Future Low Carbon Cars

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Ricardo is a leading UK based global provider of product innovation, engineering solutions, clean technology and strategic consulting in North America, Europe and Asia

RD.11/468401.1

Future Low Carbon Cars:

- **Regulation is the Key Driver for New Technology**

- **Battery Cost Will Limit EV's to Niche Markets**

- **Economics Will Drive Intelligent Electrification & Advanced ICE's**

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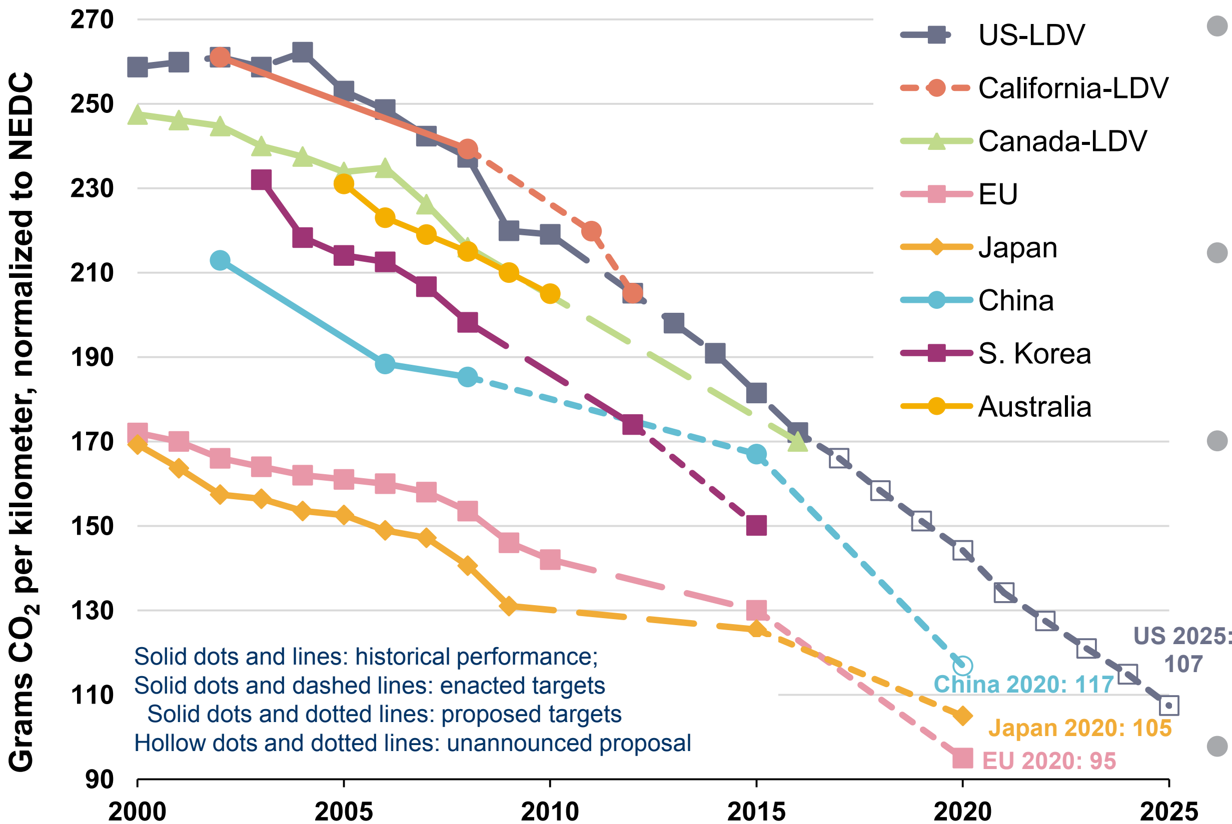
The growth of both regulation and targets for Low Carbon Vehicles sets a major challenge for the road transport sector



[1] China's target reflects gasoline fleet scenario. If including other fuel types, the target will be lower.
[2] US and Canada light-duty vehicles include light-commercial vehicles.

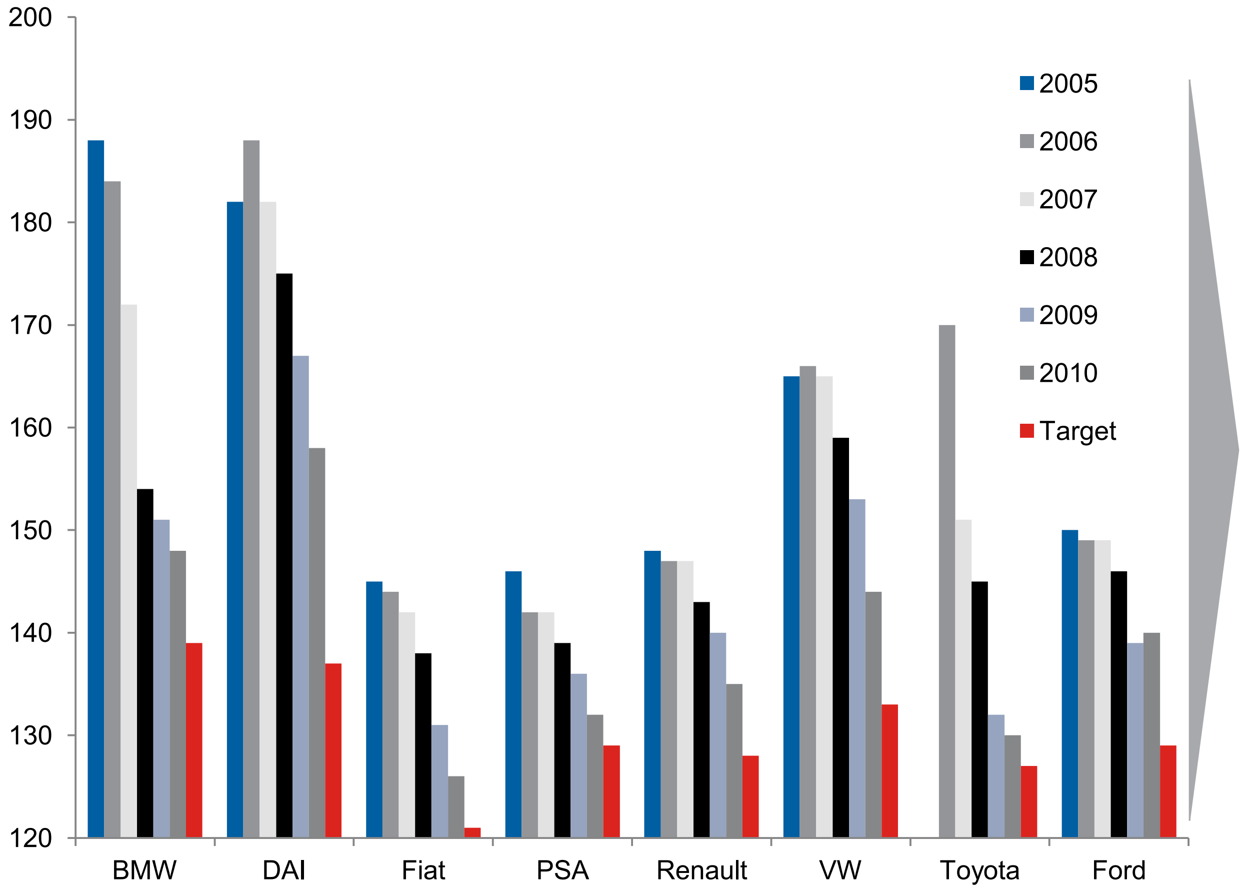
- EU, USA, Canada, Australia, China & Japan – Legislation / agreements for fuel economy or CO_2
- EU Proposal for Vans
  - 175 g/km from 2014-16
  - 135 g/km by 2020
- USA has set target of
  - 35.5 mpg by 2016
  - 54.5 mpg by 2025
  - Implemented over whole of USA by EPA
- Challenging Targets:
  - EU 3.9% pa to 2020
  - US 4.7% pa to 2025

- Japan has been the first to introduce fuel economy legislation for Heavy Duty vehicles (15% reduction from 2002 by 2015)
- US targets for Heavy/Medium duty agreed for implementation starting 2014
- European Heavy Duty CO_2 limits could be introduced from 2016–2018 post Euro 6

Sources: http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/Oct2010_Summary_Report.pdf www.theicct.org/info/documents/PVstds_update_apr2010.pdf;

Progress has been made against EU emissions legislation, but OEMs still have a lot to do in a comparatively short time

Progress against 2015 130g CO_2 / kM target

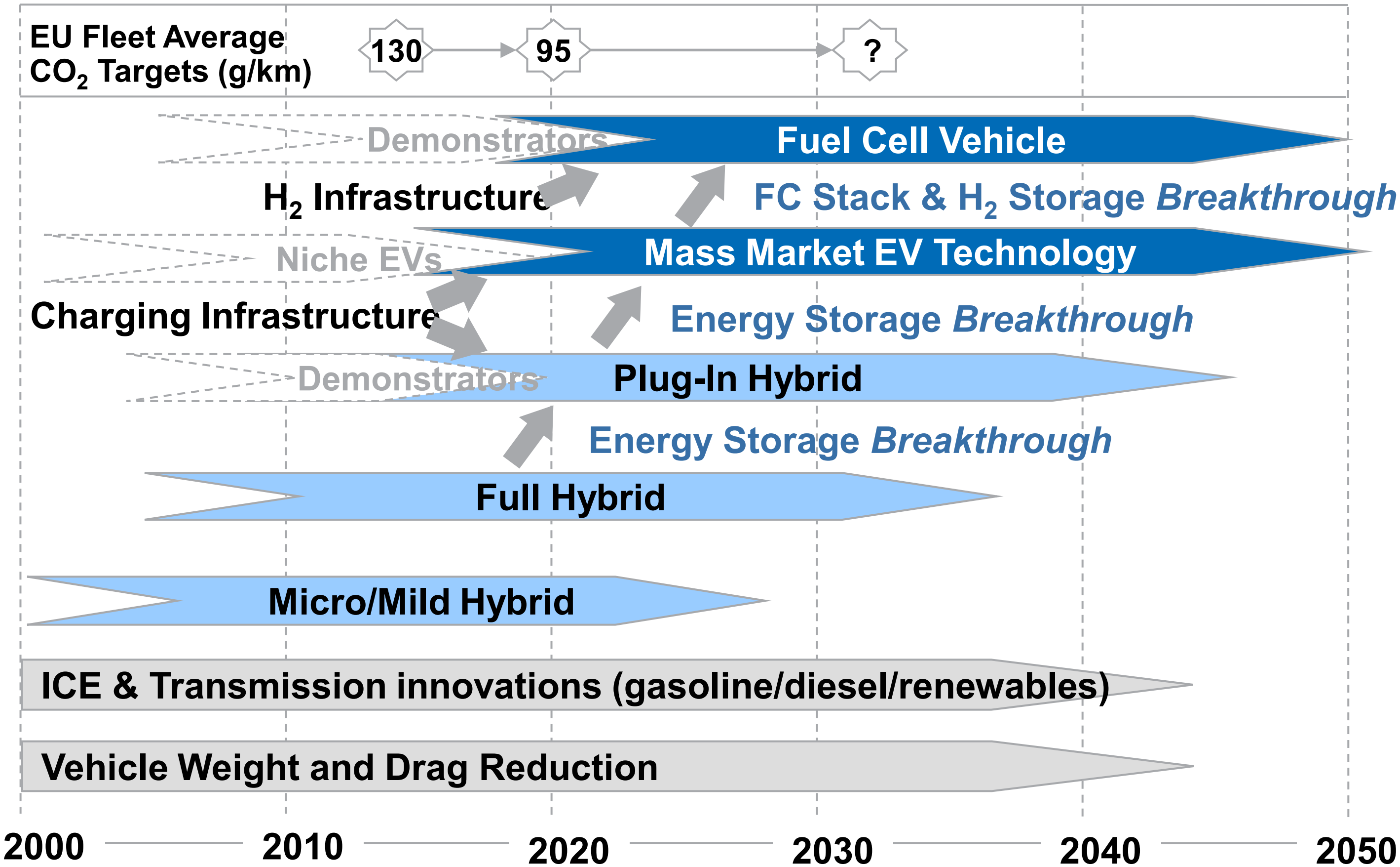


Source: Bernstein & Ricardo analysis

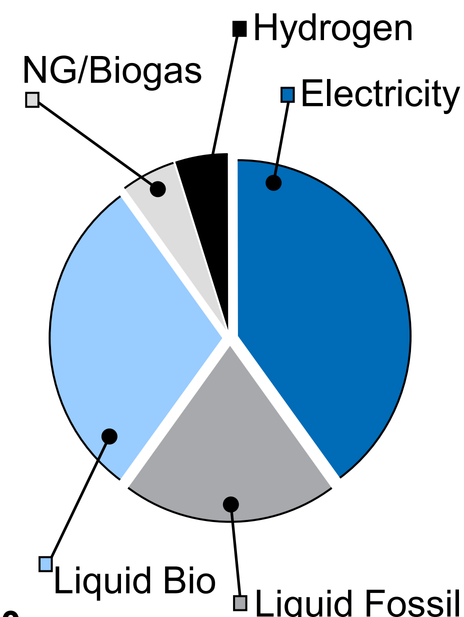
Comments

- OEMs have an average annual CO_2 reduction of ~3% since 2005
  - Toyota and BMW lead with 6.5% and 4.7%
  - Ford and Renault are laggards with 1.4% and 1.8%
- Market still has average of ~6.6% to go to hit targets
  - PSA & Toyota have ~2%
  - Daimler has 15%
- Ricardo calculated that average non-compliance penalties could be €2,900 per car
  - Up to €4,300 for Daimler

“Consensus” mass market roadmap developed by Ricardo for UK Auto Council shows that a range of technologies will be required to meet regulatory targets



Road Transport Energy Vectors 2050 Ricardo projection



Regulation Basis:

- Tailpipe CO_2 or Vehicle fuel efficiency
- Well to Wheels CO_2 & efficiency
- Life Cycle Analysis

Source: Ultra Low Carbon Vehicles in the UK – BERR/DfT; Ricardo roadmaps and technology planning; Shell Energy Scenarios to 2050 (2008)

Ricardo results show hybrids & EVs will have lower life cycle CO_2, but embedded emissions will be more significant

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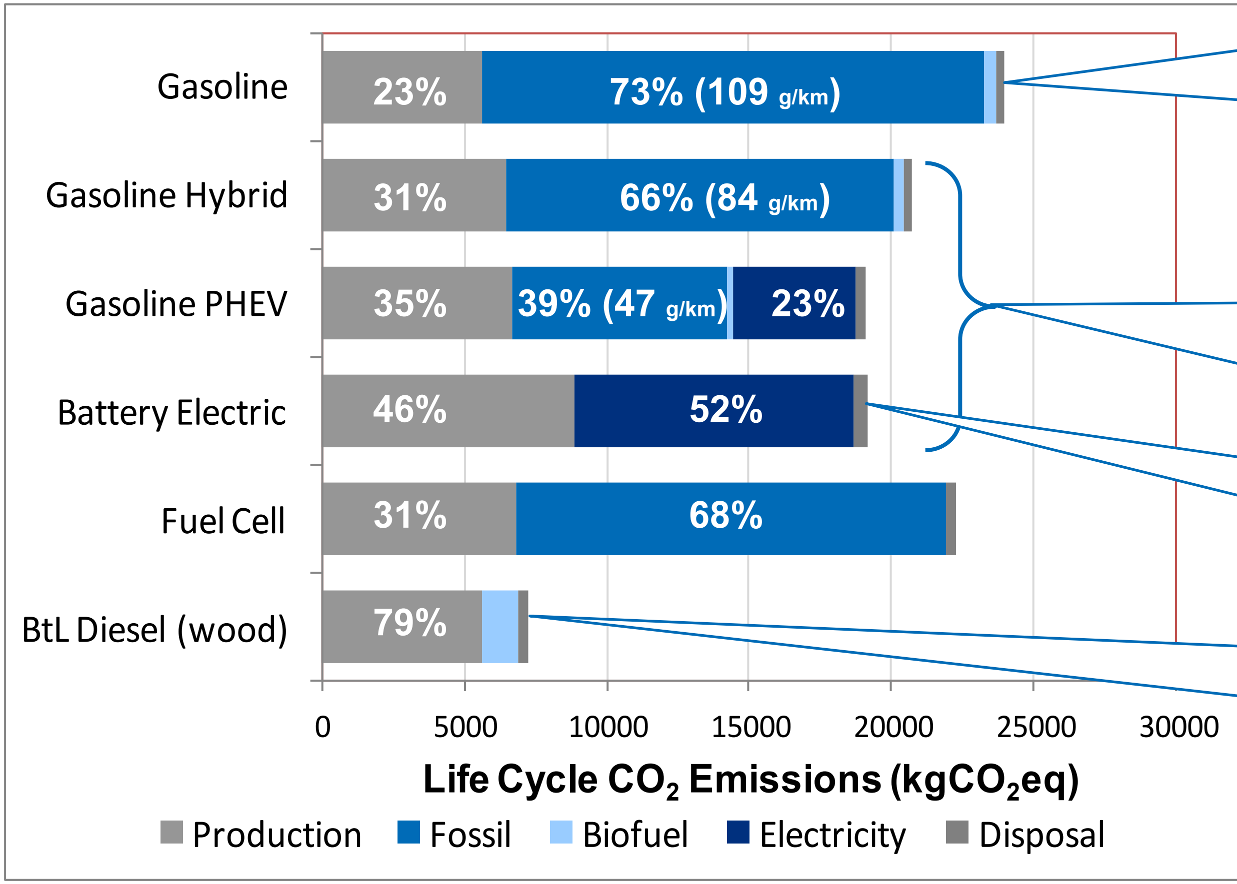
Future Technologies for Mid Size (1350-1500kg) Vehicle



Improvements in ICE powertrains will be very effective in reducing life cycle CO_2 emissions

Embedded CO_2 for electrified vehicles higher than conventional due to advanced battery packs, electronic motors and power electronics

For an EV, nearly half the life cycle CO_2 could result from production

Biomass to Liquid based on Fischer Tropsch process & farmed wood ~ very low in-use emissions

Assumptions:

Vehicle specifications based on roadmap projections for 2015.
Assumed lifetime mileage 150,000 km.
Gasoline fuel E10. Diesel fuel B7
Fischer-Tropsch diesel from farmed wood (WTW = 6 gCO2eq/MJ via UK RED)
Hydrogen carbon intensity 99.7 gCO_2e/MJ (from Natural Gas Steam Reforming)

Electricity carbon intensity assumed to be 594 gCO_2/kWh.
Hybrid Battery 1.8 kW.hr NiMH, 56 kW Motor
EV Battery 32 kW.hr Li-ion ~ 150 km range
PHEV Battery 5 kW.hr ~ 20 km range
FCEV Battery 1.8 kW.hr

Source: Ricardo report for LowCVP, “Preparing for a life cycle CO2 measure” (RD.11/124801.5), plus additional Ricardo analysis

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- **Battery Cost Will Limit EV’s to Niche Markets**
  - Electrification of powertrains will be a dominant feature for future products but batteries are not currently cost-competitive with other fuels. Projections show that a Battery Electric Vehicle will still be significantly more expensive to build than a Gasoline ICE Vehicle in 2020

- **Economics Will Drive Intelligent Electrification & Advanced ICE’s**

Ricardo's technology roadmaps identify electrification of powertrain as a key element of the automotive future

Ricardo Technology Roadmap

Short Term (today)

- Portfolio of advanced ICE-based powertrain
- **Portfolio of Hybrid (HEVs)/ electrification**
  - Micro, Mild & Full Hybrid systems
  - Battery Electric for niche segments
  - Development of non battery energy storage
- Strategic watch on H_2

Medium Term (~2025)

- Need for major powertrain technology shift in the developed world
- **Electrification will become common place, either PHEV, RE-EV or BEV**
- BUT advanced conventional engines retain a strong role

Long Term (~2050)

- Even greater demand for personal mobility
- **Migration to new energy vectors: electricity, hydrogen or sustainable liquids**
  - **All probably required**
- Parallel change in the whole energy sector

The future of the automotive powertrain is largely driven by legislation rather than consumers or even technology

There may be no single revolutionary winning technology

Source: Ricardo Analysis

Improving battery technology and light-weighting has enabled EVs to emerge from Niche to potential mainstream vehicles

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GM EV1
(1996 - 2002)
$34,000 (lease)

- 300 kg NiMH (Gen-2) battery
- 102 kW motor – 140 miles range

REVA G-Wiz
(2008)
~ $16,000

- 270 kg PbA battery
- 13 kW motor – 50 miles range

Tesla Roadster
(2008)
$109,000

- 450 kg Li-ion battery
- 185 kW motor – 221 miles range

Mitsubishi i-MiEV
(2010)
~ $50,000

- 200 kg Li-ion battery
- 47 kW motor – 80 miles range

Nissan Leaf
(2011)
$33,000

- 272 kg Li-ion battery
- 80 kW motor – 100 miles range

GM Chevrolet Volt
(2012)
$33,500

- 197 kg Li-ion battery
- 111 kW motor – 20-50 miles EV range

Batteries not currently cost-competitive with other fuels – greatest challenge is cost whilst retaining life and reliability

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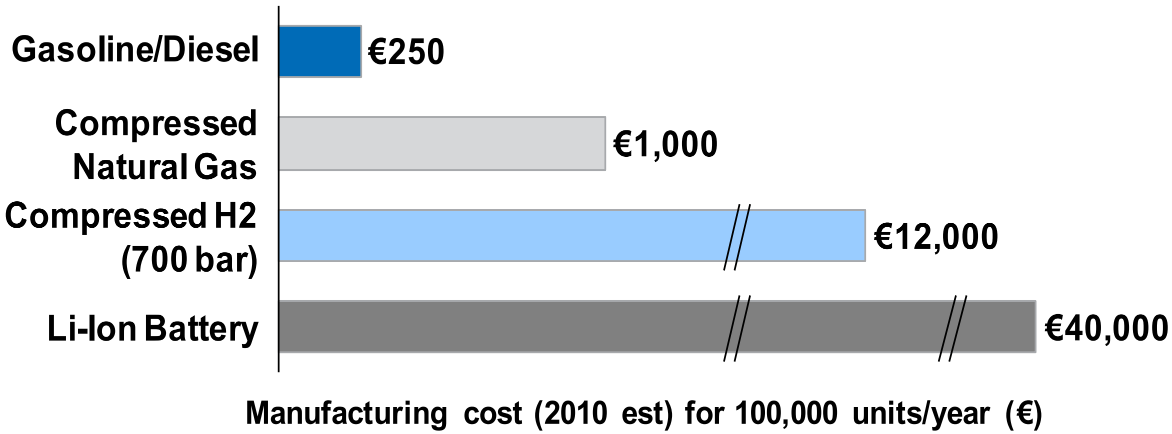
Onboard Fuel Tank System Cost (300 mile range)



- Assumes:
  - 300 mile range Li-ion battery (60 kW.hr)
  - Assuming €500/kW.hr & 80% DoD
  - Full range electric vehicle unlikely in short-medium term

- Other key battery challenges:
  - Low energy density – adds significant weight to each vehicle
  - Limited life – currently below the levels that consumers are likely to demand
  - Limited charge acceptance rate – for many chemistries insufficient for fast charging
- Current battery limitations are driving creative mitigation approaches
  - Alternative business models
  - Battery second life
  - Range extended HEVs & EVs
  - Subsidies
- Oil prices and taxation policies make "Grid connected" vehicles more attractive

Source: Ricardo & Bernstein Analysis & EU FP6 StorHy Project (http://www.storhy.net/)

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- **Economics Will Drive Intelligent Electrification & Advanced ICE’s**
  - An incremental or evolutionary route to low carbon is most cost effective featuring downsizing of combustion engines, intelligent electrification, variable systems & lower carbon fuels. EV & PHEV vehicles will be in widespread use in 20-30 years but combustion engines will still dominate

Incremental improvements are the most cost effective route and make sense in context of CO_2 / fuel consumption penalties

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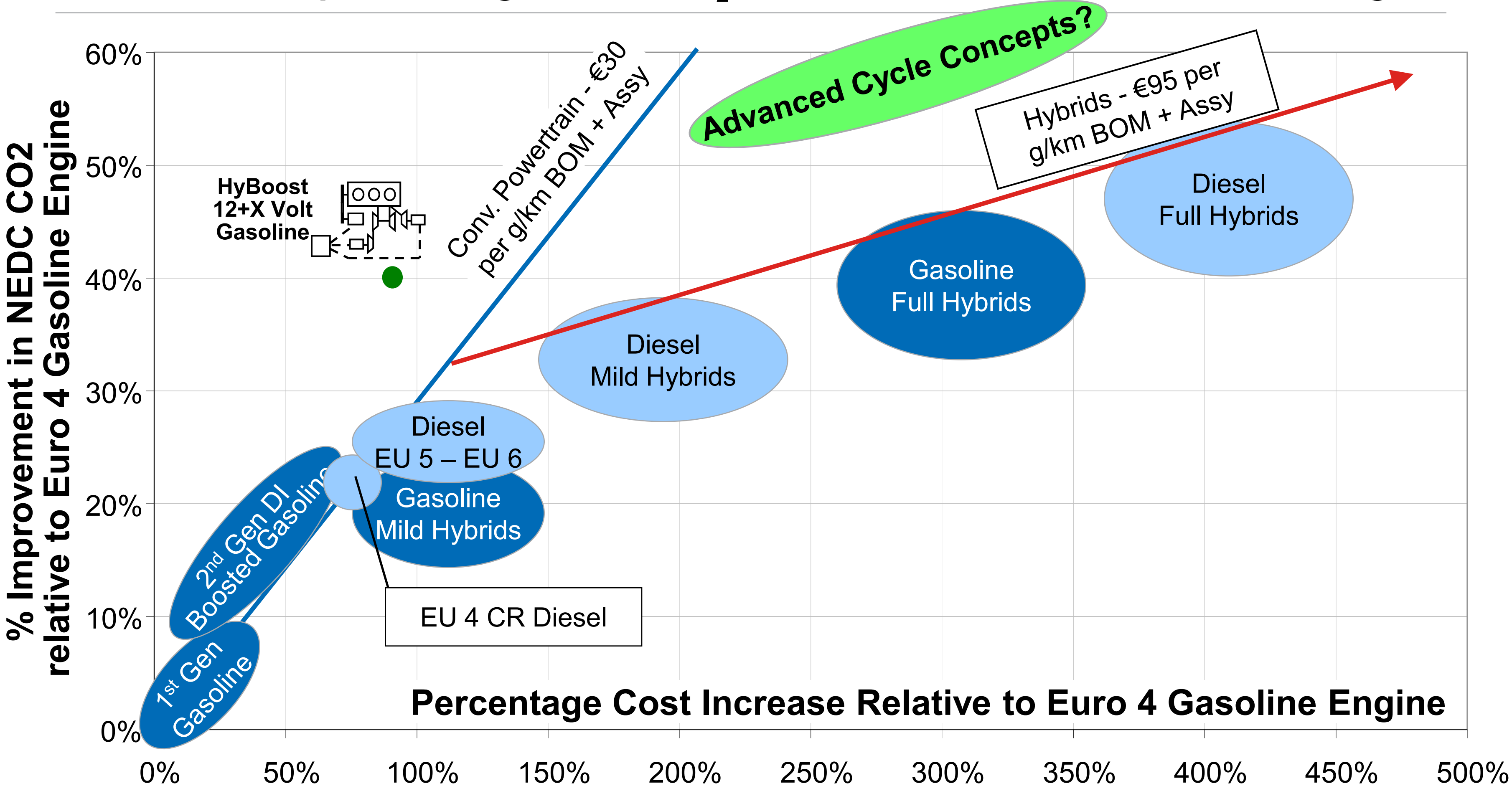
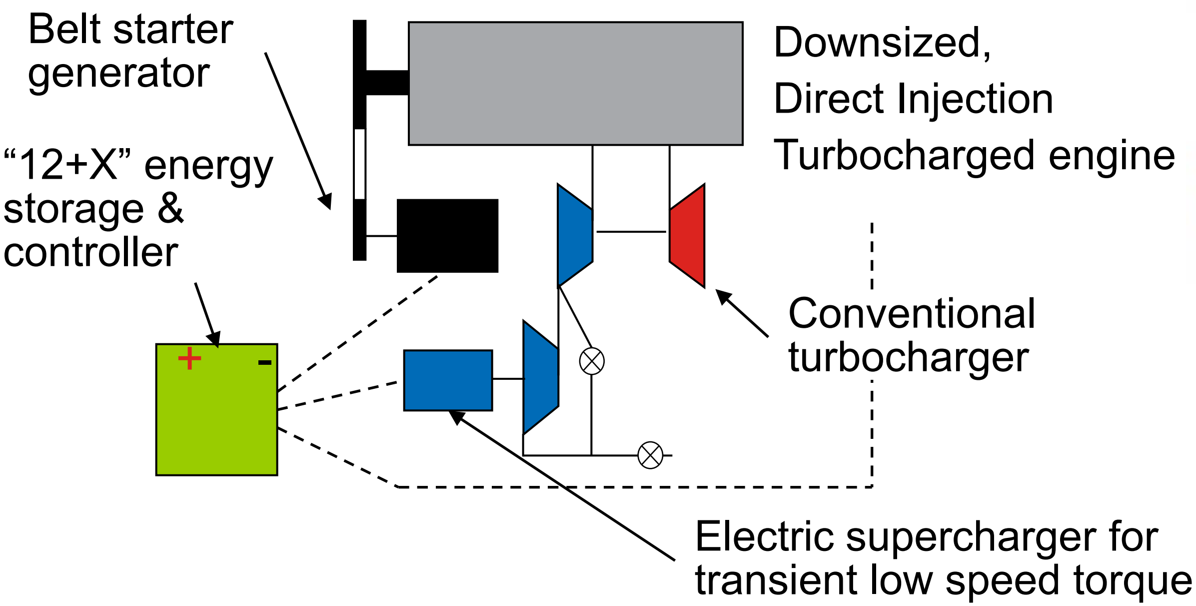
Benchmark Europe Passenger Car: - CO_2 Cost Benefit for Powertrain Technologies

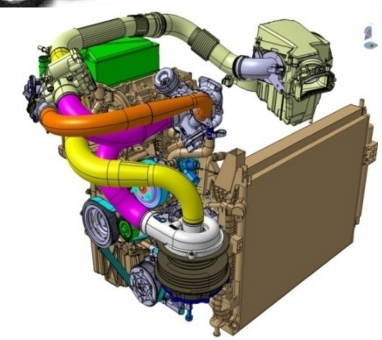


- Consumers buy vehicles – not powertrains – technologies must also compete on image, utility and lifestyle requirements and deliver fundamentally **Good Cars**

Source: Ricardo Analysis

Ricardo HyBoost concept features “Intelligent Electrification” - downsizing, e-Boost & brake energy recovery/stop/start

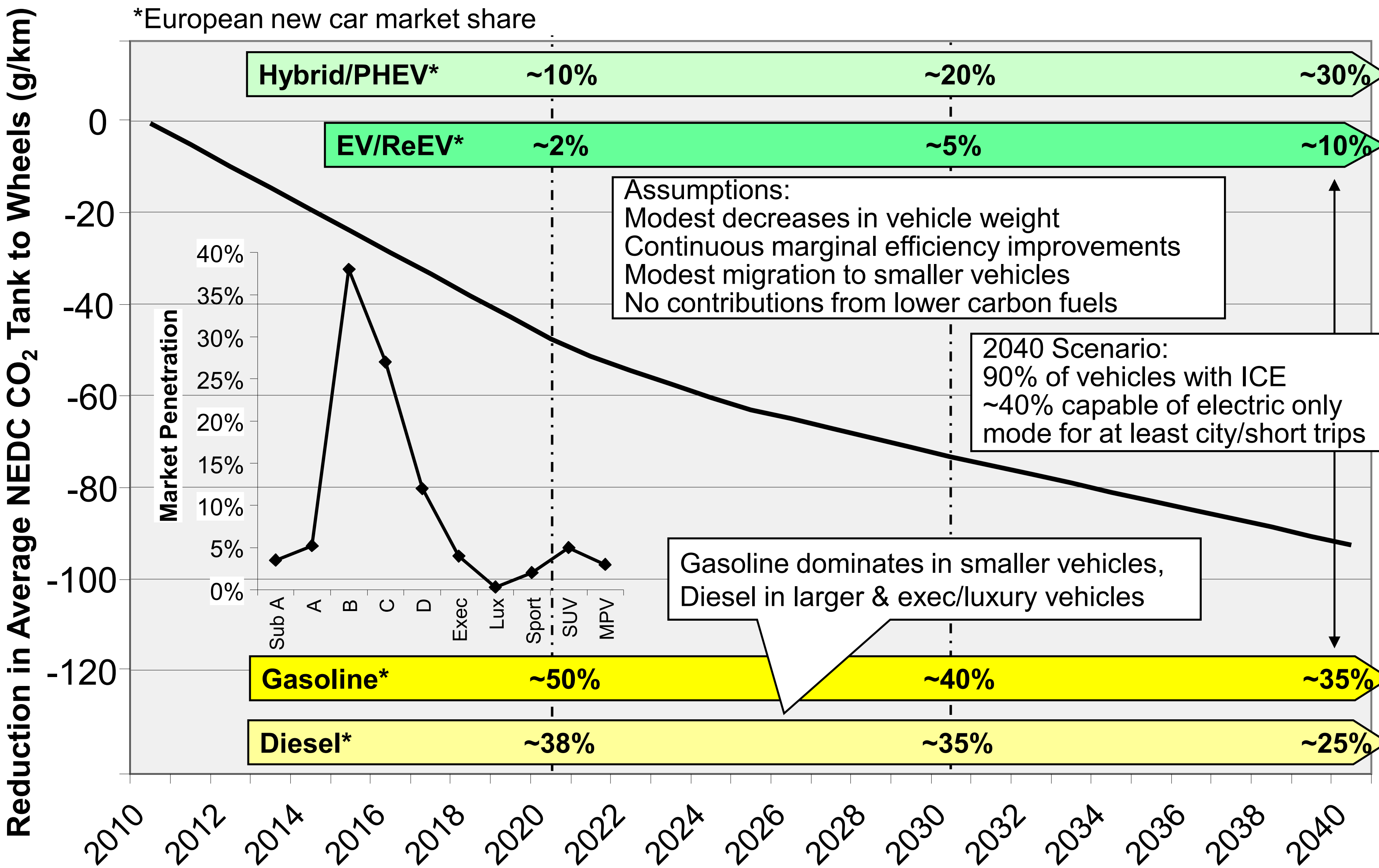




CO_2 Emissions Reduction:	
Base vehicle (Ford Focus 2.0 litre Gasoline) 107 kW:	**169g/km**
50% downsized 1 litre, Boosted DI, low friction 105 kW	-25%
Add stop-start and 6kW re-generation during deceleration	-10%
Add cooled EGR and revised turbo match via e-supercharger	-6%
High torque enables taller gear ratios + gearshift advisor	-7%
HyBoost vehicle emissions	**99.7g/km**

Technology Strategy Board
Driving Innovation

Scenario analysis shows that EV & PHEV vehicles likely to increase penetration but combustion engines will still dominate



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