Transport and Environmental Policy Research

Graz University of Technology

Cardiff Business School, Cardiff University

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Improving understanding of technology and costs for CO_2 reductions from cars and vans in the period to 2030

DG Climate Action LDV Framework

Nikolas Hill (Ricardo-AEA)

Brussels, 9th December 2014

Agenda – LDV CO2 reducing technologies to 2030

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1) Project outline: overview of the project and methodology [5 min]

2) Summary of key technical tasks and progress [35 min]

   a. Technology baseline and segmentation *[10 min]*

   b. Technology coverage and status of data collection/analysis *[5 min]*

   c. xEV powertrain technology analysis and deployment scenarios *[5 min]*

   d. Use of vehicle simulation for CO_2 savings, calibration of outputs *[5 min]*

   e. Stakeholder consultation activities *[10 min]*

3) Questions [20 min]

Project outline

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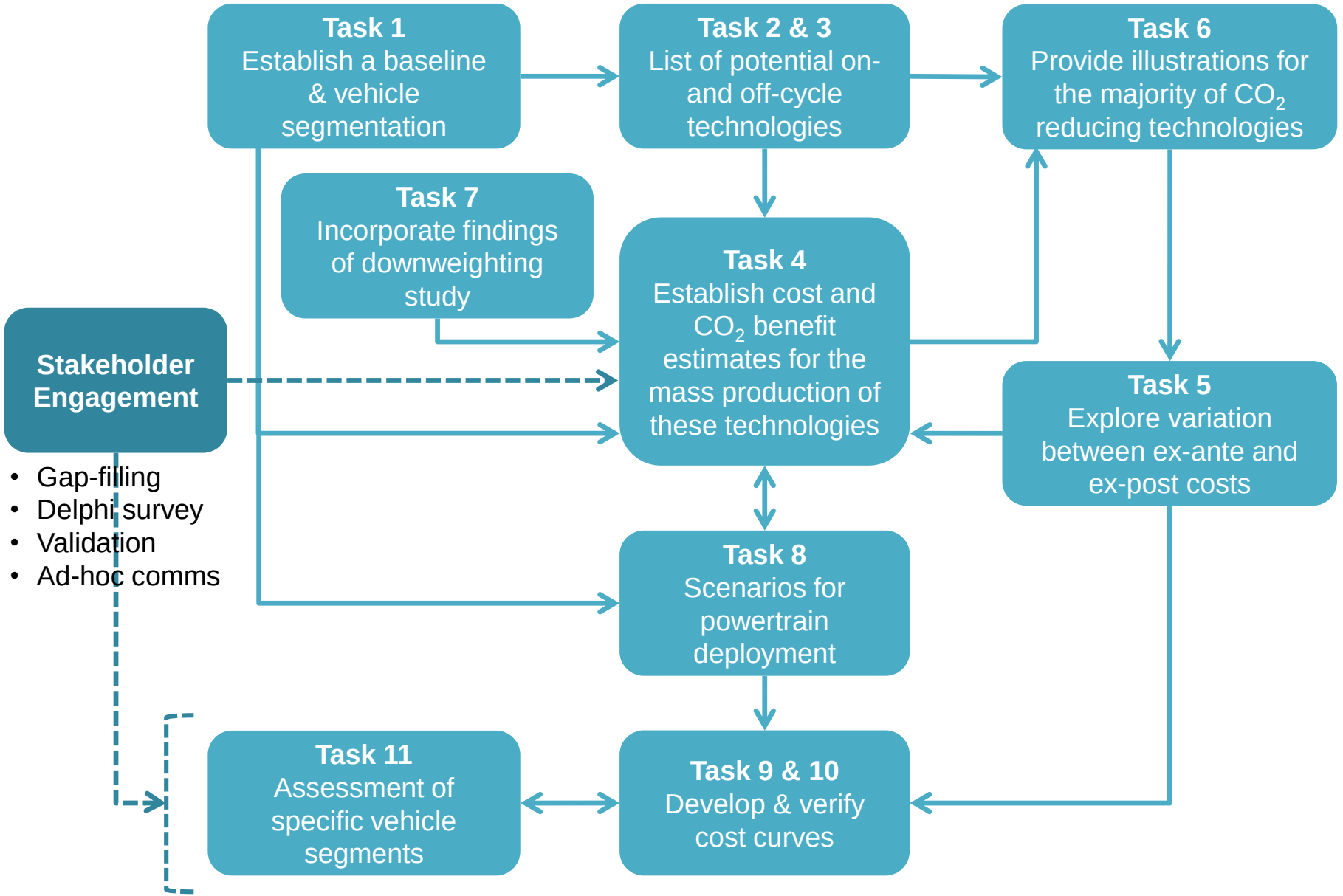
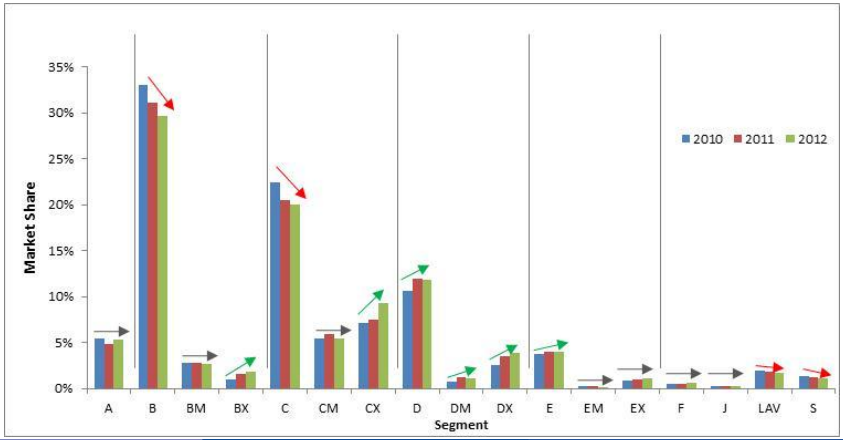


Defining the baseline and segmentation

- **Objective:** Establish new baseline against which the deployment of technologies and their costs will be compared, and also appropriate vehicle segmentation for the analysis.
- Segmentation needs to be:
  - Appropriate to sufficiently capture differences between costs and CO_2 reduction potential for different types of car and light commercial vehicles
  - Readily understood, and able to be characterised using publically available datasets as far as possible
  - Manageable and proportionate [note Task 11]
- Baseline needs to account for/reflect:
  - The most recent changes to market, characteristics and performance
  - The current impact of technology deployment
  - The level of optimisation of test vehicles by OEMs

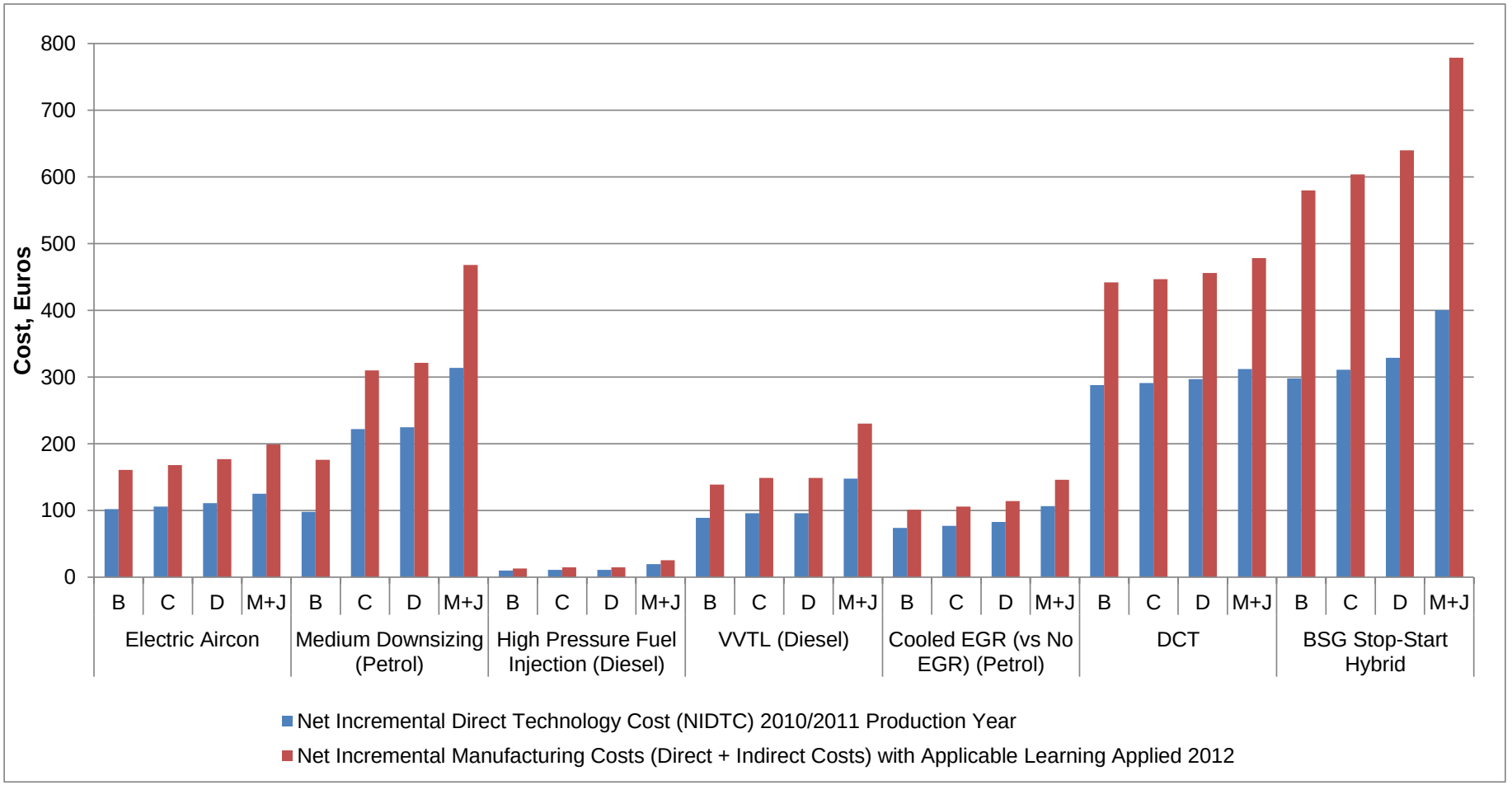
  → Build on analysis and segmentation work for downweighting project
  - Updated analysis using most recent EEA 2013 car and van monitoring DB



Defining the baseline and segmentation

Passenger Cars

- Costs for different segments from FEV / ICCT (2013) analysis:

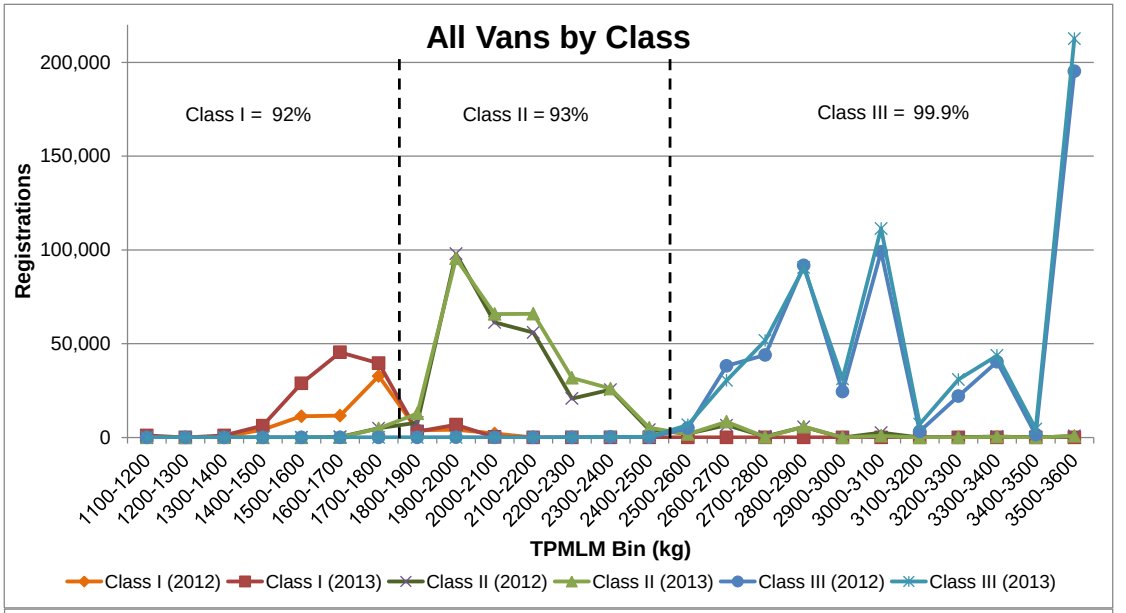


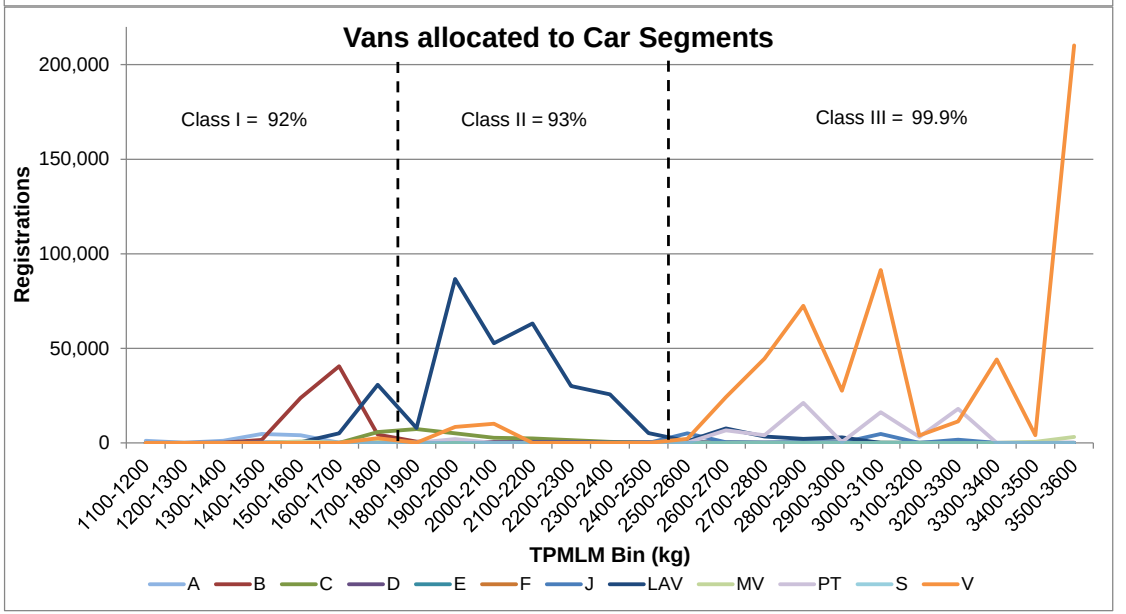
- Suggests significantly higher cost for heavier/more powerful segments
- → Value in separating them out from previous combination with D-segment

Defining the baseline and segmentation

Vans / Light Commercial Vehicles

- No obvious reason to increase the number of categories
- Current N1 'Class' based on reference weight (unladen)
  - Prone to shifts between categories for same basic vehicles
  - Likely exacerbated in the future through application of technology
- Explored possible variants / alternatives
  - Trends vs Maximum Laden Mass, body type, payload capacity were explored
  - Segmentation using Maximum Laden Mass seemed a better alternative





Defining the baseline and segmentation

Final segmentation and baseline parameters

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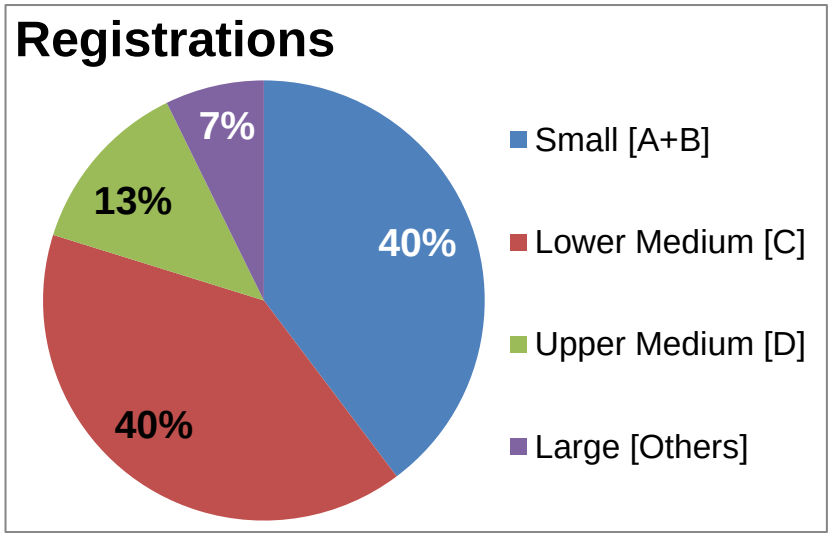
- Revised segmentation agreed with the EC:
  - Used to define 2013 baseline vehicle performance characteristics, i.e.: CO_2 / fuel consumption per km, power, weight

Cars, gCO_2/km	Petrol	Diesel	Electric	Other	Av.
Small [A+B]	118.4	104.4	0.0	113.6	**114.5**
Lower Medium [C]	136.4	124.0	0.0	143.3	**128.5**
Upper Medium [D]	151.3	134.1	0.0	140.4	**137.0**
Large [Others]	181.7	162.3	0.0	162.4	**165.9**
Average	**127.4**	**126.8**	**0.0**	**120.8**	**126.8**

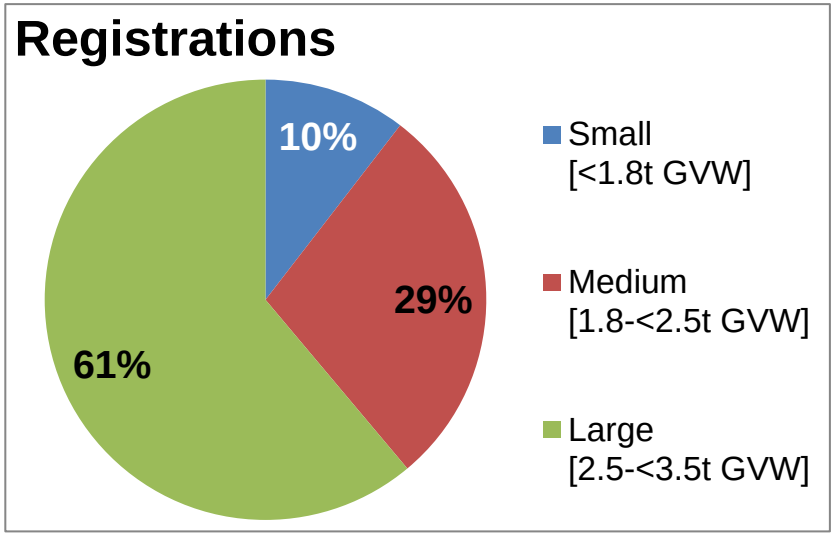
Vans, gCO_2/km	Petrol	Diesel	Electric	Other	Av.
Small [<1.8t GVW]	135.5	105.4	0.0	137.1	**109.4**
Medium [1.8-<2.5t GVW]	154.8	135.4	0.0	158.6	**134.0**
Large [2.5-3.5t GVW]	188.4	204.7	0.0	214.2	**204.6**
Average	**147.2**	**175.4**	**0.0**	**159.5**	**173.8**

- **Expanded** approach needed for baseline xEVs
  - Efficiency, technology, mass and cost from model review, and component breakdown (later slide)

Passenger Cars:



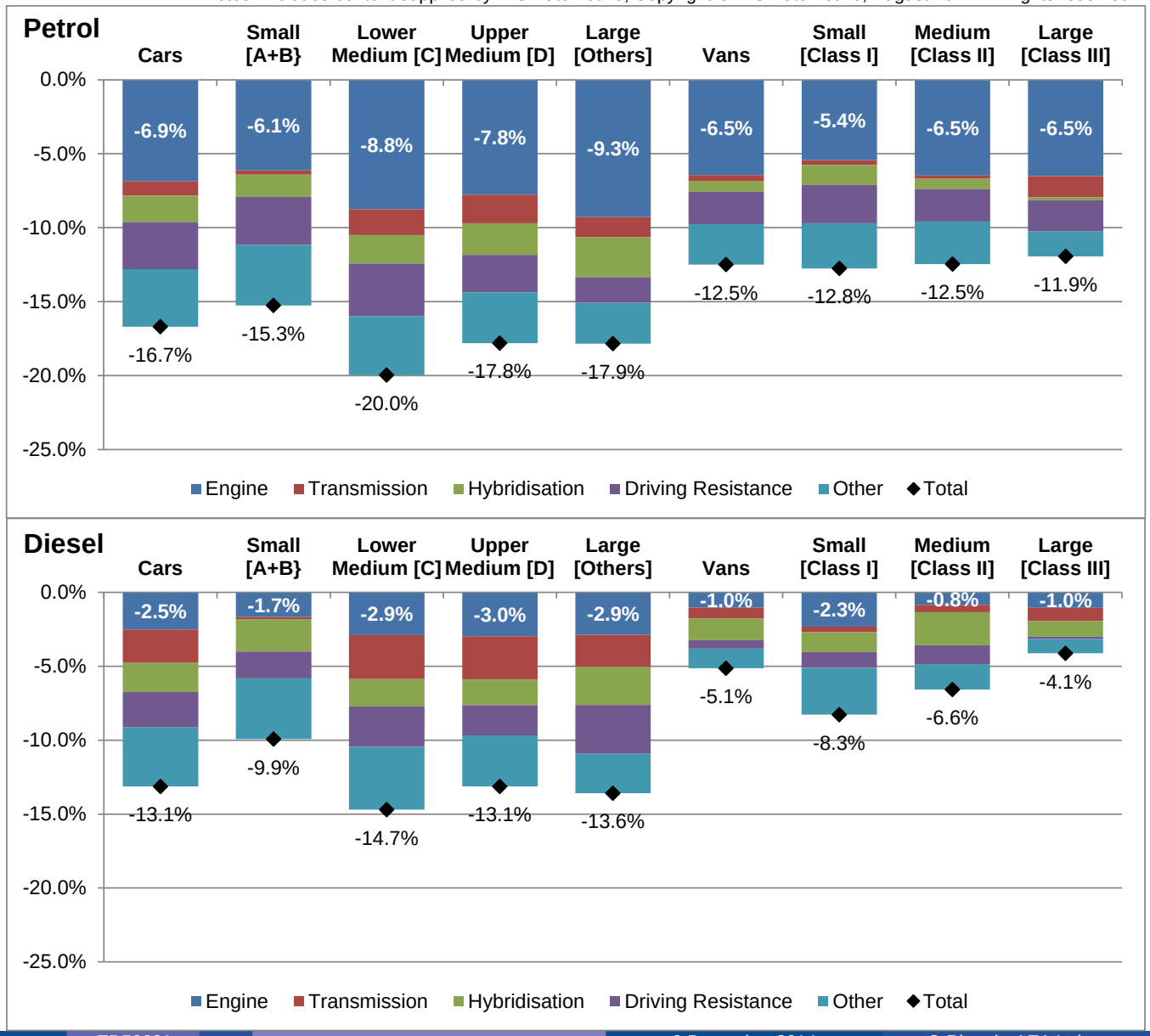
Vans / Light Commercial Vehicles:



Defining the baseline and segmentation

Current penetration and estimated CO2 benefit of technologies

- Updated technology penetration estimates to 2013 (IHS Automotive)
  → new analysis also split by vehicle segment
- Ricardo-AEA estimated CO_2 savings due to the technology application vs 2002
  → significant differences between segments
- To be used with baseline CO_2 emissions to calibrate cost-curves to 2013 situation
  (+ adjusted to WLTP)



Technology coverage, data collection and analysis

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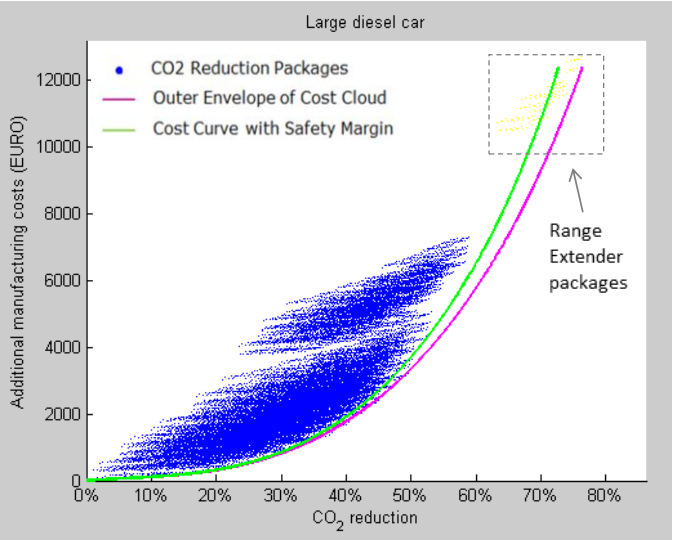
Process

- **Identification of technologies:** ✓
  - Review of previous studies
  - Search through public domain literature (journals, conference proceedings, news stories, OEM and supplier websites, etc.)
  - Initial discussions with experts to validate/check selections
- **Characterisation of identified technologies:** ✓ *(in draft)*
  - CO_2 / fuel savings
  - Costs (timing, breakdown where available, basis – i.e. incl./excl. items)
  - Compatibility (with other technologies, powertrains, segments)
- **Stakeholder consultation:**
  - Gap-filling (focus on filling gaps in data with key experts/organisations) ✓
  - Delphi survey on aspects of cost methodology ✓ *(in progress)*
  - Validation and broader discussions (i.e. full draft dataset, other questions)
  - Ad-hoc

Technology coverage, data collection and analysis

Coverage and outputs

- **Technologies:**
  - *On-cycle options*: covering conventional (+HEV), PHEV/REEV, BEV and FCEV in separate cost-curves
    - FCEV and BEV – in term of cost per MJ/km, rather than gCO_2/km
  - *Off-cycle options:* technologies with real-world savings not captured in test-cycles (e.g. eco-innovations or other)
- **Outputs similar to previously. Cost curves calibrated using:**
  - Outputs/analysis based on Delphi Survey findings
  - Simulation for Task 4.4 (individual measures) and Task 11 (verify versus packages of measures)
    - NEDC
    - WLTP
    - 'Real-world' emission cycles



- **Additional considerations for xEVs:**
  - Alternative approach to estimating 'baseline' cost for xEVs (before other tech's added)
  - Accounting for battery size / range considerations in the cost-curve

Technology coverage, data collection and analysis

Approach for xEVs

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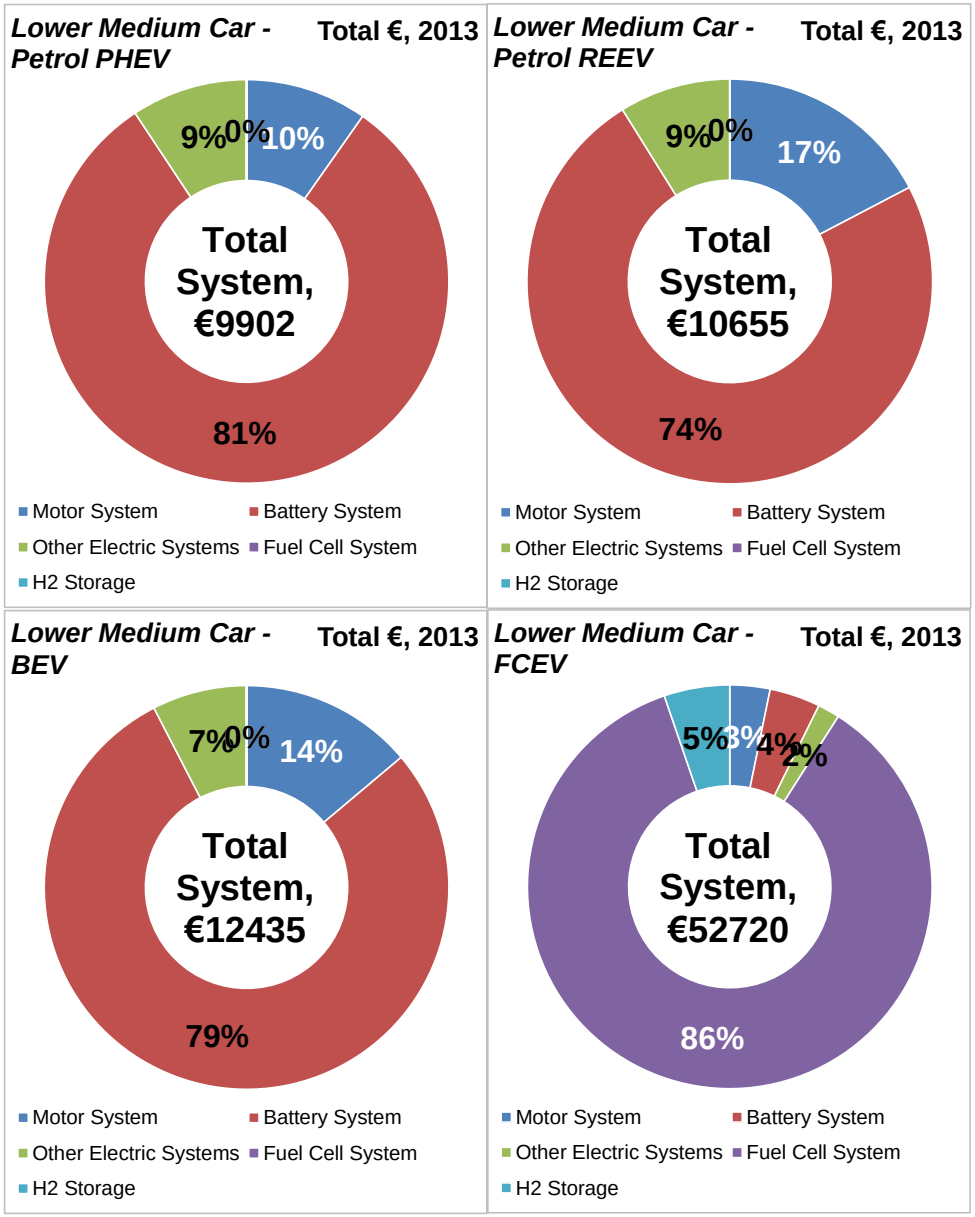
- **Detailed breakdown** of costs for xEVs provided in TNO (2011) for Commission
  - Expanded and adapted analysis to additional segments and updating key datasets and assumptions (from review)
- Use parameters (all powertrains) derived from 2013 database for baseline (CO_2 / fuel consumption per km, power, weight)
- Focus validation with stakeholders on key assumptions that have the maximum impact on costs (and efficiency):
  - Battery Costs and Weight (energy density)
  - Fuel Cell System Costs and Weight
  - Average BEV Range
  - Powertrain Factors (i.e. battery % available SOC, sizing/scaling of ICE, motor and FC)
  - Motor System Weight

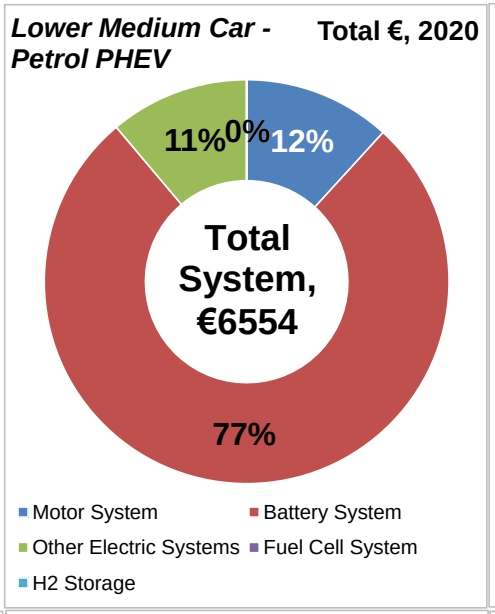


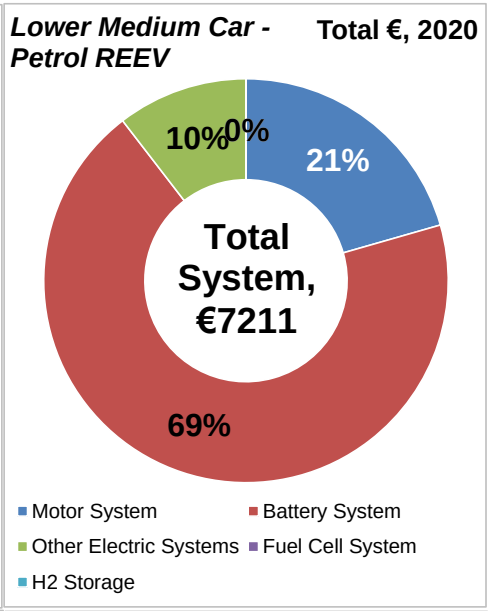
Technology coverage, data collection and analysis

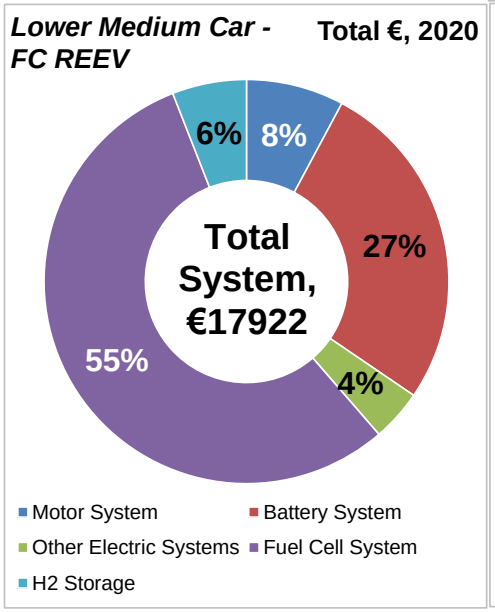
Approach for xEVs *DRAFT*

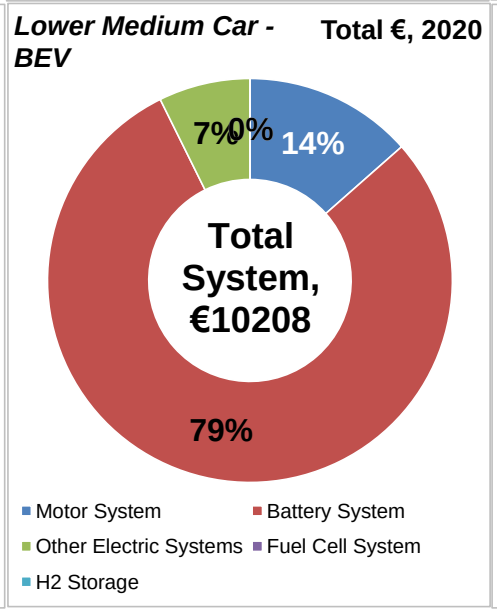
- Similar breakdown for system mass using TNO (2011) → efficiency/battery size
- Estimate baseline vehicle costs for different fuels/powertrains in future periods (2020, 2025, 2030)

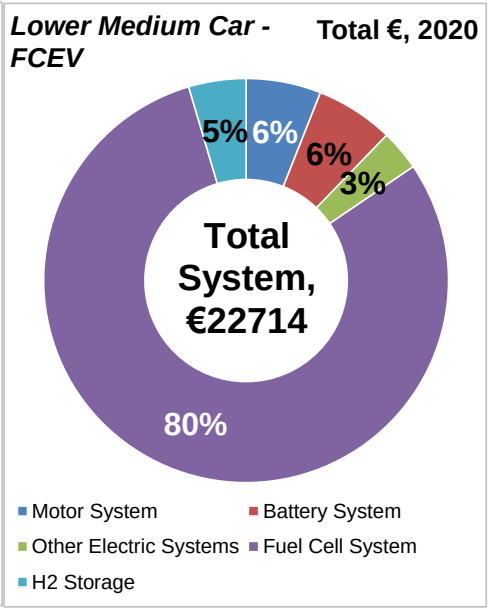
  → use as starting point in cost-curve with additional technologies
- Calculation of future costs to be aligned with overall cost -projection methodology (see later slides)







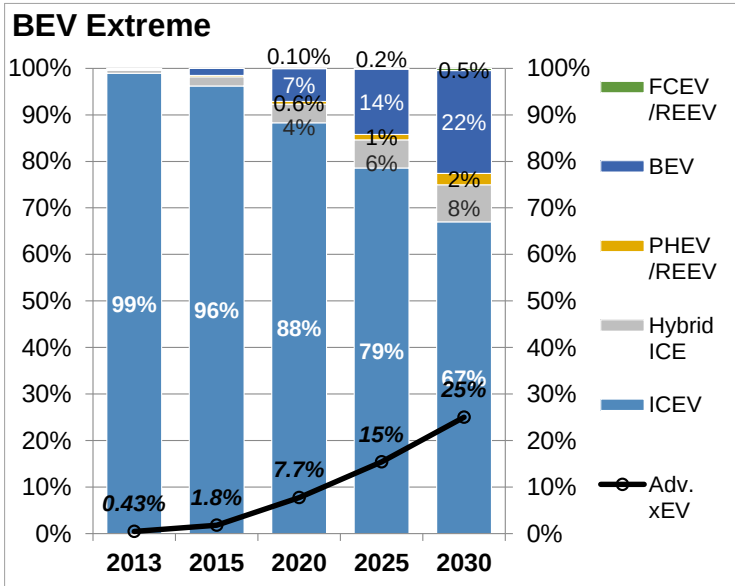


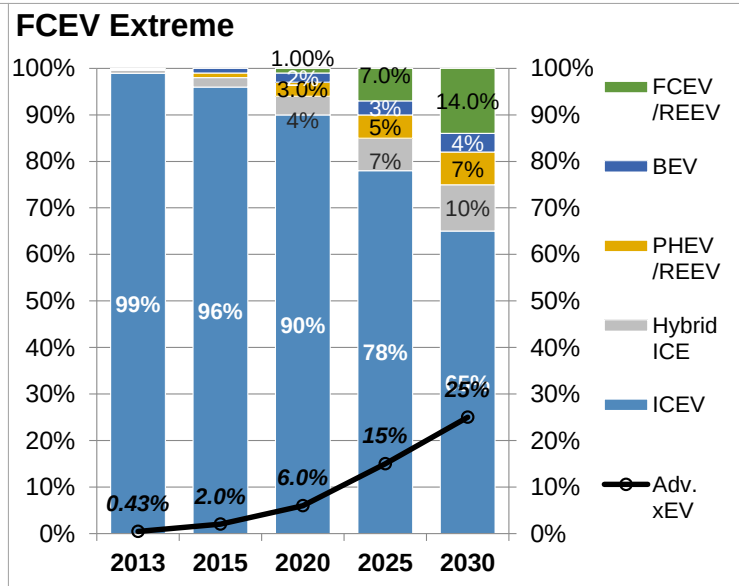


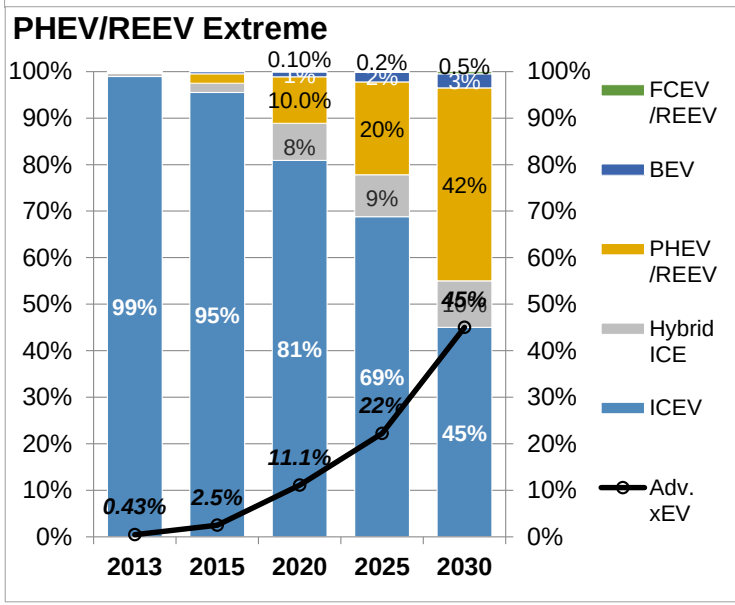
Powertrain deployment scenarios

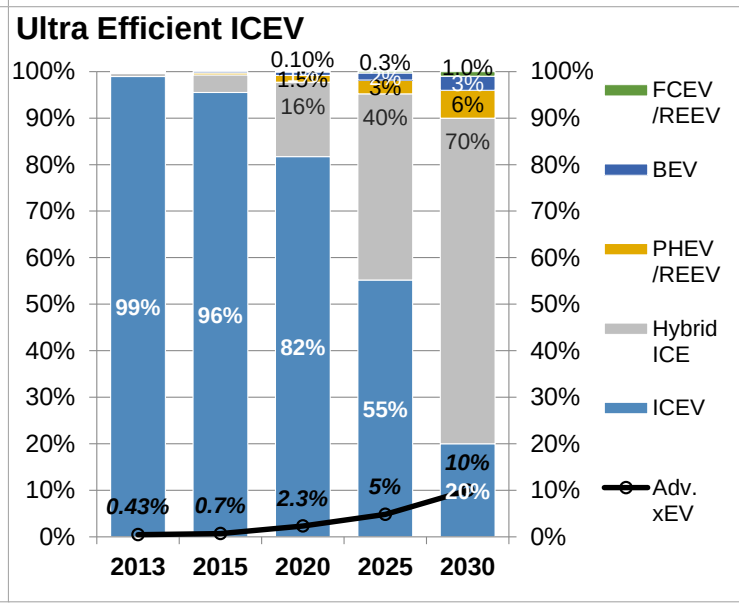
Exploration of the uncertainty in the rate xEV technology reduction

- Objective is to explore sensitivity in xEV component cost reduction via extreme scenarios
- Range of draft scenarios developed for this purpose: % share of sales in Europe
- Current working assumption is that cost reductions for most ICEV technologies will be largely unaffected due to ongoing global significance



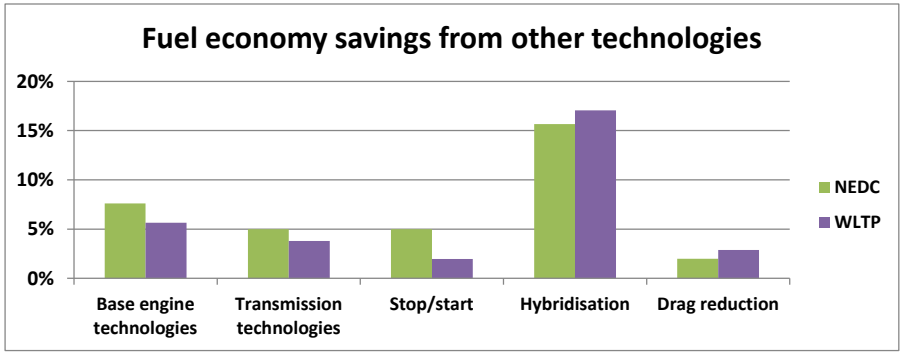


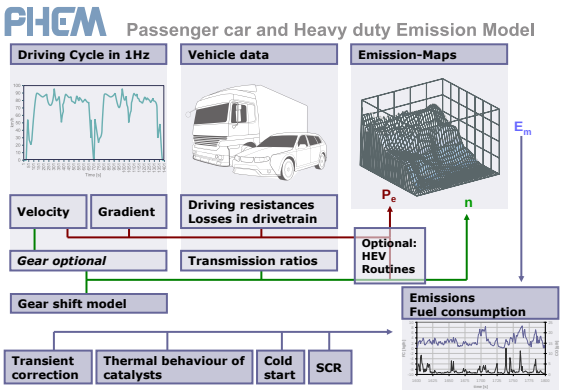




Further analysis of CO_2 benefits associated with individual technology, and selected packages

- **Objectives (Task 9 for individual technologies)**
  - Understand the incremental CO_2 benefits of individual technologies to the European context and in terms of the new WLTP basis
- **Methodology overview**
  - CO_2 benefits for technologies that reduce test cycle emissions
    - WLTP basis
    - Impacts of technology combinations (inputs)
  - Simulation of CO_2 abatement performance via PHEM modelling
    - NEDC, WLTP, CADC in "real world conditions"
      E.g. similar to downweighting project:





- **Outputs**
  - Results provided as inputs to other tasks, and ultimately Task 9 cost curves

Further analysis of CO_2 benefits associated with individual technology, and selected packages

- **Objectives (Task 10 for verification of cost curves for technology packages)**
  - Quality checks of data on CO_2 reduction and on corresponding costs fed into Task 9
  - Independent validation work especially on the CO_2 reduction values
  - Recommendations based on the findings
- **Methodology overview**
  - Verification of cost curve data using:
    - information from currently deployed vehicle types
    - complex vehicle modelling
    - component testing and simulation
  - Recommendations based on the findings from the verification procedures
- **Outputs**
  - Refinement of data inputs to Task 9 prior to running the cost-curve model for all variants

Stakeholder Consultation

Summary

- **Stakeholder consultation on various aspects and stages of the project:**
  - *Ad-hoc communications*:
    - E.g. sense-checking early technology list; meeting with ACEA CO_2 working group
  - *Gap-filling*: ✓
    - Identification of key organisations with expertise for technologies with information gaps or greater uncertainty in existing data
    - Information collected via written responses and telephone interviews with a number of OEMs and suppliers
  - *Delphi survey*: on key aspects of the cost methodology (see next slides) ✓
  - *Validation*: ***(in progress)***
    - Draft technology dataset sent for feedback/comment to OEMs, suppliers, etc.
    - Interviews being scheduled to discuss also other aspects of the project analysis
- **Considerations for non-representative segments:**
  - Feedback from interviews with stakeholders during validation process
  - Workshop with a number of smaller manufacturers planned for January 2015
- **Presentation of final project results to EC, key stakeholders at a workshop**

Stakeholder Consultation

Cost projection methodology and Delphi Survey

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From Direct *(technology)* costs in Y2013

(1) Obtain direct costs from literature (e.g. tear-down studies) or stakeholder consultation

(2) Apply **'Scaling Factors'** that adjust costs to the vehicle segment being analysed (if required)

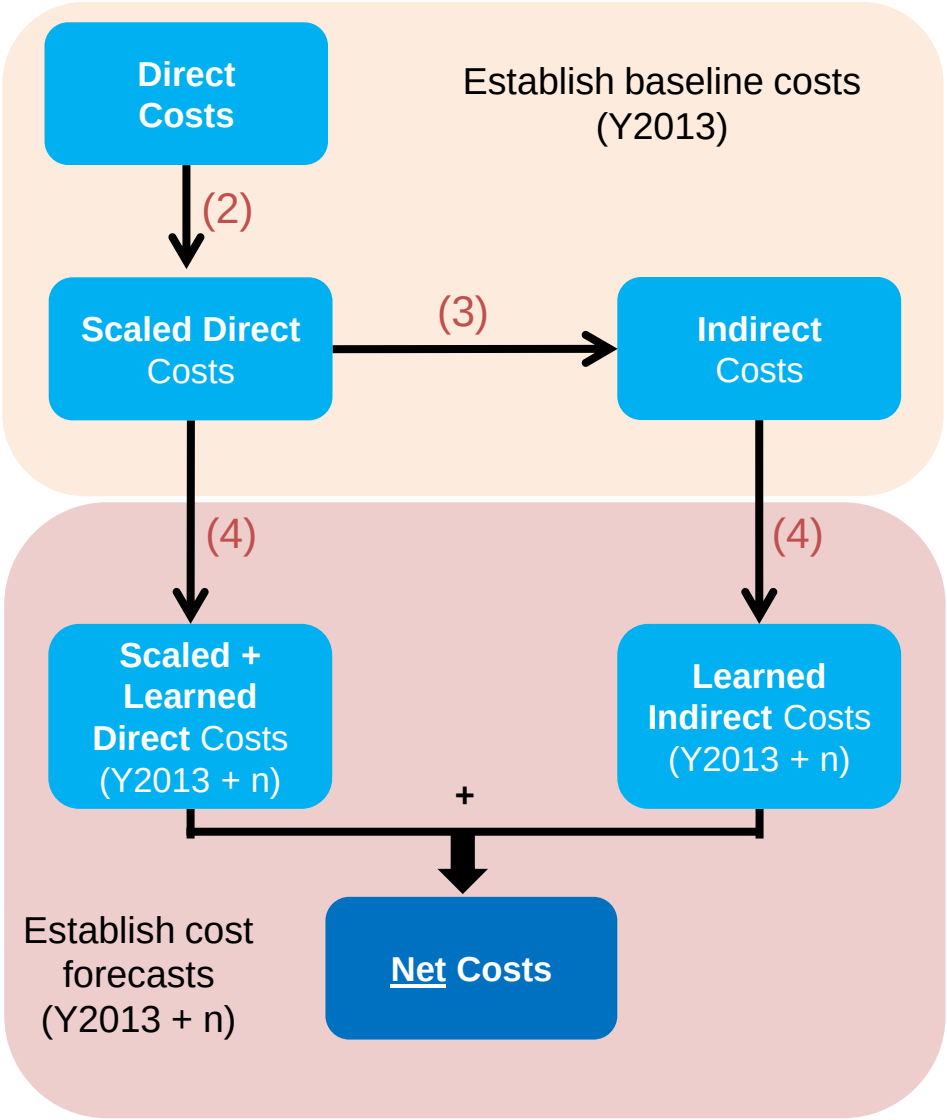
(3) Apply **'Indirect Cost Multipliers'** (ICMs) that establish indirect technology costs

(4) Apply **'Learning Factors'** that account for decreasing costs over time (→ the projection of costs into the future)

(5) Sum direct and indirect costs

To Net costs in Y2013 + n (up until 2030)

The above factors and the related methodology were subject of the *Delphi* survey



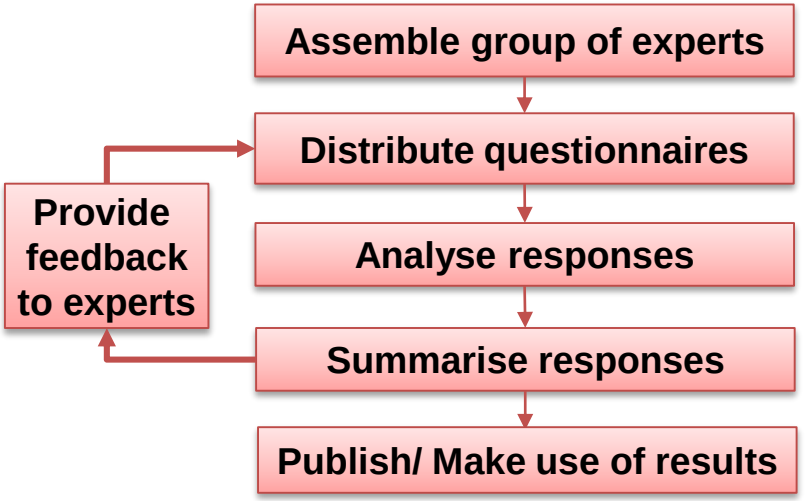
Stakeholder Consultation

The Delphi Survey Process

- **A Delphi survey**
  - Allows a group of experts to **collaborate anonymously**
  - **Aims to analyse complex issues** with high level of uncertainty
  - Aims to achieve a **consensus** among experts

- The **survey process**
  1) Seek first expert input to complex issues (1st stage)
  2) Provide experts with collated (anonymous!) feedback of the responses
  3) Seek new/updated expert input to the same and/or refined questions (2nd stage)

The Delphi Survey Process



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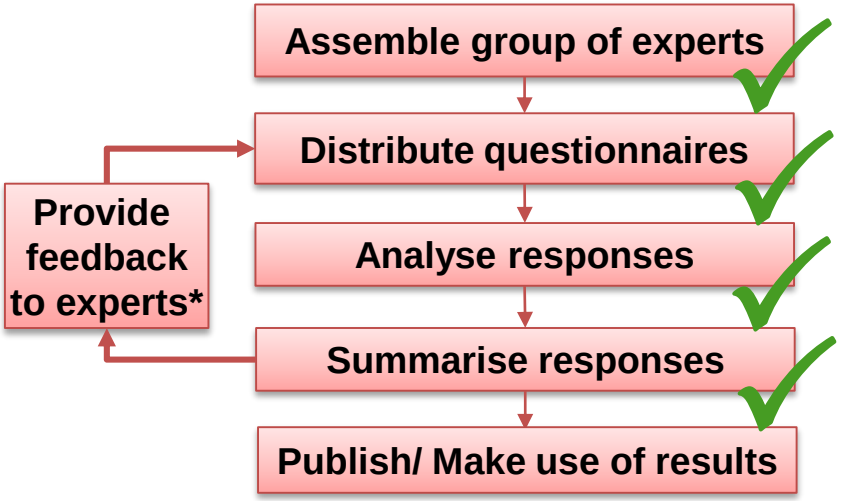


All 2nd (= final) stage responses have been received by the end of November.

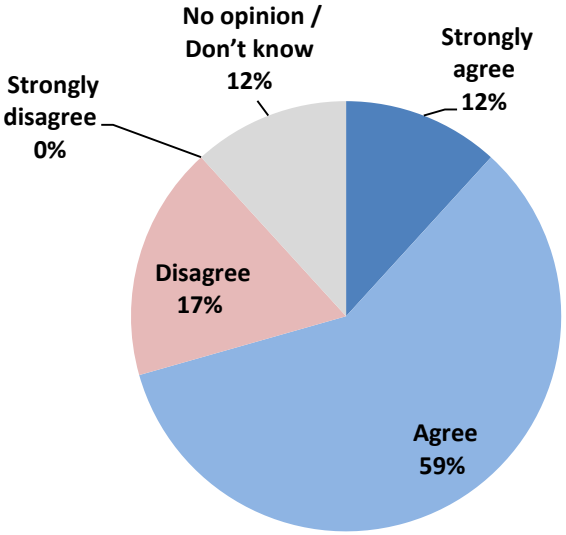
* 7 refining questions were also introduced in the second round of the survey.

Stakeholder Consultation

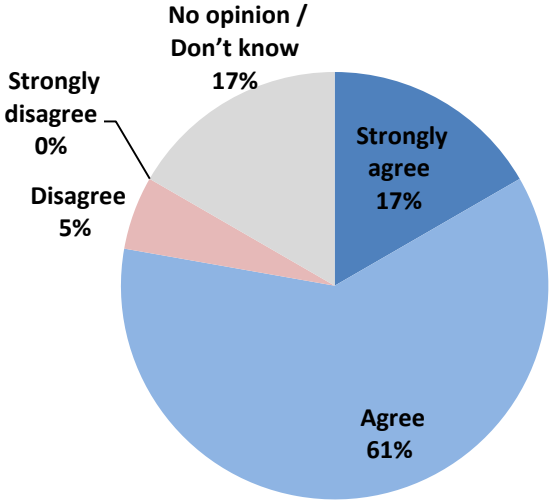
Overview and main results of the Delphi Survey

- **Participation:** 15 experts from industry (OEMs, consultancies), academia, policy makers, NGOs
- **Results included a broad agreement with the proposed cost estimation methodology:**
  - General agreement with the information sources for the scaling approach (EU-tailored and industry–derived data)
  - Overall agreement with the ICM approach for indirect manufacturing costs; EU-tailored ICMs preferred over EPA ICMs
  - Preference of the EPA/FEV learning approach over the previous EC approach to predict technology costs developments
- **Consensus that it would be preferable to also analyse the costs of whole technology packages instead of single technologies only** [see earlier slides on verification of cost curves]

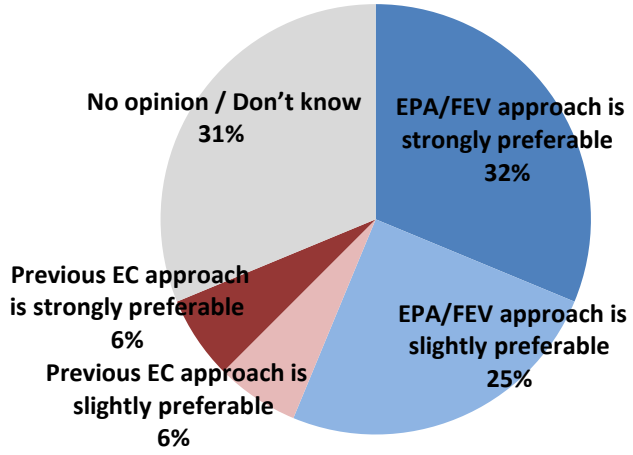
Agreement with scaling approach



Agreement with ICM approach



Agreement with US EPA/FEV learning approach



Stakeholder Consultation

Overview and main results of the Delphi Survey

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- **More diverging opinions concerning more detailed aspects of the methodology, e.g. concerning:**
  - xEV penetration rates (i.e. impacts on costs for different component types)
  - Which factors to be included in indirect costs: The opinions diverged for pension costs, health care costs, transportation costs, dealer net profit allowance, dealer selling costs and manufacturer's profit allowance
  - Specific aspects of the cost curve methodology (e.g. which learning rate to use)
  - How to account for manufacturers' strategies to reduce costs (e.g. shared platforms)
  - Handing overlaps/synergies between technologies, and
  - Handling the impacts of integrated packages vs stand-alone technology costs
- **Only very few experts reconsidered their opinion after having received feedback from the 1st stage questionnaire answers of other experts**

→ *There is still the need to make a judgement on the optimal approach*, keeping in mind that experts advocate a **'useable/practical' model/methodology** that avoids unfounded complexity, that can be broadly applied

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Stakeholder Consultation

Validation of baseline CO_2 and cost data

- Draft full dataset for conventional and xEV technologies sent for feedback

(in progress)

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SI-Petrol Technologies

DRAFT 19 November 2014

Introduction

Powertrain technologies which can be applied to conventional petrol vehicles.

Baseline: 2013 MY vehicle without any of the technologies already applied.
Technology areas: Engine, Transmission, Hybridisation.

Category	Technology	Inclusive systems, examples of variants, other notes	NEDC CO_2 Reduction (%, compared to 2013 baseline) 2015 / 2020 / 2025 / 2030	Does CO_2 reduction vary by segment?	Total additional direct manufacturing cost estimate for 2020 [Euros] Chosen Value / High / Low	Does cost vary by segment?	DRAFT 2020 Indirect Cost Multiplier (ICM)	Estimated year of mass-manufacture	Feedback/Comments *Please give precise values where possible.*

Passenger Cars
(For typical C-segment vehicle, e.g. VW Golf, Ford Focus, Peugeot 307, Opel Astra, Toyota Auris, etc.)

Category	Technology
Base Engine	Natural Gas Vehicle
Base Engine	Combustion improvements for SI engines: Level 1
Base Engine	Combustion improvements for SI engines: Level 2
Base Engine	Direct injection - homogeneous
Base Engine	Direct injection - stratified charge & lean burn
Base Engine	Thermodynamic cycle improvements (a)
Base Engine	Thermodynamic cycle improvements (b)
Base Engine	Cylinder deactivation
Base Engine	Mild downsizing (15% cylinder content reduction) + boo...
Base Engine	Medium downsizing (30% cylinder content reduction) + ...
Base Engine	Strong downsizing (>=45% cylinder content reduction) + ...
Base Engine	Cooled EGR
Base Engine	Cam-phasing
Base Engine	Variable valve actuation and lift
Base Engine	Engine friction reduction for SI engines: Level 1
Base Engine	Engine friction reduction for SI engines: Level 2
Hybridisation	Start-stop system
Hybridisation	Micro hybrid - start-stop, plus regenerative braking
Hybridisation	Mild electric hybrid - torque boost for downsizing
Hybridisation	Full electric hybrid - with limited full electric operation
Hybridisation	Air hybrid
Hybridisation	Flywheel hybrid
Transmission	Automated manual transmission (AMT)
Transmission	Dual clutch transmission (DCT)
Transmission	Continuously variable transmission (CVT)
Transmission	Optimising gearbox ratios / downspeeding

Vans / Light Commercial Vehicles
(For typical Medium / Class II van 1.8-2.5 tonnes GVW, e.g. Citro...

Category	Technology
Base Engine	Natural Gas Vehicle
Base Engine	Combustion improvements for SI engines: Level 1
Base Engine	Combustion improvements for SI engines: Level 2
Base Engine	Direct injection - homogeneous
Base Engine	Direct injection - stratified charge & lean burn
Base Engine	Thermodynamic cycle improvements (a)
Base Engine	Thermodynamic cycle improvements (b)
Base Engine	Cylinder deactivation
Base Engine	Mild downsizing (15% cylinder content reduction) + boo...
Base Engine	Medium downsizing (30% cylinder content reduction) + ...
Base Engine	Strong downsizing (>=45% cylinder content reduction) + ...
Base Engine	Cooled EGR
Base Engine	Cam-phasing
Base Engine	Variable valve actuation and lift
Base Engine	Engine friction reduction for SI engines: Level 1
Base Engine	Engine friction reduction for SI engines: Level 2
Hybridisation	Start-stop system
Hybridisation	Micro hybrid - start-stop, plus regenerative braking
Hybridisation	Mild electric hybrid - torque boost for downsizing
Hybridisation	Full electric hybrid - with limited full electric operation
Hybridisation	Air hybrid
Hybridisation	Flywheel hybrid
Transmission	Automated manual transmission (AMT)
Transmission	Dual clutch transmission (DCT)
Transmission	Continuously variable transmission (CVT)
Transmission	Optimising gearbox ratios / downspeeding
Transmission	Downspeeding via slip controlled clutch and DMF remov...
Transmission	Improved Manual Transmission

Key Assumptions for xEVs

DRAFT 19 November 2014

Introduction

Note: although at this stage we are seeking comments in particular on anticipated future cost for these technologies, it is our intention that the final methodology for future cost-projections for such elements will be aligned with that being applied to other CO2 reducing technologies (i.e. using a learning-based methodology). The views expressed on anticipated future costs by stakeholder experts will be used to help calibrate this process accordingly.

Includes: PHEVs, REEVs, BEVs, FCEVs, FC REEVs. **Total Cost or Mass** = Sum (Fixed + Variable) elements

1 Battery Costs and Weight

Cost, Euro	2013	2020	2025	2030
Battery System				
Fixed (do not scale with kWh)	200	160	144	128
Li-ion per kWh	375	245	204	163
Advanced (Li-S/Li-Air) per kWh		410	277	144

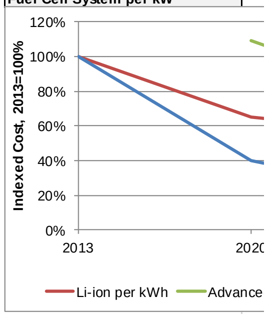
Energy Density (Wh/kg), Mass (kg)	2013	2020	2025	2030	
Battery System					
Fixed kg (do not scale with Wh)					No data - c
Li-ion, Wh/kg	110	160	230	300	Assume th
Advanced (Li-S/Li-Air), Wh/kg		300	400	500	Assume th

2 Fuel Cell System Costs and Weight

Cost, Euro	2013	2020	2025	2030
Fuel Cell System				
Fuel cell stack, per kW	350	140	70	21
FC Peripherals, per kW	250	100	50	23
TOTAL, per kW	**600**	**240**	**120**	**44**
Other Systems				
H2 Storage, per kWh	51	16	13	10
H2 Storage, per kgH2	2000	630	512	394
Cost for 4kg H2 storage	*8000*	*2520*	*2048*	*1576*

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					No data
TOTAL, per kW	**3.0**	**2.0**	**1.7**	**1.5**	
Other Systems					
H2 Storage (excl. H2), fixed kg	92	80	80	80	

Indexed Cost (vs 2013 Li-ion)
Li-ion per kWh
Advanced (Li-S/Li-Air) per kWh
Fuel Cell System per kW



Technology Compatibility

Introduction

X = Not compatible/stackable

Assumptions on technology applicability/compatibility with other technologies, powertrain types and vehicle segments.

Engine, Transmission and Hybridisation Technologies

CO_2 Reducing Technologies: Engine, Transmission and Hybridisation Technologies (columns 1–31): Natural Gas Vehicle; Combustion improvements: L...; Combustion improvements: L...; Combustion improvements: L...; Direct injection - homogeneo...; Direct injection - stratified cha...; Thermodynamic cycle impro...; Thermodynamic cycle impro...; Cylinder deactivation; Mild downsizing (15% cylinde...; Medium downsizing (30% cy...; Strong downsizing (>=45% c...; Cooled EGR; Cam-phasing; Variable valve actuation and...; Engine friction reduction: Lev...; Engine friction reduction: Lev...; In-wheel motors for xEVs; Start-stop system; Micro hybrid - start-stop, plus...; Mild electric hybrid - torque b...; Full electric hybrid - with limit...; Air hybrid; Flywheel hybrid; Automated manual transmiss...; Dual clutch transmission (DC...; Continuously variable transm...; Optimising gearbox ratios / d...; Downspeeding via slip contro...; Improved Manual Transmissi...; Multi-speed gearbox for xEVs

Powertrains (columns 1–9): Petrol ICE + HEV; Diesel ICE + HEV; Petrol PHEV; Diesel PHEV; Petrol REEV; Diesel REEV; BEV; FCEV; FC REEV

Vehicle Segments (columns 1–7): Small Car (A+B Segment); Lower Medium Car (C Segme...; Upper Medium Car (D segme...; Large Car (E/F/J/Other segm...; Small Van (<1.8 t GVW); Medium Van (1.8-<2.5 t GVW); Large Van (2.5-<3.5 t GVW)

#	Type	T#	Technology Name
1	Base Engine	1	Natural Gas Vehicle
2	Base Engine	2	Combustion improvements: Level 1
3	Base Engine	3	Combustion improvements: Level 2
4	Base Engine	4	Combustion improvements: Level 3
5	Base Engine	5	Direct injection - homogeneous
6	Base Engine	6	Direct injection - stratified charge & lean burn
7	Base Engine	7	Thermodynamic cycle improvements (a)
8	Base Engine	8	Thermodynamic cycle improvements (b)
9	Base Engine	9	Cylinder deactivation
10	Base Engine	10	Mild downsizing (15% cylinder content reduction) + boost
11	Base Engine	11	Medium downsizing (30% cylinder content reduction) + boost
12	Base Engine	12	Strong downsizing (>=45% cylinder content reduction) + boost
13	Base Engine	13	Cooled EGR
14	Base Engine	14	Cam-phasing
15	Base Engine	15	Variable valve actuation and lift
16	Base Engine	16	Engine friction reduction: Level 1
17	Base Engine	17	Engine friction reduction: Level 2
18	Base Engine	18	In-wheel motors for xEVs
19	Hybridisation	1	Start-stop system
20	Hybridisation	2	Micro hybrid - start-stop, plus regenerative braking
21	Hybridisation	3	Mild electric hybrid - torque boost for downsizing

- → *Excel worksheet*

Next steps

- Consultation:
  - Data validation and interviews (Nov ‘14 - early Jan ‘15)
- Simulation of CO_2 savings NEDC vs WLTP vs real-world
- Finalisation of powertrain deployment scenarios and technology cost uncertainty analysis (for conventional and xEV technologies)

→ final cost and CO_2 performance datasets

- Cost-curve development and verification
- Considerations for non-representative segments:
  - Feedback from interviews with stakeholders during validation process
  - Workshop with a number of smaller manufacturers planned for January 2015
- Final report and workshop

Discussion and Questions

- ?

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