroën C4 Cactus: Es geht auch einfach. By Tom Grünweg*. Retrieved from http://www.spiegel.de/auto/fahrberichte/citroen-c4-cactus-fahrbericht-mit-dem-suv-a-975913.html

Der Spiegel. (2014, 10 13). *VW-Chef Winterkorn über sein Sparprogramm: "Vielleicht weniger Leiharbeiter".* Retrieved from http://www.spiegel.de/spiegel/vorab/vw-chef-winterkorn-ueber-sein-sparprogramm-a-996663.html

Deutsche Bank. (2009). *Electric Cars: Plugged In 2 - A mega-theme gains momentum.* http://www.libralato.co.uk/docs/Electric%20Cars%20Plugged%20In%202%20Deutsche%20Bank%202009.pdf.

Diez, W. (2014). *Produktpolitik in der Automobilwirtschaft, Vorlesung Master AUM Sommersemester 2014, Institut für Automobilwirtschaft.* Retrieved from http://www.ifa-info.de/downloads/3645/Vorlesung%20Produktpolitik%20Master%20AUM%20SS%202014.pdf

EC. (1999). *Case No IV M.1406 -- HYUNDAI / KIA Notification of 17 February 1999 pursuant to Article 4 of Council Regulation No 4064/89*. Retrieved from http://ec.europa.eu/competition/mergers/cases/decisions/m1406_en.pdf

EC. (2004). *Subat - EC FW 6 Project.* European Commission, http://www.battery-electric.com/subatdocs/WP5-006.pdf.

Economist. (2010, 06 10). *Automotive alliances multiply: All together now.* Retrieved from http://www.economist.com/node/16322641

EEA. (2014). *Monitoring of CO2 emissions from passenger cars – Regulation 443/2009.* Retrieved June 2014, from http://www.eea.europa.eu/data-and-maps/data/co2-cars-emission-7

EEA. (2014a). *Monitoring of CO2 emissions from vans – Regulation 510/2011.* Retrieved June 2014, from http://www.eea.europa.eu/data-and-maps/data/vans-3

Eichlseder, H. (2012). Script on combustion engines, detailed education; Script of the Institute for Internal Combustion Engines and Thermodynamics at TU-Graz; LV-Nr: Nr. 313.008; February 2012.

Eichlseder, H., Klüting, M., & Piock, W. (2008). Grundlagen und Technologien des Ottomotors (Basics and Technologies from the SI Engine). *Hrsg Helmut List; Springer Wien New York; ISBN 978-3-211-25774-6; 2008*.

EICT. (2009). *Prospects and Opportunities of Information and Communication Technologies (ICT) and Media, International Delphi Study 2030, Nationaler IT Gipfel, Stuttgart.* Retrieved from http://www.telekom.com/static/-/15404/3/zukunftsstudie-summary-si, acessed 22/01/2015

Emisia. (2013). *TRACCS: Transport data collection supporting the quantitative analysis of measures relating to transport and climate change. "From collected data to final dataset".* A report by Emisia, Infras and IVL for DG CLIMA: European Commission. Retrieved from http://traccs.emisia.com/index.php

EPA & NHTSA. (2012). *Joint Final Technical Support Document: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards.* Available at: http://www.epa.gov/otaq/climate/documents/420r12901.pdf.

EPA. (2009a). *Automobile Industry Retail Price Equivalent and Indirect Cost Multipliers.* Available at: http://www.epa.gov/otaq/ld-hwy/420r09003.pdf.

EPA. (2009b). *Peer Review for the RTI Report, Automobile Industry Retail Price Equivalent and Indirect Cost Multipliers.* Available at: http://www.epa.gov/otaq/ld-hwy/420r09004.pdf.

European Commission. (2009). *Proposal for a Regulation of the Euorpean Parliament and Council: Setting emission performance standards for new light commercial vehicles as part of the Community's integrated approach to reduce CO2 emissions from light-duty vehicles, COM(2009) 593 final.* Retrieved from http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2009:0593:FIN:En:PDF

FEV. (2012). *Light-Duty Vehicle Technology Cost Analysis – European Vehicle Market, Additional Case Studies (Phase 2), Analysis Report BAV 11-683-001.* Washington DC: Prepared for the International Council on Clean Transportation.

FEV. (2013). *Light-Duty Vehicle Technology Cost Analysis – European Vehicle Market (Phase 1), Analysis Report BAV 10-449-001B.* Washington DC: Prepared for the International Council on Clean Transportation.

FEV. (2013a). *Light-Duty Vehicle Technology Cost Analysis – European Vehicle Market (Phase 1). Revised Final report.* A report prepared by FEV for the International Council on Clean Transportation (ICCT). Retrieved from http://www.theicct.org/sites/default/files/ICCT%20Phase%201%20Revised%20Final%20Report_Trans_%20080713B.pdf

FEV. (2013b). *Updated Indirect Cost Multiplier (ICM) Methodology.* Available at: http://www.theicct.org/sites/default/files/2013%20-%20FEV%20-%20ICM%20analysis.pdf.

FEV. (2013b). *Updated Indirect Cost Multiplier (ICM) Methodology, s.l.* http://www.theicct.org/sites/default/files/2013%20-%20FEV%20-%20ICM%20analysis.pdf: A report prepared by FEV for the International Council on Clean Transportation (ICCT).

FEV. (2014). *P2 Hybrid Electrification System Cost Reduction Potential, Analysis Report BAV 10-683-001_4.* Washington DC: Prepared for the International Council on Clean Transportation.

Fiat Chrysler Automobiles. (2014, 05 06). *Global Architectures & Standardization Presentation. Investor Day Auburn Hills.* Retrieved from http://www.chryslergroupllc.com/Investor/Webcast/Investor%20Presentations/Global%20Architectures%20and%20Standardization.pdf

Financial Times. (2013, 12 10). *Auto industry: Hybrid carmakers. By Henry Foy.* Retrieved from http://www.ft.com/intl/cms/s/2/52132bc0-583f-11e3-82fc-00144feabdc0.html#axzz3HXZ3wkWP

FISITA. (2012). *FISITA World Automotive Congress 2012*. Retrieved August 22, 2014, from http://www.fisita2012.com/programme/programme/

FISITA. (2014). *FISITA World Automotive Congress 2014*. Retrieved August 22, 2014, from http://www.fisita2014.com/programme/sessions

Flierl, R., & Paulov, M. (2011). Potenziale des vollvariablen Ventiltriebs beim Turbo –Ottomotor mit Direkteinspritzung (Potentials of full variable valve actuation at turbo-charged SI engines); Forschung Emissionen; MTZ 07-0812011; 72. Jahrgang; 2011.

Ford. (2014, 01 14). *Deutsche Bank Global Auto Industry Conference Presentation.* Retrieved from http://corporate.ford.com/doc/371/603/ir_20140114_Deutsche_Bank_Presentation,0.pdf

Frost & Sullivan. (2009). *Strategic Analysis of North American Passenger Electric Vehicle Market.* http://www.frost.com/prod/servlet/report-brochure.pag?id=N598-01-00-00-00.

General Motors. (2014, 10 01). *Investor Briefing Presentation by Mark Reuss, Executive Vice President.* Retrieved from http://online.wsj.com/public/resources/documents/GM_Reuss_slideshow10022014.pdf

Handelsblatt. (2014, 08 01). *Probleme im Werk Wolfsburg: VW schmeißt Produktionsvorstand raus.* Retrieved from http://www.handelsblatt.com/unternehmen/industrie/probleme-im-werk-wolfsburg-vw-schmeisst-produktionsvorstand-raus-seite-all/10280384-all.html

Hausberger, S. (2003). *Simulation of Real World Vehicle Exhaust Emissions.* VKM-THD Mitteilungen; Heft/Volume 82; Verlag der Technischen Universität Graz; ISBN 3-901351-74-4.

Hausberger, S. (2011). PHEM das Modell der TU Graz zur Berechnung von Kfz-Emissonen und seine Datenbasis bei Euro 5 und Euro 6. *Fachtagung Emissionen und Minderungspotenziale im Verkehrsbereich.* Stuttgart, 21.07.2011: Hausberger S., Rexeis M., Luz R.

Hausberger, S. (2012). New Emission Factors for EURO 5 & 6 Vehicles. *19th International Conference, Transport and Air Pollution, 26 – 27.11.2012.* Thessaloniki: A presentation by Hausberger S., Rexeis M., Luz R.

Hausberger, S., Ligterink, N., & et.al. (2015). *Correction algorithms for WLTP chassis dynamometer and coast-down testing.* Report for DG Enterprise; TNO, Netherlands, 2015.

Heise. (2008, Februar 5). *heise Autos.* Retrieved Mai 23, 2015, from http://www.heise.de/autos/artikel/Trocken-nachgelegt-das-neue-7-Gang-DSG-von-VW-792427.html

ICCT. (2013). *European Vehicle Market Statistics - Pocketbook 2013.* Retrieved October 3, 2014, from http://www.theicct.org/sites/default/files/publications/EU_vehiclemarket_pocketbook_2013_Web.pdf

ICCT. (2013a). *Near-term technology potential for new cars in the EU.* http://www.theicct.org/briefing-near-term-tech%20potential-new-cars-eu.

ICCT. (2014). *Data provided in the frame of this study.*

ICCT. (2015). Retrieved from Vehicle technology costs: Estimates vs. reality: http://www.theicct.org/blogs/staff/vehicle-technology-costs-estimates-vs-reality

ICF. (2011). *Comparison of Vehicle Efficiency Technology Attributes and Synergy Estimates.* http://www.nrel.gov/docs/fy11osti/47806.pdf.

IEA. (2011). *Technology Roadmap - Electric and plug-in hybrid electric vehicles.* http://www.iea.org/publications/freepublications/publication/EV_PHEV_Roadmap.pdf.

IKA. (2012). *CO2 reduction potentials for passenger cars until 2020.* http://www.bmwi.de/BMWi/Redaktion/PDF/Publikationen/Studien/co2-reduzierungspotenziale-bei-pkw-bis-2020-management-summary-en,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf.

IKA. (2012). *CO2-Reduktionspotentiale bei Pkw bis 2020. Study for BMWi.* Retrieved from http://www.bmwi.de/BMWi/Redaktion/PDF/Publikationen/Studien/co2-reduzierungspotenziale-bei-pkw-bis-2020-abschlussbericht,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf

IKA. (2014). *CO2-Emissionsreduktion bei Pkw und leichten Nutzfahrzeugen nach 2020. Study for BMWi.* Retrieved from http://www.bmwi.de/BMWi/Redaktion/PDF/Publikationen/co2-emissionsreduktion-bei-pkw-und-leichten-nutzfahrzeugen-nach-2020-abschlussbericht,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf

Infineon. (2008). *Reducing CO2 Emissions and Achieving 2020 Fuel-Efficiency Requirements: A US Perspective on Demand-driven Electric Power Control.* https://www.btipnow.com/library/white_papers/reducing_co2_emissions_and_achieving_2020.pdf.

IVT. (2013). Thermodynamik des Verbrennungsmotors (Thermodynamics of the Combustion Engine), Script of the Institute for Internal Combustion Engines and Thermodynamics at TU-Graz. TU Graz, 2013.

IW Köln. (2013, 02). *CO2-Regulierung für Pkw: Fragen und Antworten zu den europäischen Grenzwerten für Fahrzeughersteller. By Thomas Puls.* Retrieved from http://www.iwkoeln.de/_storage/asset/107033/storage/master/file/2626704/download/Brosch%C3%BCre+CO2+Grenzwerte+Druck.pdf

JEC. (2013). *Well-to-Wheels analysis of future automotive fuels and powertrains in the European context: TANK-TO-WHEELS Report Version 4.0. JEC WELL-TO-WHEELS ANALYSIS.* A report by Arno HUSS (AVL), Heiko MAAS (FORD), Heinz HASS (EUCAR/Ford); JRC-EUCAR-CONCAWE; Published by EC JRC Institute for Energy and Transport. Retrieved September 2014, from http://iet.jrc.ec.europa.eu/about-jec/sites/iet.jrc.ec.europa.eu.about-jec/files/documents/report_2013/ttw_report_v4_july_2013_final.pdf

JRC. (2009). *Plug-in Hybrid and Battery-Electric Vehicles: State of the research and development and comparative analysis of energy and cost efficiency.* EC Joint Research Center - http://ftp.jrc.es/EURdoc/JRC54699_TN.pdf.

JRC. (2011). *Well-to-Wheels analysis of future automotive fuels and powertrains in the European context: TANK-TO-WHEELS Report Version 3, TTW APPENDIX 1: Vehicle retail price estimation. JEC WELL-TO-WHEELS ANALYSIS.* A report by R. Edwards (JRC), J-F. Larivé (CONCAWE) and J-C. Beziat (Renault/EUCAR); Published by the EC JRC Institute to for Energy and Transport. Retrieved September 2014, from http://iet.jrc.ec.europa.eu/about-jec/sites/iet.jrc.ec.europa.eu.about-jec/files/documents/wtw3_ttw_appendix1_eurformat.pdf

Luz, R., & Hausberger, S. (2013). *User Guide for the Model PHEM, Version 11.2.* Institute for Internal Combustion Engines and Thermodynamics, TU Graz.

Luz, R., Hausberger, S., Rexeis, M., & al., e. (2011). *Optimisation tool for Hybrid Electric Recuperation and Operation Strategies.* Endbericht des Projektes „HERO“ finanziert im Rahmen der 2. Ausschreibung der Programmlinie a3plus des Forschungs- und Technologieprogramms iv2splus. Graz, 30.5.2011.

MDOT-CAR. (2012). *Connected Vehicle Technology - Industry Delphi Study.* Retrieved from MICHIGAN DEPARTMENT OF TRANSPORTATION & THE CENTER FOR AUTOMOTIVE RESEARCH: https://www.michigan.gov/documents/mdot/09-27-

2012_Connected_Vehicle_Technology_-_Industry_Delphi_Study_401329_7.pdf, accessed 22/01/2

Merker, G., Teichmann, R., & et.al. (2014). *Grundlagen verbrennungsmotoren (Basics on combustion engines); 7th edition; Springer Vieweg; ATZ/MTF Fachbuch; 2014.*

NAS. (2002). *Effectiveness and impact of corporate average fuel (CAFE) economy standards.* Washington D.C.: Transportation Research Board.

NAS. (2011). *Assesment of fuel economy technologies for light-duty vehicles.* Washington D.C.: The national academies press.

NHTSA. (2010). *Final Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards .* http://www.epa.gov/otaq/climate/regulations/420r10901.pdf.

NHTSA. (2012). *“Corporate Average Fuel Economy Standards for MY 2017-MY 2025 Passenger Cars and Light Trucks: Final Regulatory Impact Analysis”.* US NHTSA, August 2012. Available from: www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/FRIA_2017-2025.pdf.

NHTSA. (2012). *Corporate Average Fuel Economy for MY 2017-MY 2025 Passenger Cars and Light Trucks - Final Regulatory Impact Analysis.* US NHTSA, August 2012. Available at: http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/FRIA_2017-2025.pdf.

Nissan. (2015). *Fuel Cell Electric Vehicles (FCEV)*. Retrieved from Nissan Motor Corporation: http://www.nissan-global.com/EN/ENVIRONMENT/CAR/FUEL_BATTERY/DEVELOPMENT/FCV/

NRC. (2002). *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE). Standards Committee on the Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards. National Research Council.* Transportation Research Board. Retrieved from http://www.nap.edu/catalog/10172/effectiveness-and-impact-of-corporate-average-fuel-economy-cafe-standards

NRC. (2011). *Assessment of Fuel Economy Technologies for Light-Duty Vehicles. Committee on the Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy, National Research Council.* The national academies press. Retrieved from http://www.nap.edu/catalog/12924/assessment-of-fuel-economy-technologies-for-light-duty-vehicles

Okoli, C., & Pawlowski, S. (2004). The Delphi method as a research tool: an example, design considerations and applications. *Information & Management 42*, 15–29.

ParisTech Review. (2014, 04 30). *Mega-Platforms: martingale of the automotive industry?* Retrieved from http://www.paristechreview.com/2014/04/30/mega-platforms-automotive-industry/

Pramhas, J., Schutting, E., Eichlseder, H., & et.al. (2013). Air Management Methods for Diesel Engine Thermomanagement;. *14. Congress on the work process of combustion engines; Graz, Sept. 2013.*

PSA. (2014, 04 14). *Back in the Race: Operational framework for a turnaround.* Retrieved from http://www.autonews.com/assets/PDF/CA94156414.PDF

Radivoje, B., PEŠI, & et.al. (2010). Radivoje B. PEŠI et.al.: BENEFITS AND CHALLENGES OF VARIABLE COMPRESSIONRATIO AT DIESEL ENGINES; Faculty of Mechanical Engineering in Kragujevac, Kragujevac, Serbia. *THERMAL SCIENCE: Year 2010, Vol. 14, No. 4* , pp. 1063-1073.

Rayens, M., & Hahn, E. (2000). *Building Consensus Using the Policy Delphi Method.* Retrieved from http://www.mc.uky.edu/tobaccopolicy/ResearchProduct/BuildingConsensus.pdf, accessed 22/01/2015.

Reuters. (2013, 10 08). *Aston Martin scraps Cygnet city car after dire sales. By Rhys Jones and Kate Holton.* Retrieved from http://uk.reuters.com/article/2013/10/08/uk-britain-astonmartin-idUKBRE9970IF20131008

Reuters. (2013a, 02 11). *Insight: Has Volkswagen discovered the Holy Grail of carmakers?* Retrieved from http://uk.reuters.com/article/2013/02/11/us-autos-volkswagen-future-idUSBRE91A04D20130211

Reuters. (2014, 10 03). *Daimler, Renault-Nissan extend manufacturing alliance. By Edward Taylor.* Retrieved from http://www.reuters.com/article/2014/10/03/daimler-nissan-idUSL6N0RY1W020141003

Reuters. (2014, 10 03). *Daimler, Renault-Nissan extend manufacturing alliance. By Edward Taylor.* Retrieved from http://www.reuters.com/article/2014/10/03/daimler-nissan-idUSL6N0RY1W020141003

Reuters. (2014a, 06 05). *Arbitration court to rule on Volkswagen-Suzuki row by year-end: sources. By Andreas Cremer and Jan Schwartz.* Retrieved from http://www.reuters.com/article/2014/06/05/us-volkswagen-suzuki-motor-idUSKBN0EG1UB20140605

Rexeis, M. (2009). *Ascertainment of Real World Emissions of Heavy Duty Vehicles. Dissertation.* Institute for Internal Combustion Engines and Thermodynamics, Graz University of Technology.

Ricardo-AEA. (2013). *Fuelling Europe's Future - How auto innovation leads to EU jobs, An Economic Assessment of Low Carbon Vehicles.* A report by Cambridge Economics, Ricardo-AEA and Element Energy for the European Climate Foundation. Retrieved from http://www.camecon.com/EnergyEnvironment/EnergyEnvironmentEurope/FuellingEuropesFuture.aspx

Ricardo-AEA. (2015). *The potential for mass reduction of passenger cars and light commercial vehicles.* Service Request 1 under the LDV Emissions Framework Contract (Ref. CLIMA.C.2/FRA/2012/006). A report by Ricardo-AEA, TU Graz, TEPR and CAIR for European Commission, DG CLIMA. Available: http://ec.europa.eu/clima/policies/transport/vehicles/studies_en.htm.

Ricardo-AEA and TEPR. (2015). *Evaluation of Regulations 443/2009 and 510/2011 on the reduction of CO2 emissions from light-duty vehicles.* European Commission, DG Climate Action. Available at: http://ec.europa.eu/clima/policies/transport/vehicles/docs/evaluation_ldv_co2_regs_en.pdf. Retrieved from ???

Roland Berger. (2009). *Powertrain 2020 - China's ambition to become market leader in E-Vehicles.* http://www.rolandberger.co.uk/media/pdf/Roland_Berger_Powertrain_China_20090512.pdf.

Roland Berger. (2011). *Powertrain 2020 - The Li-Ion Battery Value Chain – Trends and implications.* http://www.rolandberger.com/media/pdf/Roland_Berger_The_Li_Ion_Battery_Value_Chain_20110801.pdf.

Roland Berger. (2013). *Fuel cells - A realistic alternative for zero emission?* Roland Berger Strategy Consultants. Available at:http://www.rolandberger.com/media/pdf/Roland_Berger_Fuel_cells_20140113.pdf. Retrieved September 26, 2014, from http://www.rolandberger.com/media/pdf/Roland_Berger_Fuel_cells_20140113.pdf

Roland Berger. (2014). *CO2 reduction 2021 and beyond: OEM strategies.* Brussels: Presented at Automotive Megatrends Europe .

Schmitt, B. (2014, December 1). *Battery-breakthrough: Nissan poised to take range off the table*. Retrieved from Daily Kanban: http://dailykanban.com/2014/12/battery-breakthrough-nissan-poised-take-range-off-table/

Schubert, J. (2015). *Messung und Simulation von motorseitigen Technologien zur CO2 Minderung bei PKW; bachelor thesis at TU-Graz; Graz 2015.*

Schutting, E., & et.al. (2007). Miller- und Atkinson-Zyklus am aufgeladenen Dieselmotor;. *MTZ 06I2007 Jahrgang 68; 2007*.

Tesla Motors. (2014, February 26). *Gigafactory*. Retrieved from Tesla Motors: http://www.teslamotors.com/de_AT/blog/gigafactory

TNO. (2012b). *Supporting Analysis regarding Test Procedure Flexibilities and Technology Deployment for Review of the Light Duty Vehicle CO2 Regulations* .

TNO et al. (2006). *Review and analysis of the reduction potential and costs of technological and other measures to reduce CO2-emissions from passenger cars.* Available at: http://ec.europa.eu/enterprise/sectors/automotive/files/projects/report_co2_reduction_en.pdf.

TNO et al. (2006). *Review and analysis of the reduction potential and costs of technological and other measures to reduce CO2-emissions from passenger cars.* Available at: http://ec.europa.eu/enterprise/sectors/automotive/files/projects/report_co2_reduction_en.pdf.

TNO et al. (2011). *Support for the revision of Regulation (EC) No 443/2009 on CO2 emissions from cars.* A report for the European Commission, DG Climate Action. Available at: http://ec.europa.eu/clima/policies/transport/vehicles/cars/docs/study_car_2011_en.pdf.

TNO et al. (2012). *Support for the revision of regulation on CO2 emissions from light commercial vehicles.* A report by TNO, Ricardo, AEA Technology, CE Delft, IHS Global Insight, TML and Okopol for the European Commission, DG Climate Action. Retrieved June 2014, from http://ec.europa.eu/clima/policies/transport/vehicles/vans/docs/report_co2_lcv_en.pdf

TNO et al. (2012a). *Supporting Analysis regarding Test Procedure Flexibilities and Technology Deployment for Review of the Light Duty Vehicle CO2 Regulations.* A report by TNO, AEA Technology, Ricardo and IHS Global Insight for the European Commission, DG Climate Action. Retrieved June 2014, from http://ec.europa.eu/clima/policies/transport/vehicles/cars/docs/note_2012_en.pdf

TU Graz/TNO/LAT. (2013). *MAC performance test procedure: Co-ordination of the pilot test phase and follow up towards the drafting of the regulatory text.* A report by TNO, TU Graz and LAT for the European Commission, DG Enterprise and Industry. Performed under FRAMEWORK CONTRACT ENTR/F1/2009/030.1, Lot no. 4: "Eco-Innovation Techniques in the field of the Automotive Industry", Specific contract SI2.600239.

US EPA. (2012). *“Regulatory Impact Analysis: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards”.* US EPA, Report no: EPA-420-R-12-016, August 2012. Available from: http://www.epa.gov/oms/climate/documents/420r12016.pdf.

US EPA and NHTSA. (2012). *"Joint Technical Support Document: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards”.* A report by the US EPA and NHTSA, Report no: EPA-420-R-12-901, August 2012. Available from: http://www.epa.gov/oms/climate/documents/420r12901.pdf.

VAG. (2014). *Future Mobility: Volkswagen Group’s Solutions for Sustainable Mobility.* Retrieved from http://www.volkswagenag.com/content/vwcorp/info_center/en/talks_and_presentations/2014/07/FM_04_07_14.bin.html/binarystorageitem/file/06_2014-07-04+Presentation+Barclays+London+Steiger+TOP+COPY.pdf

Volkswagen. (2011, 03 14). *Volkswagen – On the Road of Success, Roadshow with Deutsche Bank. By H.D. Pötsch. .* Retrieved from http://www.volkswagenag.com/content/vwcorp/info_center/en/talks_and_presentations/2011/03/Presentation_Frankfurt_Poetsch.bin.html/binarystorageitem/file/Presentation+Frankfurt+14-03-2011+Top+Copy.pdf

Volkswagen. (2012). *Der Baukasten für die Zukunft. autogramm, Ausgabe 1-2/2012.* Retrieved from http://autogramm.volkswagen.de/01-02_12/standorte/standorte_01.html

Volkswagen. (2012, 01/02). *Modular Transverse Matrix (MQB): A new level of flexibility, efficiency and model variety. Volkswagen MQB and engines workshop, Wolfsburg.* Retrieved from http://www.ausmotive.com/downloads/Volkswagen/MQB-platform-Feb2012.pdf

VVA et al. (2015). *Assessment of competitiveness impacts of post-2020 LDV CO2 regulation.* A report by Valdani Vicari & Associati (VVA), Technopolis Group (TG), Joint Institute for Innovation Policy (JIIP) / TNO for the European Commission, DG Climate Action.

Waltl, H., & Wildemann, H. (2014). *Modularisierung der Produktion in der Automobilindustrie.* Munich: TCW Transfer-Centrum.

WardsAuto. (2013, 10 28). *Big Rewards, Hurdles Seen With Next-Gen Flexible Vehicle Architectures. By David E. Zoia.* Retrieved from wardsauto.com/vehicles-amp-technology/big-rewards-hurdles-seen-next-gen-flexible-vehicle-architectures

Wells, P., Varma, A., Newman, D., Kay, D., Gibson, G., Beevor, J., & Skinner, I. (2013). Governmental regulation impact on producers and consumers: A longitudinal analysis of the European automotive market. *Transportation Research Part A: Policy and Practice 47*, 28-41.

Yousouf, M. I. (2007). Using Experts' Opinions Through Delphi Technique. *Practical Assessment, Research & Evaluation, Volume 12, Number 4*.

Zallinger, M. (2010). *Mikroskopische Simulation der Emissionen von Personenkraftfahrzeugen.* Dissertation, Institut für Verbrennungskraftmaschinen und Thermodynamik, Technische Universität Graz, April 2010.

ZEV. (2011). *A portfolio of power-trains for Europe: a fact-based analysis - The role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles.* http://www.fch-ju.eu/sites/default/files/documents/Power_trains_for_Europe.pdf.

Appendices

A1 Appendix 1 – Supporting material for baseline and segmentation

A1.1 Summary of the methodologies used to clean the car and van CO_2 monitoring databases

Introduction

- As part of the monitoring strategy of regulation (EC) No 443/2009 and of Regulation (EC) No 510/2011 the EEA collects, aggregates and releases yearly datasets that report passenger car and light commercial vehicle (van) registrations in EU Member States. The datasets are used to calculate how pools of manufacturers are progressing towards their CO_2 reduction target.
- The data is submitted by Member States and released as provisional in the first part of the year. Manufacturers can then notify the Commission in case of errors concerning their models prior to the full release towards the end of each year.

Dataset description

- The datasets include 24 fields that identify:
    - country of registration;
    - model version and manufacturer - including manufacturer’s pool as defined by the Regulation;
    - technical parameters (mass, emissions, wheelbase and axles, fuel type, engine capacity, power and electric energy consumption);
    - innovative technologies and correlated emissions reductions, which counts towards the achievement of the manufacturer’s target (Supercredits)
    - total allowed mass (vans only)
    - number of registrations (each record often contains more than one registration).
- As of July 2014, the EEA has released 4 definitive datasets (3 for passenger cars – 2010, 2011, 2012 - and 1 for vans 2012). At the date of writing, the 2013 datasets has been released in provisional version, for both Passenger Cars and Light Commercial Vehicles.

Segmentation carried out for a previous project

- Ricardo Energy & Environment has used the EEA datasets (up to 2012) to inform the data analysis for the SR1 study (Ricardo-AEA, 2015): *The potential for weight reduction of passenger cars and light commercial vehicles in relation to future CO2 regulatory requirements*. The study includes a quantitative analysis of the recent evolution of the mass of newly registered vehicles; this operation required the development of a customised segmentation methodology for passenger cars.
- Our preliminary analysis highlighted that traditional segmentation for the EU market (A, B, C, etc)[46] was not fit for the purpose of the study, because it did not allow to properly discriminate vehicles belonging to several segments which are becoming increasingly popular (such as MPVs and SUVs). For example, both the Ford Fusion and the Range Rover would be

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[46] As defined in http://ec.europa.eu/competition/mergers/cases/decisions/m1406_en.pdf

categorised as SUVs, but the disparity in mass (1167 kg versus 2527kg) is too wide to allow a meaningful weight reduction potential analysis specific to different vehicles types.

- While some years ago these vehicles would not have sensibly influenced the overall results, the increasing number of models available and the rise of their share of total sales required the development of new segments.
- The vehicle segment definitions commonly used in the European market are set out in the table below[47].

Segment label	Description
A	Mini-cars
B	Small cars (superminis)
C	Medium cars (often referred to as “lower medium” cars)
D	Large cars (often referred to as “upper medium” cars)
E	Executive cars
F	Luxury cars
S	Sport coupés
M	Multi-purpose vehicles
J	Sport utility vehicles (including off-road vehicles)

- Recent and ongoing changes in the European vehicle market mean that a number of new vehicle segments have been introduced in recent years. For the purposes of the weight reduction potential analysis, we have labelled these additional segments as follows:

Segment label	Description
BX	B-segment crossover vehicles
BM	B-segment multi-purpose vehicles
CX	C-segment crossover vehicles
CM	C-segment multi-purpose vehicles
DX	D-segment crossover vehicles
EM	E-segment multi-purpose vehicles
EX	E-segment crossover vehicles
LAV	Leisure activity vehicles
V	Van derived

Data needs

- For the purpose of the previous study, it was necessary to use segmented registration data.
- The EEA datasets do not include vehicles segmentation. It was therefore necessary to allocate each record to the relative segment.

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[47] Referred to in Regulation (EEC) No 4064/89 Merger Procedure, Case No COMP/M.1406 – Hyundai / Kia

- Before each record could be allocated to a specific segment, it was necessary to uniquely identify the vehicle model. The field “Cn” (Commercial name), contains the model and version name and was used as the main reference.
- The field however is not homogeneously populated. For example, often it only reports the model name (e.g. “Golf”), sometimes model and version (such as “GOLF / VARIANT 1.6 / TDI 4M”), sometimes the brand is included in the name (e.g. Volkswagen Golf). Across the Passenger Cars and Light Commercial Vehicle databases, the field *Cn* includes over 30,000 different text strings. In order to allocate a record to a segment it would have been necessary to match each string to one of the segments reported in table 1 and table 2.

Further data quality issues

- The datasets were found to present data quality issues in other fields as well. The more relevant issues, which would have invalidated the analysis we proposed to carry out, were:
    - high number of empty cells
    - clearly erroneous values entered for many parameters
- furthermore, other minor issues would have made the analysis process more difficult and inefficient:
    - size of the dataset[48];
    - national variations in the name of brands and models
    - inclusion of several fields not relevant the scope of the analysis
- For this reason, the data preparation methodology was based on the identification of the model name that each record refers to, and the allocation of each model to a segment.

The next paragraph describes how the issues described above have been resolved and the impact on the dataset (data loss and number of amended values).

Data cleansing methodology

The following issues in Table 10.1 have been identified and addressed using a cleansing methodology in various steps. These steps have initially been carried out for years 2010, 2011 and 2012 (final data); recently the new provisional data for 2013 has been added following a similar methodology.

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[48] During the initial stages, we considered the option to build an SQL database to store the data and carry out most of the analyses. This option was rejected after several considerations such as budget and time constraints, data validation / error checking requirements and team’s experience with database tools. We also identified the need to frequently export the data during the process, making the quality assurance process more complicated.

Table 10.1: Summary of the data cleansing issues identified and the solutions applied to mitigate for them

Issue	Solution	Impact	
		Passenger Cars	**LCV**
Size (PC only): The PC datasets is not organised efficiently: several entries show only 1 registration, for a total of 1.4 million rows across the 4 years	The aggregate dataset includes only records (rows) with over 1 registration. This has allowed to reduce the size of the dataset by over 40% (currently it includes fewer than 800,000 entries).	Loss of 1.3% of registrations across the 4 years. However, a good portion of the single registrations concerned niche models, which would have been excluded from the main analysis on a second stage. It was also observed that often single registration records presented a high frequency of empty cells and erroneous values.	No impact (all original entries included)
Erroneous values: Bad brand/model match	A new field "*Brand*" was added to the datasets. Using the field Mk, it normalises most popular brands name (as they often vary across Member states). A total of 69 brands have been identified[49].	0.05%[50] of registrations could not be allocated to a specific manufacturer	1.15% of registrations could not be allocated to a specific manufacturer
Allocating entries to models: the field *Cn* includes ~30,000 different strings. It is not uncommon to find the field empty, misspellings, or unreadable fonts (as the spreadsheet was completed in various alphabets and included special characters). In many occasions, the *make* and *model* combination was a bad match (i.e. wrong make for the model).	We added a new field ("*Model*") to the dataset. It includes the generic models' name, allocated according to the following methodology: 1. Using a long list of most popular models on sale, several string searches were performed to match full version name (field *Cn*) to parent model: • Full string match • Partial string match • Partial string match restricted to brand (it allowed us to use more loose matching formulas). 2. String searches have been carried out as an iterative process: once entries were allocated to correct models, new searches were carried out only on the remaining entries with slightly different parameters. 3. The iterative process included data validation checks, such as analysing at the spread of a technical parameter of a specific model[51]. These were conducted on a case-by-case basis. 4. When a combination brand/model was erroneous, technical parameters have been used to validate the allocation. 5. Using our knowledge of the market, if the same brand/model was sold with different names according to country, it was allocated to the more popular denomination.	Various vehicles are present in both databases. In total we identified 422 models. The passenger cars database includes 393 different models. 3.8% of registrations (4.9% of entries) could not be allocated to a specific model either because: • the field "Cn" being was left blank or incomplete (for example BMW X1, X3, X5 and X6 being generically allocated to X series). • They are niche models, with a limited number of total sales.	Various vehicles are present in both databases. In total we identified 422 models The light commercial vehicles database includes 259 different models 1.75% of registrations (2.67% of entries) could not be allocated to a specific model either because: • the field "Cn" being was left blank or incomplete. • They are niche models, with a limited number of total sales.

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[49] Manufacturer pools, as defined by the regulation, often include several brands which could alter the parent company. For example, Lancia's model were initially based on Fiat platforms and then to Chrysler platforms. The brand will now cease to exist outside Europe.

[50] Registrations and record losses from this point onwards refer to the dataset after records with one registrations have been excluded (98.3% of total passenger cars registrations between 2010 and 2013)

[51] For example, string searches may allocate Mini Clubman to Mercedes CL. Plotting on a chart the spread of the Mass parameter for the CL model would quickly reveal an anomalous shape in the curve.

<table>
<tr><th rowspan="2">Issue</th><th rowspan="2">Solution</th><th colspan="2">Impact</th></tr>
<tr><th>Passenger Cars</th><th>LCV</th></tr>
<tr>
<td>**Allocating models to segment:**

PC: There is no definitive way of allocating vehicles to segments. In particular, the size boundaries between A, B, C, and D-segment vehicles are not clear and there are differences of opinion regarding which segment a given vehicle falls into. In reality the range of models available on the market results in a continuous spectrum of vehicles, with models available at almost every length from 2.5 to 5 metres.

The long term trend for a given model to get larger each time it is updated further complicates the issue. For example, the 2012 Mercedes A-Class is almost 0.7 metres longer than the original 1997 version (a 20% increase), effectively moving it from B-segment to C-segment.

LCV: typical segmentation is carried out according to mass.</td>
<td>**PC:** The initial segmentation has been performed according to the scope of the study, therefore based on the categories in Table A1-2.

Each model has been manually assigned to a segment according to technical information available from manufacturer and our judgment.

If any of the models had sensibly varied over time (e.g. Mercedes A class), it is considered to be a different model and identified by the release year (e.g. A Class 2012).

For the scope of the current study (cost curves for fuel saving technologies), the original segmentation has been converted to 4 macro segment according to the following conversion table:

<table>
<tr><th>SR4 SEGMENT</th><th>SMALL</th><th>MEDIUM</th><th>LARGE</th><th colspan="2">EXTRA LARGE /OTHER</th></tr>
<tr><td>SR1 SEGMENT</td><td>A
B
BM
BX</td><td>C
CM
CX
LAV</td><td>D
DM
DX</td><td>E
EM
EX
F</td><td>S
J
V</td></tr>
</table>

LCV: we used the following segmentation, given in Directive 70/156/EEC**:**

<table>
<tr><th>Mass (up to)</th><th>Segment</th></tr>
<tr><td>1305 kg</td><td>CLASS I</td></tr>
<tr><td>1760 kg</td><td>CLASS II</td></tr>
<tr><td>3501 kg</td><td>CLASS III</td></tr>
</table>
</td>
<td>No loss of entries, all records for which model name was identified have been assigned to a segment.</td>
<td>1.75% of registrations (2.68% of records) could not be assigned to a segment.

LCV segmentation is based on mass, and if the parameter was missing the record could not be assigned to a segment.

Given that the segmentation is based on mass, and that segmentation refers to a version and not to a parent model, some models can fall in more than one class.

The mass parameter has been checked according to the methodology shown for the next step prior to this segmentation.</td>
</tr>
<tr>
<td>**Erroneous values identification and amendment**: several entries present values which are not credible (e.g. mass below 300 kg or more than 50% difference with respect to model average)</td>
<td>We used the model name to calculate the sales-weighted average value for each model for parameters included in the following table. Entries that fell outside of the confidence intervals (difference from sales-weighted average) as specified in the following table have been amended with the sales-weighted average value for the specific model.</td>
<td>Amendments concerned less than 0.3% of total registrations.</td>
<td>Amendments on reported values concerned 1.93% of total usable registrations.

Due to the limited number of models and versions included in the LCVs dataset, it was possible to use available records to fill gaps in the</td>
</tr>
</table>

<table>
<tr><th rowspan="2">Issue</th><th rowspan="2">Solution</th><th colspan="2">Impact</th></tr>
<tr><th>Passenger Cars</th><th>LCV</th></tr>
<tr>
<td></td>
<td>
<table>
<tr><th>Parameter</th><th>PC</th><th>LCV</th><th>Exclusion</th></tr>
<tr><td>Reference Mass – m</td><td>±30%</td><td>±20%</td><td></td></tr>
<tr><td>TPMLM</td><td>n/a</td><td>±20%</td><td></td></tr>
<tr><td>CO2 Emissions – e</td><td>±99%</td><td>±30%</td><td>Fuel type</td></tr>
<tr><td>Footprint (wheelbase*average(front axle, rear axle)</td><td>±20%</td><td>±20%</td><td></td></tr>
<tr><td>Engine capacity – ec</td><td>n/a</td><td>±30%</td><td>Fuel type</td></tr>
<tr><td>Engine power - ep</td><td>n/a</td><td>±50%</td><td>Fuel type</td></tr>
</table>
<p>Passenger cars required higher thresholds to account for higher variation in the offer of versions for the same model. For example, manufacturers often offer a high spec version of their more popular models, which may have engine and power over 100% larger than the base model.</p>
<p>Amended figures include records which have had blank fields replaced with the model’s corresponding sales-weighted average value. Blank fields were significantly more common within the LCVs dataset.</p>
<p>Fuel Type
Several model with fuel type <i>Electric</i> and Engine capacity >0 have been identified as erroneous and fuel type amended to diesel-electric or petrol electric.</p>
<p>Specific
For ENGINE POWER, many of the values were entered in watts as opposed to kilowatts. For this reason, a flat “<i>if ENGINE POWER > 1000 then divide ENGINE POWER by 1000”</i> policy was employed <i>before</i> the universal cleaning was applied.</p>
</td>
<td></td>
<td>data for missing parameters. Gap filling amendments concerned 37.48% of total usable registrations.</td>
</tr>
</table>

A1.2 Technology penetration rates for conventional vehicles

Table 10.2: Estimated market penetration of CO_2 reducing technologies for spark-ignition engines

	Technologies for spark-ignition / petrol engines	Penetration Cars			Penetration LCVs		
		[%] 2002	[%] 2010	[%] 2013	[%] 2002	[%] 2010	[%] 2013
Engine Options	Gas-wall heat transfer reduction	5.0	50.0	66.9	5.0	50.0	66.9
	Direct injection, homogeneous	1.7	19.2	33.6	0.0	5.3	16.1
	Direct injection, stratified charge	0.0	2.4	7.0	0.0	0.0	3.8
	Thermodynamic cycle improvements e.g. split cycle, PCCI/HCCI, CAI	0.0	0.0	0.0	0.0	0.0	0.0
	Mild downsizing (15% cylinder content reduction) between 50 and 75 kW/L	32.3	51.1	58.5	18.0	38.8	60.1
	Medium downsizing (30% cylinder content reduction) between 75 and 95 kW/L	1.8	7.8	15.5	0.0	0.3	4.5
	Strong downsizing (>=45% cylinder content reduction) Above 95 kW/L	0.0	0.5	0.7	0.0	0.0	0.0
	Cam-phasing	42.7	65.5	72.8	47.8	74.7	74.3
	Variable valve actuation and lift	7.2	11.9	15.2	2.6	3.6	8.4
	Low friction design and materials	34.1	59.3	74.7	18.1	39.1	64.7
	Cylinder deactivation	0.2	0.0	0.9	0.0	0.0	0.0
	Cooled EGR	0.0	0.0	0.6	0.0	0.0	0.0
Transmission Options	Optimising gearbox ratios / downspeeding (above 5)	6.2	37.7	48.3	0.1	6.0	19.9
	Automated manual transmission	2.2	4.4	3.7	0.1	0.3	0.2
	Dual clutch transmission	0.0	6.0	11.8	0.0	0.2	3.6
	Continuously variable transmission	1.3	2.6	2.1	0.0	0.0	0.1
Hybridisation	Start-stop hybridisation	0.0	11.3	43.0	0.0	11.5	18.4
	Micro hybrid - regenerative breaking	0.0	1.3	1.9	0.0	0.0	0.1
	Mild hybrid - torque boost for downsizing	0.0	0.1	0.0	0.0	0.0	0.0
	Full hybrid - electric drive	0.1	0.7	1.2	0.0	0.0	0.1
Driving Resistance Reduction	Weight reduction on whole vehicle: At least 2.5% reduction	0.0	0.0	2.3	0.0	0.0	2.1
	Weight reduction on whole vehicle: At least 5% reduction	0.0	0.0	52.2	0.0	0.0	55.0
	Weight reduction on whole vehicle: At least 7.5% reduction	0.0	0.3	0.4	0.0	0.0	0.0
	Weight reduction on whole vehicle: At least 10% reduction	0.0	0.0	0.1	0.0	0.0	0.0
	Weight reduction on whole vehicle: At least 20% reduction	0.0	0.0	0.0	0.0	0.0	0.0

	Technologies for spark-ignition / petrol engines	Penetration Cars			Penetration LCVs		
		[%]	[%]	[%]	[%]	[%]	[%]
		2002	2010	2013	2002	2010	2013
	Weight reduction on whole vehicle: At least 30% reduction	0.0	0.0	0.0	0.0	0.0	0.0
	Mild aerodynamics improvement (0.02 =< Cx reduction < 0.04)	0.0	31.5	46.7	0.0	4.8	3.9
	Strong aerodynamics improvement (Cx reduction >= 0.04)	0.0	6.6	23.8	0.0	0.0	0.0
	Low rolling resistance tyres	0.0	11.0	19.1	0.0	7.0	18.2
	Reduced driveline friction	0.0	9.8	13.5	0.0	9.8	13.5
Other	Thermo-electric waste heat recovery	0.0	0.0	0.0	0.0	0.0	0.0
	Secondary heat recovery cycle	0.0	0.6	1.0	0.0	0.0	0.0
	Auxiliary systems efficiency improvement	4.9	50.0	66.9	4.9	50.0	66.9
	Thermal management (Liquid Cooled Charge Air Coolers)	7.3	11.7	15.8	6.0	8.9	9.0
	Electric (or Electro-Hydraulic) Power Assisted Steering	0.0	89.1	88.6	0.0	38.9	47.6

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Table 10.3: Estimated market penetration of CO_2 reducing technologies for compression-ignition engines

	Technologies for compression-ignition / diesel engines	Penetration Cars			Penetration LCVs		
		[%]	[%]	[%]	[%]	[%]	[%]
		2002	2010	2013	2002	2010	2013
Engine Options	Combustion improvements	5.0	50.0	66.9	0.2	3.9	3.0
	Mild downsizing (15% cylinder content reduction) between 45 and 60 kW/L	12.4	51.2	58.0	0.0	17.4	22.2
	Medium downsizing (30% cylinder content reduction) between 60 and 75 kW/L	0.0	0.2	0.6	0.0	0.0	0.0
	Strong downsizing (>=45% cylinder content reduction) Above 75 kW/L	0.0	0.0	0.0	0.0	0.0	0.0
	Variable valve actuation and lift	0.0	9.8	10.3	0.0	8.4	11.7
Transmission Options	Optimising gearbox ratios / downspeeding (above 5)	12.7	56.7	70.7	10.2	51.5	65.0
	Automated manual transmission	1.5	2.6	3.6	2.2	1.9	2.6
	Dual clutch transmission	0.0	5.5	12.5	0.2	2.1	4.0
	Continuously variable transmission	0.7	1.6	1.1	0.0	0.0	0.0
Hybridisation	Start-stop hybridisation	0.0	22.6	55.2	0.0	17.2	29.9
	Micro hybrid - regenerative breaking	0.0	0.4	6.5	0.0	1.0	9.0
	Mild hybrid - torque boost for downsizing	0.0	0.0	0.0	0.0	0.0	0.0
	Full hybrid - electric drive	0.0	0.0	0.4	0.0	0.0	0.4

Technologies for compression-ignition / diesel engines		Penetration Cars			Penetration LCVs		
		[%]	[%]	[%]	[%]	[%]	[%]
		2002	2010	2013	2002	2010	2013
Driving Resistance Reduction	Weight reduction on whole vehicle: At least 2.5% reduction	0.0	1.0	10.9	0.0	0.0	0.1
	Weight reduction on whole vehicle: At least 5% reduction	0.0	0.1	3.5	0.0	0.0	2.2
	Weight reduction on whole vehicle: At least 7.5% reduction	0.0	0.0	0.1	0.0	0.0	0.0
	Weight reduction on whole vehicle: At least 10% reduction	0.0	0.0	0.5	0.0	3.5	3.4
	Weight reduction on whole vehicle: At least 20% reduction	0.0	0.0	0.3	0.0	0.0	0.0
	Weight reduction on whole vehicle: At least 30% reduction	0.0	0.0	0.0	0.0	0.0	0.0
	Mild aerodynamics improvement (0.02 =< Cx reduction < 0.04)	0.0	28.1	41.5	0.0	2.4	1.6
	Strong aerodynamics improvement (Cx reduction >= 0.04)	0.0	8.8	25.1	0.0	0.0	0.0
	Low rolling resistance tyres	0.0	12.2	29.8	0.0	6.3	12.6
	Reduced driveline friction	0.0	20.0	27.5	0.0	0.8	0.6
Other	Thermo-electric waste heat recovery	0.0	0.0	0.0	0.0	0.0	0.0
	Secondary heat recovery cycle	0.0	0.0	0.0	0.0	0.0	0.0
	Auxiliary systems efficiency improvement	6.0	50.0	66.5	0.1	3.9	3.0
	Thermal management (Liquid Cooled Charge Air Coolers)	0.0	1.0	9.5	0.0	0.0	0.0
	Electric (or Electro-Hydraulic) Power Assisted Steering	0.0	86.6	87.6	0.0	19.9	43.1

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A2 Appendix 2 – Datasets and assumptions used in the methodological approach for xEVs

The following sections provide a summary of the initial assumptions used in the calculation of the baseline costs and performance of xEV powertrains.

Note: 2013 values were still utilised as a common starting point for the analysis, with the forward projections to 2020, 2025 and 2030 in component costs superseded in the final analysis by the powertrain deployment scenario analysis using a more direct learning methodology. The final Mixed xEV Scenario values are presented here for comparison.

A2.1 General assumptions

Table 10.4: Baseline conventional vehicle characteristics xEV calculations

Baseline	ICE Power	MJ/km	MJ/km	MJ/km	Mass	Mass	Mass
	Total	Petrol	Diesel	Total	Petrol	Diesel	Total
Small Car	62	1.64	1.41	1.58	1091	1244	1132
Lower Medium Car	91	1.89	1.67	1.75	1380	1510	1463
Upper Medium Car	114	2.09	1.81	1.86	1523	1659	1636
Large Car	151	2.51	2.19	2.25	1582	1926	1862
Total Cars	**87**	**1.76**	**1.71**	**1.73**	**1215**	**1538**	**1383**
Small LCV	57	1.87	1.42	1.47	1091	1191	1181
Medium LCV	68	2.14	1.83	1.83	1374	1450	1452
Large LCV	95	2.61	2.76	2.76	1863	2023	2024
Total LCVs	**83**	**2.04**	**2.36**	**2.35**	**1263**	**1780**	**1766**

A2.2 Component cost assumptions

Segment-specific fixed costs

Table 10.5: Initial assumptions and final Mixed xEV scenario values for Wiring costs by segment

Wiring Harness	Initial assumptions				Mixed xEV Scenario		
	2013	2020	2025	2030	2020	2025	2030
Small Car	120	100	100	100	100	100	90
Lower Medium Car	150	120	120	120	130	120	110
Upper Medium Car	180	140	140	140	150	140	140
Large Car	220	180	180	180	190	180	170
Small LCV	150	120	120	120	130	120	110
Medium LCV	180	140	140	140	150	140	140
Large LCV	220	180	180	180	190	180	170

Table 10.6: Initial assumptions and final Mixed xEV scenario values for Regenerative braking costs by segment

Regenerative Braking System	Initial assumptions				Mixed xEV Scenario		
	2013	2020	2025	2030	2020	2025	2030
Small Car	234	211	200	189	200	190	180
Lower Medium Car	240	216	205	194	210	190	180
Upper Medium Car	243	219	208	197	210	190	180
Large Car	254	229	217	205	220	200	190
Small LCV	240	216	205	194	210	190	180
Medium LCV	243	219	208	197	210	190	180
Large LCV	254	229	217	205	220	200	190

Table 10.7: Initial assumptions and final Mixed xEV scenario values for Standard electric HVAC costs by segment

HVAC Standard Electric	Initial assumptions				Mixed xEV Scenario		
	2013	2020	2025	2030	2020	2025	2030
Small Car	220	120	115	110	190	180	170
Lower Medium Car	270	140	135	130	230	220	200
Upper Medium Car	320	160	155	150	280	260	240
Large Car	400	210	205	200	340	320	300
Small LCV	270	140	135	130	230	220	200
Medium LCV	320	160	155	150	280	260	240
Large LCV	400	210	205	200	340	320	300

Table 10.8: Initial assumptions and final Mixed xEV scenario values for Heat-pump HVAC costs by segment

HVAC Heat Pump	Initial assumptions				Mixed xEV Scenario		
	2013	2020	2025	2030	2020	2025	2030
Small Car	900	810	770	730	680	620	590
Lower Medium Car	1000	900	855	810	750	690	650
Upper Medium Car	1100	990	945	900	830	760	720
Large Car	1210	1090	1045	1000	910	840	790
Small LCV	1000	900	855	810	860	800	750
Medium LCV	1100	990	945	900	950	880	830
Large LCV	1210	1090	1045	1000	1040	970	910

Fixed costs and costs scaled by segment parameters/characteristics

Table 10.9: Initial assumptions and final Mixed xEV scenario values for Battery costs

	Initial assumptions				Mixed xEV Scenario		
Cost, Euro	2013	2020	2025	2030	2020	2025	2030
Battery System							
Fixed (do not scale with kWh)	200	160	144	128	172	160	150
Lithium-ion per kWh	375	245	204	163	198	166	146
Advanced (Li-S/solid state) per kWh		410	277	144	410	166	129

Table 10.10: Assumptions for conventional ICE system component costs

Cost, Euro	Type	2013	2020	2025	2030
Conventional System					
Baseline Petrol Engine+Transmission	per kW	26.0	24.7	24.1	23.5
Baseline Diesel Engine+Transmission	per kW	34.0	32.3	31.5	30.8
PHEV Petrol Engine+Transmission	per kW	29.4	29.4	28.7	27.9
PHEV Diesel Engine+Transmission	per kW	34.6	34.6	33.7	32.9
REEV Petrol Engine+Transmission	per kW	30.4	30.4	29.6	28.9
REEV Diesel Engine+Transmission	per kW	39.2	39.2	38.3	37.3
PHEV/REEV Petrol Engine+Transm.	per kW	29.9	29.9	29.1	28.4
PHEV/REEV Diesel Engine+Transm.	per kW	36.9	36.9	36.0	35.1
Baseline Petrol Aftertreatment	Fixed	300	300	295	285
Baseline Diesel Aftertreatment	Fixed	700	700	685	665

Note:

The engine and transmission costs for 2020 are taken from TNO et a. (2011) and were estimated by Ricardo, based on the following set of assumptions.
Assumptions for petrol:

- PHEV models feature a downsized, turbocharged 3 or 4 cylinder engine with direct injection
- EREV models feature a naturally aspirated 3 or 4 cylinder engine with low feature content and focus on light weight
- Emissions requirements for 2020 do not impose significant additional aftertreatment costs for these engine types compared with 2010

Assumptions for diesel:

- PHEV models feature a downsized, highly boosted 3 cylinder engine
- EREV models feature a downsized, highly boosted 3 cylinder engine with reduced feature content and focus on light weight
- The emissions benefits of hybridisation offset the costs of additional content required to meet 2020 noxious emissions limits
- The reduced transient response requirements for hybrid engines allow some cost reduction compared with baseline conventional engines
- Both factors also partly offset the trend increase in base engine CO_2 reduction content

Assumptions for transmissions:

- PHEV vehicles feature electrically actuated dual clutch transmissions
- EREV and EV vehicles do not require a stand-alone transmission – no speed reduction in drive to wheels by electric motors

Table 10.11: Initial assumptions and final Mixed xEV scenario values for Other xEV component costs

		Initial assumptions				Mixed xEV Scenario		
Cost, Euro	**Type**	**2013**	**2020**	**2025**	**2030**	**2020**	**2025**	**2030**
Fuel tank								
Tank	Fixed	125	125	125	125	125	125	125
Fuel	Fixed	-	-		-	-		-
Motor System								
Motor	Fixed	50	40	36	32	43.0	40.0	37.6
	per kW	8	6.4	5.75	5.1	6.9	6.4	6.0
Inverter	Fixed	50	40	36	32	43.0	40.0	37.6
	per kW	10	8	7.2	6.4	8.6	8.0	7.5
Boost converter	Fixed	10	8	7.2	6.4	8.6	8.0	7.5
	per kW	3	2.4	2.15	1.9	2.6	2.4	2.3
EV Transmission								
Single-speed gearbox	Fixed	280	220	195	170	240	225	210
Multi-speed gearbox	Fixed	580	460	410	360	500	465	435
Other Systems								
Control unit	Fixed	150	120	120	120	130	120	115
On-board charger	Fixed	350	350	315	280	255	235	225

Table 10.12: Initial assumptions and final Mixed xEV / FCEV Extreme scenario values for fuel cell system and hydrogen storage costs

	Initial assumptions				Mixed xEV Scenario			FCEV Extreme Sc		
Cost, Euro	**2013**	**2020**	**2025**	**2030**	**2020**	**2025**	**2030**	**2020**	**2025**	**2030**
Fuel Cell System										
Fuel cell stack, per kW	350	140	70	21	108	69	54	78	45	35
FC Peripherals, per kW	250	100	50	23	77	50	39	56	32	25
TOTAL, per kW	**600**	**240**	**120**	**44**	**185**	**119**	**93**	**134**	**77**	**60**
Other Systems										
H2 Storage, per kWh	51	16.0	13.0	10.0	23.8	17.9	15.2	19.3	13.6	11.4
H2 Storage, per kgH2	2000	630	512	394	938	705	599	761	536	449
Cost for 4kg H2 storage	*8000*	*2522*	*2049*	*1576*	3751	2821	2396	3042	2144	1797

A2.3 Component mass assumptions

Table 10.13: Assumptions for wiring harness mass bay segment

	Mass	Wiring Harness			
		2013	**2020**	**2025**	**2030**
Small Car	kg	15	15	15	15
Lower Medium Car	kg	17	17	17	17
Upper Medium Car	kg	19	19	19	19
Large Car	kg	21	21	21	21
Small LCV		17	17	17	17
Medium LCV		19	19	19	19
Large LCV	kg	21	21	21	21

Table 10.14: Assumptions for additional mass of Heat Pump HVAC by segment

	Extra Mass	HVAC Heat Pump			
		2013	2020	2025	2030
Small Car	kg	2.5	2.5	2.5	2.5
Lower Medium Car	kg	3.5	3.5	3.5	3.5
Upper Medium Car	Kg	4.0	4.0	4.0	4.0
Large Car	Kg	4.5	4.5	4.5	4.5
Small LCV	kg	3.5	3.5	3.5	3.5
Medium LCV	Kg	4.0	4.0	4.0	4.0
Large LCV	Kg	4.5	4.5	4.5	4.5

Table 10.15: Assumptions for battery system mass

Energy Density (Wh/kg), Mass (kg)	2013	2020	2025	2030
Battery System				
Fixed kg (do not scale with Wh)				
Lithium-ion, Wh/kg	110	160	230	300
Advanced (Li-S/ solid state), Wh/kg		300	400	500
Lithium-ion, Wh per litre	275	350	425	500
Advanced (Li-S/solid state), Wh per litre	275	350	475	600

Table 10.16: Assumptions for conventional system component masses

Cost, Euro	Mass	2013	2020	2025	2030
Conventional System					
Baseline Petrol Engine+Transmission	kg per kW	2.06	2.06	2.06	2.06
Baseline Diesel Engine+Transmission	kg per kW	2.22	2.22	2.22	2.22
PHEV Petrol Engine+Transmission	kg per kW	1.00	1.00	1.00	1.00
PHEV Diesel Engine+Transmission	kg per kW	1.42	1.42	1.42	1.42
REEV Petrol Engine+Transmission	kg per kW	1.72	1.72	1.72	1.72
REEV Diesel Engine+Transmission	kg per kW	2.14	2.14	2.14	2.14
PHEV/REEV Petrol Engine+Transm.	kg per kW	1.36	1.36	1.36	1.36
PHEV/REEV Diesel Engine+Transm.	kg per kW	1.78	1.78	1.78	1.78
Baseline Petrol Aftertreatment	Fixed kg	10	10	10	10
Baseline Diesel Aftertreatment	Fixed kg	20	20	20	20

Table 10.17: Assumptions for other xEV component masses

Cost, Euro	Mass	2013	2020	2025	2030
Fuel tank					
Tank	Fixed kg	15	15	15	15
Fuel	Fixed kg	45	45	45	45
Motor System					
Motor	kW per kg	1.25	1.4	1.5	1.6
	kg per kW	0.80	0.71	0.67	0.63
Inverter	kW per kg	9.5	11	12	13
	kg per kW	0.11	0.09	0.08	0.08
Boost converter	kW per kg	4.5	5.5	6	6.5
	kg per kW	0.22	0.18	0.17	0.15
EV Transmission					
Single-speed gearbox	Fixed kg	50	45	42.5	40

Cost, Euro	**Mass**	2013	2020	2025	2030
Multi-speed gearbox	Fixed kg	50	45	42.5	40
Battery System					
Battery	Wh/kg	110	160	230	300
	kg per kWh	9.1	6.3	4.3	3.3
Other Systems					
Control unit	Fixed kg	8	5	5	5
On-board charger	Fixed kg	5	5	5	5

Table 10.18: Assumptions for hydrogen storage and fuel cell systems

Power Density (kg/kW), Mass (kg)	**2013**	**2020**	**2025**	**2030**
Fuel Cell System				
Fuel cell stack, per kW	3.0	2.0	1.74	1.5
FC Peripherals, per kW				
TOTAL, per kW	**3.0**	**2.0**	**1.7**	**1.5**
Other Systems				
H2 Storage (excl. H2), fixed kg	92	80	80	80

A3 Appendix 3 – Materials used in the stakeholder consultation activities

The following materials are provided as a separate file archive alongside this interim report:

A. **Full summary of the results of the Delphi Survey**
   1) Delphi Survey Questionnaire and supporting technical annex
   2) Full summary of the results of the Delphi Survey

B. **Data validation template**

C. **General questionnaire for stakeholder interviews**

A4 Appendix 4 – Further information supporting the uncertainty analysis of technology costs

A4.1 Comparison of statistical sampling approaches

The range of uncertainty for cost centres (Section 7.4.2) was used as an input to statistical simulations generating probability distributions of the future costs and performance of each individual technology. These approaches rely on repetitive sampling, with a single sample drawn every iteration from each input probability distribution. As long as a sufficient number of sampling iterations are carried out, the sampled values end up being distributed in a manner which is very close to the true probability distribution of input values (in this case, the input values would be a cost data point for each vehicle technology). A key element in determining the robustness of this approach is the type of sampling methodology that is applied. In particular if one method of sampling requires more iterations than an alternative method in order to generate approximate probability distributions for the input datasets, then it is a less effective and less efficient method.

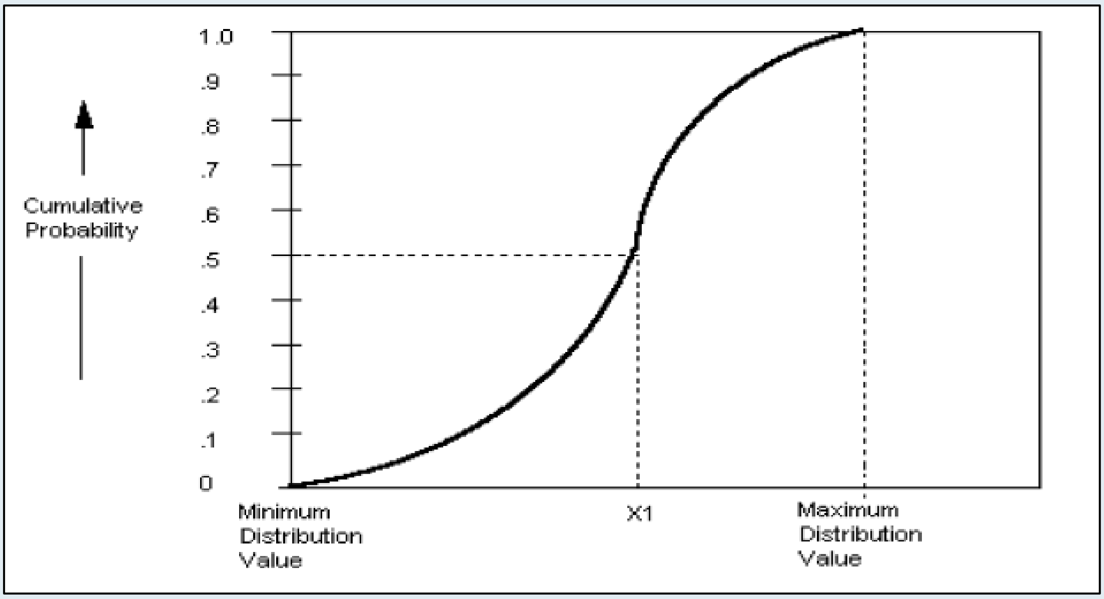
The **Monte Carlo approach** is one method by which sampling can be carried out, but there are alternative sampling approaches that have a number of benefits over the Monte Carlo method. In this study we have carried the uncertainty analysis by using the **Latin Hypercube sampling method**. The downside of the Monte Carlo approach is that it often requires a high number of samples in order for it to successfully approximate an input distribution. This is particularly a problem where the input distribution is highly skewed, or has some outcomes of low probability. In the context of this study, there was a significant risk that the input data distribution could be skewed given that there are likely to be significantly different cost estimates obtained for key vehicle technologies, and hence it was important to use statistical techniques that could overcome this problem. The Latin Hypercube sampling approach forces the samples drawn to correspond more closely with the input distribution. This has the benefit of allowing the sampling process to converge more quickly on the true statistical distribution of the input dataset. The following Box 3 provides a comparison of the two methods for information.

For the purposes of this study, the Latin Hypercube sampling approach offers significant benefits over the Monte Carlo approach as it allows much greater sampling efficiency and faster simulation runtimes, because much fewer sampling iterations are required in order to generate robust outputs. The Latin Hypercube approach is also particularly suitable for the analysis of vehicle technology costs because it has been designed to support the analysis of scenarios where low probability outcomes are represented in the input data probability distributions. The input datasets are likely to include low probability estimates for the costs of these technologies, but because the Latin Hypercube approach forces the sampling to include outlying data points, it ensures that these outliers are accurately represented in simulation outputs in a way that would be much more difficult and time consuming with Monte Carlo analysis.

Box 3: Comparison of the Monte Carlo method with the Latin Hypercube method

It is often helpful, when reviewing different sampling methods, to first understand the concept of a cumulative distribution. Any probability distribution may be expressed in cumulative form. A cumulative curve is typically scaled from 0 to 1 on the Y-axis, with Y-axis values representing the cumulative probability up to the corresponding X-axis value.

Figure 10.1: Cumulative probability distribution

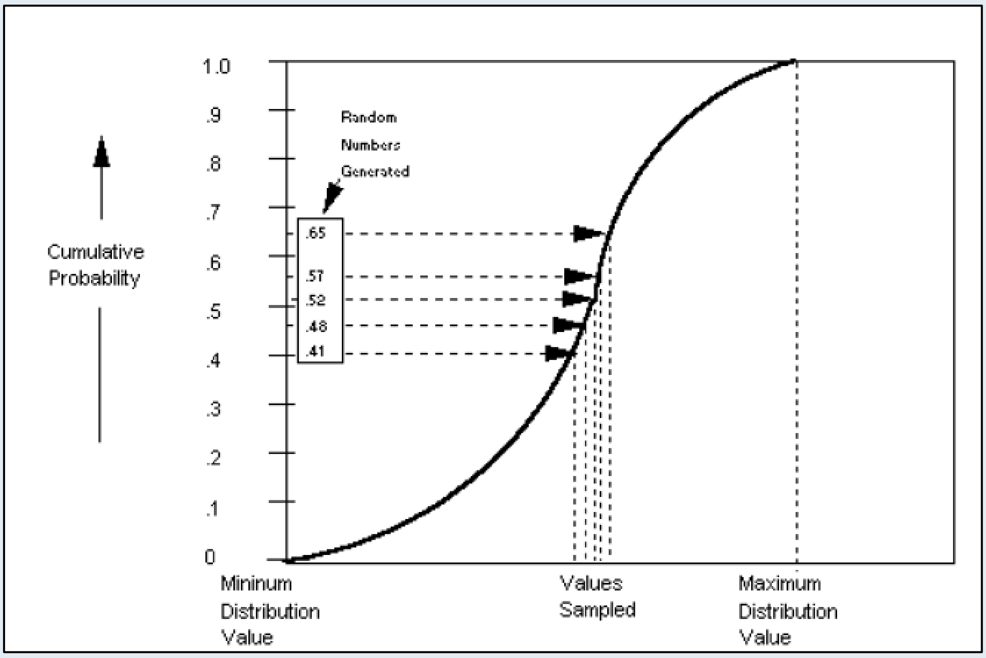


In the cumulative curve above, the 0.5 cumulative value is the point of 50% cumulative probability (0.5 = 50%). Fifty percent of the values in the distribution fall below this median value and 50% are above. The 0 cumulative value is the minimum value (i.e. 0% of the values will fall below this point) and the 1.0 cumulative value is the maximum value (100% of the values will fall below this point). The 0 to 1.0 scale of the cumulative curve is the range of the possible random numbers generated during sampling. In a typical Monte Carlo sampling sequence, the computer will generate a random number between 0 and 1 — with any number in the range equally likely to occur. This random number is then used to select a value from the cumulative curve. For the example above, if a random number of 0.5 was generated during sampling, the value sampled for the distribution shown would be X1. As the shape of the cumulative curve is based on the shape of the input probability distribution, more likely outcomes will be more likely to be sampled. The more likely outcomes are in the range where the cumulative curve is the "steepest".

Monte Carlo Sampling

Monte Carlo sampling refers to the traditional technique for using random or pseudo-random numbers to sample from a probability distribution. Monte Carlo techniques are applied to a wide variety of complex problems involving random behaviour. A large number of different algorithms are available for generating random samples from different types of probability distributions. Monte Carlo sampling techniques are entirely random — that is, any given sample may fall anywhere within the range of the input distribution. Samples, of course, are more likely to be drawn in areas of the distribution which have higher probabilities of occurrence. In the cumulative distribution shown earlier, each Monte Carlo sample uses a new random number between 0 and 1. With enough iterations, Monte Carlo sampling "recreates" the input distributions through sampling. A problem of clustering, however, arises when a small number of iterations are performed.

Figure 10.2: Five iterations of Monte Carlo sampling with clustering

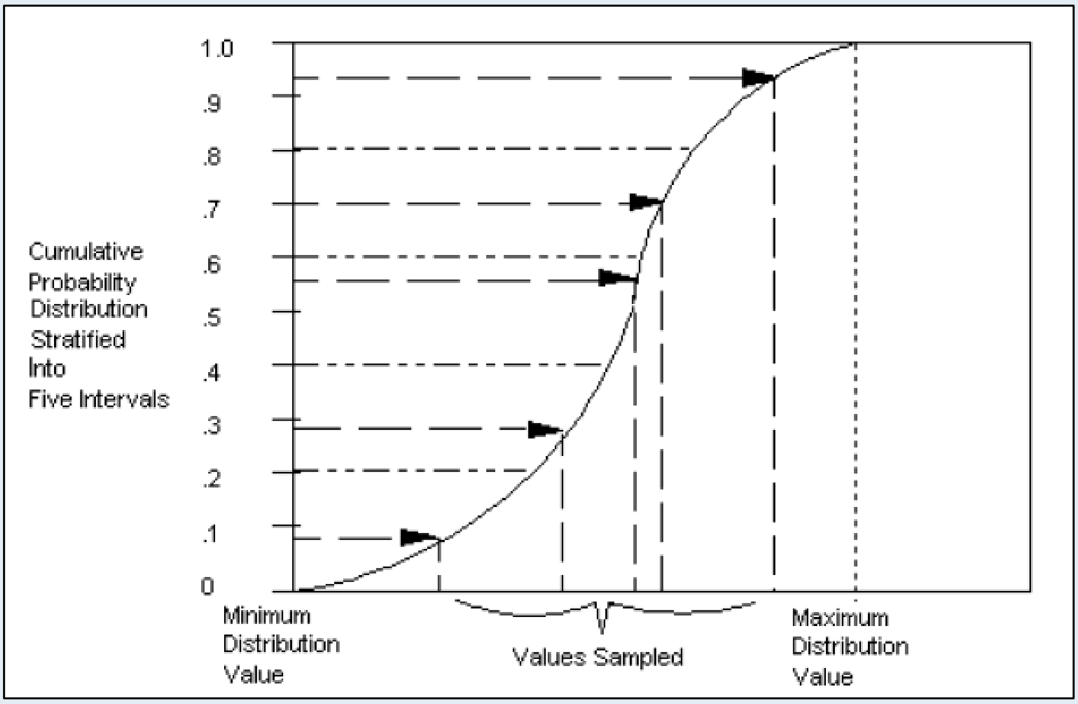


The figure above shows that each of the five samples that have been drawn, fall in the middle of the distribution. The values in the outer ranges of the distribution are not represented at all, meaning that their impact is completely excluded from the simulation output. This clustering effect is particularly problematic when a distribution includes low probability outcomes which potentially could have a significant impact on the results. These low probability data points must be included in the analysis in order to produce statistically representative results, and hence it is important that these data points are captured by the sampling technique that is used. The problem here is that if the probability associated with these data points is very low, a small number of Monte Carlo iterations will not sample a sufficient quantity of these data points in order to accurately take into account their real probability. In order to overcome this problem, stratified sampling methodologies, such as the Latin Hypercube approach have been developed.

Latin Hypercube sampling

Latin Hypercube sampling is a much more recent sampling approach that has been developed to overcome some of the inherent problems present in the Monte Carlo approach. The Latin Hypercube approach uses stratified sampling of the input probability distributions whereby the stratification procedure splits the cumulative distribution curve into equal intervals on the cumulative probability scale (i.e. the scale from 0.0 to 1.0). Samples are then randomly selected from each interval or stratification of the input distribution. In this way, the sampling is forced to represent values in each interval, thereby forcing the sample output to recreate the probability distribution of the input datasets. This approach can be seen in the figure below.

Figure 10.3: Five iterations of Latin Hypercube sampling



The Latin Hypercube approach significantly reduce the amount of sampling required because it relies on using a technique called sampling without replacement. What this means in practice is that the number of divisions or stratifications of the cumulative distribution is the same as the number of sampling iterations carried out. In the example above, a total of five stratifications were made and hence five sampling iterations were carried out. In practice, this means that each stratification is sampled only once, and the process ensures that all of the stratifications are sampled. Unlike Monte Carlo simulation, where random sampling is applied across the full sample distribution, the Latin Hypercube approach applies random sampling to each of the stratifications. In this way, a much better fit to the probability distribution can be achieved with far fewer sampling iterations.

A4.3 Technology inputs to the uncertainty analysis

Direct Manufacturing Costs (DMC)

Table 10.19: Technology input assumptions for the uncertainty analysis - DMC

#	TechCode	Mean, €	SD High %	SD Low %	SD High, €	SD Low, €
1	CNG	1629	20%	20%	331	331
2	G-WALL	50	10%	10%	5	5
3	COMPR	11	10%	10%	1	1
4	VCR	352	32%	30%	114	106
5	COMB1	51	4%	4%	2	2
6	COMB2	10	14%	14%	1	1
7	VCR-D	320	10%	10%	32	32
8	DI-H	163	22%	22%	37	37
9	DI-SC	462	15%	15%	69	69
10	TCYCLE-A	433	19%	19%	83	83
11	TCYCLE-B	443	60%	30%	266	133
12	CYLD	181	42%	30%	77	54
13	DS-MLD	102	60%	30%	61	31
14	DS-MED	181	60%	30%	108	54
15	DS-STG	359	19%	19%	67	67
16	DS-MLD-D	48	9%	9%	4	4
17	DS-MED-D	-253	10%	10%	-25	-25
18	DS-STG-D	369	30%	30%	110	110
19	C-EGR	84	39%	30%	33	25
20	C-EGR-D	90	32%	30%	28	27
21	CAM-P	61	35%	30%	21	18
22	VVA	178	45%	30%	79	53
23	VVA-D	100	60%	30%	60	30
24	E-FRIC1	47	27%	27%	13	13
25	E-FRIC2	93	19%	19%	18	18
26	S-STOP	112	46%	30%	51	33
27	H-MCR	349	25%	25%	88	88
28	H-MLD	1184	35%	30%	411	355
29	H-FLL	2888	11%	11%	324	324
30	H-AIR	1548	17%	17%	258	258
31	H-FLY	1064	9%	9%	92	92
32	AMT	266	12%	12%	31	31
33	DCT	298	32%	30%	94	89
34	CVT	612	24%	24%	146	146
35	GEAR-R	39	47%	30%	19	12
36	GEAR-R2	45	12%	12%	6	6
37	DSPD	120	12%	12%	14	14
38	IMP-MT	162	39%	30%	63	49
39	xEV-GEAR	303	10%	10%	30	30
40	WR-MLD	42	14%	14%	6	6

#	TechCode	Mean, €	SD High %	SD Low %	SD High, €	SD Low, €
41	WR-MED	243	17%	17%	40	40
42	WR-STG	1004	13%	13%	132	132
43	AERO-1	43	37%	30%	16	13
44	AERO-2	135	17%	17%	23	23
45	LRRT1	34	60%	30%	20	10
46	LRRT2	59	13%	13%	8	8
47	D-FRIC1	20	60%	30%	12	6
48	D-FRIC2	98	42%	30%	41	30
49	LD-BRAKE	55	10%	10%	6	6
50	T-MAN	134	2%	2%	3	3
51	WHR-TELEC	467	60%	30%	280	140
52	WHR-CYCL	377	37%	30%	139	113
53	WHR-BAT	397	17%	17%	69	69
54	AUX-CAR	321	28%	28%	89	89
55	AUX-THERM	98	8%	8%	7	7
56	AUX-OTHER	182	5%	5%	9	9
57	EAS	114	46%	30%	52	34
58	LED	31	2%	2%	1	1
59	IMP-SP	No data				
60	SOLAR-C	1147	40%	30%	454	344
61	SOLAR-B	1262	40%	30%	499	378
62	ENG-ENCAP	101	10%	10%	10	10
63	BAT-NAV	No data				
64	BAT-RDR	254	10%	10%	25	25
65	EFF-ALT	39	19%	19%	8	8
66	IMP-MAC	28	10%	10%	3	3
67	HP-HVAC-ICE	1156	38%	30%	440	347
68	HP-HVAC	1156	38%	30%	440	347
69	ACT-SEATV	59	60%	30%	35	18
70	ADV-CC	351	44%	30%	155	105
71	ECO-NAV	No data				
72	GLAZE	24	60%	30%	15	7
73	CST	11	10%	10%	1	1
74	ACT-WARMUP	102	7%	7%	7	7
75	ACT-AERO-1	50	10%	10%	5	5
76	ACT-AERO-2	50	10%	10%	5	5
77	TPMS	12	46%	30%	5	4
78	FQS	24	10%	10%	2	2
79	M-CONTROL	21	25%	25%	5	5
80	COLD-STOR	28	15%	15%	4	4
81	HEAT-STOR	77	19%	19%	15	15
82	LOCAL-AC	6	60%	30%	3	2

Learning Rate Multipliers (LRM)

Table 10.20: Technology input assumptions for the uncertainty analysis - LRM

#	TechCode	LRMs				Low % uncertainty				High % uncertainty			
		2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030
1	CNG	1.00	0.89	0.81	0.77	0%	-3%	-4%	-4%	0%	5%	8%	9%
2	G-WALL	1.00	0.89	0.81	0.77	0%	-3%	-4%	-4%	0%	5%	8%	9%
3	COMPR	1.00	0.89	0.81	0.77	0%	-3%	-4%	-4%	0%	5%	8%	9%
4	VCR	1.00	0.74	0.62	0.57	0%	-7%	-9%	-10%	0%	13%	18%	17%
5	COMB1	1.00	0.89	0.81	0.77	0%	-3%	-4%	-5%	0%	5%	8%	9%
6	COMB2	1.00	0.89	0.81	0.77	0%	-3%	-4%	-5%	0%	5%	8%	9%
7	VCR-D	1.00	0.74	0.62	0.57	0%	-7%	-9%	-10%	0%	13%	18%	17%
8	DI-H	1.00	0.87	0.78	0.73	0%	-3%	-5%	-5%	0%	6%	10%	11%
9	DI-SC	1.00	0.76	0.64	0.59	0%	-6%	-6%	-9%	0%	11%	15%	14%
10	TCYCLE-A	1.00	0.74	0.62	0.57	0%	-7%	-9%	-10%	0%	13%	18%	17%
11	TCYCLE-B	1.00	0.74	0.62	0.57	0%	-7%	-9%	-10%	0%	13%	18%	17%
12	CYLD	1.00	0.89	0.81	0.77	0%	-3%	-4%	-4%	0%	5%	8%	9%
13	DS-MLD	1.00	1.00	1.00	1.00	0%	0%	0%	0%	0%	0%	0%	0%
14	DS-MED	1.00	0.94	0.89	0.86	0%	-1%	-2%	-2%	0%	3%	4%	5%
15	DS-STG	1.00	0.69	0.52	0.44	0%	-8%	-11%	-9%	0%	16%	26%	27%
16	DS-MLD-D	1.00	1.00	1.00	1.00	0%	0%	0%	0%	0%	0%	0%	0%
17	DS-MED-D	1.00	1.00	1.00	1.00	0%	0%	0%	0%	0%	0%	0%	0%
18	DS-STG-D	1.00	0.69	0.52	0.44	0%	-8%	-11%	-9%	0%	16%	26%	27%
19	C-EGR	1.00	0.87	0.78	0.73	0%	-3%	-5%	-5%	0%	6%	10%	11%
20	C-EGR-D	1.00	0.87	0.78	0.73	0%	-3%	-5%	-5%	0%	6%	10%	11%
21	CAM-P	1.00	0.89	0.81	0.77	0%	-3%	-4%	-4%	0%	5%	8%	9%
22	VVA	1.00	0.89	0.81	0.77	0%	-3%	-4%	-4%	0%	5%	8%	9%
23	VVA-D	1.00	0.89	0.81	0.77	0%	-3%	-4%	-4%	0%	5%	8%	9%
24	E-FRIC1	1.00	0.89	0.81	0.77	0%	-3%	-4%	-4%	0%	5%	8%	9%
25	E-FRIC2	1.00	0.76	0.64	0.59	0%	-6%	-6%	-9%	0%	11%	15%	14%
26	S-STOP	1.00	0.76	0.64	0.59	0%	-6%	-6%	-9%	0%	11%	15%	14%
27	H-MCR	1.00	0.76	0.64	0.59	0%	-6%	-6%	-9%	0%	11%	15%	14%
28	H-MLD	1.00	0.73	0.63	0.57	0%	-7%	-8%	-20%	0%	13%	15%	18%
29	H-FLL	1.00	0.70	0.58	0.53	0%	-8%	-9%	-13%	0%	15%	19%	18%
30	H-AIR	1.00	0.74	0.62	0.57	0%	-7%	-9%	-10%	0%	13%	18%	17%
31	H-FLY	1.00	0.74	0.62	0.57	0%	-7%	-9%	-10%	0%	13%	18%	17%
32	AMT	1.00	0.87	0.78	0.73	0%	-3%	-5%	-5%	0%	6%	10%	11%
33	DCT	1.00	0.87	0.78	0.73	0%	-3%	-5%	-5%	0%	6%	10%	11%
34	CVT	1.00	0.87	0.78	0.73	0%	-3%	-5%	-5%	0%	6%	10%	11%
35	GEAR-R	1.00	0.87	0.78	0.73	0%	-3%	-5%	-5%	0%	6%	10%	11%
36	GEAR-R2	1.00	0.87	0.78	0.73	0%	-3%	-5%	-5%	0%	6%	10%	11%
37	DSPD	1.00	0.87	0.78	0.73	0%	-3%	-5%	-5%	0%	6%	10%	11%
38	IMP-MT	1.00	0.87	0.78	0.73	0%	-3%	-5%	-5%	0%	6%	10%	11%
39	xEV-GEAR	1.00	0.73	0.63	0.57	0%	-7%	-8%	-20%	0%	13%	15%	18%
40	WR-MLD	1.00	0.89	0.81	0.77	0%	-3%	-4%	-4%	0%	5%	8%	9%

#	TechCode	LRMs				Low % uncertainty				High % uncertainty			
41	WR-MED	1.00	0.69	0.52	0.44	0%	-8%	-11%	-9%	0%	16%	26%	27%
42	WR-STG	1.00	0.69	0.51	0.43	0%	-9%	-13%	-12%	0%	17%	29%	31%
43	AERO-1	1.00	0.89	0.81	0.77	0%	-3%	-4%	-4%	0%	5%	8%	9%
44	AERO-2	1.00	0.89	0.81	0.77	0%	-3%	-4%	-4%	0%	5%	8%	9%
45	LRRT1	1.00	0.89	0.81	0.77	0%	-3%	-4%	-4%	0%	5%	8%	9%
46	LRRT2	1.00	0.76	0.64	0.59	0%	-6%	-6%	-9%	0%	11%	15%	14%
47	D-FRIC1	1.00	0.87	0.78	0.73	0%	-3%	-5%	-5%	0%	6%	10%	11%
48	D-FRIC2	1.00	0.86	0.76	0.70	0%	-3%	-5%	-6%	0%	6%	11%	13%
49	LD-BRAKE	1.00	1.00	1.00	1.00	0%	0%	0%	0%	0%	0%	0%	0%
50	T-MAN	1.00	0.87	0.78	0.73	0%	-3%	-5%	-5%	0%	6%	10%	11%
51	WHR-TELEC	1.00	0.74	0.62	0.57	0%	-7%	-9%	-10%	0%	13%	18%	17%
52	WHR-CYCL	1.00	0.74	0.62	0.57	0%	-7%	-9%	-10%	0%	13%	18%	17%
53	WHR-BAT	1.00	0.74	0.62	0.57	0%	-7%	-9%	-10%	0%	13%	18%	17%
54	AUX-CAR	1.00	0.85	0.74	0.66	0%	-4%	-6%	-7%	0%	7%	12%	16%
55	AUX-THERM	1.00	0.85	0.74	0.66	0%	-4%	-6%	-7%	0%	7%	12%	16%
56	AUX-OTHER	1.00	0.85	0.74	0.66	0%	-4%	-6%	-7%	0%	7%	12%	16%
57	EAS	1.00	0.87	0.78	0.73	0%	-3%	-5%	-5%	0%	6%	10%	11%
58	LED	1.00	0.89	0.81	0.77	0%	-3%	-4%	-4%	0%	5%	8%	9%
59	IMP-SP	1.00	0.87	0.78	0.73	0%	-3%	-5%	-5%	0%	6%	10%	11%
60	SOLAR-C	1.00	0.69	0.52	0.44	0%	-8%	-11%	-9%	0%	16%	26%	27%
61	SOLAR-B	1.00	0.69	0.52	0.44	0%	-8%	-11%	-9%	0%	16%	26%	27%
62	ENG-ENCAP	1.00	0.87	0.78	0.73	0%	-3%	-5%	-5%	0%	6%	10%	11%
63	BAT-NAV	1.00	0.76	0.64	0.59	0%	-6%	-6%	-9%	0%	11%	15%	14%
64	BAT-RDR	1.00	0.76	0.64	0.59	0%	-6%	-6%	-9%	0%	11%	15%	14%
65	EFF-ALT	1.00	0.87	0.78	0.73	0%	-3%	-5%	-5%	0%	6%	10%	11%
66	IMP-MAC	1.00	0.87	0.78	0.73	0%	-3%	-5%	-5%	0%	6%	10%	11%
67	HP-HVAC-ICE	1.00	0.74	0.62	0.57	0%	-7%	-9%	-10%	0%	13%	18%	17%
68	HP-HVAC	1.00	0.74	0.62	0.57	0%	-7%	-9%	-10%	0%	13%	18%	17%
69	ACT-SEATV	1.00	0.80	0.71	0.65	0%	-5%	-7%	-9%	0%	9%	12%	14%
70	ADV-CC	1.00	0.80	0.71	0.65	0%	-5%	-7%	-9%	0%	9%	12%	14%
71	ECO-NAV	1.00	0.76	0.64	0.59	0%	-6%	-6%	-9%	0%	11%	15%	14%
72	GLAZE	1.00	0.89	0.81	0.77	0%	-3%	-4%	-4%	0%	5%	8%	9%
73	CST	1.00	0.87	0.78	0.73	0%	-3%	-5%	-5%	0%	6%	10%	11%
74	ACT-WARMUP	1.00	0.80	0.71	0.65	0%	-5%	-7%	-9%	0%	9%	12%	14%
75	ACT-AERO-1	1.00	0.88	0.79	0.74	0%	-3%	-4%	-5%	0%	5%	9%	10%
76	ACT-AERO-2	1.00	0.88	0.79	0.74	0%	-3%	-4%	-5%	0%	5%	9%	10%
77	TPMS	1.00	0.89	0.81	0.77	0%	-3%	-4%	-5%	0%	5%	8%	9%
78	FQS	1.00	0.72	0.57	0.51	0%	-8%	-10%	-10%	0%	15%	22%	22%
79	M-CONTROL	1.00	0.74	0.62	0.57	0%	-7%	-9%	-10%	0%	13%	18%	17%
80	COLD-STOR	1.00	0.76	0.64	0.59	0%	-6%	-6%	-9%	0%	11%	15%	14%
81	HEAT-STOR	1.00	0.74	0.62	0.57	0%	-7%	-9%	-10%	0%	13%	18%	17%
82	LOCAL-AC	1.00	0.76	0.64	0.59	0%	-6%	-6%	-9%	0%	11%	15%	14%

Indirect Cost Multipliers (ICM)

Table 10.21: Technology input assumptions for the uncertainty analysis - ICM

#	TechCode	ICMs				Low % uncertainty				High % uncertainty			
		2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030
1	CNG	0.296	0.208	0.084	0.084	-21%	-19%	-6%	-6%	38%	22%	103%	6%
2	G-WALL	0.296	0.208	0.084	0.084	-21%	-19%	-6%	-6%	38%	22%	103%	6%
3	COMPR	0.296	0.208	0.084	0.084	-21%	-19%	-6%	-6%	38%	22%	103%	6%
4	VCR	0.617	0.382	0.238	0.099	-17%	-13%	-44%	-7%	10%	30%	59%	109%
5	COMB1	0.296	0.208	0.084	0.084	-21%	-19%	-6%	-6%	38%	22%	103%	6%
6	COMB2	0.204	0.119	0.108	0.108	-37%	-9%	-7%	-7%	77%	17%	14%	7%
7	VCR-D	0.617	0.382	0.238	0.099	-17%	-13%	-44%	-7%	10%	30%	59%	109%
8	DI-H	0.428	0.277	0.169	0.082	-16%	-14%	-39%	-6%	10%	29%	57%	84%
9	DI-SC	0.296	0.208	0.084	0.084	-21%	-19%	-6%	-6%	38%	22%	103%	6%
10	TCYCLE-A	0.454	0.330	0.099	0.099	-20%	-22%	-7%	-7%	36%	21%	161%	7%
11	TCYCLE-B	0.454	0.330	0.099	0.099	-20%	-22%	-7%	-7%	36%	21%	161%	7%
12	CYLD	0.408	0.281	0.096	0.096	-19%	-21%	-7%	-7%	32%	25%	134%	7%
13	DS-MLD	0.296	0.208	0.084	0.084	-21%	-19%	-6%	-6%	38%	22%	103%	6%
14	DS-MED	0.428	0.285	0.183	0.100	-16%	-14%	-36%	-7%	10%	27%	51%	69%
15	DS-STG	0.454	0.454	0.330	0.099	-10%	-20%	-34%	-7%	10%	10%	26%	212%
16	DS-MLD-D	0.296	0.208	0.084	0.084	-21%	-19%	-6%	-6%	38%	22%	103%	6%
17	DS-MED-D	-0.405	-0.297	-0.046	-0.046	-20%	-26%	-17%	-17%	34%	82%	381%	17%
18	DS-STG-D	0.454	0.454	0.330	0.099	-10%	-20%	-34%	-7%	10%	10%	26%	212%
19	C-EGR	0.407	0.213	0.128	0.082	-19%	-16%	-29%	-6%	10%	41%	49%	47%
20	C-EGR-D	0.480	0.270	0.168	0.088	-18%	-14%	-37%	-7%	10%	35%	54%	73%
21	CAM-P	0.384	0.262	0.101	0.101	-21%	-20%	-7%	-7%	38%	24%	112%	7%
22	VVA	0.327	0.224	0.089	0.089	-21%	-19%	-7%	-7%	38%	23%	106%	7%
23	VVA-D	0.346	0.234	0.095	0.095	-21%	-19%	-7%	-7%	38%	24%	103%	7%
24	E-FRIC1	0.164	0.099	0.091	0.091	-35%	-8%	-7%	-7%	74%	16%	13%	7%
25	E-FRIC2	0.147	0.090	0.083	0.083	-34%	-8%	-6%	-6%	72%	15%	12%	6%
26	S-STOP	0.279	0.200	0.076	0.076	-24%	-20%	-6%	-6%	45%	18%	113%	6%
27	H-MCR	0.278	0.198	0.074	0.074	-23%	-20%	-6%	-6%	44%	18%	116%	6%
28	H-MLD	0.382	0.238	0.099	0.099	-13%	-26%	-7%	-7%	30%	51%	58%	7%
29	H-FLL	0.604	0.409	0.144	0.144	-17%	-21%	-8%	-8%	27%	29%	129%	8%
30	H-AIR	0.454	0.330	0.099	0.099	-20%	-22%	-7%	-7%	36%	21%	161%	7%
31	H-FLY	0.562	0.365	0.192	0.099	-18%	-13%	-52%	-7%	10%	20%	88%	58%
32	AMT	0.571	0.396	0.250	0.098	-16%	-13%	-45%	-7%	10%	25%	60%	120%
33	DCT	0.566	0.393	0.248	0.098	-16%	-13%	-45%	-7%	10%	25%	60%	119%
34	CVT	0.413	0.245	0.158	0.084	-18%	-13%	-36%	-6%	10%	32%	51%	71%
35	GEAR-R	0.569	0.350	0.212	0.098	-17%	-15%	-41%	-7%	10%	31%	59%	92%
36	GEAR-R2	0.413	0.245	0.158	0.084	-18%	-13%	-36%	-6%	10%	32%	51%	71%
37	DSPD	0.296	0.107	0.092	0.087	-23%	-10%	-10%	-7%	10%	59%	15%	11%
38	IMP-MT	0.296	0.107	0.092	0.087	-23%	-10%	-10%	-7%	10%	59%	15%	11%
39	xEV-GEAR	0.245	0.158	0.084	0.084	-13%	-22%	-6%	-6%	32%	42%	39%	6%
40	WR-MLD	0.157	0.095	0.087	0.087	-35%	-8%	-7%	-7%	73%	16%	13%	7%

#	TechCode	ICMs				Low % uncertainty				High % uncertainty			
41	WR-MED	0.296	0.296	0.208	0.084	-10%	-21%	-30%	-6%	10%	10%	28%	136%
42	WR-STG	0.454	0.454	0.330	0.099	-10%	-20%	-34%	-7%	10%	10%	26%	212%
43	AERO-1	0.175	0.105	0.096	0.096	-35%	-9%	-7%	-7%	75%	16%	13%	7%
44	AERO-2	0.210	0.123	0.111	0.111	-37%	-9%	-7%	-7%	77%	17%	14%	7%
45	LRRT1	0.126	0.079	0.073	0.073	-33%	-8%	-6%	-6%	69%	14%	11%	6%
46	LRRT2	0.092	0.062	0.058	0.058	-29%	-6%	-5%	-5%	61%	12%	9%	5%
47	D-FRIC1	0.413	0.245	0.158	0.084	-18%	-13%	-36%	-6%	10%	32%	51%	71%
48	D-FRIC2	0.296	0.296	0.208	0.084	-10%	-21%	-30%	-6%	10%	10%	28%	136%
49	LD-BRAKE	0.280	0.113	0.099	0.095	-26%	-11%	-10%	-7%	10%	16%	13%	9%
50	T-MAN	0.617	0.382	0.238	0.099	-17%	-13%	-44%	-7%	10%	30%	59%	109%
51	WHR-TELEC	0.454	0.330	0.099	0.099	-20%	-22%	-7%	-7%	36%	21%	161%	7%
52	WHR-CYCL	0.454	0.330	0.099	0.099	-20%	-22%	-7%	-7%	36%	21%	161%	7%
53	WHR-BAT	0.454	0.330	0.099	0.099	-20%	-22%	-7%	-7%	36%	21%	161%	7%
54	AUX-CAR	0.306	0.306	0.237	0.081	-10%	-18%	-32%	-6%	10%	10%	22%	177%
55	AUX-THERM	0.471	0.471	0.361	0.111	-10%	-19%	-34%	-7%	10%	10%	23%	206%
56	AUX-OTHER	0.157	0.157	0.095	0.087	-10%	-35%	-10%	-7%	10%	10%	20%	15%
57	EAS	0.296	0.107	0.092	0.087	-23%	-10%	-10%	-7%	10%	59%	15%	11%
58	LED	0.157	0.095	0.087	0.087	-35%	-8%	-7%	-7%	73%	16%	13%	7%
59	IMP-SP	0.413	0.245	0.158	0.084	-18%	-13%	-36%	-6%	10%	32%	51%	71%
60	SOLAR-C	0.296	0.296	0.208	0.084	-10%	-21%	-30%	-6%	10%	10%	28%	136%
61	SOLAR-B	0.296	0.296	0.208	0.084	-10%	-21%	-30%	-6%	10%	10%	28%	136%
62	ENG-ENCAP	0.296	0.107	0.092	0.087	-23%	-10%	-10%	-7%	10%	59%	15%	11%
63	BAT-NAV	0.157	0.095	0.087	0.087	-35%	-8%	-7%	-7%	73%	16%	13%	7%
64	BAT-RDR	0.296	0.208	0.084	0.084	-21%	-19%	-6%	-6%	38%	22%	103%	6%
65	EFF-ALT	0.413	0.245	0.158	0.084	-18%	-13%	-36%	-6%	10%	32%	51%	71%
66	IMP-MAC	0.296	0.107	0.092	0.087	-23%	-10%	-10%	-7%	10%	59%	15%	11%
67	HP-HVAC-ICE	0.296	0.208	0.084	0.084	-21%	-19%	-6%	-6%	38%	22%	103%	6%
68	HP-HVAC	0.296	0.208	0.084	0.084	-21%	-19%	-6%	-6%	38%	22%	103%	6%
69	ACT-SEATV	0.296	0.208	0.084	0.084	-21%	-19%	-6%	-6%	38%	22%	103%	6%
70	ADV-CC	0.233	0.134	0.084	0.084	-13%	-24%	-6%	-6%	20%	48%	6%	6%
71	ECO-NAV	0.233	0.134	0.084	0.084	-13%	-24%	-6%	-6%	20%	48%	6%	6%
72	GLAZE	0.296	0.208	0.084	0.084	-21%	-19%	-6%	-6%	38%	22%	103%	6%
73	CST	0.157	0.095	0.087	0.087	-35%	-8%	-7%	-7%	73%	16%	13%	7%
74	ACT-WARMUP	0.413	0.245	0.158	0.084	-18%	-13%	-36%	-6%	10%	32%	51%	71%
75	ACT-AERO-1	0.233	0.134	0.084	0.084	-13%	-24%	-6%	-6%	20%	48%	6%	6%
76	ACT-AERO-2	0.374	0.233	0.134	0.084	-19%	-13%	-41%	-6%	10%	20%	69%	39%
77	TPMS	0.374	0.233	0.134	0.084	-19%	-13%	-41%	-6%	10%	20%	69%	39%
78	FQS	0.157	0.095	0.087	0.087	-35%	-8%	-7%	-7%	73%	16%	13%	7%
79	M-CONTROL	0.296	0.296	0.208	0.084	-10%	-21%	-30%	-6%	10%	10%	28%	136%
80	COLD-STOR	0.296	0.208	0.084	0.084	-21%	-19%	-6%	-6%	38%	22%	103%	6%
81	HEAT-STOR	0.296	0.208	0.084	0.084	-21%	-19%	-6%	-6%	38%	22%	103%	6%
82	LOCAL-AC	0.296	0.208	0.084	0.084	-21%	-19%	-6%	-6%	38%	22%	103%	6%

Segment Multipliers (SM)

Table 10.22: Technology input assumptions for the uncertainty analysis - SM

#	TechCode	Small Car	Lower Medium Car	Upper Medium Car	Large Car	Small LCV	Medium LCV	Large LCV
1	CNG	95%	100%	100%	155%	100%	100%	155%
2	G-WALL	100%	100%	100%	100%	100%	100%	100%
3	COMPR	90%	100%	100%	100%	100%	100%	100%
4	VCR	100%	100%	100%	140%	100%	105%	140%
5	COMB1	100%	100%	100%	100%	180%	180%	180%
6	COMB2	90%	100%	100%	175%	100%	100%	175%
7	VCR-D	100%	100%	100%	140%	100%	105%	140%
8	DI-H	100%	100%	100%	140%	100%	105%	140%
9	DI-SC	80%	100%	120%	140%	100%	105%	140%
10	TCYCLE-A	100%	100%	105%	140%	100%	105%	140%
11	TCYCLE-B	100%	100%	105%	140%	100%	105%	140%
12	CYLD	100%	100%	100%	100%	100%	100%	100%
13	DS-MLD	80%	100%	120%	105%	100%	105%	105%
14	DS-MED	70%	100%	110%	105%	100%	105%	105%
15	DS-STG	90%	100%	115%	105%	100%	105%	105%
16	DS-MLD-D	100%	100%	100%	140%	80%	85%	90%
17	DS-MED-D	95%	100%	110%	140%	80%	85%	90%
18	DS-STG-D	85%	100%	115%	140%	80%	85%	90%
19	C-EGR	95%	100%	110%	140%	100%	110%	140%
20	C-EGR-D	100%	100%	100%	100%	100%	100%	100%
21	CAM-P	95%	100%	100%	155%	100%	100%	155%
22	VVA	95%	100%	100%	155%	100%	100%	155%
23	VVA-D	95%	100%	100%	155%	60%	60%	85%
24	E-FRIC1	100%	100%	100%	100%	100%	150%	200%
25	E-FRIC2	100%	100%	100%	100%	100%	150%	200%
26	S-STOP	90%	100%	110%	130%	95%	105%	120%
27	H-MCR	95%	100%	105%	130%	95%	105%	120%
28	H-MLD	90%	100%	105%	125%	95%	105%	115%
29	H-FLL	85%	100%	110%	130%	95%	110%	140%
30	H-AIR	85%	100%	110%	130%	95%	110%	140%
31	H-FLY	90%	100%	105%	125%	95%	105%	115%
32	AMT	100%	100%	100%	105%	100%	100%	135%
33	DCT	95%	100%	105%	105%	115%	130%	185%
34	CVT	100%	100%	100%	105%	115%	130%	185%
35	GEAR-R	100%	100%	100%	100%	100%	100%	100%
36	GEAR-R2	100%	100%	100%	100%	100%	100%	100%
37	DSPD	100%	100%	100%	105%	100%	100%	135%
38	IMP-MT	100%	100%	100%	105%	100%	100%	135%
39	xEV-GEAR	75%	100%	125%	150%	100%	125%	150%
40	WR-MLD	80%	100%	115%	135%	95%	115%	215%
41	WR-MED	80%	100%	115%	130%	165%	190%	355%

#	TechCode	Small Car	Lower Medium Car	Upper Medium Car	Large Car	Small LCV	Medium LCV	Large LCV
42	WR-STG	80%	100%	115%	130%	220%	260%	480%
43	AERO-1	100%	100%	115%	130%	100%	125%	150%
44	AERO-2	100%	100%	115%	130%	100%	125%	150%
45	LRRT1	90%	100%	110%	100%	265%	335%	480%
46	LRRT2	100%	100%	100%	100%	100%	100%	100%
47	D-FRIC1	100%	100%	100%	100%	160%	160%	180%
48	D-FRIC2	100%	100%	100%	100%	160%	160%	180%
49	LD-BRAKE	100%	100%	100%	100%	100%	100%	100%
50	T-MAN	100%	100%	100%	115%	55%	80%	115%
51	WHR-TELEC	100%	100%	100%	135%	100%	100%	135%
52	WHR-CYCL	100%	100%	100%	100%	200%	200%	300%
53	WHR-BAT	85%	100%	110%	130%	95%	110%	140%
54	AUX-CAR	95%	100%	105%	120%	55%	55%	60%
55	AUX-THERM	95%	100%	100%	120%	75%	85%	90%
56	AUX-OTHER	95%	100%	110%	125%	55%	60%	65%
57	EAS	95%	100%	105%	120%	55%	55%	60%
58	LED	100%	100%	100%	100%	100%	100%	100%
59	IMP-SP	95%	100%	105%	120%	55%	55%	60%
60	SOLAR-C	95%	100%	100%	120%	75%	85%	90%
61	SOLAR-B	95%	100%	100%	120%	75%	85%	90%
62	ENG-ENCAP	95%	100%	100%	120%	75%	85%	90%
63	BAT-NAV	100%	100%	100%	100%	100%	100%	100%
64	BAT-RDR	100%	100%	100%	100%	100%	100%	100%
65	EFF-ALT	100%	100%	100%	100%	100%	100%	100%
66	IMP-MAC	95%	100%	100%	120%	75%	85%	90%
67	HP-HVAC-ICE	95%	100%	100%	120%	75%	85%	90%
68	HP-HVAC	95%	100%	100%	120%	75%	85%	90%
69	ACT-SEATV	95%	100%	100%	120%	75%	85%	90%
70	ADV-CC	95%	100%	100%	120%	75%	85%	90%
71	ECO-NAV	100%	100%	100%	100%	100%	100%	100%
72	GLAZE	100%	100%	100%	100%	100%	100%	100%
73	CST	90%	100%	110%	100%	265%	335%	480%
74	ACT-WARMUP	100%	100%	100%	100%	100%	100%	100%
75	ACT-AERO-1	95%	100%	100%	120%	75%	85%	90%
76	ACT-AERO-2	100%	100%	120%	135%	100%	120%	135%
77	TPMS	100%	100%	110%	115%	100%	110%	115%
78	FQS	100%	100%	100%	100%	100%	100%	100%
79	M-CONTROL	100%	100%	100%	100%	100%	100%	100%
80	COLD-STOR	100%	100%	100%	100%	100%	100%	100%
81	HEAT-STOR	95%	100%	100%	120%	75%	85%	90%
82	LOCAL-AC	95%	100%	100%	120%	75%	85%	90%

A5 Appendix 5 – Additional technical detail relevant to the PHEM simulation analysis by TU Graz

The following sections provide a technical summary of the basis of and key assumptions used in the development of simulations for different LDV technology types.

A5.1 SI Engine Technologies simulated

Below the engine technologies and the corresponding methods for the simulation are described.

To simulate fuel saving engine technologies the engine fuel maps have been adjusted compared to the fuel maps for the base engines The base SI and CI engine fuel maps have been defined based on measured engines from model year 2002, as far as possible, to reflect engines without the technologies to be simulated later on.

The percentage improvements due to the advanced technologies have been subtracted for each load point from the base engine map to produce the fuel maps for the advanced engines. The information on the percentage improvements are based on different sources:

- From engines measured with and without a technology
- From vehicles measured with and without a technology
- From literature
- From simplified simulations.

In the following the technologies simulated are described.

A5.1.1 Cylinder deactivation (CYLD)

Measured values from a petrol engine tested once with and once without cylinder deactivation were analysed. The savings for each load point of the engine map were applied to the basic petrol engine to simulate the technology effects consistently.

The simulation showed fuel saving potentials up to 5.7% on the NEDC. Due to fewer part load operation points in WLTC, CADC and RWC the saving potentials are lower for these cycles.

A5.1.2 Mild, Medium and Strong downsizing (DS-MLD, DS-MED and DS-STG)

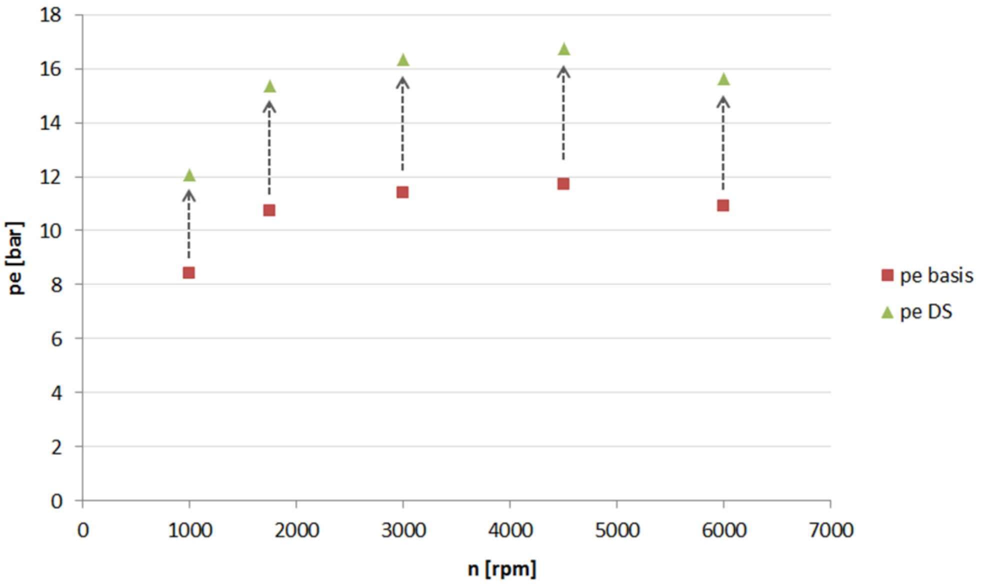
The downsizing steps simulated have been defined by a 15% (DS-MLD), 30% (DS-MED) and >=45% (DS-STG) cylinder content reduction, respectively.

The vehicles had a similar utility after the cylinder content reduction, thus:

- The engine power remained constant compared to the basis vehicles.
- Rated engine speed n_{rated} was kept constant. Thus the reduction of cylinder content required an increase of the mean effective pressure in the basic engine maps. Thus the change in mean effective pressure was calculated for each load point from the defined reduction in the cylinder volumes. The efficiencies at the single rpm/pe combinations in the engine map were kept constant. This gives the engine fuel map for the downsized engines.

The fuel saving potential with this technology is about 3-4% with mild downsizing, 6-8% with medium downsizing and 12% with strong downsizing on the NEDC. For the other cycles the saving potentials are lower.

Figure 10.4: Example for the mean effective pressure (pe) for the basis engine and for the down sized engine (DS)



A5.1.3 Start-stop system (S-STOP)

The PHEM tool includes a start/stop model which was applied for the simulation. In the NEDC after standstill the engine is switched off until the driver starts again (no time delay and already at first stop phase, thus the system is rather a future technology). In WLTC, CADC and RWC the engine is already switched off if the vehicle velocity is < 3km/h before standstill (recommended for WLTC simulations by LAT and also assumed for CADC and RWC). The idling shares of the NEDC however, are much higher than found in WLTC or typical real world driving. The simulation in PHEM showed an average saving potential about 5% for the NEDC. On WLTC, CADC and RWC the saving potential is lower, because the stop shares in the cycles are also lower.

A5.1.4 Combustion Improvements SI engines Level 1 (“G-Wall”)

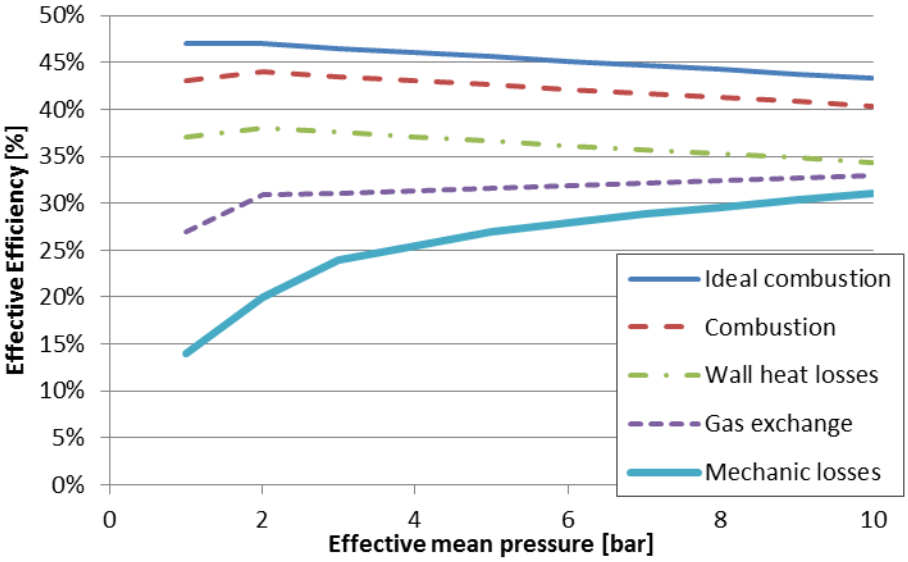
Combustion engines transform chemical energy into heat energy which is then converted into mechanical work during the expansion stroke of the gas in the cylinder. Thus losses of heat as well as too short expansion phases reduce the share of energy transformed into useful work.

The heat transfer from the gas to the cylinder wall and consequently to the coolant and to the ambient are determined by the temperature difference between the gas and the cylinder walls and by the pressure and turbulence in the cylinder.

A reduction of the heat losses in the combustion was assumed from a combination of EGR (reduced temperature in the cylinder) but mainly by demand controlled coolant flow management. The management could, for example, separate the cooling circuits of cylinder wall and cylinder head and control the coolant flow towards maximum temperature given by material durableness.

Wall-heat losses contribute approximately 6 percentage points to the energy losses in the SI engine (Figure 10.5). A reduction of approximately 10% of the heat losses was assumed to be gained on average in the NEDC. Demand controlled coolant pumps can also reduce the power demand from the pump at engine loads where less cooling is demanded. Thus a higher fuel efficiency improvement was assumed in the engine map for the lower engine loads compared to high loads. With these reduction values the engine fuel map was adjusted compared to the base SI fuel map. The simulation with PHEM showed on average over the vehicle classes a 2.5% fuel consumption improvement in the NEDC for this technology. For WLTC 2.3% fuel reduction has been computed which is lower than in the NEDC due to the higher engine loads in the WLTP. The fuel saving potential is 2.1% in the RWC.

Figure 10.5: Generic engine efficiencies for SI engine for the ideal combustion process without losses and for cumulative add-ons of the real world losses for an SI engine (simplified data, basis from (IVT, 2013))



A5.1.5 Increased compression ratio ("COMPR")

The theoretical efficiency of the ideal combustion (Figure 10.5) increases with an increased compression ratio since more heat energy can be converted to mechanical energy. The theoretical efficiency can be calculated from the ideal thermodynamic process as follows:

$$Efficiency = 1 - \frac{1}{CR^{k-1}}$$

Where CR...............Compression ratio

k..................isentropic exponent of the gas in the corresponding temperature range

The geometrical compression ratio differs from the effective compression ratio which is influenced also by the valve actuation and the combustion timing. The geometric compression ratio is mainly limited at SI engines by knocking in full load. Since knocking depends on the fuel used and on other variable conditions, the compression ratio can be approximated to the maximum if a knocking sensor is used which can be used to control injection and ignition timing in case knocking is registered.

The measure was defined with 1 point increase of the compression ratio. The base effect was calculated from the equation given above where the efficiency was computed for a CR of 12.5:1 compared to 11.5:1 in the base engine which leads to approximately a 2% efficiency improvement. Since the compression ratio is limited for SI engines mainly due to knocking tendencies at high engine loads the effect of the increase in the compression ratio was assumed to be reduced close to the full load due to measures to limit knocking (adjustments of timing of ignition and injection). The fuel map of the base engine was adjusted accordingly against the map of the base engine. A fuel saving of 1.7 to 1.9% was computed for the different vehicle classes in the 4 different test cycles.

A5.1.6 Variable compression ratio ("VCR")

Systems to allow variable compression ratio (VCR) are designed via complex crankshafts to allow variable compression and expansion ratios. Different concepts have been developed for a VCR, e.g. (Eichlseder, 2008) which all are mechanically complex. The basic target is to maximise the expansion ratio (where the heat energy is converted into mechanical work) while limiting the compression ratio to the technical feasible level (e.g. due to knocking). At low loads the effect of VCR is rather small, since already the base engine does not waste much heat energy at the end of the expansion cycle; at high loads the efficiency of the combustion process can be much more improved. In the simulation a 10% improvement in the engine efficiency of the ideal combustion was assumed at full load and 2% at part load. The reduction rates versus the base SI engine map have been interpolated between motoring and full load accordingly to produce the engine map for VCR.

In NEDC on average a 4.1% fuel reduction has been simulated with PHEM compared to the base SI vehicles. In the WLTP a higher fuel saving potential (5.9%) was found due to the higher engine loads in the WLTP.

A5.1.7 Direct Injection homogeneous combustion ("DI-H")

Direct injection has a cooling effect to the cylinder charge due to fuel evaporation. This reduces the knocking tendency and allows for a higher compression ratio. In addition the density of the charge air is increased due to the lower temperature allowing higher specific work per cylinder volume. Since in the actual simulation for assessing the fuel saving potential the rated engine power is always kept constant the direct injection allows for a slightly smaller engine.

In contrary to the stratified and lean DI engine concept the homogeneous stoichiometric DI can make use of the well-established and highly efficient 3-way catalyst technology for pollutant control but has less fuel saving potential since the load change and wall-heat losses are not influenced much. Homogeneous DI is already a widely used technology in current vehicle models. The fuel saving was again applied as the reduction against the base SI engine map assuming a higher compression ratio (for the approach see Section A5.1.5) and slight downsize effects resulting in approximately a 3.8% fuel efficiency improvement. The reduction simulated with PHEM for the different vehicle classes and cycles is 3.5 to 3.8% compared to the SI base vehicles.

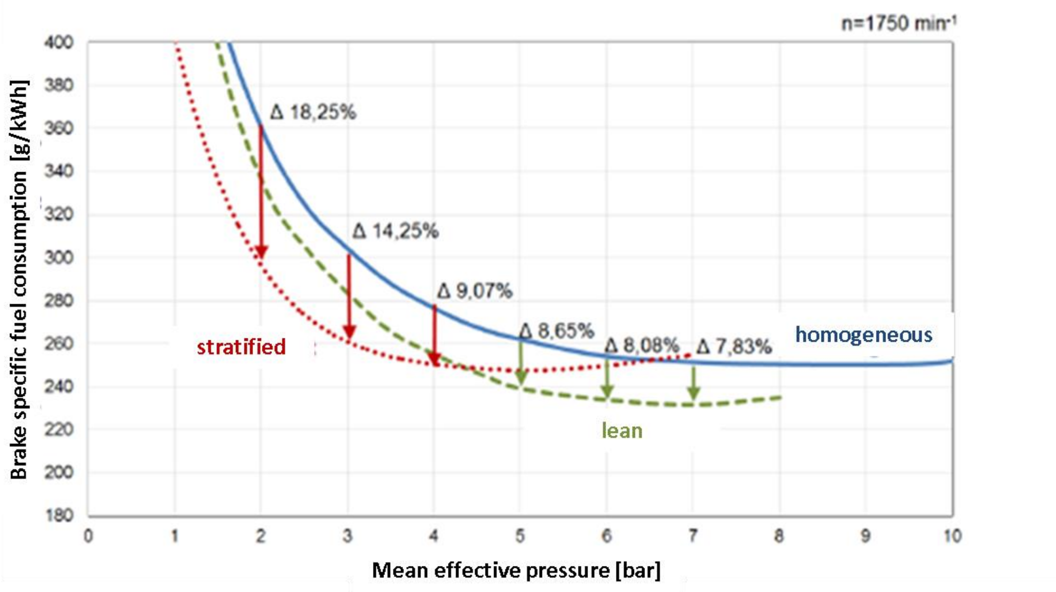
A5.1.8 Direct injection stratified charge and lean burn combustion ("DI-SC")

In addition to the homogeneous direct injection the lean burn concept avoids throttling the intake air to a large extent. This leads to a lean cylinder charge which is designed at low engine loads so as to have higher concentrations of fuel around the spark plugs so as to have flammable charge conditions. At higher engine loads a homogeneous but still lean mixture is used. At high loads a stoichiometric air to fuel ratio is used to maintain the engine power.

This, the effects of the combustion concept are quite different over the engine fuel map points. The reduction potentials given in the literature are in the meantime often based on measurements and give reduction rates of around 10% compared to the stoichiometric engine. The reduction rates are much higher at low loads (where the pumping losses are highest at the stoichiometric engine) than at high loads (mainly higher compression ratio effects). In (Planer, 2013) measurements and simulations have been performed to assess the reduction potential at different engine speeds and loads compared to a stoichiometric DI combustion concept. The reduction rates are given in (Planer, 2013) for different engine speeds (example for 1750 rpm in Figure 10.6). These values have been added to the reduction rates calculated for the DI stratified combustion versus the base port fuel injection engine.

The resulting NO_x emissions are lower than at stoichiometric combustion but much too high for actual emission limits. Since the 3-way catalyst does not reduce NO_x in the lean exhaust conditions a NO_x storage catalyst is necessary for NO_x control. EGR can be employed for NO_x control but is treated here as separate technology (see Section A5.1.11).

Figure 10.6: Fuel reduction due to stratified and lean combustion compared to a stoichiometric DI petrol engine at 1750 rpm (Planer, 2013)

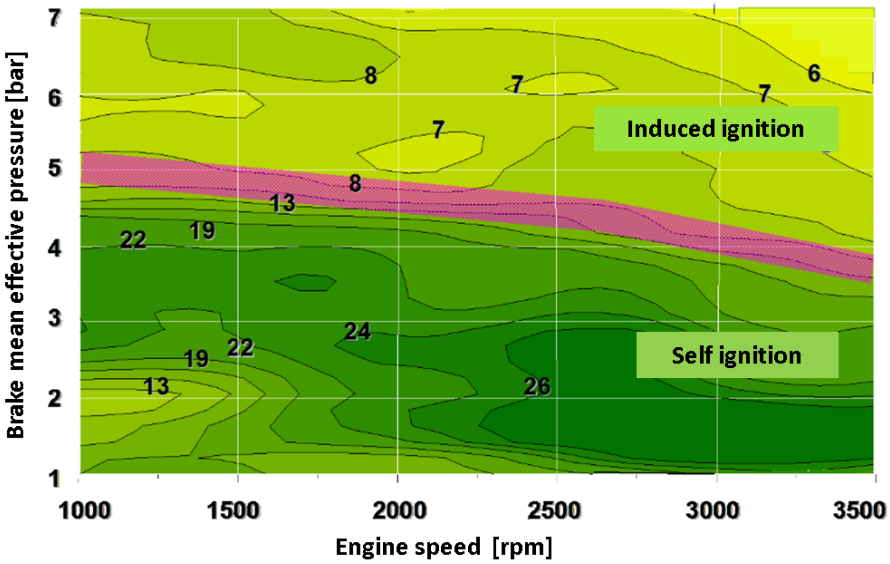


A5.1.9 HCCI combustion concept ("Tcycle-a")

In order to assess "Thermodynamic cycle improvements (a)", a homogeneous charge compression ignition (HCCI) was simulated. The engine runs with a lean air to fuel ratio and a high compression ratio. The auto ignition is controlled by EGR rates and injection timing. The HCCI concept works only at low engine loads and speeds and is difficult to control. The combustion concept leads to low flame temperatures which lead to low NO_x exhaust emissions but higher HC and CO values.

The reduction rates against the base engine were taken from Figure 10.6. Above 4000 rpm and above 8 bar brake mean effective pressure a conventional stoichiometric combustion was assumed with no reduction compared to the base engine. To convert the resulting fuel saving map into the standard PHEM formats (with n_{norm} and P_{norm}) the rated power was assumed to be 5000 rpm and 12 bar.

Figure 10.7: Percentage fuel saving due to HCCI compared to stoichiometric intake manifold fuel injection (Eichlseder, 2012)



The HCCI fuel map was used to simulate all vehicle classes in the 4 cycles. As described before, the normalised fuel map is adjusted to the rated power and rated engine speed of each vehicle class. For the NEDC fuel savings between 13% and 20% were computed. The higher reduction rates are found for the vehicle classes with high power to weight ratios due to the more frequent low load driving conditions. In the WLTC (-7% to -18% depending on the vehicle class) and in the real world cycle less reduction potential was calculated due to the higher engine power demand in these speed patterns.

A5.1.10 Miller cycle (“Tcycle-b”)

In order to assess “Thermodynamic cycle improvements (b)”, a Miller cycle was simulated. The aim of the Miller cycle is to increase the expansion ratio against the compression ratio. The Miller cycle applies a variable valve actuation where the intake valve closes earlier. Thus the air to fuel ratio in the cylinder is controlled to stoichiometric conditions as in the base engine. However, the cylinder charge is cooled in the remaining expansion phase after the valve has closed. Thus the knocking tendency is reduced and earlier combustion or higher compression ratio is possible compared to the base engine. The charge cycle work is reduced against the base engine and the expansion ratio is increased against the compression ratio which results in a higher degree of useful expansion work. The Atkinson cycle in comparison closes the intake valve later and thus shifts back cylinder load during the beginning of the compression ratio. This also allows less throttling of intake air and reduces the real compression ratio without a reduction of the expansion ratio and thus has similar effects than the Miller cycle.

The Miller cycle is typically combined with turbo charging and direct injection to compensate for the lower cylinder filling rate[52]. Thus simulating a Miller cycle for the base engine technology is not meaningful and therefore the reduction rates have been assessed compared to a rather modern turbocharged DI engine. This assumption allows the later combination of Miller cycle reduction rates in the engine map with other DI technologies to simulate advanced future engine technologies. Nevertheless, in the simulation of the reduction potentials of the base technology the reduction had to be simulated for the vehicle equipped with the base port injection engine. Since the proportional reduction potential was assessed based on a turbocharged DI engine, but the reduction is applied in the analysis of the single technology to the base engine, the result is a virtual engine with Miller potential for modern engines applied to the absolute fuel consumption of an old engine. This calculation strategy was necessary to fit into the overall method of the project.

The fuel saving values in the engine map compared to the base engine were calculated from a combination of reduced pumping losses and an increased compression ratio. The simulation with PHEM showed a 12% to 14% reduction potential in the NEDC with the lower value for the large LCV due to the high engine loads in this vehicle class. In the WLTP a 9% to 12% reduction has been calculated, for the RWC it was 8% to 11%.

A5.1.11 Cooled low pressure EGR (“C-EGR”)

Exhaust Gas Recirculation (EGR) is widely used in Diesel engines for NO_x control. In petrol engines EGR is useful mainly for fuel efficiency improvements. The following effects are considered in the elaboration of the SI engine fuel map for cooled EGR:

- The recirculated exhaust gas has a higher heat capacity than air and thus lowers the combustion temperatures. This reduces knocking tendencies and thus allows in SI engines a higher compression ratio which however is assumed to be a small effect since EGR rates at full load will be rather low in order to maintain engine full load performance.
- Cooled EGR increases the effect mentioned above but is assumed mainly to be applied to increase the density of the gas in the cylinder to maintain a sufficient cylinder charging.
- The lower temperatures lead to a reduction of wall heat losses.

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[52] The actual Prius uses an engine with Atkinson without turbocharging. Since the electric motor can compensate for reduced specific power in the Prius, the cheaper natural aspirated version is very reasonable there but seems not to be applicable for the conventional vehicles here.

- EGR leads to a reduction of pumping losses since EGR replaces fresh air with a 21% oxygen content by CO_2 and water, which allows less throttling of the fresh intake air and still running under stoichiometric combustion conditions. Stoichiometric conditions are important for an efficient emission reduction in the 2-way catalyst.

The effects were assessed for approximately 20% EGR at low engine loads. Changes against the base SI engine map were based on the share of losses for gas exchange and wall-heat losses shown before in Figure 10.5.

The simulation with PHEM showed on average a 6.1% CO_2 reduction for the vehicle classes in the NEDC. In the WLTP a 4.5% reduction were calculated, while for the RWC this was 3.9%. The reductions are higher in lower engine load areas than at high loads, thus cooled EGR shows higher potential in the NEDC than in the WLTC and in real world cycles. The reduction effect is also more pronounced in vehicle classes with high power to weight ratios compared to low motorised vehicles such as LCVs.

A5.1.12 Variable Cam phasing (“CAM-P”)

Cam-phasing is a basic form of a variable timing for opening and closing the valves. The angle of the camshaft is rotated relative to the crankshaft, thus opening or closing the valves earlier or later. The angle of rotation is controlled for best conditions at the actual engine operation conditions. The targets of the control system are similar as for the fully variable valve actuation (see Section A5.1.13) but the simpler system provides less variance. The angle of the intake camshaft is typically used to control the air supply and thus can avoid pumping losses while the exhaust camshaft can be used to control exhaust residual shares (i.e. internal EGR rates).

The effects have been assessed in a similar way as that described in Section A5.1.13 but with 40% less reduction potential to reach the reduction levels analysed in the literature review (see Section 4). The fuel savings against the base SI engine map were used to set up the engine fuel map for the SI engine with variable cam phasing. The resulting fuel savings from this technology are higher in low loads than in full load due to the higher share of pumping losses at low loads (Figure 10.5).

The simulation with PHEM showed on average for all vehicle classes a 3.3% CO_2 reduction in the NEDC and 2.5% in the WLTP. The results for the real world cycles are in the range of the WLTC results. Also for this technology the reductions are higher in lower engine load areas than at high loads.

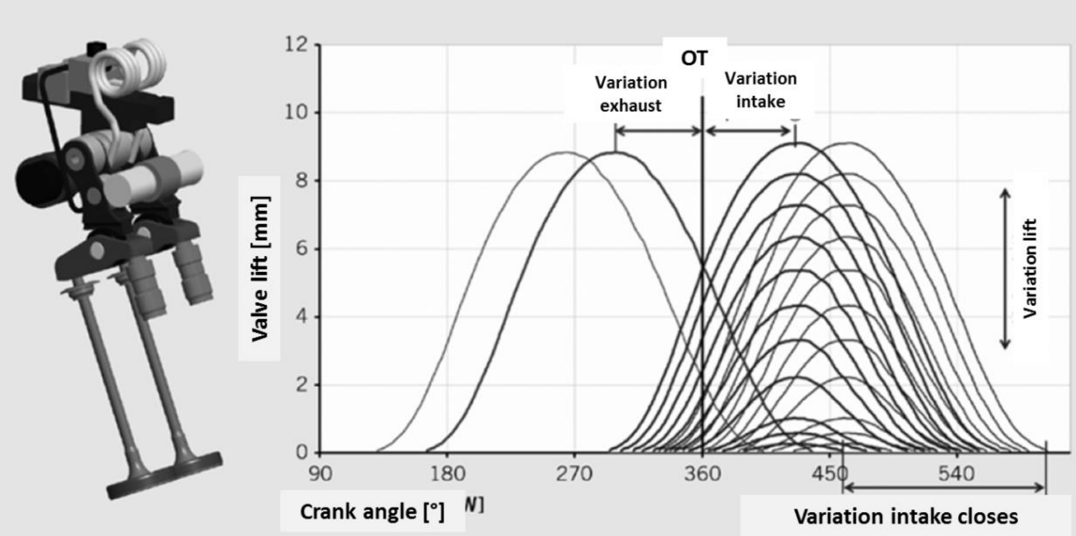
A5.1.13 Variable valve actuation (“VVA”)

Variable valve actuation allows for the control of the timing and the height of valve events. Thus the degree of freedom to control gas exchange in the cylinder is larger than for the cam-phasing (discussed in Section A5.1.12).

To assess the engine fuel map a fully variable control of valve actuation and lift was assumed. This allows the control of stoichiometric air to fuel ratio in the cylinder under reduced throttling effects of the intake air compared to the base engine. Thus losses during charge changing are much lower than in a conventional SI engine. Figure 10.8 shows a schematic picture of such a system which can vary the actuation time of intake and exhaust valves as well as their lift.

VVT also allows for an increase in the full load torque at lower engine speeds and for the maintenance of a higher exhaust gas mass flow to reduce the turbo lag at full load accelerations. Both effects support the downsizing of engines and are thus covered in a separate technology option and thus are not included in the reduction potential simulated here.

Figure 10.8: Schematic picture of a fully variable valve actuation [Flierl, 2011]



To calculate the reduction of fuel flow in the single load points of the engine map compared to the base engine a reduction of pumping losses was assumed. According to (Flierl, 2011) in part load conditions (2000 rpm und 2bar) 25% reduction of pumping losses with approximately 10% fuel efficiency were introduced. The effect was reduced as the simulation modelled loads closer to the full load condition to a 1% fuel saving.

The simulation with PHEM showed on average for all vehicle classes an 8.2% CO_2 reduction in the NEDC and a 6.3% reduction in the WLTP. The results for the real world cycles are in the range of the WLTC results. Also for this technology the reductions are higher in lower engine load areas than at high loads.

A5.1.14 Engine Friction Reduction (E-Fric1 & E-Fric2)

Engine friction can be reduced e.g. through the use of more lubricating multi-viscosity oils, optimised allocation of the lube oil to rotating parts and improved piston and crankshaft design. An internet research and the Technology Results Data Fiche (see Section 7) showed that the percentage savings are up to 2%. An advanced friction reduction (redesign of engine components like valve-train, bearings, injection systems…), called E-Fric2, elevate the savings up to 3%.

A5.1.15 CNG

Compressed Natural Gas (CNG) could be used instead of petrol if the engine is appropriately tuned. The advantage of CNG is the high octane rating which allows for a higher compression ratio and a comparatively low carbon content. The reduction potential for CNG was taken from two measured similar engines, one running on petrol, the other on CNG. The relative change in gCO_2/h for each load point was calculated from these data and applied to the base engine map to produce the engine map for the simulation of CNG within PHEM. The effects include a possibly higher compression ratio for CNG and especially a lower carbon content per kWh energy (Schubert, 2015)

The simulation showed a reduction of CO_2 emissions with CNG engines of up to 23%.

A5.2 CI Engine Technologies simulated

Below the compression ignition (CI) diesel engine technologies and the corresponding methods for the simulation are described.

The methods used to elaborate the fuel maps for the single technologies are similar to the ones described for the SI engines. To simulate fuel saving engine technologies the base engine fuel map has been adjusted to represent the technology under consideration. The base CI engine fuel map has been defined based on measured engines from model year 2002, as far as possible, to reflect engines without the technologies to be simulated later on.

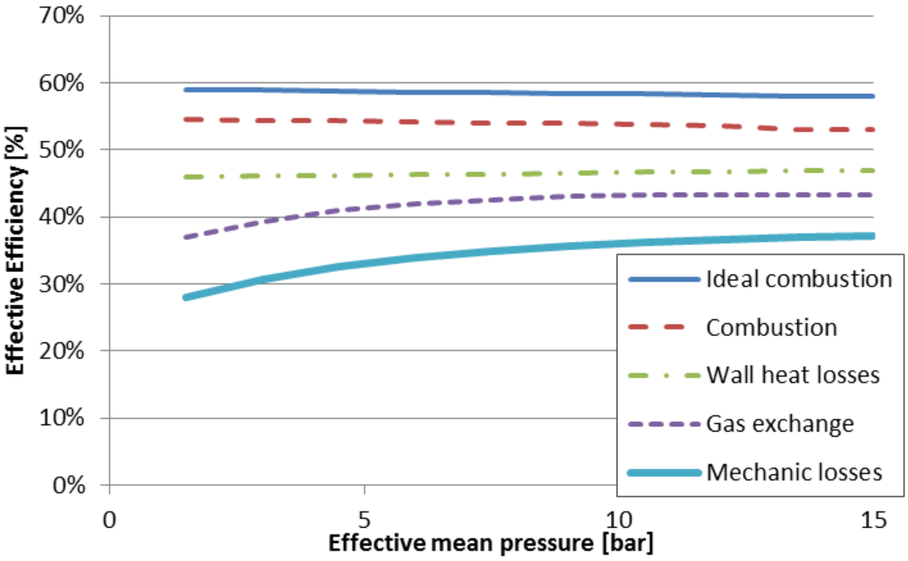
The percentage improvements due to the advanced technologies have been subtracted in each load point from the base engine map to produce the fuel maps for the advanced engines. The information on the percentage improvements are based on different sources:

- From engines measured with and without a technology
- From vehicles measured with and without a technology
- From literature
- From simplified simulations.

All technologies are simulated to meet EURO 6c exhaust gas limits[53]. Since the base engine had to use low EGR (even uncooled EGR to be able to provide reduction values for the technology “cooled EGR”) the NO_x level is quite high for the base engine and would lead to worse fuel consumption at higher engine loads if NO_x levels were kept at reasonable levels for cycles other than the NEDC. Thus the base engine has low NO_x only in the NEDC while the combinations of engine and after treatment technologies have to meet EURO6c emission limits also in future RDE legislation scenarios. Thus the reduction rates given against the base engine technology include also a change in the exhaust gas legislation. The more stringent NO_x test procedure in future will reduce fuel reduction potentials compared to the base engine. For the simulation a target engine with a NO_x emission level of 2 g/kWh with exhaust gas after-treatment efficiencies above 75% was assumed.

Compared to the SI engine (A5.1) the diesel engine has a higher efficiency in the ideal combustion process due to the higher compression ratio (Figure 10.9) Consequently the wall heat losses are typically higher for CI engines than for SI engines. Pumping losses are lower at low loads for the diesel engine while mechanical losses are higher than for SI engines at higher engine loads.

Figure 10.9: Generic engine efficiencies for CI engine for the ideal combustion process without losses and for cumulative add-ons of the real world losses for an SI engine (simplified data, basis from (IVT, 2013))



In the following the technologies simulated are described. For the following technologies, the approach is the same as for SI engines (see Section A5.1), and so is not described again here:

- Mild, Medium and Strong downsizing (DS-MLD, DS-MED and DS-STG)
- Start-stop system (S-STOP)

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[53] For EURO 6c the implementation of the RDE legislation is assumed which measures pollutant emissions with on-board equipment under real driving conditions and allows maximum 2 times higher g/km in the real driving conditions compared to the type approval limit in the chassis dyno test.

- Engine friction reduction (E-Fric 1 & E-Fric 2)

A5.2.1 Combustion improvements for CI engines: Level 1 (“COMB1”)

The incremental improvements in the CI engine combustion that are considered as part of the ”Level 1” improvements include: Increased compression ratio and expansion ratio; optimised combustion chamber architecture and optimised combustion control by injection timing; rate shaping and air to fuel ratio control mechanisms.

An increased compression ratio increases fuel efficiency but also NO_x formation due to a higher temperature level. Thus a higher EGR rate is necessary to maintain the NO_x level in combination with higher injection pressure to maintain PM levels for the higher EGR rates. Alternatively a higher efficiency of the NO_x after-treatment systems allows for a higher compression ratio.

The changes in the fuel efficiency compared to the base CI engine were assumed to have effects dominated by an increased compression ratio and have been calculated with the basic equations already shown in Section A5.1.5. Since the base engine needs a rather low compression ratio to meet NO_x limits in the year 2002, the compression ratio of the “COMB1” engine was increased by slightly more than 2 points. With the other improvements approximately a 3% reduction in the specific fuel consumption has been implemented compared to the base CI engine map.

A5.2.2 Combustion improvements for CI engines: Level 2 (“COMB2”)

The “Level 2” of combustion improvements for CI engines covers improvements in the fuel injection system.

The effects introduced into the engine fuel map are based on descriptions on the DENSO i-ART (intelligent-Accuracy Refinement Technology) which was developed by Denso and introduced in 2011. Toyota and Volvo use the technology in diesel engines. The technology allows a closed-loop control system which adjusts the fuel injection quantity and timing based on feedback from injectors. To do this, each injector is equipped with a pressure sensor that communicates its fuel pressure to the engine ECU (Green Car Congress, 2015)[54].

By featuring pressure feedback from each fuel injector instead of using a traditional single pressure sensor in the common rail, i-ART makes it possible to continuously monitor and adapt fuel injection per combustion in each of the four cylinders. The technology is announced to be combined with an increased injection pressure of up to 2500bar. In the literature no details on the fuel saving effects where found. Better fuel dosing control is assumed here to support lower NO_x and soot formation in diesel combustion and thus to allow more fuel efficient injection design. Information on the extent to which these effects can be used in the different areas of the engine map was not found in literature. A fuel saving potential is given in the range of 2% compared to an uncontrolled injector[55]. Further improvements until 2015 are assumed so a 3% reduction potential has been implemented in the entire engine map. Secondary effects, such as a combination with downsizing, are not considered here since these are separate technologies in this study.

The simulation of the fuel saving effects with PHEM resulted in slightly less than a 3% fuel saving in all cycles for all vehicle classes. Due to the uncertainties described above a high uncertainty exists in the engine map and the differences between cycles and vehicle classes may differ substantially from the simulation results.

A5.2.3 Combustion improvements for CI engines: Level 3 (“COMB3”)

The “Level 3” of combustion improvements for CI engines covers variable compression ratios. Diesel engines need a minimal compression ratio (CR) to ensure that the engine starts via self-ignition in cold conditions. At high loads the maximum exhaust gas temperature but also NO_x emissions typically limits the CR. Thus the CR of a diesel engine has to be a compromise. With an increased compression ratio the indicated thermal efficiency of the combustion process increases while typically

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[54] http://www.greencarcongress.com/2013/04/iart-20130408.html visited on 06.02.2015

[55] http://articles.sae.org/12418/ visited on 06.02.2015

the mechanical losses also increase. This leads to the effect that the effective engine efficiency does not steadily increase with increased CR but decreases again after an optimum (Radivoje, 2010). If low engine NO_x emissions have to be maintained, a lower CR is helpful since a lower combustion temperature is generated. This effect can also help to achieve better fuel efficiency at lower CRs by shifting the centre of combustion towards a more efficient timing.

In the case of diesel engines, few useful studies for the fuel saving effects of a mechanical variable compression ratio were found. The already high compression ratio with the low energy content which is typically left at the end of a diesel expansion cycle seems to leave only a small potential which can be gained by a variable compression ratio in standard operation. Since a longer expansion would use more of the remaining energy in the cylinder it would also reduce the enthalpy of the exhaust gas and thus reduce the energy available at the turbo charger. This effect would most likely also limit EGR possibilities and thus would limit the fuel saving potential due to lower NO_x formation.

Mechanical VCR therefore does not seem to be a cost efficient diesel technology from this point of view but some additional benefits may be identified in future. For the actual simulation a small benefit against the base engine was assumed (-1%). This potential cannot be combined in later steps of the simulation with high rates of cooled EGR gained by efficient turbo charging in downsized CI engines due to overlapping.

As expected the simulation with PHEM reproduced the fuel savings assumed as constant value in the engine map of -1% for all cycles and vehicle classes.

A5.2.4 Improved EGR (“C-EGR_D”)

EGR has been a standard NO_x reduction technology for diesel engines for years. Thus the simulation of the fuel consumption reduction from cooled versus un-cooled EGR is quite meaningless and not covered here. For the calculation of the fuel consumption effects of “improved EGR” the introduction of additional low pressure EGR with improved cooling was assumed. This technology in principle reduces the NO_x emission level due to higher possible EGR rates. If instead the engine shall maintain constant NO_x emission levels the fuel consumption can be reduced by a more fuel efficient injection timing and shape (assuming that the low NO_x emission limits demand fuel injection strategies that are not ideal for fuel efficiency). The improved cooling system increases the fuel saving potential. Base trends for the fuel efficiency with moving from high to low pressure EGR were taken from (Merker, 2014; page 187 ff). At low engine loads up to 8% fuel savings have been introduced compared to the base CI engine map. The improvement is reduced towards full load to slightly less than 1%.

A5.2.5 Variable valve actuation and lift for CI engines (“VVA-D”)

Using the possibilities given by a variable valve timing the effective compression ratio and the expansion ratio of CI engines can be influenced. Today the Miller or Atkinson cycle are used for diesel engines to reduce the compression end temperature and thus the NO_x emission level. The Miller cycle needs to be combined with improved turbo charging systems to maintain the cylinder filling and thus the oxygen availability for the combustion.

Compared to the usual NO_x controlling by EGR the Miller or Atkinson cycle seems not to have any advantage in terms of fuel efficiency. Instead for CO and PM disadvantages are seen (Schutting, 2007). This effect is attributed to the relatively smaller compression ratio against expansion ratio in the Miller cycle which reduces exhaust volume flows compared to an EGR option. Thus the charge air pressure drops which seems to lead to less oxygen availability for the combustion compared to the EGR solution.

In total this technology seems not to be relevant for 2025 diesel engines. In the simulation we assumed a possible NO_x reduction rate by 15% against the “base engine with low EGR rates” which may be used to set e.g. injection time earlier to get better fuel consumption with the same NO_x emissions as the base engine. This gives approximately a 0.75% fuel efficiency improvement. A simulation of load dependencies of this effect was not performed but a constant reduction rate was implemented against the base engine map.

In combination with NO_x catalysts, which may need active heating strategies in future, variable valve actuation with the Miller cycle or similar options to reduce the exhaust gas volume without throttling the intake air are able to help to reduce the (additional) fuel consumption for heating the exhaust after-treatment systems. This option however can hardly be implemented in a comparison against the base engine which also has no heating strategies for catalysts implemented.

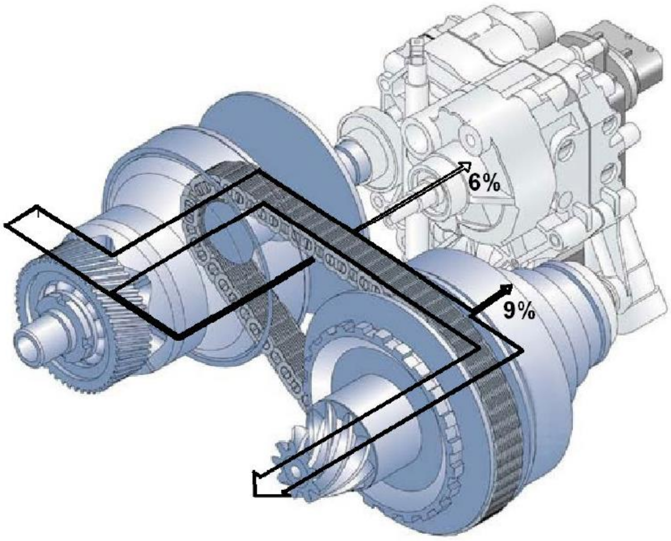
A5.3 Transmission systems simulated

The transmission systems presented in the following sections typically have the potential to run the engine in more fuel efficient operation points. Thus generic control algorithms had to be elaborated. In addition the transmission systems partially have different losses compared to the base manual gear box.

A5.3.1 Continuously variable transmission (CVT)

The continuously variable transmission (CVT) was simulated via post processing in MS Excel since PHEM does not offer this transmission type. In the case of passenger cars a CVT is the combination of cones with a variable width in between and a flexible metal belt for the power transmission. This offers the possibility for a continuous change of the speed ratio. Dependent on the required power, the engine can be operated as close to the lowest specific fuel consumption as possible. The ratio of maximum to minimum output speed at the same input speed was chosen as 7, the lowest speed ratio was near the value of the corresponding spur gearbox. The first input value for the simplified model was the cardan shaft speed from the DCT model, where no traction interruption occurred, which is also the case for CVT vehicles. Second, the cardan driving or braking power was calculated with the wheel power and differential losses of 4%. The average transmission losses of CVTs in the NEDC are about 15% (see Figure 10.10), and were added to the cardan power.

Figure 10.10: Losses in a CVT (Faust, 2002-04)



The result of the calculation was the necessary values for output speed (= n_{card}) and input power (= P_{wheel} + 4 % $P_{loss,diff}$ + 15 % $P_{loss,CVT}$). If possible, the engine was operated on the curve of the lowest specific fuel consumption at the given power demand. This was limited by the necessary output speed and the minimum and maximum speed ratios of the CVT model. Examples for the results are shown in Figure 10.11 and Figure 10.12.

Figure 10.11. Example for speed and power values with CVT, Van I Petrol on NEDC

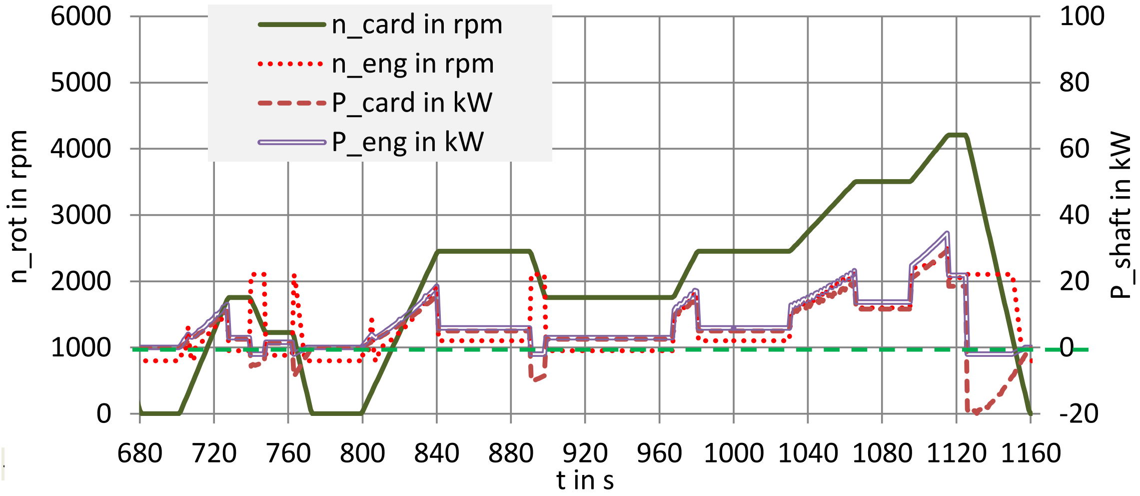
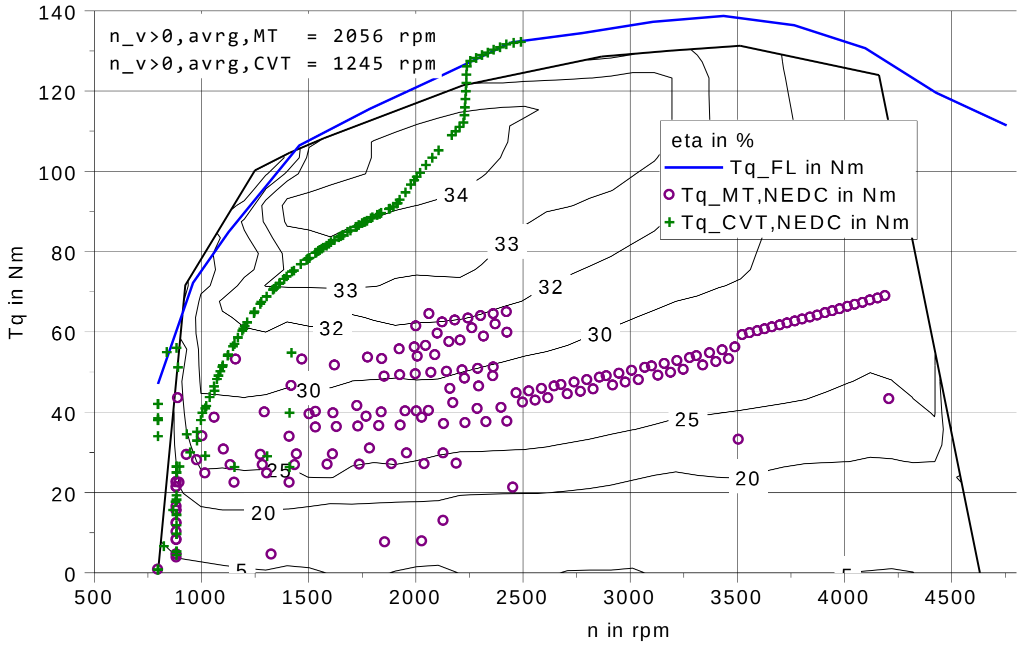


Figure 10.12. Example for the engine operating points, MT and CVT, Van I Petrol in the NEDC



There was a range in the results for fuel consumption, compared to the base vehicles, from - 21 to + 7%, which seemed to be unrealistic. One reason was probably the missing dependency of the CVT losses on load and speed ratio; this value was always 15%. But no information was found on the influence of the transmitted torque and speed ratio on the transmission losses, so these were kept constant. For the petrol and diesel vehicles the overall average results were chosen. These are in line with measured CO_2 changes of real CVT vehicles from literature (see Table 10.23).

Table 10.23. CO2 saving potential CVT, measured cars

Manu-facturer	Type	Pro-duction	Cycle	No. of gears MT	CO2 in g/km		Deviation CO_2 (basis: MT)	Source
					MT	CVT	[%]	
Toyota	Corolla S 1.8 (97 kW) Petrol	2015	US-cycle	6	177	171	-3.4%	Toyota 2014-08
Audi	A4 Avant 2.0 TFSI (165 kW)	2015	NEDC	6	138	136	-1.4%	Audi 2015-01
Honda	Jazz V-Tec 1.4 (73 kW) Petrol	2015	NEDC	5	126	125	-0.8%	Honda 2015-02a 2015-02b
Audi	A4 Avant 3.0 TDI (150 kW)	2015	NEDC	6	135	135	0.0%	Audi 2015-01
Audi	A4 1.8 TFSI (125kW)	2015	NEDC	6	134	134	0.0%	Audi 2015-01
Mitsubishi	Space Star 1.2 MIVEC (59 kW) Petrol	2015	NEDC	5	100	101	1.0%	Mitsubishi 2014-06
Audi	A4 Avant 2.0 TDI (110 kW)	2015	NEDC	6	124	129	4.0%	Audi 2015-01
Subaru	Outback 2.0 D (127 kW)	2015	NEDC	6	155	166	7.1%	Subaru 2013-01
Jeep	Patriot 2.4 Limited (125 kW) Petrol	2010	NEDC	5	196	210	7.1%	autozeitung.de 2015-02c 2015-02d
Fiat	Punto Dynamic 1.2 16V (59 kW) Petrol	2006	NEDC	5	142	155	9.2%	autozeitung.de 2015-02e 2015-02f
Ford	Focus C-Max 1.8 Durashift (92 kW) Petrol	2006	NEDC	5	170	186	9.4%	autozeitung.de 2015-02g 2015-02h
Jeep	Compass 2.4 Limited (125 kW) Petrol	2009	NEDC	5	206	226	9.7%	autozeitung.de 2015-02e 2015-02f
Dodge	Caliber 2.0 SE (115 kW) Petrol	2010	NEDC	5	175	192	9.7%	autozeitung.de 2015-02a 2015-02b
Seat	Exeo 2.0 TDI CR Reference (105 kW)	2013	NEDC	6	129	146	13.2%	Seat 2011-10

A5.3.2 Automated manual transmission (AMT)

An automated manual transmission (AMT) is of the same mechanical structure as a manual transmission (MT): Engine - friction clutch - spur gearbox. The difference is that the clutch and the gearbox are actuated automatically and not manually. An AMT should not be confused with an automatic transmission (AT), where the structure is: Engine - hydraulic torque converter - planetary gearbox. In this project ATs are not covered, because in most cases the fuel consumption is higher due to the hydraulic losses in the converter.

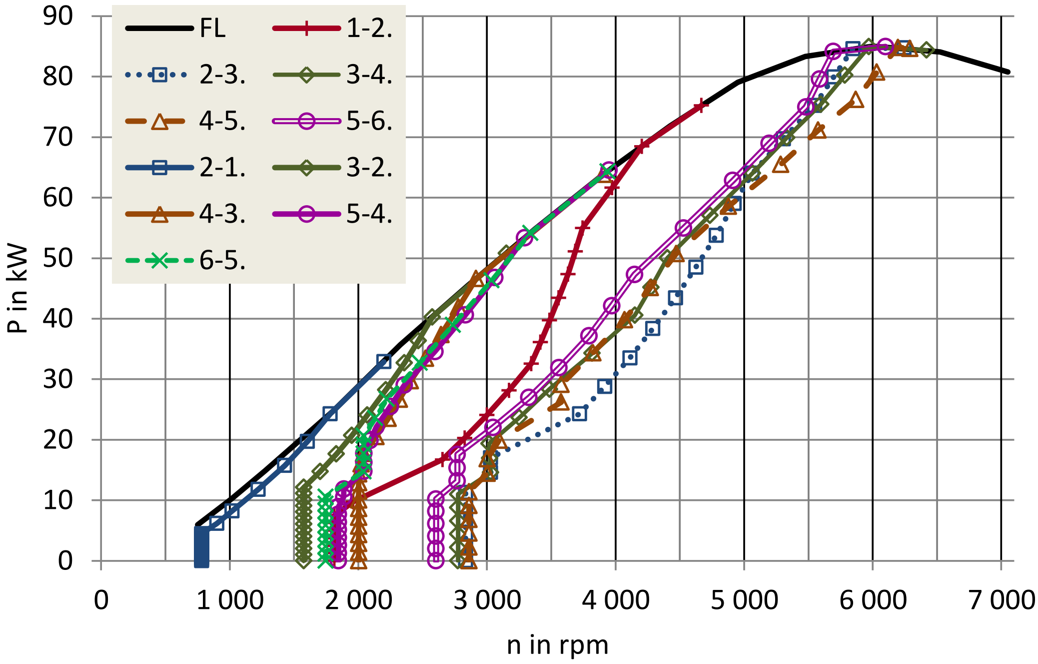
The difference between AMT and MT in the simulation model is another gearbox control with early upshift, in order to keep the engine speed low. Due to the lower average speed there is less engine friction, the efficiency increases and the fuel consumption at the same power decreases. In addition the shifting duration is 0.5 seconds instead of 1 second for the MT.

In the case of AMTs the driving cycles CADC, RWC and WLTC were simulated with the PHEM shifting model. PHEM offers six parameters to calibrate the shifting behaviour (a detailed description of these is provided in Section A5.3.4 and A5.3.5). The parameters were calibrated to depict an AMT-like shifting behaviour.

Future passenger cars will be certified in the WLTC. It was assumed that the gearbox control will upshift a little earlier than under the WLTC shifting model so as to offer a fuel consumption saving potential. Because the WLTC rules lead already to very early upshifts, a reasonable compromise had to be found. The vehicle model with a petrol engine and the lowest power-to-mass ratio, the LCV III petrol (43.3 kW/t), should be able to follow the target speed of the WLTC as close as the MT model did. The gear shift parameters in PHEM were calibrated to reach this objective. With these parameters all AMT models on the cycles CADC, RWC and WLTC were simulated.

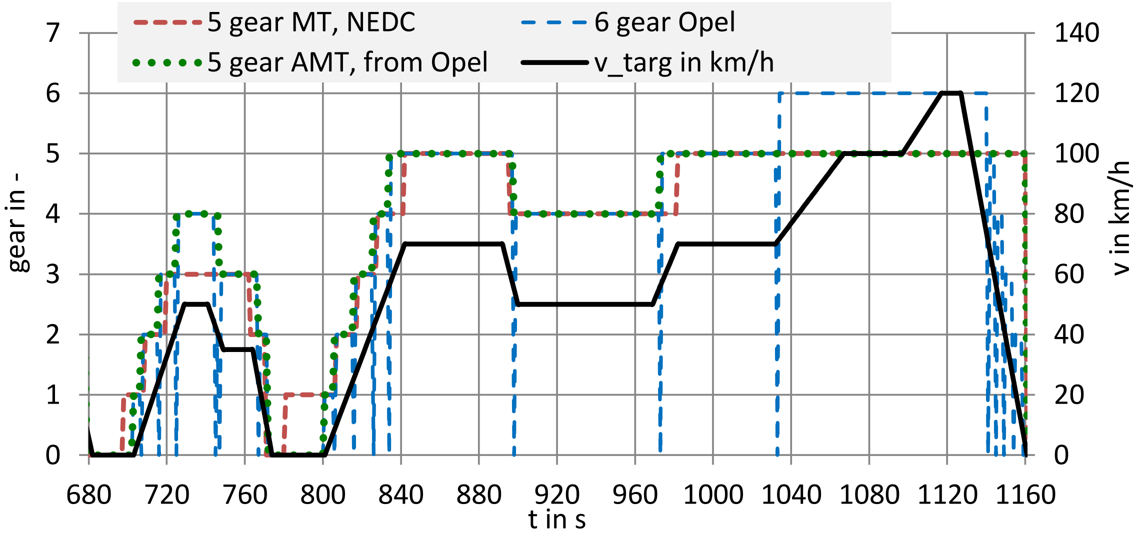
In the case of the NEDC the approach was different because the gears are prescribed for MT where no shifting model is used. For a passenger car with 6 gear AT, i.e. the Opel Astra 1.6 petrol, the shifting curves were known (see Figure 10.13).

Figure 10.13. Shifting curves Opel Astra 1.6 petrol, calculated from (Bednarek 2010-04)



The vehicle model Opel Astra with the shifting curves was simulated (without torque converter) in the program VECTO on the NEDC. This program offers the possibility to use shifting curves. The outputs were the selected gears on the NEDC, where in general an earlier upshift occurred (see Figure 10.14).

Figure 10.14: Gears on the NEDC



The simulated gears 1 - 5, with 5 as the maximum, were used as input for the AMT vehicle models with 5 gears on the NEDC. The result was a fuel consumption decrease from 7.2 to 2.5 % on the NEDC in comparison to the basis vehicles. These values are near the measured values for some real cars (see Table 10.24).

Table 10.24: CO2 saving potential AMT, measured cars

Manu-facturer	Type	Pro-duction	Cycle	No. of gears MT	No. of gears AMT	CO_2 in g/km		Deviation CO_2 (basis: MT)	Source
						MT	AMT	[%]	
Peugeot	208 1.2 PureTech (60kW) Petrol	2015	NEDC	5	5	104	95	-8.7%	Peugeot 2015-02
Opel	Corsa 1.4 ecoFlex (66kW)	2015	NEDC	5	5	117	112	-4.3%	Opel 2014-08
Skoda	Citigo 1.0 (55kW) Petrol	2015	NEDC	5	5	108	105	-2.8%	Skoda 2014-11
VW	Up (55 kW) Petrol	2015	NEDC	5	5	108	105	-2.8%	VW 2014-10
Skoda	Citigo 1.0 (44kW) Petrol	2015	NEDC	5	5	105	103	-1.9%	Skoda 2014-11
VW	Up (44 kW) Petrol	2015	NEDC	5	5	105	103	-1.9%	VW 2014-10
Toyota	Yaris 1.4 Diesel, (66kW), Active/Lounge	2015	NEDC	6	6	99	105	6.1%	Toyota 2013-12

So for the NEDC an *actual* gearbox control was simulated and for CADC, RWC and WLTC an *assumed future* control was simulated.

The runs of the VECTO model for the Opel Astra also showed that a new gearbox control algorithm seems to be necessary to achieve fuel savings with AMT in the WLTC. With the actual shifting curves in the NEDC the average normalised engine speed during driving (($n_{v>0,avrg}$ - n_{idle}) / (n_{rated} - n_{idle})) decreased from 0.23 (6 gear MT, prescribed gears) to 0.18 (6 gear AMT, Opel shifting curves). With the same vehicle model on the WLTC this value increased from 0.21 (6 gear MT, WLTP shifting model) to 0.26 (6 gear AMT, Opel shifting curves) which leads to a higher fuel consumption.

A5.3.3 Dual clutch transmission (DCT)

Dual Clutch Transmission (DCT) uses two separated clutches and gear sets and often includes the option of semi-automatic mode. The advantages are that there is no traction interruption when shifting gears and the efficiency is high compared to hydraulic automated transmissions. The automatic mode allows for the operation of 7 or more gears which could not easily be managed by a driver of a manual gear box. The gear shift without traction interruption leads to faster accelerations and reduces the highly transient engine operation which occurs at gear shifts with manual transmissions.

In PHEM a DCT was depicted by setting the shifting duration to zero seconds. All other settings, such as gear ratios, gear shift parameters and prescribed gears, were the same as for the AMT models since no further measurement data were available at this stage.

A5.3.4 Optimising gear box ratios/downspeeding Level 1 (GEAR-R)

A reduction of the average engine speed results in lower engine friction and in better efficiencies with the effect of less fuel consumption. So, the 5-speed transmission was replaced by a 6-speed transmission. Due to vehicle mass and engine power differences between the “virtual” baseline and available date on series vehicles, gear ratios from existing 6-speed transmission were not applicable. The procedure used was to introduce a sixth gear in the 5-speed gearbox of the base vehicles (ratios as calculated with the gearbox simulation tool provided by JRC) with the same ratio from 5th gear to 6th gear as a similar 6-speed transmission in practice. With this new gear box data all vehicle segments and cycles have been simulated with PHEM to produce the fuel consumption and CO_2 results.

A5.3.5 Optimising gear box ratios/down-speeding Level 2 (GEAR-R2)

For the simulation in PHEM a generic gear shift model for an 8 gear DCT was developed and suitable transmission ratios had to be elaborated for each vehicle segment.

For the calculation of the gear shift points for up- and down-shifting PHEM uses a linear equations (see below) containing two variables and three constants was used, The “***shift parameters***”, which were unknown for a DCT, had to be investigated based on vehicle measurements performed within this project on a Seat Leon with DCT.

The variables V_{norm} and AP10 take into account the influence of the current vehicle speed and engine power.

$$nn_{up} = A_{up} + B_{up} * V_{norm} + C_{up} * AP10$$

Eq. 10.1

$$nn_{down} = A_{down} + B_{down} * V_{norm} + C_{down} * AP10$$

Eq. 10.2

with

$nn_{up/down}$…normalized switching speed

$A_{up/down}$, $B_{up/down}$, $C_{up/down}$…PHEM shift parameters

V_{norm}…current normalized vehicle speed

AP10…averaged engine power -/+ 5 s

The basis for the assessment of the shift parameters for DCT was a Seat Leon with a 7-speed DCT and a petrol engine. From the measurement on the test bench at TUG (see Section 8.2.4) the shift points for NEDC, WLTP and RWC were given. Based on this data a linear regression analysis was made to determine the parameters A, B and C for the linear equations for each cycle as well as for a combined data set including all cycles.

For the validation and fine tuning of the gear shift parameters the Seat Leon was simulated with PHEM with the PHEM-gear-shift-model for different statistically calculated shift parameters. The simulation covered the cycles that had been measured: NEDC, WLTP and RWC. Afterwards the simulated engine speeds in each gear and the calculated fuel flow were compared against the measured values.

Table 10.25 gives an overview of the average absolute deviation for NEDC, WLTP and RWC in each gear for engine speed and fuel consumption with the gear shift parameters calculated from different cycles or combinations of cycles. Since the DCT gear shift algorithm of the Seat Leon most likely has different equations than the PHEM-model, an exact agreement between measurement and simulation was not possible. However, since the target is the elaboration of basic gear shift strategies for the simulation of future average DCT gear boxes, an exact agreement with the Seat test data is not necessary.

Table 10.25: Deviation of engine speed per gear from the simulation and measurement of NEDC, WLTC and RWC with gear shift parameters determined from different tests

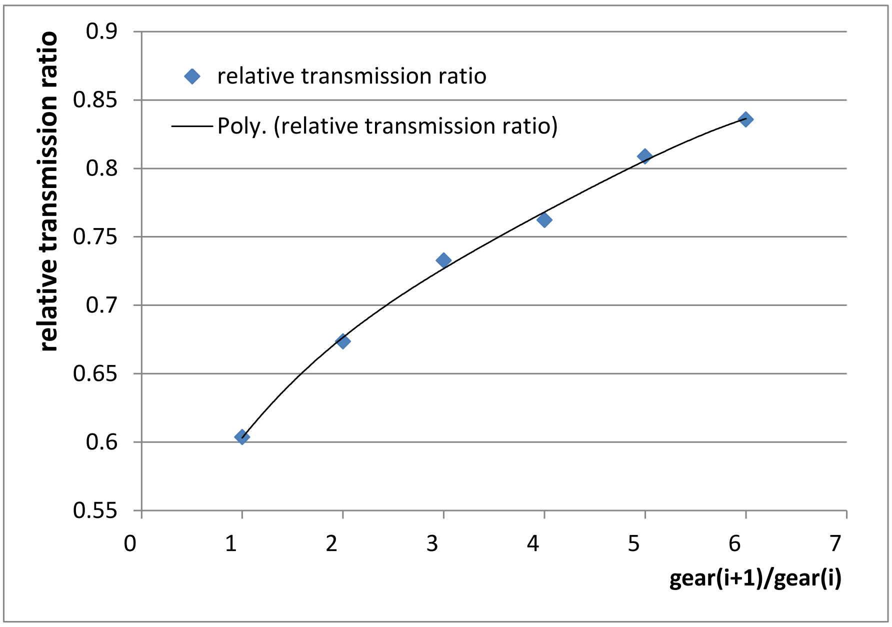
TOTAL	Deviation (absolute value)								
data for linear regression from:	1. gear	2. gear	3. gear	4. gear	5. gear	6. gear	7. gear	Total	FC
	n_1	n_2	n_3	n_4	n_5	n_6	n_7		
	[1/min]	[1/min]	[1/min]	[1/min]	[1/min]	[1/min]	[1/min]		
NEDC	6.96%	6.74%	6.76%	10.53%	11.04%	9.92%	15.58%	9.65%	1.26%
WLTP	10.11%	10.14%	3.96%	4.45%	6.47%	15.98%	5.11%	8.03%	0.37%
RWC	14.42%	6.79%	3.86%	4.09%	11.05%	38.29%	15.91%	13.49%	1.19%
NEDC+WLTP	11.56%	10.59%	5.86%	4.25%	6.25%	19.51%	6.48%	9.21%	0.43%
NEDC+RWC	13.56%	9.19%	2.75%	4.04%	9.63%	35.80%	15.76%	12.96%	1.13%
WLTP+RWC	14.81%	9.66%	4.47%	4.18%	8.59%	30.96%	14.18%	12.41%	0.85%
all cycles	13.52%	9.56%	5.44%	4.01%	8.30%	30.00%	13.60%	12.06%	0.83%
Try and Error	21.98%	3.74%	11.67%	4.72%	8.01%	17.31%	5.98%	10.49%	0.79%

Finally the shift parameters with the smallest deviations were used as the basis for further calculations (WLTP). The shift parameters were adjusted for the different vehicle segments because of the dependency of the calculated shift parameters on different engine idle and rated speeds.

To elaborate suitable ***transmission ratios*** for 8 speed DCT a differentiation between SI-engines and CI-engines was made because of the different engine speed levels.

For SI engines, the basis for the 8-speed DCT was again the 7-speed DCT from the Seat Leon. To add the 8th gear the trend of the relative transmission ratio from one gear to another was approximated by a polynomial function to extrapolate the missing 8th gear (see Figure 10.15).

Figure 10.15: relative transmission ratio Seat Leon 7-speed DCT



Afterwards the transmission ratios (the same for all vehicle segments) were calculated and checked for plausibility. VW's 7-speed DCT has a transmission stepping of 6.5 for petrol vehicles and VW claims that a maximum of 8.1 is practicable (Heise, 2008).

The Seat Leon can be defined as a segment C vehicle and therefore the engine speed in each gear in the different driving cycles was compared between the Seat Leon and the PHEM simulation for the segment C vehicle with the 8-speed transmission. Because of deviations and the additional 8th gear the calculated 8-speed transmission was shortened by 7.5% (see Table 10.26). For all of the other segments the transmission was adjusted similarly. To prove plausibility the location of the load points in the engine characteristics map was checked to lead to operation ranges in points with high engine efficiency.

Table 10.26: 8-speed DCT applied to the segment C petrol vehicle

gear	transmission ratio
1	17.544
2	10.592
3	7.135
4	5.228
5	3.985
6	3.222
7	2.693
8	2.284
transmission stepping	7.682

For CI engines, the basis for the 8-speed DCT was the 6-speed DCT from an Audi A3 with a diesel engine (Audi, 2007). The method was broadly the same as for the spark ignition DCT with the difference being that the calculated 8-speed DCT was used as basis for the segment D vehicle because of the higher power to weight ratio of the Audi A3. Table 10.27 shows the transmission ratios for a segment C diesel vehicle.

The transmission stepping of VW's 7-speed DCT is about 7.26 but a maximum of 8.1 is practicable (Heise, 2008).

Table 10.27: 8-speed DCT applied to the segment C diesel vehicle

gear	transmission ratio
1	14.968
2	8.868
3	5.624
4	3.893
5	2.904
6	2.426
7	2.159
8	1.879
transmission stepping	7.968

Figure 10.16 and Figure 10.17 give an overview of the fuel saving for the WLTP cycle achieved with an 8-speed DCT in comparison to a 5-speed manual transmission for different vehicle segments with SI- and CI-engines simulated in PHEM.

Figure 10.16: Fuel consumption values simulated with PHEM for the petrol segments in the WLTC

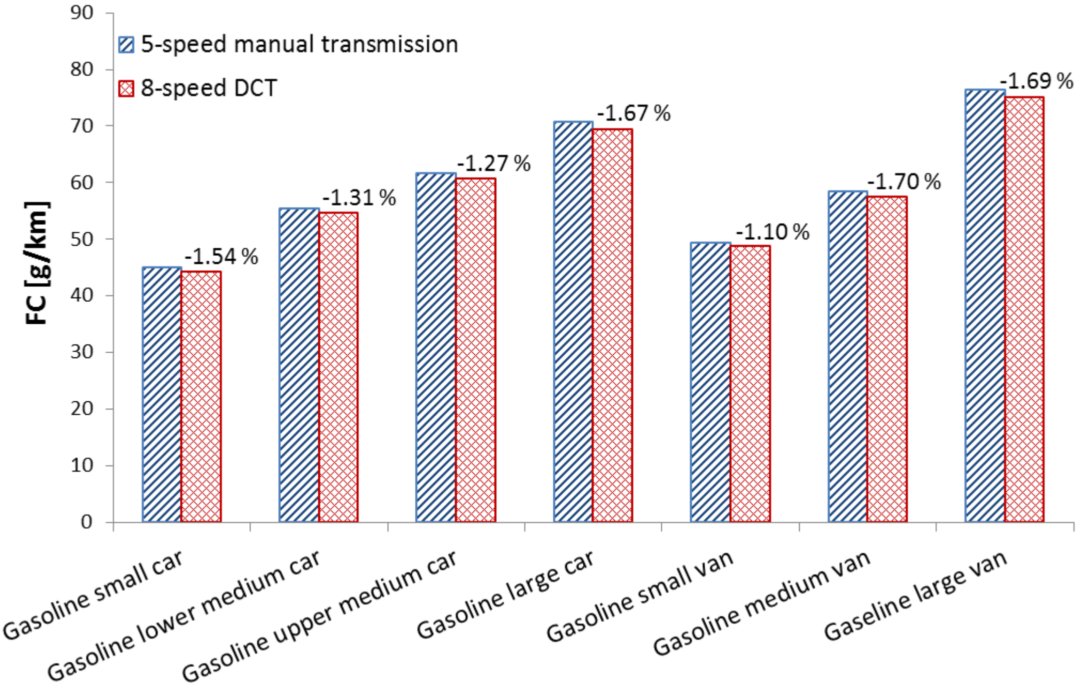
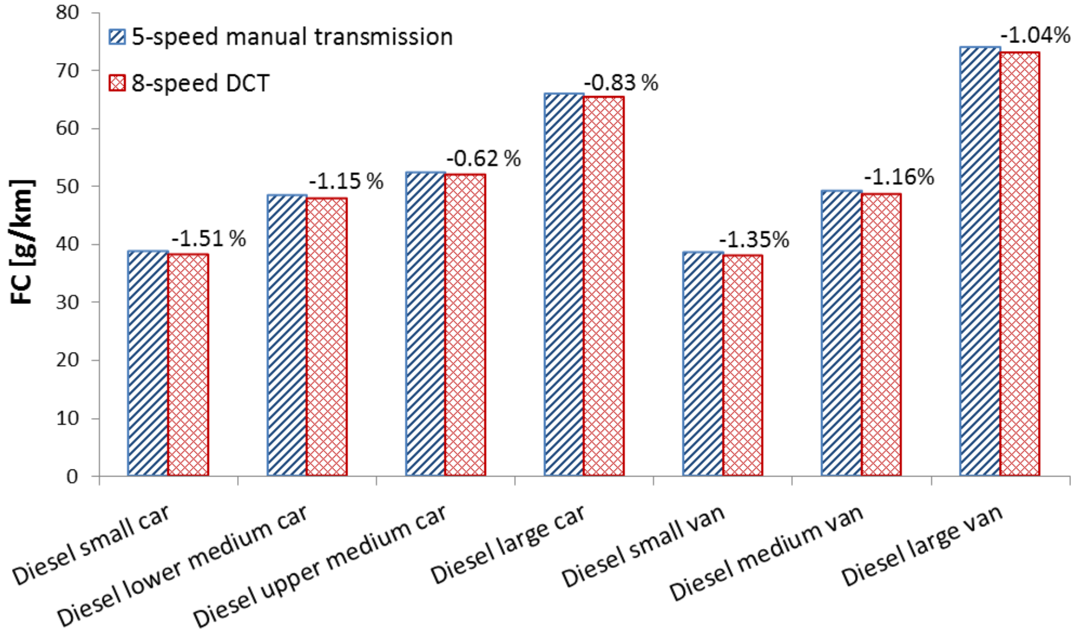


Figure 10.17: Fuel consumption values simulated with PHEM for the diesel segments in the WLTC



All results of the simulation (all segments in all cycles) are in the results table and have been used to set up the cost curves.

A5.3.6 Multi-speed gearbox for xEVs (xEV-GEAR)

As mentioned in Section A5.3.4 the number of gears influences the efficiency of an engine and as a result also the fuel consumption. The same is valid for an electric vehicle where better efficiency results in less electricity consumption.

In the baseline configuration the BEVs have only one gear. For this technology the 1-speed transmission was replaced by a 3-speed transmission. The gear ratios were designed with the gearbox simulation tool provided by JRC. Afterwards the ratios were overworked to meet the areas of highest efficiency in the efficiency map of the electric motor of the BEVs.

A5.4 Vehicle technologies simulated

A5.4.1 Mild, Medium and Strong weight reduction (WR-MLD, WR-MED and WR-STG)

The mass reduction was assumed to be -10% for the mild case (WR-MLD), -20% for the medium case (WR-MED) and -30% in the strong case (WR-STG) and is applied to the unladen vehicle mass. In order that the vehicles have a similar utility after weight reduction:

- The payload of each vehicle was taken to remain constant.
- The full load acceleration of the vehicles was taken to remain constant, thus the engine power was reduced together with the mass to obtain the same full load acceleration as the base vehicle.

A5.4.2 Aerodynamics improvement 1 & 2 (AERO-1 and AERO-2)

For aerodynamics improvement AERO-1 the c_d x A per segment is reduced by 10% and for aerodynamics improvement 2 by 20%. Higher velocity in WLTC, CADC and RWC leads to more influence of aerodynamic design in these cycles.

A5.4.3 Low rolling resistance tyres 1 & 2 (LRRT1 and LRRT2)

The RRC reduction was defined with a -15% for low rolling resistance tyres level 1 and by -30% for low rolling resistance tyres level 2. The rolling resistance coefficients f0 and f1 in the PHEM input data have been reduced accordingly. As a simplification the speed independent of RRC and the speed dependent RRC have been reduced by the percentage defined above.

A5.4.4 Reduced driveline friction 1 & 2 (D-FRIC1 and D-FRIC2)

To investigate the influence of driveline friction on fuel consumption the power loss in the driveline was reduced for two different levels: by 20% (D-FRIC1) and by 50% (D-FRIC2). The same percentage reduction was introduced over all rotational speed and input torque ranges.

A5.5 Off-Cycle technologies simulated

A5.5.1 High efficiency alternator (EFF-ALT)

The efficiency of a standard alternator was assumed to be 67% as mentioned in the WLTC draft, e.g. (Hausberger, 2015). For an alternator with higher efficiency this figure is raised up from 67% to 75% based on the technology results data fiche (Section 7) and internet research. The higher efficiency of the alternator gives the highest savings for the RWC since in real driving auxiliaries like headlamps, air conditioning etc. are activated. In terms of numbers, the savings are up to 0.4 %. There is no reduction potential on the NEDC since the electrical power during the cycle is provided by the battery and the regenerative alternator use in the base vehicles.

A5.5.2 Electrical assisted steering (EAS)

Hydraulic powered steering has the disadvantage of idling losses when the steering wheel is not turned. For a C-Segment the hydraulic steering pump power in idling is about 70W. There are no idling losses present if this system is replaced by an electric motor which slides the steering rack when the steering wheel is turned. Simulations in PHEM showed a saving potential of around 0.3% on the NEDC, WLTC and CADC. Due to high share of time steering in real driving the saving potential for the RWC is lower and amounts to 0.03%.

A5.5.3 LED lighting (LED)

Most of the vehicles use halogen headlamps which have an average power consumption of about 150W. Light emitting diodes (LEDs) consume less electricity and have a longer lifetime compared to halogen lamps. Since in the dynamometer tests the headlamps are switched off, this technology only has a fuel saving potential on the RWC of up to 0.1%.

A5.5.4 Tyre pressure monitoring systems (TPMS)

Recently, investigations regarding the fuel reduction potential of TPMS have been undertaken (GRRF TPMS Task Force Conclusions). The result was that for a minimal threshold (the system abreacts about 0.3 bar deviation from the target) the fuel consumption potential is approximately 1.12% on the RWC

A5.5.5 Engine compartment encapsulation (ENG-ENCAP)

With engine encapsulation heat loss may be stored longer to increase oil and coolant temperature upon restart. A study determined that 7°C higher temperatures could be expected 12 hours after the switching off of the engine.

As mentioned in the WLTC correction functions report (Hausberger, 2015) the extra cold start factor may be calculated by following formula:

$$\text{ExtraColdStartFaktor} = -4{,}14 * \ln(x) + 18{,}63 \qquad \text{Eq. 10.3}$$

In Table 10.28 the ratio between the additional fuel consumption (FCextra) at T_{ref} and the additional fuel consumption (FCextra) at T_{ref}+7K is shown. The additional fuel consumption for a cold start on the RWC is thus reduced by approximately 22%. For the NEDC and WLTC the cold start reduction is about 19%. No fuel saving potential exists for the CADC since this cycle is always simulated with a hot start.

Table 10.28: Engine compartment encapsulation data

	NEDC	WLTC	RWC
T_{ref}	25 °C	23 °C	14 °C
TENG-ENCAP	32 °C	30 °C	21 °C
Ratio FCextra@TENG-ENCAP/FCextra@Tref	0,81	0,81	0,78

The simulation in PHEM showed fuel consumption savings about 1.4% on NEDC, 0.6% on WLTC and 1% on RWC.

A5.5.6 Thermal management (T-MAN)

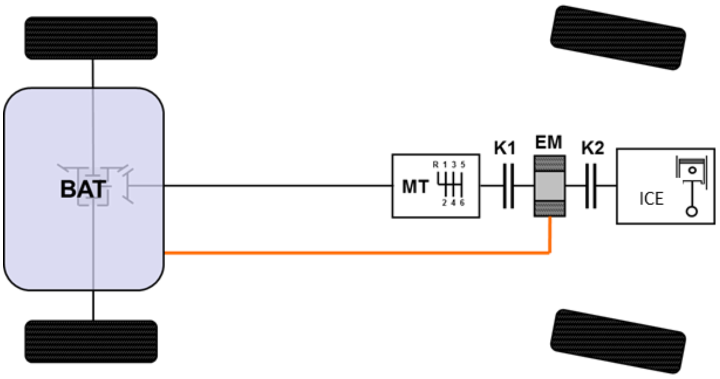
This technology captures thermal energy from the engine to reduce fuel consumption during warm-up. The system is based on the closed-loop control of the coolant circuits. So, hot coolant can be stored for several hours. JRC investigated this technology and measured engines with and without thermal management and suggested the percentage savings of fuel consumption for this study. The savings in each load point of the engine map are applied to the base engine to simulate the technology effects consistently.

The fuel saving potential with thermal management is up to 2.5% on the NEDC, 1.5% on the WLTC and 1.4% on the RWC.

A5.6 Hybrid Electric Vehicles (HEV)

PHEM offers the option to simulate hybrid vehicles with a parallel architecture of combustion engine and electric motor with a battery as the energy storage device (Figure 10.18). This HEV design was used for all HEV simulations in this study.

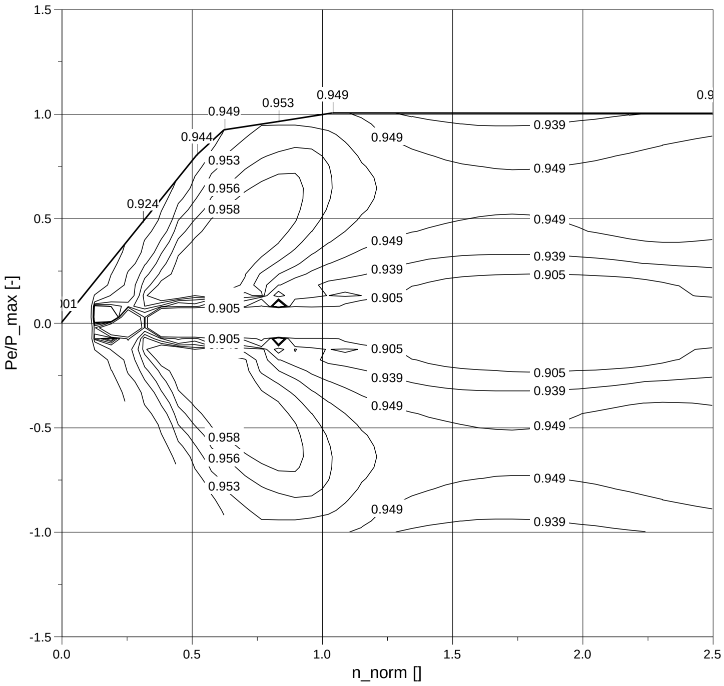
Figure 10.18: Schematic picture of the HEV architecture simulated (BAT = Battery, MT = Transmission, k = Clutch, ICE = Internal Combustion Engine)



The electric motor is defined by an efficiency map over rpm and power (see Figure 10.19). The speed is normalised to the lowest speed value where the maximum power is available. The power is normalised by division by the rated power. The efficiency represents a modern technology and also includes losses in the power electronics. The engine speed range and the maximum power were adjusted for each segment. The battery capacity was adjusted to the maximum power of the electric motor installed.

The losses in the battery are simulated by the internal resistance and the actual energy flow and voltage (252 V used here). The parameters for a lithium-ion battery have been used for the simulation. The battery model from PHEM is described in (Luz, 2011).

Figure 10.19: Efficiency map of the electric motor used for the HEV simulations (normalised speed and power are adjusted to the absolute values per segment)

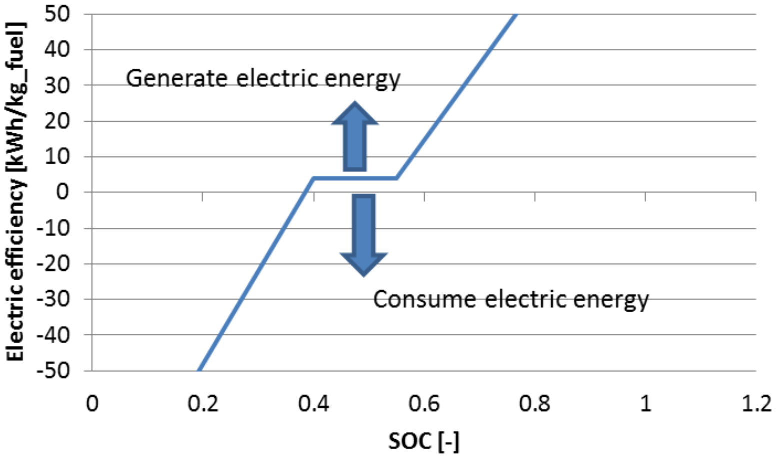


The HEV controller selects in each second one of the following options:

- Electric driving
- Assist combustion engine with the motor
- Generate electric energy by power increase of the combustion engine
- Recuperation of brake energy

The control strategy follows a general energy efficiency target which is defined by an electric efficiency value [kWh/kg$_{fuel}$]. As long as the electric energy is produced over the entire cycle with a higher efficiency value than the electric energy consumed during electric driving or assisting to save fuel for the combustion engine, the system efficiency increases. The equilibrium value is calculated for the base system and then used to set up the control curve as shown in Figure 10.20. If the battery state of charge is low, electric energy is generated under worse efficiency conditions while at a high SOC electric driving is done if the ICE runs under efficient conditions to empty the battery to a level that allows recuperating the brake energy of the next braking event. In general brake energy recuperation has priority level one in the decision hierarchy. Other controller rules are included as described in (Luz, 2011). This control strategy produces robust and energy efficient operation strategies with low effort for adjustment to vehicle data of the single segments which have been simulated.

Figure 10.20: Base control algorithm in the HEV model applied in PHEM



The vehicle weight was adjusted against the weight of the base conventional vehicle based on specific weight values [kg/kWh] for the ICE and for the electric motor and for the additional battery weight. The ICE rated power was reduced by the installed electric power to maintain the acceleration level of the base vehicle[56].

Table 10.29: Gravimetric densities applied to calculate changes in the vehicle empty weight for HEVs compared to the base conventional vehicle

System	Gravimetric density	Value assumed for 2025
Lithium-ion Battery	kg per kWh	4.30
Electric Motor System	kg per kW	0.92
Baseline SI Engine+Transmission	kg per kW	2.06
Baseline CI Engine+Transmission	kg per kW	2.22

Figure 10.21 compares the reduction rates simulated for the base HEV vehicles compared to the base conventional vehicles. In the NEDC on average a 26% reduction has been achieved with higher reductions for petrol than for diesel vehicles. Since the SI engine has a more pronounced deterioration of the efficiency towards low loads the electric driving and the torque shifts from the HEV result in higher efficiency gains compared to the diesel engines. In the WLTC approximately a 20% reduction is simulated on average over all of the segments. Since the base conventional vehicle has

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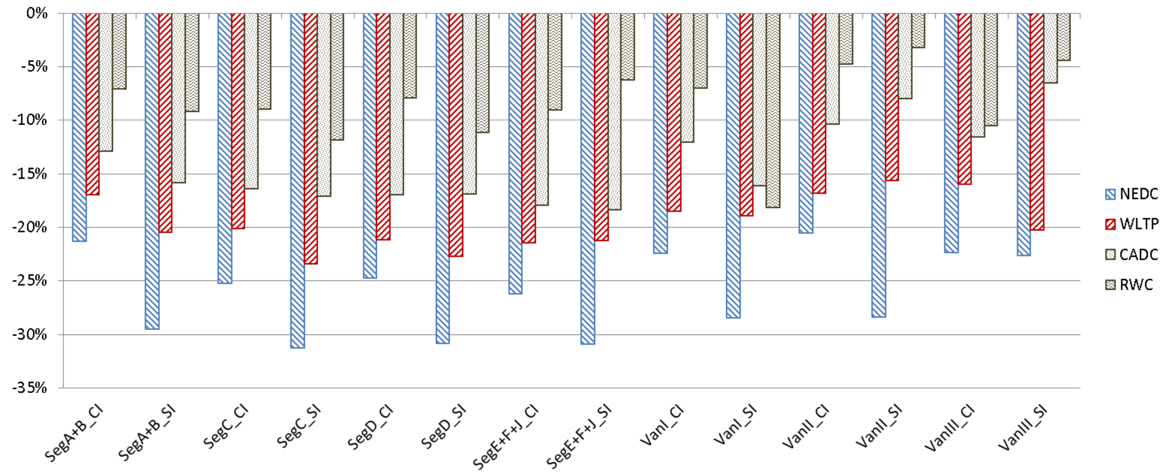
[56] In later simulations of HEV with reduced weight the ICE power had to be adjusted to the power necessary to maintain the maximum highway velocities of the RWC and WLTP even with empty battery although this led to somewhat better acceleration levels than the base vehicle has. With too low ICE power the vehicle would discharge the battery in longer highway cycles and would then run with reduced velocity at ICE full load since the electric motor cannot assist anymore with an empty battery. Without torque reserve the ICE cannot generate electric power in such driving conditions.

no engine start-stop but the HEV has, the high shares of idling phases in the NEDC explain the higher reduction potential in the NEDC compared to the other cycles. Furthermore the lower average engine loads in the NEDC lead to more pronounced benefits in propulsion efficiency due to electric driving and torque shifts compared to the WLTC, CADC and RWC. Also in the WLTP a lower reduction potential was simulated on average for the diesel engine vehicles. The reduction in the RWC is lowest due to the high mileage share of highway driving where only small effects from brake energy recuperation and from electric driving and torque shifts can be maintained due to high and constant velocities. As described before, the EU average has most likely lower shares of highway driving than the RWC.

Figure 10.21: Reduction rates simulated for the base HEV vehicles compared to the base conventional vehicles



A5.6.1 Validation of the HEV model in PHEM

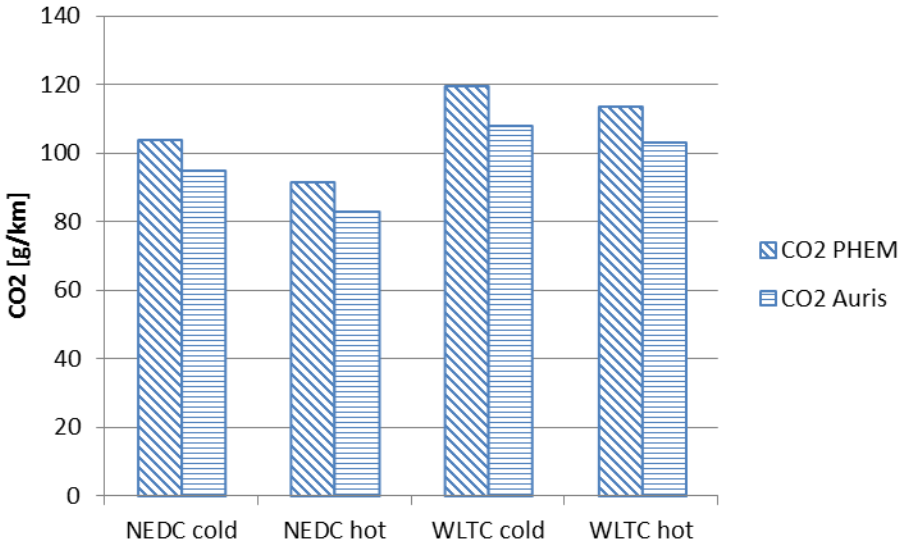
The main aim of the test program was to identify if PHEM can predict the differences between the NEDC and the WLTC for a hybrid vehicle correctly to ensure that the reduction potentials simulated were in the right order of magnitude for both cycles. For this validation and also for the fine tuning of the HEV model in PHEM, measurements of a Toyota Auris have been performed on TUG's chassis dyno. Each cycle was measured several times as foreseen in the corresponding regulation and the CO_2 emissions for the SOC neutral condition were interpolated from the single test results based on the measured energy flows from and to the battery.

Figure 10.22 compares the test results for the Toyota Auris with the simulation results for the "base HEV segment C car". The PHEM results overestimate the test data for the AURIS by 10% in all cycles. The main differences of the measured Toyota Hybrid compared to the base HEV are:

- The "base HEV car" uses a virtual SI engine which was produced by subtracting the main technologies for 2013 engines from the base SI-engines as described in Section A5.1, while the Toyota applies an Atkinson cycle.
- The "base HEV car" has a manual 5 gear transmission to use the technology of the base SI car (2002 technology), while the Toyota has a sophisticated planetary gear box.
- The "base HEV car" has the auxiliary efficiencies from the base SI-vehicle, while the Toyota has up to date technologies.

These differences suggest that the "base HEV car" shall have higher fuel consumption values than the actual Toyota Auris which is the case. The exact reproduction of the Auris test results was not a target of the project.

Figure 10.22: Comparison of the measured CO2 emissions at the Toyota Auris on the chassis dyno from TUG with the simulation results for the "base HEV segment C car"



A5.7 PHEV, BEV, REEV, FCEV

The simulation of hybrid vehicles needed well balanced hardware (ICE, motor, battery, gear box) and corresponding control strategies to define in each second of the test cycle the HEV mode (i.e. ICE only, Motor only, boosting, generating electric energy by ICE load increase, recuperation of brake energy). The simulation of different HEV systems using the engine and gear box technologies from the base vehicles was undertaken. Also the battery systems and electric motor efficiencies applied are base technologies rather than 2025 values to be consistent with the ICE base cars. Also sensitivity runs with different electric power levels installed to analyse if the reduction potential reacts differently in the 4 test cycles were undertaken.

Table 10.30: Specifications of the hybrid power train systems simulated

Technology	Extra mass	Rated power E-Motor	Rated power ICE	Battery capacity	Electric range[1]
	[% from base]	[% from ICE]	[% from base]	[kWh]	[km]
Start-Stop	0%	0%	100%	0.9	0
Micro HEV[2]	0%	0%	100%	0.9	0
Mild HEV	1-2%	5%	95%	0.35-0.80	1.0-2.4
Full HEV[3]	2%-6%	20%	85%	0.77-1.77	2.3-5.2
PHEV [4]	0%-6%	55%	80%	6-13	50
BEV	6%-20%	100% [5]	0%	19-76	210-425
REEV	6%-10%	160%	54%	11-20	80
FCEV	11%-20%	100% [5]	0%	1.4-2.7	5

Notes:

(1) Electric range from electricity gained from loading at the electric grid.

(2) Combines start/stop system with regenerative usage of 12V alternator.

(3) In a sensitivity analysis it is planned to simulate also HEVs with 50% higher electric motor power and increased battery capacity.

(4) Simulated by linear combination of BEV and HEV. For all HEV versions costs data and simulated electric power need to be balanced.

(5) 100% E-Motor power, percentage figure is not applied to the “rated power ICE”-column.

A5.8 Improvements in the auxiliary systems

Figure 10.23 shows a typical auxiliary system. A belt drive is used to transmit the power from the crankshaft of the combustion engine to the water pump, the steering pump, the alternator, and the switchable a/c compressor. The ratios between the components and the crankshaft are defined by the diameters of the corresponding pulleys. Usually, the ratios are constant. The torque from the combustion engine splits into one part for the power train and another part for the auxiliary system. The torque applied to each component itself depends on the requests of the corresponding components (Lindemann, 2013).

Figure 10.23: Typical alignment of a belt-drive accessory system

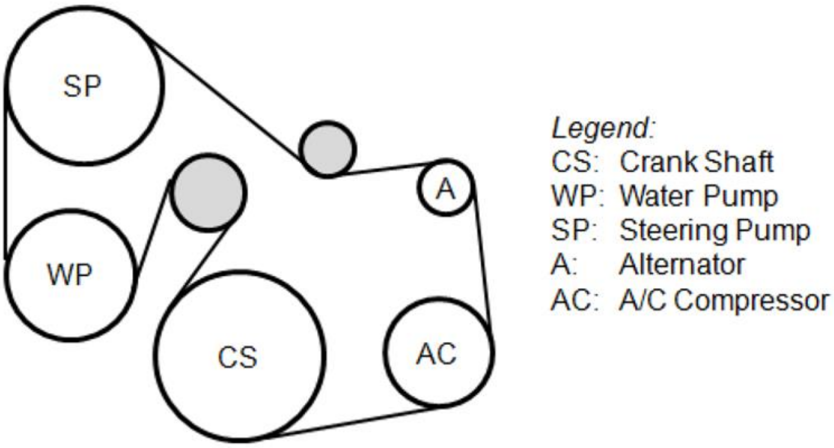


Fig. 1: Typical Alignment of a Belt-Driven Accessory System

The improvement of auxiliaries can be achieved by different options, which are discussed below.

If not defined differently in the text, the effects of optimising auxiliaries were simulated with the model PHEM by changing the mechanical power demands of the auxiliaries in the input file. Changes in the electric power demands and/or efficiency were converted in pre-processing into mechanical power by the alternator efficiency. As basis for the assessment of power demand reduction the component data shown in Table 10.31 was used.

Table 10.31: Main effects on auxiliary efficiency (Lindenmann, 2013)

Component	Quantity 1	Quantity 2	Assumed properties for base technology
Water Pump	Component Speed	Coolant Pressure	Max flow 1000l/min nominal pressure 1.2 bar transmission 1.2
Alternator	Component Speed	Electric Current	Max. power 1.8kW Nominal Voltage 12V transmission 2.7
Steering Pump	Component Speed		Max flow 100l/min nominal pressure 6 bar transmission 1.2
A/C Compressor	Flow Rate	Compression Pressure	Max flow 25l/min pressure 3 to 20 bar transmission 1.5

A5.8.1 Improved Auxiliary Efficiencies (AUX-Car)

In this technology package a switch from a 12 Volt to a 48 Volt system voltage was assumed. This allows for the electrification of auxiliaries even in combination with start/stop systems. 48 Volt also allows for mild hybridisation, although this is not simulated in the technology package here. The higher voltage in the supply net reduces the losses due to the ohmic resistances. These are however only a few watts in a conventional system. Thus the main effect results from the demand oriented operation of the auxiliaries which do not produce idling losses if they do not deliver useful work in the case of electric auxiliaries.

The following auxiliaries have been considered:

- Coolant pump[57]
- Electric steering pump (48V)
- Electric AC compressor
- 48V board net assumed with high efficiency alternator and lower losses for charging and discharging of the battery

Starting from the power consumption values of these auxiliaries from the base vehicle the reduction of power consumption was assessed that results from the elimination of idling power demands. The mechanical power of the auxiliaries was then converted via an efficiency of the motor and the 48 V alternator into the power demand at the combustion engine.

Table 10.32: Reduction in mechanical power demand at the engine from the auxiliaries assumed for the simulation

	Coolant pump	Steering pump + AC compressor	Battery losses	Ohmic losses	Total
	[$W_{mechanic}$]				
NEDC	-50.8				-50.8
WLTC	-49.4		-8.5	-2.3	-60.2
CADC	-59.2		-8.5	-2.3	-70.0
RWC	-61.8	-404.2	-8.5	-2.3	-476.8

The power demand of auxiliaries was reduced accordingly in the simulation with PHEM. For the chassis dyno cycles the effects are below 1%. The reduction of power demand for steering and air conditioning is only relevant in the RWC. There a fuel saving of slightly more than 2% was calculated on average over the vehicle segments.

A5.8.2 Improved Auxiliary Efficiencies for LCVs/Vans

The technology was simulated as already described for cars (Section A5.8.1). The explanations are not repeated here. A CO_2 saving of 0.3% was calculated for NEDC and WLTP. In the RWC on average 2% CO_2 reduction was simulated.

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[57] Also considered in “reduced wall heat transfer” (mainly thermal effect there)

A6 Appendix 6 – Formulae for the developed cost curves

A6.1 Formulae for developed cost curves

Data tables with the formulae for the final cost-curves will be added to this appendix for the final report, and are also provided in a separate Excel file alongside this report. All costs are in 2015 Euro.

A6.1.1 Cost curves for 2015

Table 10.33: LDV cost curves (€) for 2015 (WLTP basis), excluding off-cycle technologies.

		Cost curve relative to vehicle baseline for SI+Hybrid and CI+Hybrid $y = C + c / (x - x_0)$						
Powertrain	**Segment**	**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	-1253.67	-565.83	0.453719	0.28%	39.17%	€1.24	€7,876.49
	Car: Lower Medium	-1430.79	-591.35	0.413833	0.38%	35.57%	€11.43	€8,740.49
	Car: Upper Medium	-1665.67	-685.69	0.413030	0.26%	35.10%	€5.16	€9,384.08
	Car: Large	-1890.27	-764.89	0.405470	0.25%	34.64%	€7.73	€11,047.83
	LCV: Small	-1382.83	-634.32	0.467571	1.08%	40.49%	€5.86	€8,735.16
	LCV: Medium	-1982.70	-937.74	0.471809	0.28%	39.39%	€16.67	€10,050.27
	LCV: Large	-2710.74	-1263.25	0.473275	0.81%	39.28%	€4.74	€12,995.48
CI+Hybrid	Car: Small	-909.31	-373.91	0.412022	0.08%	36.70%	€0.01	€7,394.04
	Car: Lower Medium	-1245.72	-527.29	0.428096	0.61%	37.24%	€3.77	€8,218.19
	Car: Upper Medium	-1333.54	-570.99	0.438151	1.24%	38.46%	€7.70	€9,320.23
	Car: Large	-2006.82	-881.13	0.445636	0.83%	37.72%	€7.77	€10,863.89
	LCV: Small	-1351.82	-633.44	0.476783	1.49%	41.39%	€19.54	€8,713.91
	LCV: Medium	-1309.36	-601.91	0.464987	0.66%	41.34%	€3.85	€10,348.47
	LCV: Large	-1683.50	-791.66	0.484832	2.03%	42.89%	€20.56	€12,471.93

A6.1.2 Cost curves for 2020

Table 10.34: LDV cost curves (€) for 2020 (WLTP basis), excluding off-cycle technologies.

		Cost curve relative to vehicle baseline for SI+Hybrid and CI+Hybrid $y = C + c / (x - x_0)$						
Powertrain	**Segment**	**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	-988.05	-536.72	0.546533	0.59%	47.56%	€4.66	€6,581.15
	Car: Lower Medium	-1354.55	-704.78	0.520057	0.43%	43.99%	€11.92	€7,434.92
	Car: Upper Medium	-1531.22	-793.22	0.518197	0.03%	43.20%	€0.45	€7,672.27
	Car: Large	-1724.79	-872.36	0.505943	0.07%	42.71%	€1.81	€9,335.49
	LCV: Small	-943.73	-514.17	0.545071	0.05%	49.39%	€0.42	€9,106.67
	LCV: Medium	-1581.53	-883.42	0.563132	0.67%	48.38%	€6.16	€9,556.44
	LCV: Large	-1965.32	-1081.18	0.556764	0.90%	48.66%	€8.63	€13,441.28
CI+Hybrid	Car: Small	-990.64	-542.60	0.557806	1.05%	47.95%	€0.73	€5,940.69
	Car: Lower Medium	-1416.02	-829.59	0.589818	0.54%	48.80%	€3.48	€6,730.78
	Car: Upper Medium	-1337.68	-780.00	0.586122	0.43%	49.90%	€2.84	€7,612.59
	Car: Large	-1867.82	-1110.57	0.598515	0.69%	49.13%	€9.47	€8,488.71
	LCV: Small	-1188.58	-694.87	0.595341	2.35%	52.19%	€26.47	€8,269.26
	LCV: Medium	-1153.50	-659.86	0.583028	1.45%	52.32%	€7.18	€9,870.49
	LCV: Large	-1260.25	-729.58	0.583258	0.72%	53.63%	€6.20	€14,260.60

A6.1.3 Cost curves for 2025

Table 10.35: LDV cost curves (€) for 2025 (WLTP basis), excluding off-cycle technologies.

		Cost curve relative to vehicle baseline for SI+Hybrid and CI+Hybrid $y = C + c / (x - x_0)$						
Powertrain	**Segment**	**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	-733.83	-422.52	0.574615	0.20%	50.07%	€4.07	€4,984.30
	Car: Lower Medium	-855.51	-459.78	0.538470	0.42%	47.08%	€5.13	€5,934.03
	Car: Upper Medium	-740.45	-385.63	0.520393	0.06%	46.21%	€1.42	€5,871.64
	Car: Large	-780.28	-400.38	0.514825	0.39%	46.16%	€3.32	€6,738.61
	LCV: Small	-755.99	-436.11	0.583482	0.98%	52.40%	€4.22	€6,578.66
	LCV: Medium	-1321.20	-790.70	0.610866	1.56%	50.96%	€7.04	€6,483.71
	LCV: Large	-1496.38	-866.88	0.593696	1.76%	51.77%	€8.25	€9,906.01
CI+Hybrid	Car: Small	-802.07	-471.71	0.598131	1.05%	51.33%	€0.65	€4,761.59
	Car: Lower Medium	-1037.10	-639.31	0.619940	0.54%	52.37%	€3.20	€5,603.11
	Car: Upper Medium	-1095.04	-688.74	0.631739	0.43%	53.51%	€2.60	€6,029.54
	Car: Large	-1526.48	-980.72	0.644085	0.69%	52.71%	€12.75	€6,856.41
	LCV: Small	-954.99	-601.19	0.637379	2.35%	55.67%	€24.26	€6,497.81
	LCV: Medium	-972.15	-599.67	0.627219	1.45%	55.81%	€6.57	€7,699.33
	LCV: Large	-1106.22	-691.47	0.629054	0.72%	57.07%	€5.68	€10,745.34

Table 10.36: xEV LDV cost curves (€) for 2025 (WLTP basis), excluding off-cycle technologies (% CO_2 reduction for PHEV/REEV, % energy reduction for BEV/FCEV)

		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 (%)*[58]**	**x_max = Max reduction (%)***	**y_min = Min additional cost[59]**	**y_max = Max additional cost**
SI PHEV	Car: Small	-22,465.6888	21,730.0645	-153.5170	0.8566	67.7%	81.5%	€ 5,270.35	€ 6,510.92
	Car: Lower Medium	-21,774.2726	22,374.6716	-97.1898	0.8376	66.6%	81.0%	€ 5,810.92	€ 7,305.11
	Car: Upper Medium	-22,331.4571	23,099.0652	-89.6629	0.8418	66.5%	81.6%	€ 5,993.74	€ 7,439.43
	Car: Large	-25,609.1948	27,382.2085	-77.1388	0.8437	67.1%	82.3%	€ 7,290.11	€ 8,846.15
	LCV: Small	-15,285.9208	16,282.1366	-69.0531	0.8125	62.9%	79.6%	€ 4,570.28	€ 7,414.48
	LCV: Medium	-17,935.1917	19,526.8897	-74.2526	0.8162	65.4%	80.0%	€ 5,556.68	€ 8,810.96
	LCV: Large	-28,686.9588	30,437.3819	-90.2336	0.8435	71.0%	83.2%	€ 7,827.57	€ 13,103.22
CI PHEV	Car: Small	-23,936.7333	22,769.1290	-209.2197	0.8938	72.1%	84.2%	€ 5,182.48	€ 6,238.48
	Car: Lower Medium	-22,979.9243	22,708.0480	-143.6544	0.8725	70.7%	83.5%	€ 5,436.73	€ 6,790.65
	Car: Upper Medium	-24,835.5106	23,681.5303	-188.7295	0.8784	70.5%	83.6%	€ 5,437.64	€ 6,878.55
	Car: Large	-27,025.3129	27,422.1926	-123.8727	0.8694	71.5%	84.0%	€ 6,595.02	€ 8,241.31
	LCV: Small	-16,141.9170	16,705.8921	-86.5286	0.8575	70.8%	83.7%	€ 4,315.36	€ 6,893.82
	LCV: Medium	-20,142.0216	20,616.7359	-108.9337	0.8612	70.7%	83.9%	€ 5,213.66	€ 8,119.43
	LCV: Large	-31,545.3639	31,275.5943	-135.1764	0.8495	69.6%	83.3%	€ 7,364.16	€ 12,188.26
SI REEV	Car: Small	-34,471.5870	33,853.9889	-126.6135	0.8853	75.5%	85.1%	€ 6,884.64	€ 7,504.77
	Car: Lower Medium	-34,626.1676	35,923.8832	-71.8338	0.8753	75.4%	85.4%	€ 7,997.95	€ 8,749.47
	Car: Upper Medium	-36,452.8815	38,399.6657	-64.3416	0.8807	75.6%	86.1%	€ 8,706.25	€ 9,311.04
	Car: Large	-41,966.0662	45,157.1478	-55.5844	0.8781	75.3%	86.2%	€ 10,645.32	€ 11,195.32
	LCV: Small	-23,155.9911	25,317.4416	-47.7741	0.8507	72.8%	83.8%	€ 6,550.06	€ 8,830.61
	LCV: Medium	-29,807.8305	32,168.2784	-56.2305	0.8538	73.5%	84.1%	€ 8,014.30	€ 10,513.38
	LCV: Large	-50,069.9274	52,353.5578	-73.9293	0.8725	76.8%	86.3%	€ 11,387.90	€ 15,484.48
CI REEV	Car: Small	-35,656.4877	34,517.2260	-166.9990	0.9076	76.8%	86.5%	€ 6,678.87	€ 7,107.03
	Car: Lower Medium	-37,734.7800	37,772.2826	-122.9190	0.8991	77.0%	86.8%	€ 7,663.93	€ 8,306.93

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[58] 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

[59] 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

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 (%)*[58]	x_max = Max reduction (%)*	y_min = Min additional cost[59]	y_max = Max additional cost
	Car: Upper Medium	-39,936.7349	40,284.2774	-128.3525	0.9008	77.1%	87.0%	€ 8,304.59	€ 8,987.08
	Car: Large	-46,056.2890	47,771.7790	-97.7201	0.8947	77.6%	87.2%	€ 10,160.91	€ 10,926.89
	LCV: Small	-28,427.9185	28,967.1434	-84.4083	0.8765	75.3%	85.7%	€ 6,378.60	€ 8,364.73
	LCV: Medium	-35,730.2882	36,013.5857	-111.6332	0.8810	75.4%	86.0%	€ 7,717.40	€ 9,909.82
	LCV: Large	-55,026.6516	54,773.6153	-128.2834	0.8757	75.7%	86.0%	€ 11,007.51	€ 14,796.58
BEV	Car: Small	-28,082.2683	26,566.1435	-19.2614	0.8304	74.5%	81.5%	€ 4,432.47	€ 4,275.14
	Car: Lower Medium	-58,544.8378	51,635.0106	-94.4463	0.8525	74.2%	81.9%	€ 6,930.63	€ 5,838.93
	Car: Upper Medium	-66,124.1335	58,692.0293	-138.7578	0.8588	74.9%	82.1%	€ 8,135.42	€ 7,302.85
	Car: Large	-112,032.4033	96,431.4584	-521.7374	0.8929	74.9%	82.6%	€ 13,000.67	€ 11,019.68
	LCV: Small	-30,454.6725	27,801.0711	-29.1246	0.8206	73.8%	81.0%	€ 4,285.91	€ 5,382.15
	LCV: Medium	-52,995.9680	48,606.4864	-42.7012	0.8158	72.9%	80.4%	€ 7,759.29	€ 8,468.95
	LCV: Large	-92,660.1458	84,187.7522	-74.4937	0.8193	72.4%	80.8%	€ 13,159.42	€ 14,112.65
FCEV	Car: Small	-42,669.9447	39,274.9670	-147.9193	0.6935	50.0%	63.8%	€ 9,734.63	€ 10,365.73
	Car: Lower Medium	-62,599.5225	52,009.6511	-693.8325	0.7577	50.3%	65.1%	€ 13,046.56	€ 13,840.45
	Car: Upper Medium	-77,639.7398	62,089.3144	-1,126.8470	0.7748	51.1%	65.2%	€ 15,726.88	€ 16,659.24
	Car: Large	-101,245.8250	68,581.7814	-4,087.7207	0.8645	51.3%	66.3%	€ 20,166.30	€ 21,243.41
	LCV: Small	-41,198.7736	37,666.1666	-91.2122	0.6578	49.2%	63.3%	€ 9,108.93	€ 10,946.07
	LCV: Medium	-51,386.1906	45,647.4796	-128.6296	0.6548	48.4%	62.7%	€ 10,808.88	€ 13,020.24
	LCV: Large	-77,882.9090	66,083.6488	-222.2018	0.6564	46.7%	62.9%	€ 15,048.60	€ 18,888.79

Table 10.37: LDV cost curves (€) for 2025 (WLTP basis), including off-cycle technologies

		Cost curve relative to vehicle baseline for SI+Hybrid and CI+Hybrid $y = C + c / (x - x_0)$						
Powertrain	**Segment**	**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	-604.27	-374.29	0.631298	2.02%	58.08%	€8.16	€6,806.69
	Car: Lower Medium	-729.89	-437.99	0.599973	0.05%	54.83%	€0.73	€7,744.41
	Car: Upper Medium	-713.78	-419.33	0.587815	0.05%	53.71%	€0.26	€7,553.90
	Car: Large	-779.25	-440.73	0.580541	1.53%	53.37%	€0.52	€8,630.12
	LCV: Small	-611.06	-391.76	0.646348	0.95%	60.05%	€4.07	€7,926.05
	LCV: Medium	-924.73	-599.84	0.661154	1.82%	59.91%	€8.27	€8,736.85
	LCV: Large	-1008.20	-658.58	0.655167	0.28%	60.62%	€1.27	€12,449.36
CI+Hybrid	Car: Small	-589.05	-401.98	0.688120	1.11%	63.54%	€4.70	€7,042.71
	Car: Lower Medium	-703.71	-485.66	0.691967	0.44%	63.65%	€2.63	€8,055.30
	Car: Upper Medium	-751.03	-527.50	0.703052	0.12%	64.63%	€0.58	€8,548.72
	Car: Large	-934.09	-646.57	0.697335	0.56%	63.69%	€0.67	€9,759.91
	LCV: Small	-759.26	-551.00	0.730943	0.66%	67.16%	€1.39	€8,529.30
	LCV: Medium	-773.26	-548.88	0.728062	2.33%	67.85%	€5.57	€10,296.75
	LCV: Large	-790.67	-573.03	0.730258	0.72%	69.12%	€1.81	€13,893.20

Table 10.38: xEV LDV cost curves (€) for 2025 (WLTP basis), including off-cycle technologies (% CO_2 reduction for PHEV/REEV, % energy reduction for BEV/FCEV)

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 (%)*[60]	x_max = Max reduction (%)*	y_min = Min additional cost[61]	y_max = Max additional cost
SI PHEV	Car: Small	-15,926.1465	18,125.6895	-53.9202	0.8572	67.8%	84.5%	€ 5,268.27	€ 8,468.69
	Car: Lower Medium	-18,118.7346	20,300.1657	-59.8312	0.8505	66.8%	83.9%	€ 5,804.27	€ 9,357.71
	Car: Upper Medium	-19,859.0803	21,686.8552	-68.6733	0.8569	66.6%	84.4%	€ 5,993.15	€ 9,299.40
	Car: Large	-24,197.2118	26,564.5551	-72.3860	0.8611	67.3%	84.9%	€ 7,304.25	€ 10,919.80
	LCV: Small	-14,964.7345	16,042.3950	-85.8770	0.8436	63.1%	82.9%	€ 4,568.73	€ 8,960.24
	LCV: Medium	-17,740.5464	19,383.6916	-93.6424	0.8480	65.7%	83.4%	€ 5,568.32	€ 10,421.26
	LCV: Large	-26,500.6687	28,984.2401	-99.6393	0.8709	71.2%	86.0%	€ 7,830.88	€ 14,785.54
CI PHEV	Car: Small	-15,400.6594	17,803.0729	-60.4431	0.8901	72.4%	87.7%	€ 5,181.38	€ 8,375.94
	Car: Lower Medium	-17,756.7031	19,621.2491	-79.3117	0.8850	70.9%	87.0%	€ 5,434.91	€ 8,996.64
	Car: Upper Medium	-18,603.5978	20,123.5474	-92.7679	0.8876	70.8%	87.1%	€ 5,438.51	€ 9,013.59
	Car: Large	-22,600.3552	24,656.0472	-90.2828	0.8882	71.7%	87.4%	€ 6,586.33	€ 10,727.80
	LCV: Small	-15,605.7117	16,318.6935	-106.8498	0.8903	71.1%	87.3%	€ 4,310.78	€ 8,698.37
	LCV: Medium	-19,356.5782	20,004.7933	-138.9925	0.8966	71.0%	87.8%	€ 5,190.87	€ 10,015.08
	LCV: Large	-28,503.4287	29,157.1797	-165.2632	0.8883	69.9%	87.2%	€ 7,325.18	€ 14,185.52
SI REEV	Car: Small	-24,962.7653	27,577.8007	-37.9676	0.8844	75.6%	87.6%	€ 6,877.41	€ 9,345.74
	Car: Lower Medium	-29,698.2994	32,563.8579	-43.2539	0.8857	75.5%	87.7%	€ 7,988.35	€ 10,632.75
	Car: Upper Medium	-33,080.6717	36,079.1281	-48.1990	0.8925	75.8%	88.3%	€ 8,701.84	€ 11,001.06
	Car: Large	-40,162.9698	43,905.1113	-52.7150	0.8925	75.5%	88.3%	€ 10,640.31	€ 13,068.12
	LCV: Small	-23,384.4343	25,448.7136	-61.5168	0.8764	72.9%	86.6%	€ 6,541.86	€ 10,257.80
	LCV: Medium	-29,592.3365	32,010.2571	-70.5223	0.8793	73.7%	86.8%	€ 8,016.35	€ 11,961.45
	LCV: Large	-46,612.2501	49,772.5562	-81.5594	0.9006	77.6%	89.2%	€ 11,211.08	€ 16,682.26

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[60] 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

[61] 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

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 (%)*[60]	x_max = Max reduction (%)*	y_min = Min additional cost[61]	y_max = Max additional cost
CI REEV	Car: Small	-24,890.4709	27,374.8217	-46.3532	0.9051	77.0%	89.5%	€ 6,666.52	€ 9,174.10
	Car: Lower Medium	-30,121.1301	32,569.6166	-62.1846	0.9081	77.2%	89.6%	€ 7,648.97	€ 10,330.08
	Car: Upper Medium	-32,814.9552	35,432.4280	-70.6870	0.9107	77.3%	89.8%	€ 8,291.89	€ 10,946.44
	Car: Large	-39,993.6731	43,448.7168	-70.6296	0.9101	77.8%	89.9%	€ 10,131.67	€ 13,214.12
	LCV: Small	-26,964.1599	27,906.7902	-99.2440	0.9047	75.5%	88.9%	€ 6,362.35	€ 9,997.53
	LCV: Medium	-33,289.5268	34,220.5423	-130.1724	0.9106	75.7%	89.3%	€ 7,680.67	€ 11,591.56
	LCV: Large	-49,197.2446	50,479.0530	-145.8555	0.9074	75.9%	89.4%	€ 10,947.08	€ 16,466.06
BEV	Car: Small	-34,564.2336	30,242.3521	-147.9593	0.8830	74.0%	85.3%	€ 4,486.39	€ 5,535.72
	Car: Lower Medium	-65,757.9454	54,823.6034	-403.2299	0.9071	73.6%	85.6%	€ 7,081.70	€ 6,592.61
	Car: Upper Medium	-63,909.6006	56,218.3025	-275.5363	0.8971	74.3%	85.7%	€ 8,278.90	€ 8,163.15
	Car: Large	-105,620.1570	91,253.4845	-668.7364	0.9208	74.3%	86.1%	€ 13,256.93	€ 11,472.28
	LCV: Small	-29,740.8495	26,701.9882	-97.9135	0.8667	73.2%	84.9%	€ 4,333.85	€ 6,678.96
	LCV: Medium	-49,277.9661	45,388.7730	-111.9322	0.8612	72.5%	84.4%	€ 7,836.77	€ 9,602.42
	LCV: Large	-79,774.0369	74,588.2527	-119.6350	0.8601	73.0%	84.7%	€ 12,845.38	€ 14,901.32
FCEV	Car: Small	-47,086.0385	35,783.3401	-1,172.7384	0.8246	49.1%	71.1%	€ 9,733.59	€ 11,981.49
	Car: Lower Medium	-62,270.3610	41,273.1361	-3,161.1451	0.8964	49.2%	72.2%	€ 13,050.10	€ 15,446.05
	Car: Upper Medium	-72,215.3445	53,273.2400	-2,682.2977	0.8754	49.9%	72.2%	€ 15,728.70	€ 18,325.23
	Car: Large	-90,425.1635	58,991.6012	-5,801.1176	0.9364	50.1%	73.1%	€ 20,180.93	€ 23,033.28
	LCV: Small	-39,751.3259	35,190.2262	-377.7141	0.7566	48.1%	70.7%	€ 9,100.35	€ 12,584.05
	LCV: Medium	-46,550.7999	41,860.9654	-385.2830	0.7478	47.5%	70.2%	€ 10,794.07	€ 14,884.15
	LCV: Large	-62,914.0440	58,325.0548	-374.6602	0.7379	47.9%	70.4%	€ 14,950.38	€ 20,933.16

A6.1.4 Cost curves for 2030

Table 10.39: LDV cost curves (€) for 2030 (WLTP basis), excluding off-cycle technologies

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	-573.07	-332.05	0.580980	0.21%	51.30%	€0.56	€4,312.42
	Car: Lower Medium	-558.84	-302.54	0.538685	0.17%	48.11%	€4.53	€4,696.58
	Car: Upper Medium	-521.47	-281.22	0.539528	0.07%	49.00%	€0.40	€5,151.95
	Car: Large	-546.01	-290.83	0.535107	1.21%	49.05%	€10.05	€5,966.59
	LCV: Small	-624.49	-365.06	0.598513	1.91%	53.94%	€5.56	€5,555.03
	LCV: Medium	-954.49	-565.58	0.612340	2.44%	52.97%	€7.47	€5,892.23
	LCV: Large	-1065.34	-618.67	0.599096	2.60%	53.07%	€14.27	€7,985.70
CI+Hybrid	Car: Small	-633.97	-378.85	0.607472	1.05%	52.91%	€0.64	€4,197.39
	Car: Lower Medium	-852.85	-539.85	0.636165	0.54%	54.11%	€3.00	€4,825.35
	Car: Upper Medium	-875.30	-561.75	0.644240	0.43%	55.30%	€2.47	€5,280.75
	Car: Large	-1212.93	-778.51	0.651988	1.76%	54.49%	€14.25	€6,057.52
	LCV: Small	-768.58	-496.97	0.651309	2.35%	57.37%	€22.96	€5,631.96
	LCV: Medium	-847.13	-540.52	0.647928	1.45%	57.47%	€6.22	€6,529.48
	LCV: Large	-966.38	-624.43	0.649758	0.72%	58.70%	€5.37	€8,987.76

Table 10.40: xEV LDV cost curves (€) for 2030 (WLTP basis), excluding off-cycle technologies (% CO_2 reduction for PHEV/REEV, % energy reduction for BEV/FCEV)

		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 (%)*[62]**	**x_max = Max reduction (%)***	**y_min = Min additional cost[63]**	**y_max = Max additional cost**
SI PHEV	Car: Small	-18,826.2960	18,941.5523	-117.3053	0.8616	68.2%	82.1%	€ 4,814.86	€ 5,754.77
	Car: Lower Medium	-19,193.0061	19,942.7188	-97.9928	0.8543	67.1%	82.0%	€ 5,274.88	€ 6,304.90
	Car: Upper Medium	-19,660.0792	20,590.4016	-84.6537	0.8574	67.0%	82.9%	€ 5,421.84	€ 6,501.12
	Car: Large	-22,338.4279	24,288.9956	-69.4446	0.8583	67.6%	83.6%	€ 6,591.42	€ 7,754.46
	LCV: Small	-13,619.4966	14,575.0678	-74.2578	0.8267	63.4%	80.4%	€ 4,151.26	€ 6,167.66
	LCV: Medium	-15,296.1025	17,163.4499	-60.7000	0.8261	66.0%	80.8%	€ 5,030.54	€ 7,304.60
	LCV: Large	-22,480.9364	25,317.7454	-60.6667	0.8574	72.2%	84.6%	€ 7,008.76	€ 10,660.13
CI PHEV	Car: Small	-20,208.3560	19,768.4114	-182.0583	0.9021	72.2%	84.7%	€ 4,748.59	€ 5,552.15
	Car: Lower Medium	-19,990.3782	19,998.1701	-138.5547	0.8831	70.8%	84.1%	€ 4,929.96	€ 5,973.71
	Car: Upper Medium	-21,604.5404	20,729.3081	-193.8402	0.8924	70.7%	84.2%	€ 4,904.17	€ 5,975.19
	Car: Large	-23,871.5255	24,291.7393	-127.2785	0.8805	71.6%	84.6%	€ 5,929.97	€ 7,177.22
	LCV: Small	-11,467.2942	13,146.4522	-54.8222	0.8621	71.0%	84.3%	€ 3,913.88	€ 5,860.84
	LCV: Medium	-14,853.3137	16,513.2149	-73.9191	0.8664	70.8%	84.5%	€ 4,712.24	€ 6,836.22
	LCV: Large	-24,807.8011	25,881.9565	-105.0020	0.8562	69.7%	83.8%	€ 6,645.10	€ 10,156.13
SI REEV	Car: Small	-28,044.8800	28,584.2287	-85.8252	0.8876	75.9%	85.6%	€ 6,205.13	€ 6,606.10
	Car: Lower Medium	-29,975.7799	31,506.6278	-68.5868	0.8880	75.8%	86.2%	€ 7,186.07	€ 7,539.73
	Car: Upper Medium	-31,654.7804	33,783.0597	-58.1494	0.8921	76.0%	87.1%	€ 7,833.14	€ 8,137.38
	Car: Large	-36,343.3707	39,634.0732	-48.9598	0.8893	75.7%	87.2%	€ 9,547.55	€ 9,779.22
	LCV: Small	-19,524.6136	21,911.3694	-43.2818	0.8603	73.2%	84.5%	€ 5,913.29	€ 7,441.88
	LCV: Medium	-25,372.0338	28,026.2587	-44.2795	0.8617	73.9%	84.8%	€ 7,213.17	€ 8,813.25
	LCV: Large	-39,874.4972	43,420.2737	-46.9564	0.8829	77.7%	87.4%	€ 10,105.36	€ 12,700.29
CI REEV	Car: Small	-30,504.6170	29,918.9973	-157.5149	0.9168	76.9%	86.9%	€ 6,037.03	€ 6,274.46
	Car: Lower Medium	-32,114.6894	32,634.2811	-112.7114	0.9072	77.1%	87.3%	€ 6,897.66	€ 7,290.89

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[62] 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

[63] 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

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 (%)*[62]	x_max = Max reduction (%)*	y_min = Min additional cost[63]	y_max = Max additional cost
	Car: Upper Medium	-34,284.4458	35,008.8654	-122.8033	0.9101	77.2%	87.5%	€ 7,479.94	€ 7,878.42
	Car: Large	-40,292.3593	42,088.5231	-96.9390	0.9036	77.8%	87.7%	€ 9,127.46	€ 9,590.72
	LCV: Small	-21,379.7465	23,202.1330	-54.0631	0.8801	75.4%	86.3%	€ 5,769.21	€ 7,183.46
	LCV: Medium	-26,716.9842	28,668.6123	-70.4368	0.8846	75.5%	86.5%	€ 6,957.17	€ 8,450.00
	LCV: Large	-43,366.1064	44,950.1052	-95.0616	0.8816	75.9%	86.6%	€ 9,908.15	€ 12,500.98
BEV	Car: Small	-26,063.1045	24,576.2111	-19.9299	0.8360	74.8%	81.7%	€ 4,030.21	€ 3,749.58
	Car: Lower Medium	-51,355.5471	45,746.5787	-99.9112	0.8615	74.6%	82.2%	€ 6,413.04	€ 5,426.94
	Car: Upper Medium	-63,037.0312	55,820.6298	-152.2678	0.8683	75.2%	82.3%	€ 7,650.16	€ 6,617.24
	Car: Large	-101,989.6619	87,848.1209	-531.9780	0.9042	75.3%	82.9%	€ 11,846.31	€ 9,807.47
	LCV: Small	-25,990.9359	24,164.8849	-21.5958	0.8230	74.1%	81.2%	€ 3,902.94	€ 4,535.67
	LCV: Medium	-45,963.5919	43,003.7893	-29.3763	0.8183	73.3%	80.7%	€ 7,172.13	€ 7,354.01
	LCV: Large	-83,112.1822	76,687.9669	-57.1833	0.8221	73.9%	81.0%	€ 11,964.86	€ 12,351.27
FCEV	Car: Small	-35,642.6798	31,813.4360	-183.5978	0.7134	50.5%	64.2%	€ 7,856.87	€ 8,298.98
	Car: Lower Medium	-51,222.8965	40,717.7924	-807.2253	0.7838	50.8%	65.5%	€ 10,392.47	€ 10,952.49
	Car: Upper Medium	-62,676.7077	47,959.1501	-1,253.1147	0.8014	51.6%	65.6%	€ 12,449.11	€ 13,110.74
	Car: Large	-78,874.2966	51,270.2359	-3,891.9773	0.8886	51.9%	66.7%	€ 15,894.88	€ 16,665.40
	LCV: Small	-32,613.0213	30,167.4230	-72.1251	0.6622	49.5%	63.5%	€ 7,373.50	€ 8,682.35
	LCV: Medium	-39,780.3080	36,216.0407	-91.9290	0.6575	48.8%	63.0%	€ 8,742.18	€ 10,326.14
	LCV: Large	-58,118.6257	51,284.3717	-154.1183	0.6592	49.4%	63.2%	€ 12,084.08	€ 14,844.11

Table 10.41: LDV cost curves (€) for 2030 (WLTP basis), including off-cycle technologies

		Cost curve relative to vehicle baseline for SI+Hybrid and CI+Hybrid $y = C + c / (x - x_0)$						
Powertrain	**Segment**	**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	-495.59	-319.34	0.645628	0.21%	59.48%	€0.66	€5,791.68
	Car: Lower Medium	-570.00	-347.71	0.613097	0.43%	56.14%	€1.10	€6,160.37
	Car: Upper Medium	-550.76	-329.96	0.607925	0.89%	56.16%	€0.09	€6,572.26
	Car: Large	-584.41	-351.63	0.602228	0.57%	55.87%	€5.03	€7,488.46
	LCV: Small	-516.58	-334.93	0.664378	1.88%	62.10%	€2.22	€7,205.26
	LCV: Medium	-703.37	-476.80	0.674087	0.09%	61.71%	€4.93	€7,662.15
	LCV: Large	-831.07	-551.59	0.673008	1.14%	62.29%	€2.70	€10,170.05
CI+Hybrid	Car: Small	-536.65	-380.16	0.713690	1.11%	65.50%	€4.45	€5,944.79
	Car: Lower Medium	-624.93	-446.49	0.716267	0.44%	65.66%	€2.28	€6,859.66
	Car: Upper Medium	-653.23	-474.06	0.726335	0.12%	66.66%	€0.55	€7,288.46
	Car: Large	-823.86	-590.33	0.721490	0.56%	65.70%	€0.79	€8,330.79
	LCV: Small	-669.01	-502.09	0.755622	0.66%	69.15%	€1.29	€7,165.53
	LCV: Medium	-700.10	-516.40	0.755504	2.33%	69.85%	€5.16	€8,365.66
	LCV: Large	-732.67	-550.73	0.757131	0.72%	71.17%	€1.68	€11,402.92

Table 10.42: xEV LDV cost curves (€) for 2030 (WLTP basis), including off-cycle technologies (% CO_2 reduction for PHEV/REEV, % energy reduction for BEV/FCEV)

		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 (%)*[64]**	**x_max = Max reduction (%)***	**y_min = Min additional cost[65]**	**y_max = Max additional cost**
SI PHEV	Car: Small	-15,191.1429	16,942.2651	-64.4549	0.8703	68.1%	85.4%	€ 4,833.99	€ 7,297.57
	Car: Lower Medium	-17,324.8734	18,925.7753	-77.5156	0.8690	67.0%	85.1%	€ 5,293.43	€ 7,793.08
	Car: Upper Medium	-18,942.8431	20,172.6163	-89.4873	0.8767	66.9%	85.7%	€ 5,449.41	€ 7,899.79
	Car: Large	-22,124.6639	24,143.4961	-81.2301	0.8782	67.5%	86.2%	€ 6,616.47	€ 9,362.07
	LCV: Small	-13,524.9191	14,472.6189	-94.6172	0.8590	63.3%	84.0%	€ 4,160.75	€ 7,555.68
	LCV: Medium	-15,325.7721	17,134.6088	-83.2795	0.8602	65.9%	84.5%	€ 5,050.22	€ 8,852.63
	LCV: Large	-21,501.5658	24,668.4941	-72.1092	0.8795	71.3%	86.9%	€ 7,092.05	€ 12,343.66
CI PHEV	Car: Small	-13,796.7927	16,039.4169	-66.0387	0.9027	72.5%	88.6%	€ 4,748.76	€ 7,245.48
	Car: Lower Medium	-16,150.6700	17,709.3848	-94.9554	0.9002	71.0%	87.9%	€ 4,930.00	€ 7,654.94
	Car: Upper Medium	-17,084.9494	18,189.4012	-117.2179	0.9047	70.9%	88.1%	€ 4,906.74	€ 7,616.72
	Car: Large	-19,266.6507	21,397.5603	-90.5440	0.9005	71.8%	88.3%	€ 5,926.33	€ 9,122.36
	LCV: Small	-12,548.4783	13,723.9239	-95.5839	0.9026	71.3%	88.3%	€ 3,910.75	€ 7,300.45
	LCV: Medium	-15,266.2209	16,608.7331	-118.5562	0.9084	71.1%	88.7%	€ 4,692.06	€ 8,363.09
	LCV: Large	-22,104.5879	23,985.8923	-129.9481	0.8992	70.0%	88.2%	€ 6,610.24	€ 11,733.92
SI REEV	Car: Small	-22,967.8528	25,213.4555	-42.9807	0.8946	75.8%	88.3%	€ 6,229.58	€ 8,055.58
	Car: Lower Medium	-27,087.3450	29,556.1998	-50.9344	0.8993	75.7%	88.7%	€ 7,208.79	€ 8,895.21
	Car: Upper Medium	-30,223.7198	32,782.8729	-57.4670	0.9065	75.9%	89.3%	€ 7,862.28	€ 9,438.59
	Car: Large	-35,871.0154	39,302.6453	-56.5107	0.9054	75.6%	89.4%	€ 9,590.74	€ 11,258.78
	LCV: Small	-20,754.5409	22,710.7157	-65.6662	0.8887	73.1%	87.5%	€ 5,927.14	€ 8,672.01
	LCV: Medium	-25,530.9484	28,095.3038	-62.0460	0.8893	73.9%	87.7%	€ 7,234.52	€ 10,185.54
	LCV: Large	-37,820.6911	41,849.7254	-55.2439	0.9073	77.7%	89.9%	€ 10,109.74	€ 14,085.27

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[64] 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

[65] 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

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 (%)*[64]	x_max = Max reduction (%)*	y_min = Min additional cost[65]	y_max = Max additional cost
CI REEV	Car: Small	-22,188.7534	24,444.4724	-53.6741	0.9165	77.1%	90.3%	€ 6,027.54	€ 7,824.26
	Car: Lower Medium	-26,507.9871	28,785.5716	-69.5750	0.9196	77.3%	90.4%	€ 6,886.27	€ 8,836.00
	Car: Upper Medium	-29,460.3100	31,704.5767	-87.4470	0.9239	77.4%	90.6%	€ 7,470.81	€ 9,337.33
	Car: Large	-34,371.7589	37,831.1183	-71.4057	0.9206	78.0%	90.7%	€ 9,104.62	€ 11,310.59
	LCV: Small	-22,159.3966	23,623.0604	-89.5194	0.9153	75.6%	89.8%	€ 5,755.88	€ 8,461.88
	LCV: Medium	-26,695.5822	28,481.8361	-109.1132	0.9209	75.8%	90.2%	€ 6,924.86	€ 9,767.09
	LCV: Large	-38,959.4335	41,659.1414	-112.0085	0.9167	76.1%	90.3%	€ 9,854.74	€ 13,754.32
BEV	Car: Small	-41,119.1128	32,709.4897	-447.5251	0.9238	74.3%	86.0%	€ 4,079.02	€ 4,739.72
	Car: Lower Medium	-69,107.6295	52,997.7324	-1,132.4608	0.9593	74.0%	86.3%	€ 6,536.80	€ 6,042.15
	Car: Upper Medium	-74,692.8673	59,921.6048	-947.6237	0.9498	74.6%	86.5%	€ 7,787.10	€ 7,095.40
	Car: Large	-108,230.3656	88,103.4109	-1,447.9960	0.9646	74.7%	86.9%	€ 12,081.32	€ 9,965.18
	LCV: Small	-26,901.9394	24,023.7951	-121.6397	0.8827	73.5%	85.6%	€ 3,946.00	€ 5,455.89
	LCV: Medium	-44,755.1498	41,377.1303	-125.6129	0.8762	72.8%	85.2%	€ 7,243.66	€ 7,971.02
	LCV: Large	-71,157.0264	67,747.7977	-100.2904	0.8698	73.3%	85.4%	€ 12,152.74	€ 12,500.19
FCEV	Car: Small	-39,316.5699	22,053.5435	-2,783.9596	0.9185	49.6%	72.6%	€ 7,855.42	€ 9,729.90
	Car: Lower Medium	-46,036.2442	20,178.5251	-5,856.9195	0.9960	49.7%	73.5%	€ 10,395.20	€ 12,415.59
	Car: Upper Medium	-54,737.6884	27,816.4215	-5,966.4729	0.9876	50.5%	73.7%	€ 12,450.10	€ 14,556.27
	Car: Large	-66,400.2193	33,290.6054	-8,156.1746	1.0137	50.7%	74.5%	€ 15,907.82	€ 18,290.85
	LCV: Small	-32,868.7584	27,267.9091	-590.3701	0.8004	48.5%	72.1%	€ 7,365.00	€ 9,974.70
	LCV: Medium	-37,787.9424	32,693.9831	-531.8840	0.7852	47.9%	71.6%	€ 8,727.56	€ 11,741.29
	LCV: Large	-48,038.9616	45,639.5564	-340.7835	0.7586	48.3%	71.8%	€ 12,073.34	€ 16,390.20

A6.2 Post processing steps and datasets

Step 1. 2013 Baseline adjustment: This takes into account the percentage CO_2 savings resulting from technologies that have already been applied to the 2013 baseline vehicles (specific to the relevant LDV segment). Here, a simple scaling back (in the negative x-axis direction) of the raw data curve (step 0) takes place to account for this (as well as a corresponding vertical negative adjustment on the y-axis). The assumed % savings (based on the IHS technology penetration datasets) for different vehicle segments and powertrain types are presented in Table 10.43.

Mathematically for each point (x, y) of the cost curve its new coordinates (x', y') are calculated as:

$$x' = \begin{cases} x - x_a & if\ x > x_a \\ discarded & otherwise \end{cases}$$

$$y' = \begin{cases} y - y_a & if\ x > x_a \\ discarded & otherwise \end{cases}$$

The values of the translation parameters (x_a, y_a) are calculated by taking the 2 points having an abscissa enclosing the appropriate value of the baseline adjustment (BA) in Table 10.43 expressed in fraction, and then linearly interpolating their ordinates to compute the appropriate y_a value corresponding to BA. In formulas, if (x_i, y_i) and (x_{i+1}, y_{i+1}) are the points enclosing BA, $x_i \leq BA \leq x_{i+1}$:

$$x_a = BA$$

$$y_a = y_i + \frac{y_{i+1} - y_i}{x_{i+1} - x_i} \cdot (BA - x_i)$$

If BA is lower than the first point: $BA \leq x_1$, no translation is made.

Table 10.43: Step 1 - 2013 Baseline Adjustment (all cost-curve years)

Segment	Cycle	Technology % CO2 (or energy*) savings potential already taken in 2013							
		SI ICE+HEV	CI ICE+HEV	SI PHEV	CI PHEV	SI REEV	CI REEV	BEV	FCEV
Small Car	NEDC	11.2%	7.9%	6.7%	4.5%	6.4%	4.3%	1.7%	1.7%
Lower Medium Car	NEDC	19.3%	11.1%	11.6%	7.5%	10.6%	6.7%	2.4%	2.4%
Upper Medium Car	NEDC	21.4%	10.9%	11.3%	7.3%	10.1%	7.0%	1.5%	1.5%
Large Car	NEDC	24.3%	13.5%	12.9%	8.8%	11.7%	8.4%	1.8%	1.8%
Small LCV	NEDC	8.8%	6.0%	5.1%	3.9%	4.9%	3.8%	0.9%	0.9%
Medium LCV	NEDC	9.0%	4.3%	5.7%	1.8%	5.5%	1.5%	0.4%	0.4%
Large LCV	NEDC	7.5%	3.1%	4.7%	1.7%	4.2%	0.9%	0.5%	0.5%
Small Car	WLTP	9.6%	7.3%	5.7%	4.2%	5.5%	4.0%	1.6%	1.6%
Lower Medium Car	WLTP	14.7%	9.4%	8.8%	6.4%	8.1%	5.7%	2.0%	2.0%
Upper Medium Car	WLTP	16.7%	8.8%	8.8%	5.8%	7.8%	5.6%	1.2%	1.2%
Large Car	WLTP	17.9%	10.1%	9.5%	6.6%	8.6%	6.3%	1.3%	1.3%
Small LCV	WLTP	7.3%	5.4%	4.2%	3.5%	4.1%	3.4%	0.8%	0.8%
Medium LCV	WLTP	6.3%	3.4%	4.0%	1.4%	3.9%	1.2%	0.3%	0.3%
Large LCV	WLTP	4.9%	1.9%	3.1%	1.0%	2.8%	0.5%	0.3%	0.3%
Small Car	RWC	11.9%	10.2%	7.1%	5.9%	6.8%	5.6%	2.2%	2.2%
Lower Medium Car	RWC	16.6%	12.6%	10.0%	8.5%	9.2%	7.6%	2.7%	2.7%
Upper Medium Car	RWC	17.8%	12.2%	9.4%	8.1%	8.4%	7.8%	1.6%	1.6%
Large Car	RWC	18.9%	13.1%	10.1%	8.5%	9.1%	8.1%	1.7%	1.7%
Small LCV	RWC	10.3%	9.2%	6.0%	6.0%	5.8%	5.8%	1.4%	1.4%
Medium LCV	RWC	8.3%	2.1%	5.2%	0.9%	5.1%	0.7%	0.2%	0.2%
Large LCV	RWC	7.0%	1.5%	4.5%	0.8%	4.0%	0.4%	0.2%	0.2%

Notes: * For BEVs and FCEVs = % energy savings; for all other powertrain types = % CO_2 savings.

Step 2. Scaling for batteries (xEVs only): This step vertically shifts the data points down (negative y-axis direction) to account for battery cost savings resulting from an ability to further downsize the battery (for the same range) following the addition of other efficiency improvements. The reduction in cost per % CO_2 improvement can be found in Table 10.44.

Mathematically, for each point (x, y) obtained at Step 1 (and with x expressed in fraction), its new coordinates (x', y') are given by:

$$x' = x$$
$$y' = y - BCS * 100 * x$$

where BCS is the appropriate battery cost scaling factor for the case, obtained from Table 10.44

Table 10.44: Step 2 - Battery Cost Scaling (xEVs only) (€), by cost scenario

Year	Segment	Costs	Euro per % CO2 (or energy*) savings reduction for xEVs					
			SI PHEV	CI PHEV	SI REEV	CI REEV	BEV	FCEV
2025	Small Car	Typical	€ 19.4	€ 19.4	€ 32.6	€ 32.6	€ 41.8	€ 11.4
2025	Lower Medium Car	Typical	€ 21.6	€ 21.6	€ 36.3	€ 36.3	€ 79.5	€ 12.7
2025	Upper Medium Car	Typical	€ 22.9	€ 22.9	€ 38.6	€ 38.6	€ 78.1	€ 13.5
2025	Large Car	Typical	€ 27.7	€ 27.7	€ 46.4	€ 46.4	€ 121.3	€ 16.3
2025	Small LCV	Typical	€ 18.1	€ 18.1	€ 30.4	€ 30.4	€ 39.1	€ 10.6
2025	Medium LCV	Typical	€ 22.7	€ 22.7	€ 38.1	€ 38.1	€ 70.4	€ 13.3
2025	Large LCV	Typical	€ 33.4	€ 33.4	€ 57.1	€ 57.1	€ 116.0	€ 20.0
2030	Small Car	Typical	€ 17.0	€ 17.0	€ 28.4	€ 28.4	€ 38.4	€ 10.6
2030	Lower Medium Car	Typical	€ 18.9	€ 18.9	€ 31.6	€ 31.6	€ 66.6	€ 11.8
2030	Upper Medium Car	Typical	€ 20.1	€ 20.1	€ 33.6	€ 33.6	€ 74.5	€ 12.5
2030	Large Car	Typical	€ 24.2	€ 24.2	€ 40.3	€ 40.3	€ 111.6	€ 15.1
2030	Small LCV	Typical	€ 15.8	€ 15.8	€ 26.5	€ 26.5	€ 35.9	€ 9.9
2030	Medium LCV	Typical	€ 19.8	€ 19.8	€ 33.2	€ 33.2	€ 65.6	€ 12.3
2030	Large LCV	Typical	€ 29.2	€ 29.2	€ 49.7	€ 49.7	€ 110.7	€ 18.5
2025	Small Car	Low	€ 14.8	€ 14.8	€ 25.4	€ 25.4	€ 31.4	€ 8.7
2025	Lower Medium Car	Low	€ 17.0	€ 17.0	€ 29.3	€ 29.3	€ 52.2	€ 9.6
2025	Upper Medium Car	Low	€ 18.5	€ 18.5	€ 31.8	€ 31.8	€ 62.2	€ 10.2
2025	Large Car	Low	€ 23.3	€ 23.3	€ 40.0	€ 40.0	€ 100.9	€ 12.4
2025	Small LCV	Low	€ 13.7	€ 13.7	€ 23.7	€ 23.7	€ 29.3	€ 8.1
2025	Medium LCV	Low	€ 17.9	€ 17.9	€ 30.8	€ 30.8	€ 54.8	€ 10.1
2025	Large LCV	Low	€ 27.4	€ 27.4	€ 47.2	€ 47.2	€ 92.4	€ 15.2
2030	Small Car	Low	€ 12.7	€ 12.7	€ 21.8	€ 21.8	€ 28.1	€ 7.9
2030	Lower Medium Car	Low	€ 14.7	€ 14.7	€ 25.1	€ 25.1	€ 47.4	€ 8.8
2030	Upper Medium Car	Low	€ 15.8	€ 15.8	€ 27.1	€ 27.1	€ 57.5	€ 9.4
2030	Large Car	Low	€ 19.9	€ 19.9	€ 34.0	€ 34.0	€ 89.7	€ 11.3
2030	Small LCV	Low	€ 11.9	€ 11.9	€ 20.3	€ 20.3	€ 26.3	€ 7.4
2030	Medium LCV	Low	€ 15.4	€ 15.4	€ 26.4	€ 26.4	€ 49.8	€ 9.2
2030	Large LCV	Low	€ 23.5	€ 23.5	€ 40.2	€ 40.2	€ 85.4	€ 13.9
2025	Small Car	High	€ 25.5	€ 25.5	€ 43.8	€ 43.8	€ 54.2	€ 13.5
2025	Lower Medium Car	High	€ 29.0	€ 29.0	€ 49.9	€ 49.9	€ 88.9	€ 15.0
2025	Upper Medium Car	High	€ 31.2	€ 31.2	€ 53.7	€ 53.7	€ 104.8	€ 15.9
2025	Large Car	High	€ 38.6	€ 38.6	€ 66.2	€ 66.2	€ 167.1	€ 19.3
2025	Small LCV	High	€ 23.8	€ 23.8	€ 40.9	€ 40.9	€ 50.6	€ 12.6

Year	Segment	Costs	Euro per % CO2 (or energy*) savings reduction for xEVs					
			SI PHEV	CI PHEV	SI REEV	CI REEV	BEV	FCEV
2025	Medium LCV	High	€ 30.4	€ 30.4	€ 52.3	€ 52.3	€ 93.3	€ 15.8
2025	Large LCV	High	€ 46.3	€ 46.3	€ 79.5	€ 79.5	€ 155.8	€ 23.7
2030	Small Car	High	€ 22.7	€ 22.7	€ 38.9	€ 38.9	€ 50.2	€ 12.1
2030	Lower Medium Car	High	€ 25.9	€ 25.9	€ 44.4	€ 44.4	€ 83.8	€ 13.5
2030	Upper Medium Car	High	€ 27.9	€ 27.9	€ 47.8	€ 47.8	€ 101.3	€ 14.3
2030	Large Car	High	€ 34.6	€ 34.6	€ 59.1	€ 59.1	€ 156.1	€ 17.3
2030	Small LCV	High	€ 21.2	€ 21.2	€ 36.3	€ 36.3	€ 46.9	€ 11.3
2030	Medium LCV	High	€ 27.2	€ 27.2	€ 46.6	€ 46.6	€ 87.9	€ 14.1
2030	Large LCV	High	€ 41.4	€ 41.4	€ 70.8	€ 70.8	€ 150.5	€ 21.2

Notes: * For BEVs and FCEVs = % energy savings; for all other powertrain types = % CO_2 savings.

Step 3. Scaling for overlapping technologies: The fundamental mathematics behind the model is that technology packages are made up from individual technologies. Packages are derived from the sum of the individual technology costs and the multiplying together of individual CO_2 reduction values. Due to the nature of this multiplicative process, the overall CO_2 reduction potential is a first order estimation which may in fact over estimate the total reduction. This 'safety margin' was also applied by TNO in previous cost curve work (TNO et al., 2011) and counteracts any overestimation that may occur. To obtain this scaled back curve the x-axis value (percentage CO_2 reduction) of every data point is multiplied by (1 – γ) with γ linearly scaling from zero to its maximum value (See Table 10.45 for these maximum values) between x = 0 and the maximum reduction potential indicated by the outer envelope. Here the costs remain constant.

Mathematically, for each point (x, y) obtained at Step 2 (and with x expressed in fraction), its new coordinates (x', y') are given by:

$$x' = x \cdot \left(1 - TO \cdot \frac{x}{\max(x)}\right)$$

$$y' = y$$

where the factor TO is the technology overlap for the appropriate case as given in Table 10.45.

Table 10.45: Step 3 – Technology Overlap (all cost-curve years)

Segment	Cycle	Technology % CO2 (or energy*) savings maximum overlap							
		SI ICE+HEV	CI ICE+HEV	SI PHEV	CI PHEV	SI REEV	CI REEV	BEV	FCEV
All	NEDC	12.3%	0.3%	12.3%	0.3%	12.3%	0.3%	0.0%	0.0%
All	WLTP	14.0%	0.0%	14.0%	0.0%	14.0%	0.0%	0.0%	0.0%
All	RWC	17.0%	4.6%	17.0%	4.6%	17.0%	4.6%	0.0%	0.0%

Notes: * For BEVs and FCEVs = % energy savings; for all other powertrain types = % CO_2 savings.

Step 4. Rebaseline xEV relative to 2013 conventional (xEVs only): In order to present xEV cost curves as relative to conventional 2013 powertrains (i.e. including the benefits of moving from baseline ICE to xEV), xEVs have been re-baselined relative to relevant 2013 conventional vehicle (see Table 10.46 and Table 10.47 for the relevant values).

Mathematically, for each point (x, y) obtained at Step 3, its new coordinates (x', y') are given by:

$$x' = 1 - \left((1-x)\cdot\left(1 - R_{CO_2}\right)\right)$$

$$y' = y + R_C$$

Where R_{CO_2} is the rebaseline for CO_2 factor for the case from Table 10.46 (expressed in fraction, not in percent), and R_C is the rebaseline for cost factor, as given in Table 10.47.

Table 10.46: Step 4 – Rebaseline xEV CO2 relative to 2013 conventional (xEVs only)

Year	Segment	Cycle	% CO2 (or energy*) savings relative to 2013 conventional ICE+HEV					
			SI PHEV	CI PHEV	SI REEV	CI REEV	BEV	FCEV
2025	Small Car	NEDC	74.5%	77.4%	82.8%	84.8%	77.5%	52.3%
2025	Lower Medium Car	NEDC	75.2%	77.4%	83.3%	84.7%	77.3%	52.5%
2025	Upper Medium Car	NEDC	74.5%	77.4%	82.8%	84.7%	77.3%	52.7%
2025	Large Car	NEDC	74.9%	77.4%	83.1%	84.8%	77.4%	53.0%
2025	Small LCV	NEDC	71.0%	77.4%	80.5%	84.8%	77.4%	52.1%
2025	Medium LCV	NEDC	74.2%	77.4%	82.6%	84.8%	77.2%	52.0%
2025	Large LCV	NEDC	79.3%	77.4%	86.0%	84.8%	77.3%	51.9%
2025	Small Car	WLTP	68.7%	72.7%	76.2%	77.2%	73.2%	47.5%
2025	Lower Medium Car	WLTP	68.6%	71.9%	76.7%	77.8%	72.8%	47.6%
2025	Upper Medium Car	WLTP	68.5%	71.6%	76.9%	77.9%	73.5%	48.4%
2025	Large Car	WLTP	69.3%	72.7%	76.8%	78.5%	73.5%	48.6%
2025	Small LCV	WLTP	63.5%	71.2%	73.2%	75.6%	72.4%	46.5%
2025	Medium LCV	WLTP	66.0%	70.1%	73.9%	74.9%	71.6%	45.9%
2025	Large LCV	WLTP	71.2%	69.0%	76.9%	75.2%	72.2%	46.3%
2025	Small Car	RWC	65.3%	69.6%	73.4%	73.4%	70.4%	44.6%
2025	Lower Medium Car	RWC	64.7%	68.4%	73.8%	74.3%	70.1%	44.6%
2025	Upper Medium Car	RWC	63.9%	67.3%	73.5%	74.0%	70.2%	44.8%
2025	Large Car	RWC	64.9%	68.8%	73.2%	75.1%	69.9%	44.8%
2025	Small LCV	RWC	61.2%	66.9%	70.7%	71.9%	69.9%	44.0%
2025	Medium LCV	RWC	62.0%	66.5%	70.5%	71.3%	68.4%	42.5%
2025	Large LCV	RWC	65.5%	66.8%	72.8%	72.6%	68.6%	42.4%
2030	Small Car	NEDC	74.7%	77.5%	83.0%	84.9%	77.9%	52.8%
2030	Lower Medium Car	NEDC	75.3%	77.5%	83.4%	84.9%	77.7%	53.0%
2030	Upper Medium Car	NEDC	74.7%	77.5%	83.0%	84.9%	77.7%	53.2%
2030	Large Car	NEDC	75.1%	77.5%	83.3%	84.9%	77.9%	53.6%
2030	Small LCV	NEDC	71.2%	77.5%	80.7%	84.9%	77.8%	52.5%
2030	Medium LCV	NEDC	74.4%	77.5%	82.8%	84.9%	77.6%	52.4%
2030	Large LCV	NEDC	79.4%	77.6%	86.2%	84.9%	77.7%	52.3%
2030	Small Car	WLTP	68.9%	72.8%	76.4%	77.3%	73.5%	48.0%
2030	Lower Medium Car	WLTP	68.8%	72.0%	76.9%	77.9%	73.2%	48.1%
2030	Upper Medium Car	WLTP	68.7%	71.7%	77.0%	78.0%	73.8%	49.0%
2030	Large Car	WLTP	69.5%	72.8%	76.9%	78.7%	73.9%	49.2%

Year	Segment	Cycle	% CO2 (or energy*) savings relative to 2013 conventional ICE+HEV					
			SI PHEV	CI PHEV	SI REEV	CI REEV	BEV	FCEV
2030	Small LCV	WLTP	63.7%	71.4%	73.4%	75.7%	72.7%	46.9%
2030	Medium LCV	WLTP	66.2%	70.2%	74.1%	75.0%	72.0%	46.3%
2030	Large LCV	WLTP	71.3%	69.1%	77.0%	75.4%	72.5%	46.7%
2030	Small Car	RWC	65.4%	69.7%	73.5%	73.6%	70.7%	45.0%
2030	Lower Medium Car	RWC	64.9%	68.6%	74.0%	74.5%	70.4%	45.0%
2030	Upper Medium Car	RWC	64.1%	67.4%	73.6%	74.1%	70.5%	45.3%
2030	Large Car	RWC	65.1%	69.0%	73.4%	75.3%	70.4%	45.3%
2030	Small LCV	RWC	61.4%	67.1%	70.8%	72.0%	70.2%	44.3%
2030	Medium LCV	RWC	62.1%	66.6%	70.6%	71.4%	68.8%	42.8%
2030	Large LCV	RWC	65.6%	66.9%	72.9%	72.7%	68.9%	42.7%

Notes: * For BEVs and FCEVs = % energy savings; for all other powertrain types = % CO_2 savings.

Table 10.47: Step 4 – Rebaseline xEV costs (€) relative to 2013 conventional (xEVs only), by cost scenario

Year	Segment	Costs	Additional costs of xEV relative to 2013 conventional ICE+HEV					
			SI PHEV	CI PHEV	SI REEV	CI REEV	BEV	FCEV
2025	Small Car	Typical	€ 5,228	€ 5,163	€ 6,806	€ 6,638	€ 4,604	€ 9,760
2025	Lower Medium Car	Typical	€ 5,711	€ 5,378	€ 7,827	€ 7,564	€ 7,312	€ 13,080
2025	Upper Medium Car	Typical	€ 5,892	€ 5,388	€ 8,539	€ 8,204	€ 8,505	€ 15,761
2025	Large Car	Typical	€ 7,159	€ 6,513	€ 10,410	€ 10,004	€ 13,611	€ 20,220
2025	Small LCV	Typical	€ 4,552	€ 4,304	€ 6,513	€ 6,352	€ 4,445	€ 9,126
2025	Medium LCV	Typical	€ 5,550	€ 5,252	€ 7,986	€ 7,788	€ 8,041	€ 10,827
2025	Large LCV	Typical	€ 7,828	€ 7,418	€ 11,375	€ 11,111	€ 13,186	€ 15,003
2025	Small Car	Low	€ 4,577	€ 4,513	€ 5,812	€ 5,644	€ 3,618	€ 6,897
2025	Lower Medium Car	Low	€ 4,991	€ 4,658	€ 6,728	€ 6,465	€ 5,686	€ 9,006
2025	Upper Medium Car	Low	€ 5,128	€ 4,625	€ 7,376	€ 7,040	€ 6,597	€ 10,703
2025	Large Car	Low	€ 6,238	€ 5,593	€ 9,003	€ 8,598	€ 10,500	€ 13,600
2025	Small LCV	Low	€ 3,947	€ 3,700	€ 5,588	€ 5,427	€ 3,532	€ 6,510
2025	Medium LCV	Low	€ 4,790	€ 4,493	€ 6,823	€ 6,626	€ 6,320	€ 7,697
2025	Large LCV	Low	€ 6,683	€ 6,274	€ 9,620	€ 9,358	€ 10,285	€ 10,583
2025	Small Car	High	€ 6,442	€ 6,383	€ 8,623	€ 8,466	€ 6,321	€ 12,363
2025	Lower Medium Car	High	€ 7,052	€ 6,723	€ 9,835	€ 9,579	€ 10,067	€ 16,704
2025	Upper Medium Car	High	€ 7,311	€ 6,812	€ 10,662	€ 10,335	€ 11,712	€ 20,212
2025	Large Car	High	€ 8,870	€ 8,236	€ 12,962	€ 12,578	€ 18,615	€ 26,029
2025	Small LCV	High	€ 5,678	€ 5,434	€ 8,201	€ 8,047	€ 6,043	€ 11,503
2025	Medium LCV	High	€ 6,963	€ 6,669	€ 10,106	€ 9,914	€ 10,947	€ 13,687
2025	Large LCV	High	€ 9,959	€ 9,555	€ 14,567	€ 14,315	€ 17,995	€ 19,081
2030	Small Car	Typical	€ 4,795	€ 4,733	€ 6,165	€ 6,003	€ 4,187	€ 7,880
2030	Lower Medium Car	Typical	€ 5,206	€ 4,881	€ 7,069	€ 6,813	€ 6,729	€ 10,423
2030	Upper Medium Car	Typical	€ 5,355	€ 4,863	€ 7,722	€ 7,395	€ 8,003	€ 12,480
2030	Large Car	Typical	€ 6,492	€ 5,863	€ 9,387	€ 8,995	€ 12,407	€ 15,944
2030	Small LCV	Typical	€ 4,147	€ 3,905	€ 5,903	€ 5,747	€ 4,048	€ 7,389
2030	Medium LCV	Typical	€ 5,035	€ 4,745	€ 7,209	€ 7,018	€ 7,434	€ 8,758
2030	Large LCV	Typical	€ 7,091	€ 6,691	€ 10,252	€ 9,997	€ 12,478	€ 12,122
2030	Small Car	Low	€ 3,975	€ 3,910	€ 4,932	€ 4,766	€ 2,944	€ 5,610
2030	Lower Medium Car	Low	€ 4,299	€ 3,972	€ 5,702	€ 5,443	€ 4,662	€ 7,214

Year	Segment	Costs	Additional costs of xEV relative to 2013 conventional ICE+HEV					
			SI PHEV	CI PHEV	SI REEV	CI REEV	BEV	FCEV
2030	Upper Medium Car	Low	€ 4,374	€ 3,880	€ 6,244	€ 5,914	€ 5,476	€ 8,505
2030	Large Car	Low	€ 5,292	€ 4,657	€ 7,583	€ 7,180	€ 8,455	€ 10,736
2030	Small LCV	Low	€ 3,392	€ 3,149	€ 4,764	€ 4,605	€ 2,901	€ 5,326
2030	Medium LCV	Low	€ 4,082	€ 3,790	€ 5,767	€ 5,573	€ 5,252	€ 6,289
2030	Large LCV	Low	€ 5,609	€ 5,206	€ 8,013	€ 7,753	€ 8,650	€ 8,612
2030	Small Car	High	€ 5,929	€ 5,873	€ 7,858	€ 7,708	€ 5,846	€ 9,591
2030	Lower Medium Car	High	€ 6,487	€ 6,166	€ 8,979	€ 8,732	€ 9,485	€ 12,795
2030	Upper Medium Car	High	€ 6,700	€ 6,213	€ 9,730	€ 9,413	€ 11,266	€ 15,362
2030	Large Car	High	€ 8,137	€ 7,522	€ 11,834	€ 11,468	€ 17,410	€ 19,703
2030	Small LCV	High	€ 5,207	€ 4,970	€ 7,486	€ 7,337	€ 5,603	€ 8,962
2030	Medium LCV	High	€ 6,376	€ 6,089	€ 9,217	€ 9,031	€ 10,330	€ 10,650
2030	Large LCV	High	€ 9,114	€ 8,721	€ 13,277	€ 13,035	€ 17,368	€ 14,835

A7 Appendix 7 – Peer Review

The following appendix provides the review by Peter Wells on the final project report, covering the final completed tasks of the project.

Review from:

Professor Peter Wells

Centre for Automotive Industry Research

Cardiff University

26/06/2015

Overview

The primary purpose of this review is to comment on the cost curves generated for the various carbon reduction technologies in the report. However, to put those comments in context some preliminary considerations are useful.

The report provides a comprehensive and detailed analysis of the discrete technology choices and combinations of choices available to vehicle manufacturers in the period to 2030 in order to achieve reductions in per-vehicle carbon emissions, along with cost curves associated with the technologies. The focus is on the European Union market, with the recognition that notwithstanding global convergence on the regulation of carbon emissions from vehicles, and increasing global integration of the industry itself, there remain differences between the EU and other locations that could have a material impact on choices and associated costs.

Available in tandem with the report is a large data file (Excel spreadsheet) which provides the baseline starting points for the analysis from 2013, along with detailed technology cost curves for each selected carbon reduction technology. Hence much of the detail and the computations are in this separate file rather than the main body of the report.

The report provides a careful account of the methodologies used in identifying the candidate technologies, understanding the carbon reduction potential, and in constructing the cost curves. Importantly, the report makes clear which sources have been used and also the judgements made on key variables where absolute data is lacking. This is important to allow transparency, so that it is possible to replicate or indeed dispute the outcomes. A failing with many previous studies is that some underlying assumptions or judgements are not clear, which makes it difficult to interpret and compare results. However, the report does endeavour to link with those previous studies considered sufficiently robust and comparable in order to allow readers to understand what is new and different with the report. The report also makes clear the methodological steps taken in the analysis and seeks to provide a reasoned justification for those steps. Key assumptions on e.g. learning rates and indirect cost multipliers are given greater attention.

Overall the report has a relatively narrow brief, in part because other issues are likely to be subject to other projects. Hence the report is only concerned with the cost of a vehicle at the point and time of sale, not with total cost of ownership, the impact of practices such as car-sharing, or with wider considerations beyond carbon emissions. Where such other studies have recently been done (e.g. the SR1 'downweighting' study) these have been built into the analysis. However, the report does not consider, for example, how far vehicle manufacturers individually or collectively are able to pursue cost recovery rather than cost reduction in the market. This is particularly pertinent in those instances where vehicle manufacturers that have traditionally been regarded as having 'premium' brands have sought to enter the smaller size segments in the market where cost sensitivities are usually highest. The focus on cost is thus somewhat distorting as it understates the extent to which vehicle manufacturers may be able to charge some form of premium for the extra performance or perceived quality that carbon reduction technology may bring to the vehicles.

The focus on cost calculations and their attendant uncertainties is the main pre-occupation here. In this sense the question of the carbon emissions reduction performance potential of the various technologies is not given such detailed consideration. That is to say, the report does not seek to analyse how far the expected (range) of carbon emission reductions is likely to be realised.

A separate discussion of low volume manufacturers is offered, which if nothing else indicates how diverse this category is. An interesting consideration, however, is how far this particular category may grow in the future as new entrants seek opportunities around emergent vehicle technologies.

The original task structure is outlined below. However the report structure does not exactly follow this task structure.

- **Technology baseline and vehicle segmentation (Task 1).**
- **Development of a list of CO2 reducing technologies (Task 2 and 3)**
- **Data gathering and analysis of benefits of each technology (Task 4)**
- **Explore variation between ex-ante and ex-post costs (Task 5)**
- **Provide illustrations of the CO2 reduction technologies (Task 6)**
- **Incorporate findings of downweighting study (Task 7)**
- **Scenarios for powertrain deployment (Task 8)**
- **Development and verification of cost curves (Task 9and 10)**
- **Assessment of specific vehicle segments (Task 11)**

The report had the following primary objectives:

- Establish an appropriate baseline, including a relevant vehicle segmentation
- Develop a list of technologies that could be applied to cars and LCVs between 2020 and 2030 to reduce their CO2 emissions, including both on- and off-cycle emissions
- Collate, understand and confirm, as far as is possible, the costs and CO2 reduction potential associated with these technologies
- Develop and present of cost curves for 2015, 2020, 2025 and 2030 by segment.

Notwithstanding the detail considerations below it is reasonable to conclude that the report has delivered against these objectives.

1. Introduction
2. Technology baseline and vehicle segmentation
3. Technologies to reduce LDV CO_2 emissions
4. Review of evidence on cost and performance of CO_2 reduction technologies
5. Exploration of factors influencing future technology costs
6. Analysis of the CO_2 benefits of each technology
7. Final methodological development and technology analysis results
8. Development and verification of cost curves
9. Project management

Technology baseline and vehicle segmentation

In most regards this is an uncontroversial discussion in that the baseline position is broadly understood. A key problem is to reconcile the desire to capture a ‘representative’ picture of the market, with the need to retain a data set that is of manageable proportions and to provide broad results that are clear to a wide range of potential readers. The report recognises that vehicle segmentation has proliferated over the years, making for a more complex market structure. Given in particular the growth in ‘cross-over’ segments (as also covered in the SR1 study) there is a stronger case for the separate identification of such vehicles, but in most cases the differences between these and the standard segment vehicles are largely cosmetic (body shape and proportions) with some changes to ride height, frontal area profile and often a significant gain in weight). Hence the report makes a sensible case for the restriction of segment variety on the basis of controlling complexity, with the benefit that a large number of technology choices can then be explored in the data set. A more detailed analysis of the significance of so-called platform or architecture strategies in which multiple models are based upon a core common design would have been useful, not least to understand where the additional weight, complexity and/or cost arises from when cross-over or MPV versions are created. Equally, such an understanding would also be useful to illustrate potential cost savings through enhanced volumes via platform strategies, which is after all the primary reason such strategies are adopted. Section 5.1 gives a good overview of these issues, but it is not absolutely clear how the discussion then informs (if at all) the projected future costs of carbon reduction technologies. It is notable, for example, that most of these technologies are ‘under the hood’ or otherwise not necessarily visible differentiators for consumers, a factor that may allow greater levels of commonality across models and platforms and hence greater cost reductions.

The report does not present an analysis of the change in models and variants over time, in which it would become clear that there has been a substantial proliferation of diversity in the vehicles offered in the market. In effect, this proliferation of models and variants offered by manufacturers has tended to erode still further the margins and distinctions between segments, making the construction of such segmentation accounts ever-more artificial. While it is recognised that segmentation is a means of simplifying the problem of data acquisition and analysis, it is likely that going forward into the future the traditional approach to segmentation will become even more problematic.

However, it is apparent from the report that the available data sets had to be ‘cleaned’ for various mistakes and dubious entries. One important decision was to separate out the larger size vehicles from the D segment. These tended to show substantially higher direct and indirect costs associated with the deployment of illustrative carbon reduction technologies both on and off cycle; the decision also speaks to the desire from ACEA to treat the luxury and premium brand vehicles differently. A slight concern here is the neglect of the ways in which vehicle manufacturers can achieve lower costs for particular technologies or features than those indicated in the larger size or more specialist segments by utilising components already in production for other cars.

The baseline for petrol and diesel cars does not differ substantially from the previous study on cars (TNO et al., 2011) for the European Commission; that for LCVs does not differ substantially from the previous study (TNO et al., 2012). The technology penetration baseline was elaborated from SR6 with the same data supplier (IHS Automotive) which helped to ensure similarity of coverage.

LCVs were segmented by weight, with the data showing ‘natural’ break points between small, medium and large LCVs – which also tend to be informed by national Member State taxation and other factors.

The report does not distinguish so-called ‘multi-stage vehicles’, which may be a potential weakness. In the absence of data, it is difficult to know how significant such a gap might be, but given the many variants of low volume that are likely to be involved the inclusion of such vehicles into the report might generate substantial complexity for relatively little added insight. The main differences in these sorts of vehicle are likely to be aerodynamic profile and weight while powertrain and much of the bodywork will remain the same as the standard vehicle. A more detailed study on this type of vehicle may be called for in the future, particularly as there is strong growth in the EU LCV segment overall.

Typically, studies use scaling factors when translating cost estimates for a technology into specific larger or smaller segments, an approach which is broadly sufficient within the relatively narrow band of size, footprint, weight and other parameter variations found in the car market overall. On the other hand, the exclusion of vehicles from, say, the French vsp segment may become an issue in the future as the deployment of very lightweight vehicles may be a useful means to achieve substantial reductions in CO_2 emissions. The issue of more minimalist designs is explored in the report in section 5.1.2.

The technology baseline in terms of which technologies to be included in the study for both on cycle and off cycle conditions is again not overly controversial in that the vast majority of such technologies are to some degree in the public domain, albeit with greatly varying amounts of supporting information on actual performance and cost. The report identifies a long list of candidate technologies to be modelled. The great bulk of the data are provided in the Excel file rather than the main body of the report. The technology baseline approach might penalise those manufacturers that have pioneered CO_2 reduction technologies (notably in the higher size segments and with the ‘premium’ brands) where the early costs of deployment have been borne. It is surprising that the CO_2 reduction baseline from 2002 (Figures 2.6 and 2.7) are so different for LCVs compared with cars, and that the performance of the C segment cars is also so different compared with other car segments. These differences are not explained in the report.

The use of existing data from public sources on already deployed xEVs might introduce a degree of conservatism in the baseline (see section 2.4.2) as with these early introductions vehicle manufacturers may have taken a more cautious approach (e.g. on battery size or the extent to which the battery is allowed to be run down) than strictly necessary.

Review of evidence on cost and performance of CO_2 reduction technologies

The core of the report and the work undertaken (as reflected in both the report and in the Excel spreadsheet) is the evidence gathered for an understanding of the cost and performance of CO_2 reduction technologies.

The key precursor reports focus on the EU or North America market respectively, and involve methodologies not necessarily appropriate to this study. The teardown studies of individual models represent a very different approach to understanding the cost of technologies, components and materials, and hence a different take on 'representativeness' to that taken in this report. However, all the key sources in the public domain appear to have been identified in the report. It is unfortunate that no sources from Japan could be identified, as the vehicle manufacturers headquartered there have been at the forefront of both technology deployment for enhanced efficiency and cost reductions for many years. Much could be learned, for example, from the experience of Toyota with the Prius and subsequent models using the Hybrid Synergy Drive system. Previous reports such as from TNO give support to the notion that ex ante cost estimates tend to be higher than ex post outcomes for innovative technologies. This is a theme that recurs in the report, and probably demands more consideration than is currently given. A deeper explanation of these outcomes is urgently needed, but confronted with the unwillingness of the vehicle manufacturers to have detailed discussions it is understood that there are real restrictions in developing such an explanation. For example, it may be that in the design and engineering of discrete CO_2 reduction technologies as they are integrated into a vehicle there are opportunities for parts consolidation or multi-functional parts that deliver unanticipated cost savings. Inevitably, the report develops what may be termed generic cost curves which can be understood as a broad industry average. This approach is again logical and coherent, but should come with the understanding that individual vehicle manufacturers and/or their suppliers may develop their own scale and learning economies arising out of their (strategic) decisions to develop and deploy particular technologies. Hence the actual cost reductions achieved over time might be steeper than a hypothetical industry average. Again, this seems to be the case with Toyota and hybrid technology and may well apply in other instances where discrete examples of technology leadership have been shown. Thus, different manufacturers following different strategies or pathways for the achievement of CO_2 emissions reductions may show different (steeper) cost reduction curves.

A definitional weakness in the report is that of 'mass deployment' or (slightly differently) 'mass production'. Confusion over this term as it might apply to a single vehicle (or single application of a technology), single manufacturer, or the entire industry might underpin some of the divergent views uncovered in the stakeholder engagement stage of the research process. Mass production can be understood traditionally as referring to the scale of production of a particular model, or of a manufacturing plant. In either case the underlying assumptions relate to specific technology choices around pressing, welding and painting all-steel vehicle bodies. As a guide, mass production in this sense is taken to mean 2 million units per annum as the minimum economies of scale in steel body production. Breakeven volumes are substantially less than this. With respect to manufacturing capacity, breakeven volume at a plant level is rather less fixed in the modern era as much depends upon shift patterns and working arrangements. So by way of illustration, can the BMWi3 be considered a mass produced or mass deployed technology? Set against the industry as a whole, producing say 70 million units per annum globally, the 50-60,000 pa i3 capacity is tiny. Set against previous deployments of carbon fibre reinforced plastic vehicle structures it is a quantum leap in scale, and such a leap could be seen as a non-linear step change in the per unit cost of producing such a vehicle.

The approach taken in the report, which is to focus on cost reduction curves rather than sequential step changes, provides a smoothing of individual corporate decisions or individual deployments of technology. In the context of the task undertaken this is an entirely reasonable approach.

The methodology is clearly stated. Secondary sources of a wide variety are used to provide an initial population of candidate technologies and estimates of the cost curves likely to be appropriate. Validation was sought through direct interviews with vehicle manufacturers and suppliers, and representative bodies; and then supplemented via a Delphi survey process. Peer review provides a final check. Unfortunately, vehicle manufacturers were not particularly forthcoming with information to support the analysis, while that supplied by representative bodies tended to be of a more general nature. A second problem with the methodology is that of reconciling expert opinion with previously published sources – particularly where those sources are thought to be generally robust. The approach taken in the report is pragmatic, which is to generally side with the published sources unless compelling evidence to the contrary can be offered. It is worth noting that the more esoteric the technology concerned, the more it is outside the traditional scope of the automotive industry, the more difficult it is for the industry adequately to estimate future cost reductions. An approach that could have been taken in the report, but was not, would be to use the long-run cost reductions of previous technologies as a template for future cost curves (e.g. for successive generations of ABS brakes).

A generic issue with the modelling of the cost curves is that the focus is on additional cost, and as such it is not always clear in previous reports what allowance if any has been made for the cost reduction of removing previous or alternative technologies where there are instances of such substitutions. In the report, here an attempt is made to allow for such savings as is indicated in section 4.5.

Many decisions are taken in the report regarding the basis for the cost calculations; and these are more or less open to some debate. It is accepted that such decisions need to be made in order to conduct the baseline and the projected future cost analysis. Hence for example it is assumed that improved battery performance over time is taken as the basis for cost reduction in small car segments, but more as range improvement in larger cars, on the basis that the small car segment tends to be more price sensitive. This is a reasonable assumption. In the case of PHEVs, the situation is more difficult in that for any one user the precise mix of pure electric mode over ICE mode is crucial in determining the overall powertrain strategy and hence issues such as battery pack size. In practice, different vehicle manufacturers are likely to pursue different product and powertrain strategies more precisely to target specific user patterns.

The report provides an account of the process for cost estimation:

> *"Broadly, the proposed estimation of future costs is a sequential process that departs from so-called 'direct incremental technology costs'. These direct technology costs are incurred by the integration of a new technology into the vehicle, such as material and direct manufacturing costs. They can largely be obtained from previous studies, such as so-called tear-down studies that dismantled whole vehicles in order to explore these costs. The 'net incremental technology costs' (the total net costs incurred due to the integration of a new technology and removal of the old one, which also includes non-direct factors), are then derived by applying the following factors to the direct incremental costs (as indicated in Figure 4.8 by (1), (2) and (3)):*
>
> 1. ***Scaling factors** that account for the fact that the cost of technologies might be different for different vehicle segments;*
> 2. ***Indirect cost multipliers (ICMs)** that account for cost items not directly attributable to the integration of the technology in a vehicle, such as R&D, overheads or selling costs; and*
> 3. ***Learning factors** that account for increasing efficiency of production (and better technology integration) over time/with increasing production volumes due to learning.*
>
> *Applying scaling factors and indirect cost multipliers allows for the establishment of the correct baseline costs, i.e. the costs as incurred in the base year of the analysis (i.e. 2013). When applying learning factors, these base year costs are brought forward, to a future year, hence cost projections are developed."*

Hence from a baseline starting point the above factors are considered, along with an uncertainty analysis that seeks to make some judgement as to how robust the data sources are in each technology case. The scaling factors result in higher unit costs to deploy a given technology in the larger segment vehicles. However, the report does not present this information as a % of total vehicle cost or retail price, which would be useful as a means of assessing the relative significance of the technology cost to the overall vehicle. Smaller vehicles with a lower price are less able to absorb the increased cost of technologies, and probably there is less scope for direct pass-through of cost increases to consumers in the form of increased retail prices. It is notable that larger vehicles and sports cars have been early beneficiaries of hybrid technologies, for example.

In this account, it is recognised that obtaining data on all three factors is problematic. On the other hand, the report had previously noted a substantial difference between ex-ante and ex-post costs for new technologies, much of which is presumably attributable to learning factors (mostly though not entirely scale related). In many instances, an increase in volume beyond a certain point can entail a new sort of tooling and / or a step change in levels and kinds of automation, which can increase capital investment but reduce per unit costs – so long as the capacity utilisation is high enough.

It is understood that the use of indirect cost multipliers (ICMs) is often preferable to the use of a 'retail price equivalent' methodology because the latter may incorporate operational aspects that do not derive from choices on technology – such as healthcare costs for example. The ICMs do however offer a further area of contention in terms of those items that should or should not be included, as was evident from the Delphi process in this study.

The separation of technologies into different levels of complexity was somewhat problematic, as it is not clearly defined what was meant by the term. That the Delphi process showed overall agreement with the designated complexity levels is encouraging, but may equally reflect a lack of understanding of what was meant by complexity. Different ICMs were attributed to different levels of complexity, hence generating some of the possible areas of contention with this report as noted above. However, again it should be stressed that this report a) drew on previous studies in the characterisation of complexity and b) made the process and the values so attributed very transparent.

It is not clear whether the learning rate (the rate at which costs are reduced as output is doubled) applies to the industry as a whole or to a specific instance of the application of a technology. Hence the confusion over whether or not BEV technologies were already in mass production. This issue is something of a difficult one for the report, particularly as many technologies are 'ring fenced' by various forms of IPR protection that may constrain wider industry learning – though note the points regarding learning by individual vehicle manufacturers made above. Moreover, deployment rates are necessarily constrained in the sense that no one technology or package of technologies is likely to be dominant up to the 2030 time period. Regulators tend to prefer to be neutral on technology choices in order to allow discretionary choice over the solutions offered, but by so doing sometimes a de facto solution emerges anyway or, alternatively, the fragmentation of possible solutions increases overall costs.

It is evident from the discussions in the report around interviews with key stakeholders that considerably divergent opinions were available on the key issues addressed in the report. The comments regarding the hybrid-air energy recuperation system are illustrative, with a supplier suggesting that the costs are perhaps 5x those defined in the report.

With regards to supplier pressures to reduce costs on an annual basis (in the order of 1.5% to 3.0% pa) it is perhaps pertinent to note that mature technologies have less 'room' for cost reductions in any case compared with new technologies. These annual cost reductions, sometimes augmented by one-off larger reductions demanded by vehicle manufacturers, are thus enforced when the technology in question is already well down the learning cost reduction curve. In practice vehicle manufacturers operate a diverse array of procurement systems and are assiduous in their search for cost reductions both through engineering approaches such as 'value engineering' and through innovative supplier-customer relations. In addition, vehicle manufacturers will engage in joint ventures and shared projects with other vehicle manufacturers to reduce per unit development, procurement and manufacturing costs. Such activities long predate the issues discussed in the report and can be regarded as 'normal' for the industry. Hence in broad terms the expectations for annual cost reductions do not appear to be excessive.

The development of alternative powertrain scenarios to explore the impact of assumptions on the deployment rate of PHEV, REEV, BEV and FCEV technologies is reasonable, but an underlying concern must be with the overall volume projections. Given the thrust of EU policies elsewhere, it is by no means certain that per annum sales volumes will retain their contemporary level let alone grow. While this issue is outside of the scope of the report, the underlying assumption of 'business as usual' in terms of overall production volumes necessarily forms the backdrop to the assumptions on mass production exploitation of specific technologies and the associated cost reductions. The tensions between platform/architecture strategies on the one hand, and variant proliferation on the other are note explored in this report – but the proliferation of core available technologies (enhanced ICEs plus PHEV, REEV, BEV and FCEV) is likely to fragment the market further. It is pertinent to the cost curve discussions that the interview programme reveals a range of perspectives on the expected penetration rates of technologies in terms of PHEV, REEV, BEV and FCEV.

Chapter 5 discusses a range of strategies related to cost reductions. These are widely understood and accepted in the industry, and are largely uncontroversial. However, it is worth noting that where a platform or modular supply strategy does go wrong, the results are disproportionately expensive for the vehicle manufacturer because they impact upon a wider range of brands, models and variants than would hitherto be the case. Hence it can be observed that large-scale recalls cutting across brands, models and variants have been instituted by companies such as Toyota because of the failure of relatively simple components – at considerable direct financial cost as well as cost to the value of the brand.

In discussing the costs of xEV vehicles it might be helpful to include comment (where data are available) on the relative contribution of the battery pack cost to the total powertrain system cost given that much attention is devoted to driving down future battery pack costs. The data at a more detailed level are reported in the Appendix, but it might be useful to clarify the current position in the main body of the report. The mass breakdown data are presented in the report, but these may not directly correlate with cost. Later in the report (section 4.5.2) the data are given for BEV and FCEV.

The next Audi eTron variant is reportedly going to be made available with inductive charging. However, as the report notes there are considerable problems with attempting to install a suitable public infrastructure.

The review of previous studies is helpful in understanding the developments offered by this report. The differing approaches such as simulation and tear-down analysis have their various merits and disadvantages. The treatment of indirect cost multipliers is a particular area for debate, and was considered in the methodology of this report by the use of the Delphi process, stakeholder interviews, and comparison with the other major studies in the EU and US. In the EPA report for example the development of specific indirect learning rates to future warranty costs for is justifiable for more complex carbon reduction technologies.

This report provides a useful review of the main previous studies. However, it also shows some limitations in terms of the ability of differing projects to utilise previous work. Although the studies are all variously funded by public sources in the US or EU, it was found to be the case that, for example, the FEV studies using tear-down analysis could not provide an input into this study:

> *"Without access to more detailed underlying data (which FEV was not happy to provide), only the over-arching methodological approach using learning rates on the total direct manufacturing costs and the use of the already developed ICMs (indirect cost multipliers) was possible."*

In addition, the report has identified a very long list of candidate technologies, which in itself provides a constraint on the level of detail to be explored in each case. As such, the learning rates approach combined with indirect cost multipliers, while an approximation of a more complex reality, is a sound basis upon which to proceed. The value of this approach is that it is consistent across all the technologies and the entire timeframe. Moreover, should new data come to light it is possible to adjust the learning rates accordingly. The use of the indirect cost multipliers furthermore tends to mean that the results give a 'fair' treatment of the total cost of bringing a technology to market, and are transparent in what is or is not included in that cost. As a consequence, the final figures are defensible rather than being unduly optimistic about future (low) costs.

One issue not considered in the report is that of the introduction of other technologies, materials and systems by vehicle manufacturers in the future which are not connected to the question of carbon reduction. Many of these features are not strictly functional (let us take ambient lighting as an example), and will certainly add cost. Others are associated with a different agenda, such as autonomous vehicles and road traffic safety. Hence the study does not seek to position the investment and resource burden of developing these new carbon reduction technologies in the wider context of other technology developments. In a similar manner, it could be argued that on a global scale the industry faces major geo-economic restructuring issues that might well entail the cost of rationalisation in some locations, and the expansion of production in others. These costs, along with items such as proliferating model ranges and possible increased raw material costs in certain classes of material due to impending scarcity are all part of the wider picture within which the low carbon technologies may need to be developed.

The learning and scaling factors discussed in Chapter 7 are well justified and argued for in the report. While individual vehicle manufacturers were not very forthcoming with supporting data, it is notable that some support was offered by one OEM. As the report notes, the learning factor rates over the time period also depend crucially on when mass manufacture is achieved.

Inevitably, the report relies upon a range of scenarios to inform the learning rates adopted – and those scenarios are susceptible to challenge. Hence if the consequence of the future scenario is that the volumes for a particular technology application grow and then fall, then the basis for long-term continuous learning based on volume is also susceptible to challenge. However, again the assumptions in the report are very clear and building in such complexities into the analysis would involve both considerably more computing time and more controversy over those future scenarios.

The approach to learning uncertainty is a little unclear (using adjustment factors to shift the year in which mass manufacture is achieved) as the basis for this adjustment is not really explained.

The uncertainly scaling factors (up to 20% for medium and large vans) are generous, and reflect the overall cautious approach taken in the study. The methodology with regard to such matters is consistent throughout. Where data are available they are used, where not then an attempt is made at a reasonable assumption based on the closest example for which data are available. It is reasonable that uncertainty should reduce over time for a given technology as the technology is developed and deployed; however, the future uncertainty of a technology as viewed from the present will show greater levels of uncertainty over time (the further into the future, the more unknowable the outcomes). This point is a little unclear in the analysis.

The use of a Latin Hypercube Sampling (LHS) process to calculate the results is justified and explained relatively briefly (there is more detail in the appendix). The asymmetric nature of the probability distribution of total direct costs is an interesting feature arising out of the approach adopted though it is not immediately clear what the implications of this outcome are.

An important problem addressed in Chapter 8 is that of managing the large number of data points in the modelling process to obtain cost curves and carbon reduction levels against many potential technologies. The report adopts an optimisation approach that significantly reduces the number of data points to be processed, and thus allows more technologies to be analysed at one run, and for a run to completed very quickly. The team behind the report should be commended for developing an innovative means of handling the sheer volume of data in order to process the cost curves.

Conclusions

In summary, the approach adopted in this report is first and foremost clearly explained. Given the complexity of the issues and the high levels of future uncertainty, it is vital that assumptions used in trying to understand future costs and carbon emission reduction potentials are made clear – which this report seeks to achieve. Where others may disagree with assumptions it is therefore possible to make the required changes and hence model new outcomes.

There is a strong evidence base for the work, drawing on secondary sources, the Delphi process and extensive stakeholder engagement – even though the contribution from the automotive industry itself could have been stronger. There are some ambiguities such as the meaning of mass deployment and the approach to accounting for uncertainty in learning, but these are relatively minor issues in the overall context of the scope and depth of the work undertaken. The report is assiduous in the coverage of technologies and in seeking to account for the realities of the automotive industry within the constraints of time and resource available. The overall tone is conservative and cautious with regards to future carbon reduction potentials and cost reductions over time.

Ricardo
Energy & Environment

The Gemini Building
Fermi Avenue
Harwell
Didcot
Oxfordshire
OX11 0QR
United Kingdom

t: +44 (0)1235 753000
e: enquiry@ricardo.com

ee.ricardo.com