Greenhouse Gas Reduction Potential

Estimations for Light-Duty Vehicle Technologies in 2020–2025

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Agenda

- **Introduction to Ricardo**
- Technology Roadmaps
- Light Duty Vehicle Greenhouse Gas Reduction Potential

Ricardo Overview

Ricardo delivers world class strategy, engineering and technology programs to the global automotive, transportation, defense, and energy industries

Company

- Established in 1915 and independent
- £196.5 million revenue (FY 10/11)
- More than 1,500 employees with more than 1,300 technically qualified and engineering staff
- Global presence in 16 locations

Values

RESPECT · INTEGRITY · CREATIVITY & INNOVATION · PASSION

Positioning

- Emphasis on achieving enhanced value propositions for our clients
- Multi-sector oriented with relevant domain expertise
- Global footprint with local understanding
- Strategic perspectives and consulting
- Unique holistic vehicle and powertrain experience
- Systems engineering approach that considers integrated solutions for the entire product lifecycle
- Significant self-funded R&D investment
- Technology led product innovation
- Extensive production vehicle and major sub-system introduction experience
- Delivery focused
- Specialist manufacturing and assembly capability for niche product applications

Ricardo History

Almost 100 years of successful project delivery

1915 Engine Patents Ltd. Est.	Harry Ricardo formed Engine Patents Ltd, the precursor of today's Ricardo Plc becoming famous for the design of a revolutionary engine which was utilised in tanks, trains and generators
1930 Fundamental Fuel Research	Development of a variable compression engine which was used to quantify the performance of different fuels. This was the forerunner of today's octane rating scale (RON)
1931 Comet Combustion Chamber	The famous Ricardo Comet IDI diesel Combustion system for high-speed diesel engines was developed for AEC for use in London Buses
1935 Citroën Rosalie	The world's first diesel production passenger car was introduced featuring a Comet Mk III combustion chamber. Derivatives of this design are still used by the major OEMs of today
1951 Fell Locomotive	The 2000bhp Fell Locomotive was the world's first diesel mechanical locomotive, with a novel transmission invented by Lt. Col Fell. It was powered by four Paxman-Ricardo engines.

1966 Jensen FF	The 4WD system of the world's first 4WD passenger car, was developed by Ferguson Research Ltd (which later became part of Ricardo) and was launched at the British Motor Show
1986 Voyager	The first aircraft to fly around the world non-stop without refuelling. Ricardo redesigned the Teledyne Continental engine, thus improving fuel economy and reducing the aircraft's drag
1999 Le Mans Success	Advanced technology helped Audi to secure its special place in motorsport history with a novel transmission to win 5 races out of 6 entries at the 24-hour race of Le Mans
2006 Record Breaking Year	Development of the world's fastest diesel engine for JCB. The DieselMax set the diesel land speed record at Bonneville with a speed of 350 mph (563 kph)
2008 Olympic Games, Beijing	50 off "Olympic Green Messenger" vehicles co-developed by Chery Automobile and Ricardo

Ricardo Client Base

Represented across a number of key market sectors each with unique drivers

Passenger Car

High Performance Vehicles & Motorsport

Commercial Vehicles

Agricultural & Industrial Vehicles

Motorcycles & Personal Transportation

Marine

Rail

Clean Energy & Power Generation

Defence

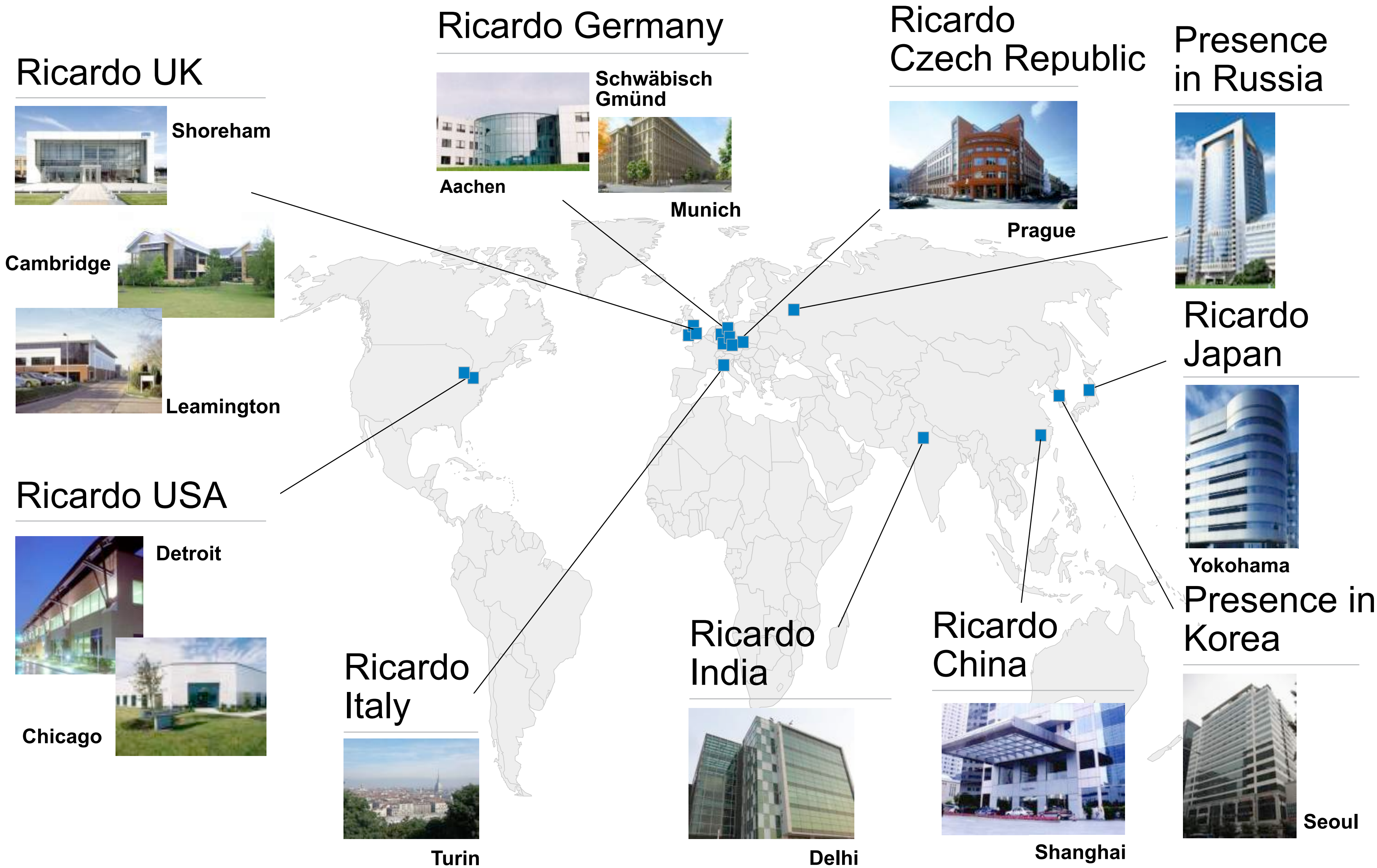
TACOM

UK MoD

Government

Ricardo Locations

Our Global footprint allows us to understand the local needs of our clients



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- **Technology Roadmaps**
- Light Duty Vehicle Greenhouse Gas Reduction Potential

Future Trends in Vehicle Technology

- **Regulation is driving new technology & innovation to higher efficiency**
  - Accelerating the rate of technology introduction to passenger cars
  - European regulation likely for Commercial vehicles following US/Japan lead
- **Passenger car efficiency dominated by ICE technologies in the short/med term**
  - There is no “silver bullet” - we will need a range of technologies to meet targets
  - A better understanding of life cycle emissions will enable more informed choices
  - Electrification is a longer term trend but we need a breakthrough in batteries
- **Both evolutionary and disruptive technologies are likely to be successful**
  - Intelligent Electrification is a key approach to enable more radical ICE technology
  - Mechanical Hybrids could offer substantial cost reductions over electric systems

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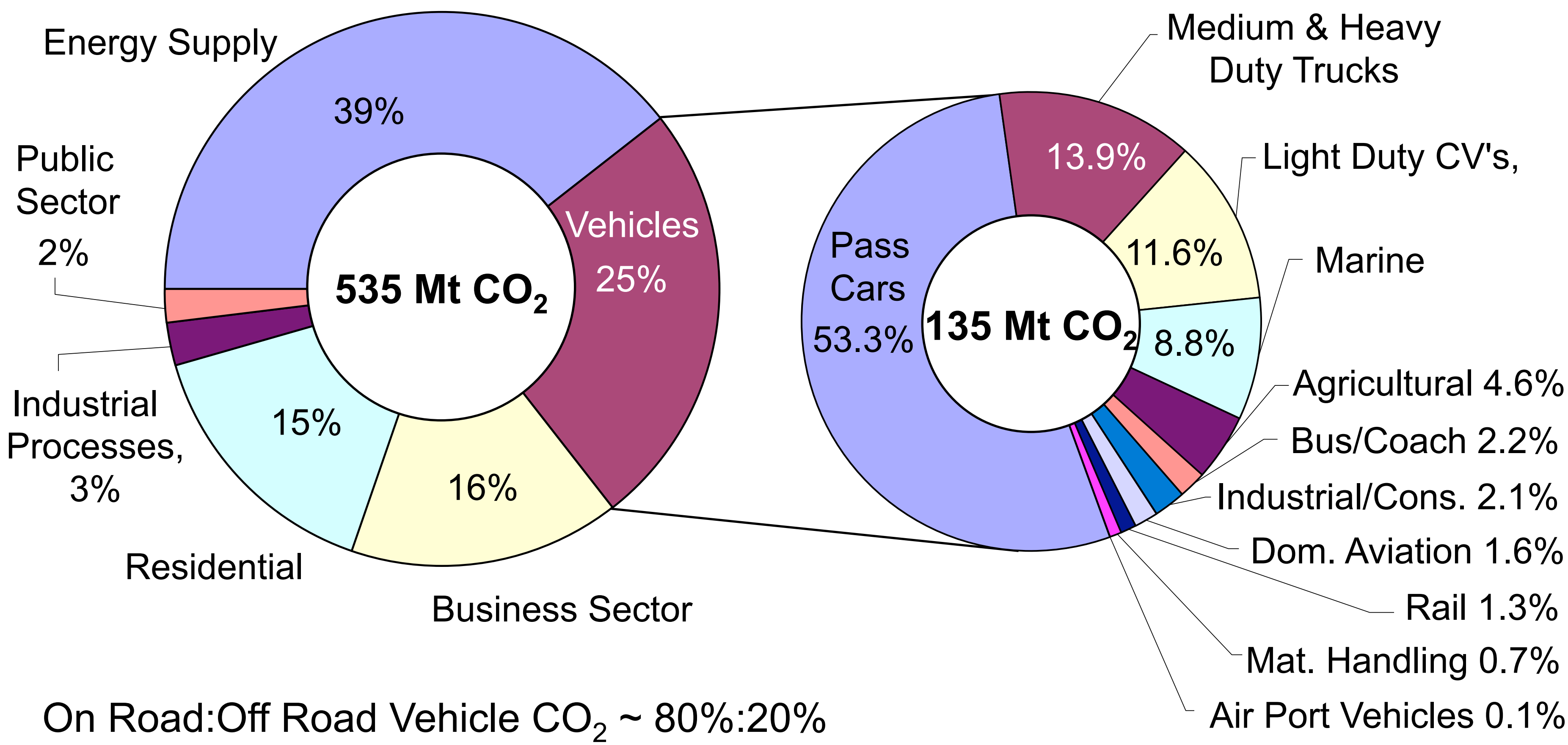
Recent CO_2 focus on passenger car but governments are expanding GHG targets to other applications

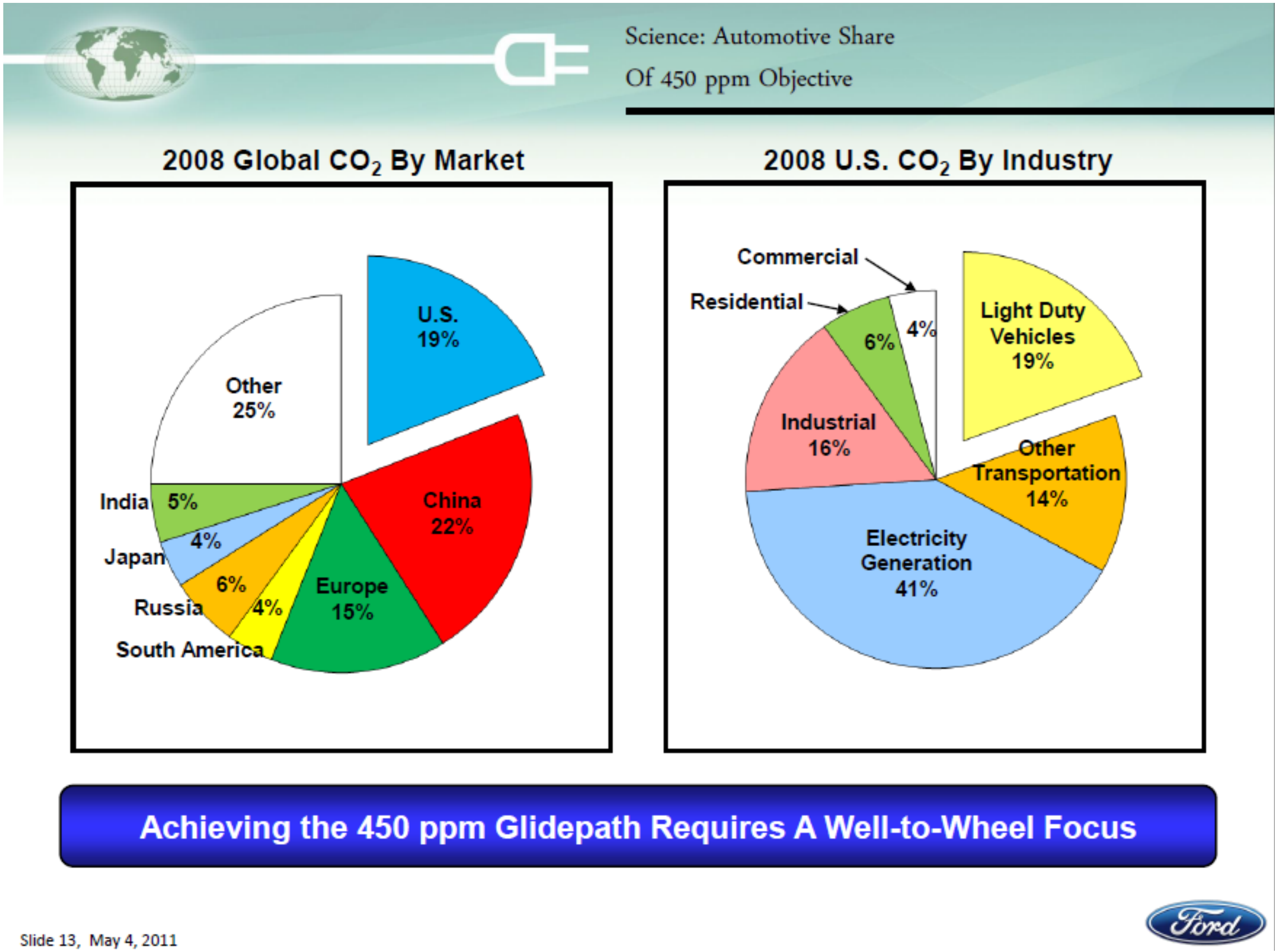
- UK emissions data: Only half of vehicle CO_2 is produced by passenger cars



On Road:Off Road Vehicle CO_2 ~ 80%:20%

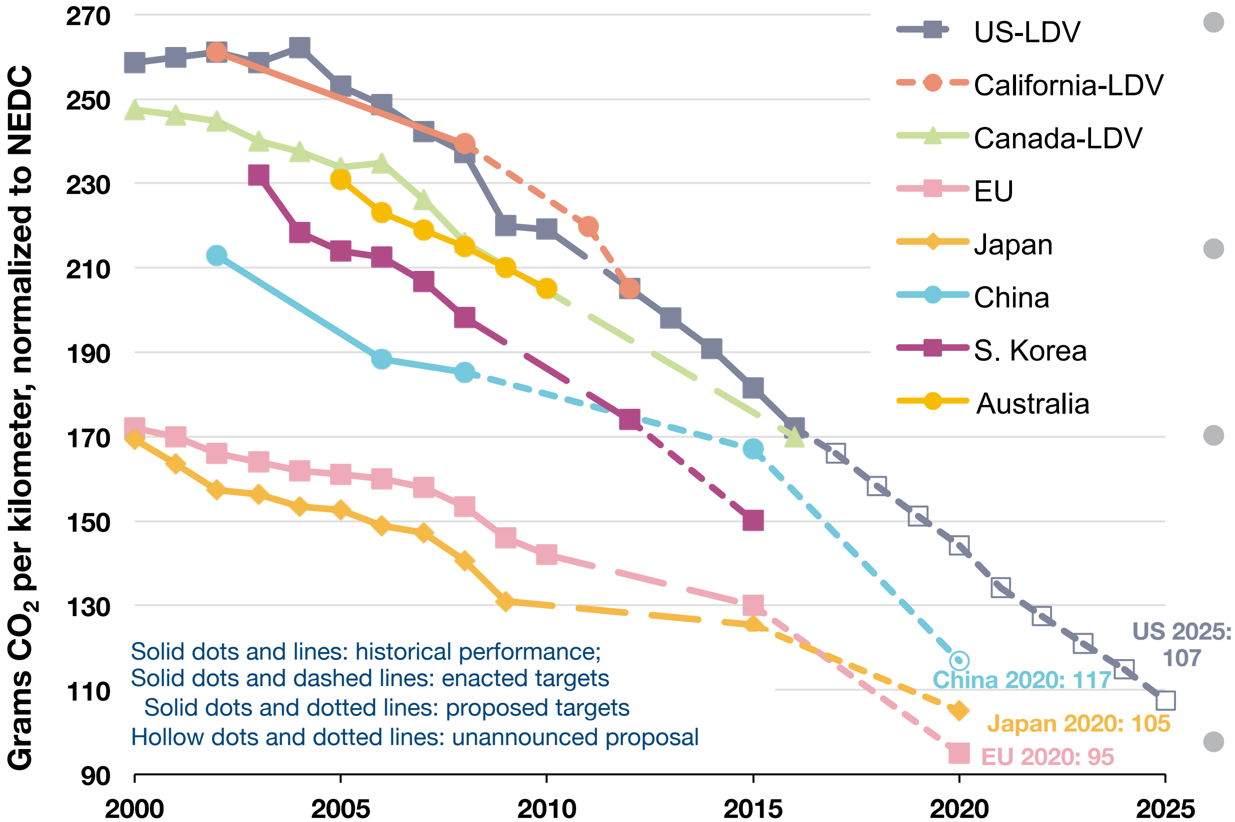
Source: DECC & Ricardo analysis

Similarly in U.S., light-duty vehicles account for 57% of CO_2 emissions—a comprehensive approach is required



Source: Nancy Gioia, 4 May 2011, "Key Trends and Drivers for the Future"

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

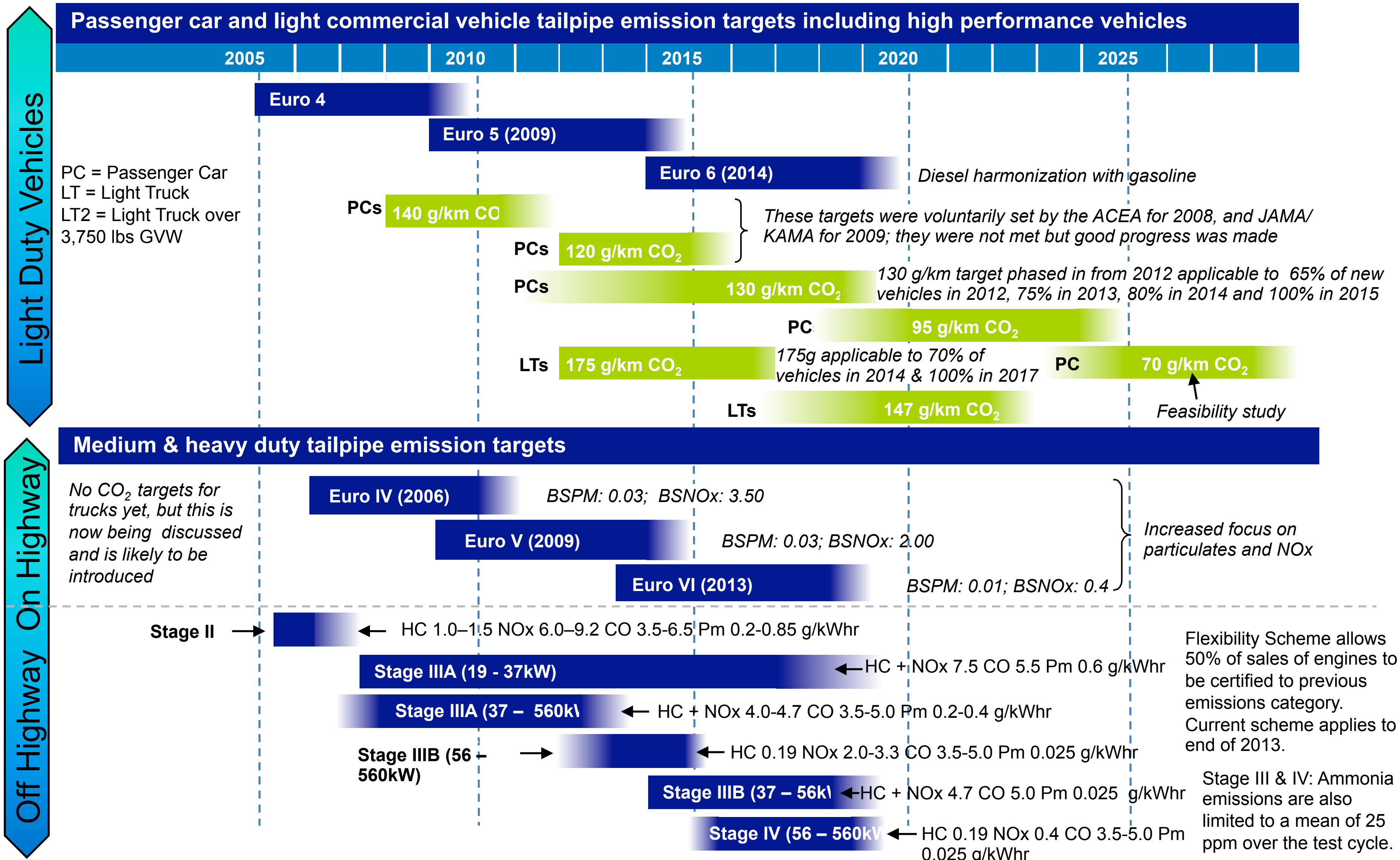


[1] China's target reflects gasoline fleet scenario. If including other fuel types, the target will be lower.
[2] US and Canada light-duty vehicles include light-commercial vehicles.

- 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 proposed 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

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

European regulation will continue to drive lower toxic emissions with additional CO_2 legislation likely

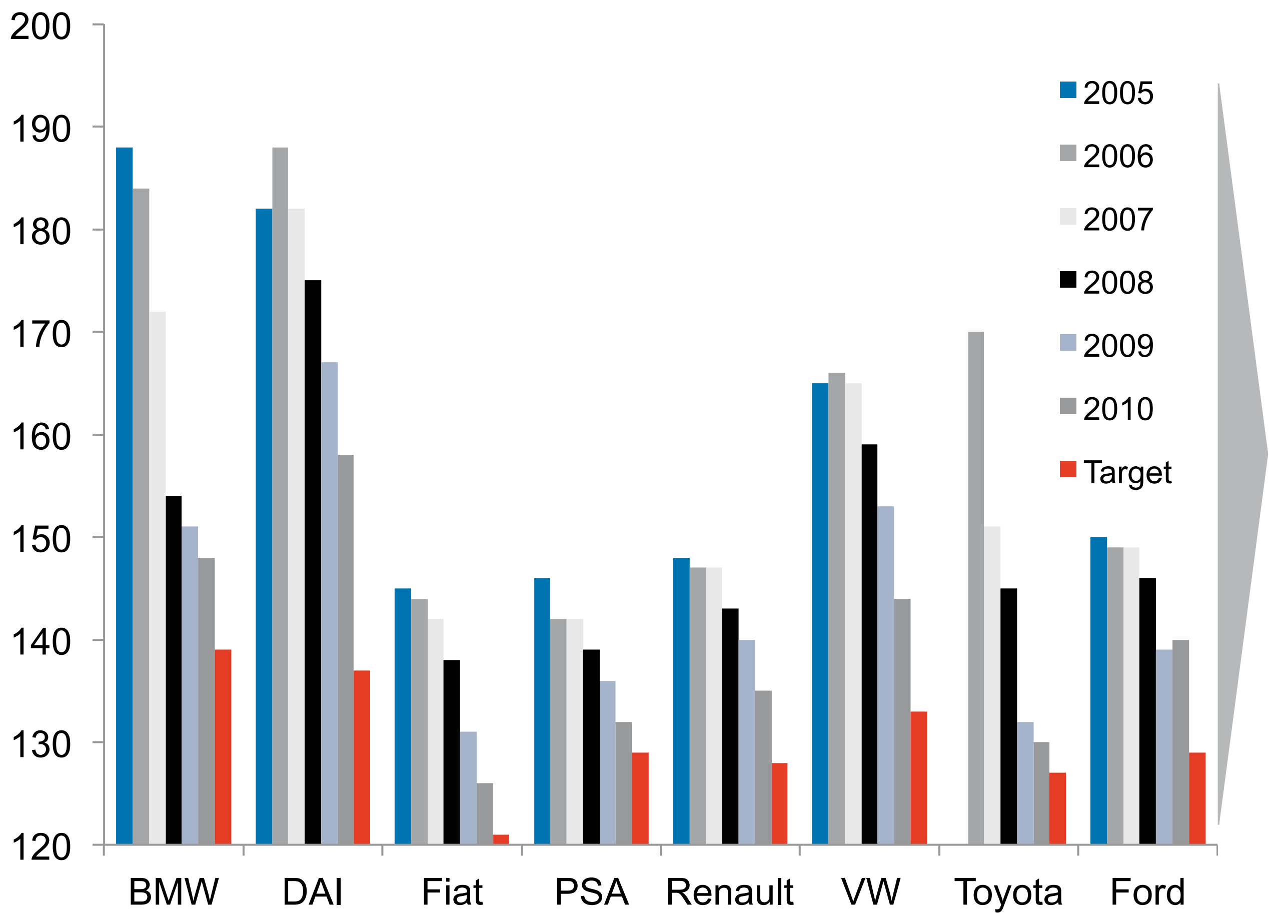


Key: tailpipe emission target — CO_2 emissions / fuel economy target

Sources: Ricardo & National government publications.

Progress has been made against EU emissions legislation, but Pass Car OEMs 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

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There are three interlinked phases of change required to current light duty powertrain technology and strategy

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SHORT TERM: ~2015

- Boosting & downsizing
  - Turbocharging
  - Supercharging
- Low speed torque enhancements
- Stop/Start & low cost Micro Hybrid technology
- Friction reduction
- Advanced thermal systems
- Niche Hybrid, PHEV's and Electric Vehicles

MEDIUM TERM: ~2025

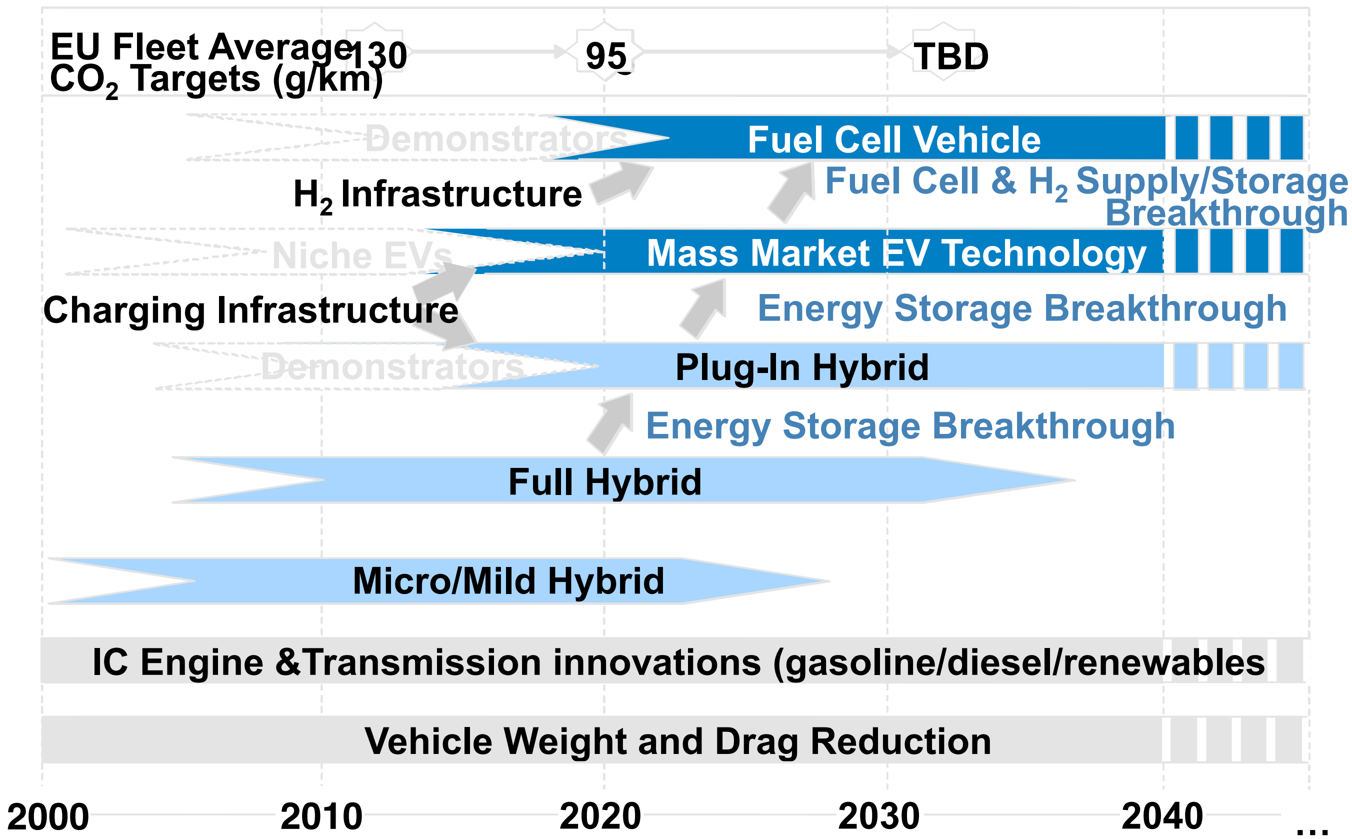
- High Efficiency Advanced Combustion:
  - Lean Stratified SI
  - Low temperature combustion
- Combined turbo/ supercharging systems
- Advanced low carbon fuel formulations
- PHEV's in premium & performance products
- EV's for city vehicles

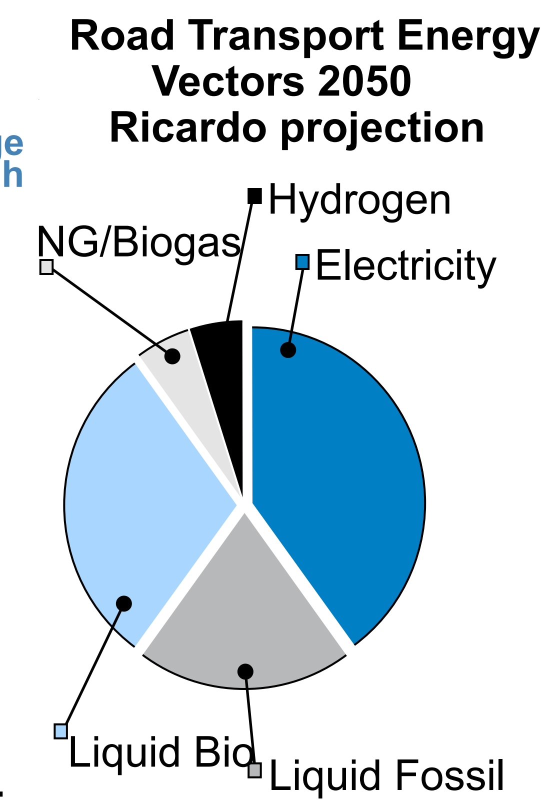
LONG TERM: ~2050

- Plug-in/Hybrid electric systems dominate
  - Very high specific power ICE's
- Range of application specific low carbon fuels
- Exhaust & Coolant energy recovery
- Advanced thermodynamic Cycles
  - Split Cycle?
  - Heat Pumps?

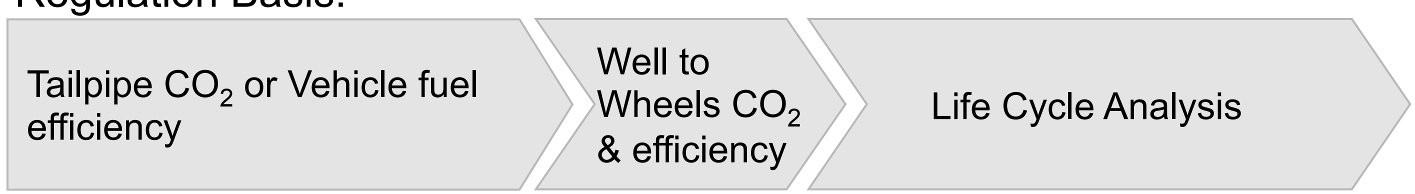
Source: Ricardo Technology Roadmaps, Ricardo Analysis

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



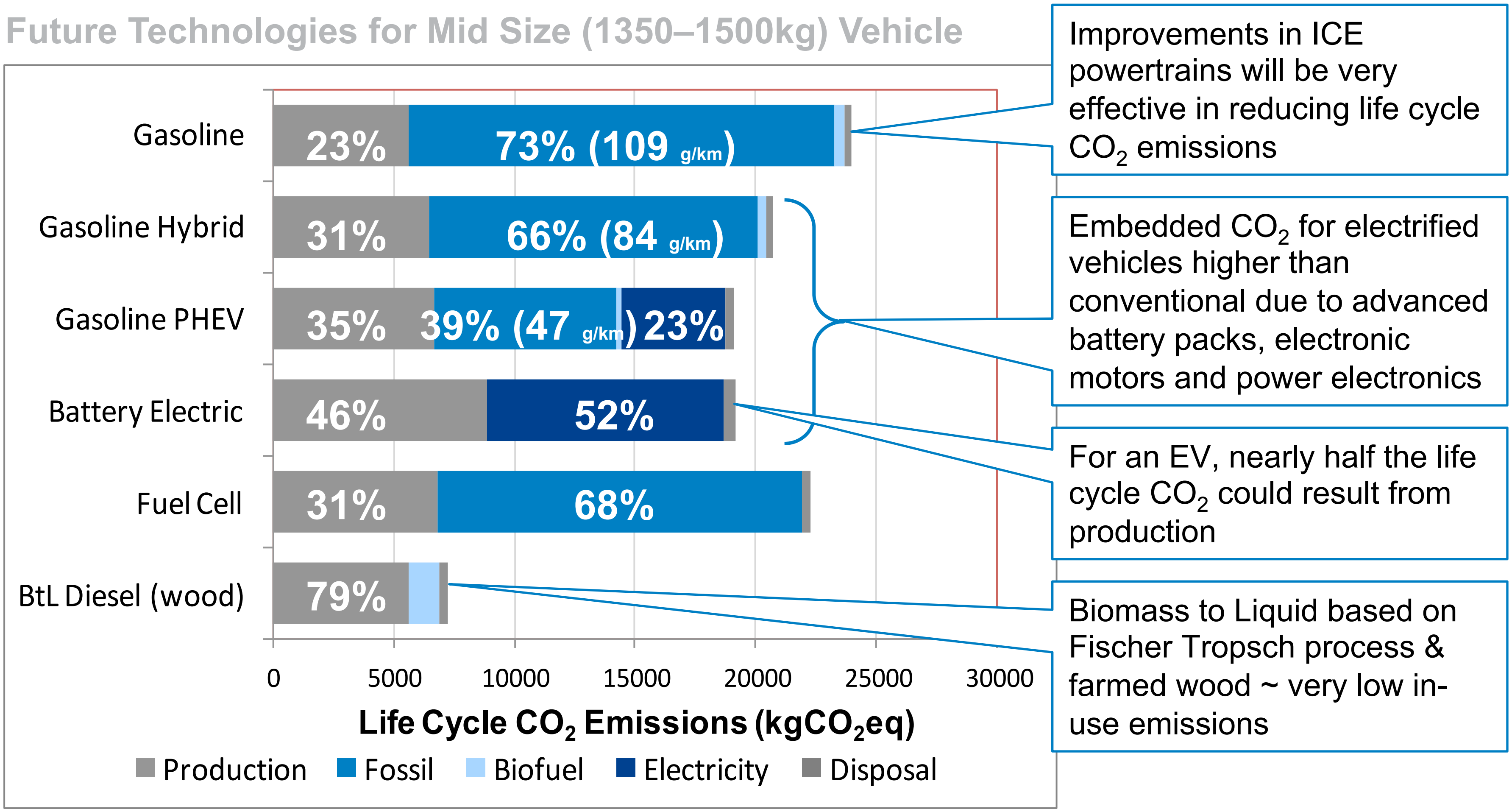


Regulation Basis:



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



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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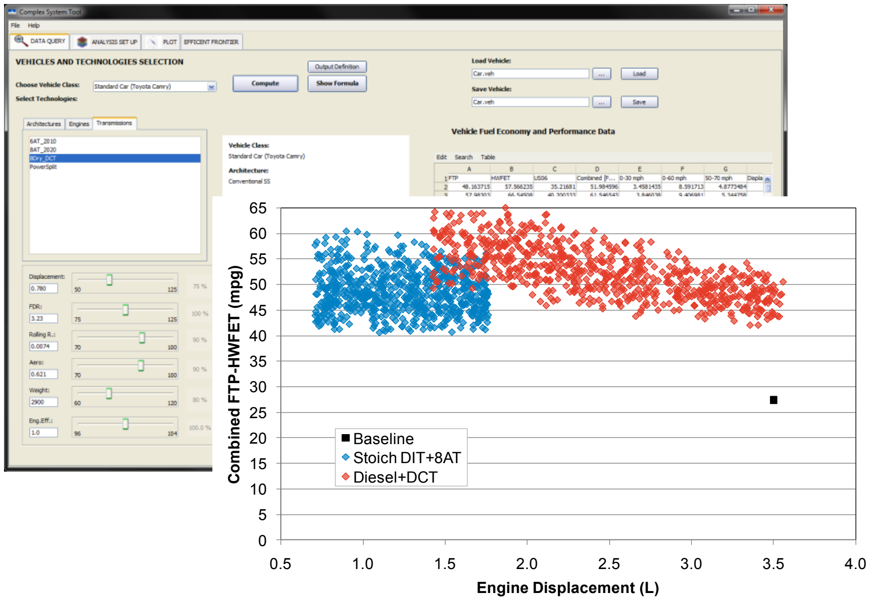
Technical Input to EPA for 2017–2025 Light Duty Vehicle Greenhouse Gas Proposed Rule



Approach

- Ricardo team identified future technology packages and estimated their effects on fuel consumption
- Created new vehicle classes, implemented hybrid powertrains and controls (P2 and Powersplit), and incorporated new technology packages to define a broad design space
- Ricardo's complex systems modeling approach used to examine the extensive design space

Situation and objective

- EPA wanted objective technical input to support Notice of Proposed Rule Making (NPRM)
- Analysis estimates greenhouse gas emissions of future vehicles based on future technology packages and combinations thereof
- Use a defensible rationale for technology section revisions to rule including new/ revised technology definitions, technology selection logic, vehicle classes, and applicability

Results and benefits

- Improved accuracy of technology applicability, and a defensible rationale for rule making
- Broad design space allows examination of several combinations of technologies, and their synergistic effects
- Data visualization tool facilitates exploration of the design space
- Fully documented approach and results for use in rule by EPA

Ricardo brought its global expertise to bear, first for EPA looking at the U.S. market, then for ICCT looking at the EU

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Project Leadership
Chief Engineer
Program Manager

RICARDO

Subject Matter Experts
Engines
Transmissions
Hybrid Systems
Vehicle Systems

Simulation Team
Vehicle Performance Simulation
Hybrid Controls

Report Review Team
Global, cross-functional team to review program report

EPA United States Environmental Protection Agency

SRA INTERNATIONAL, INC.

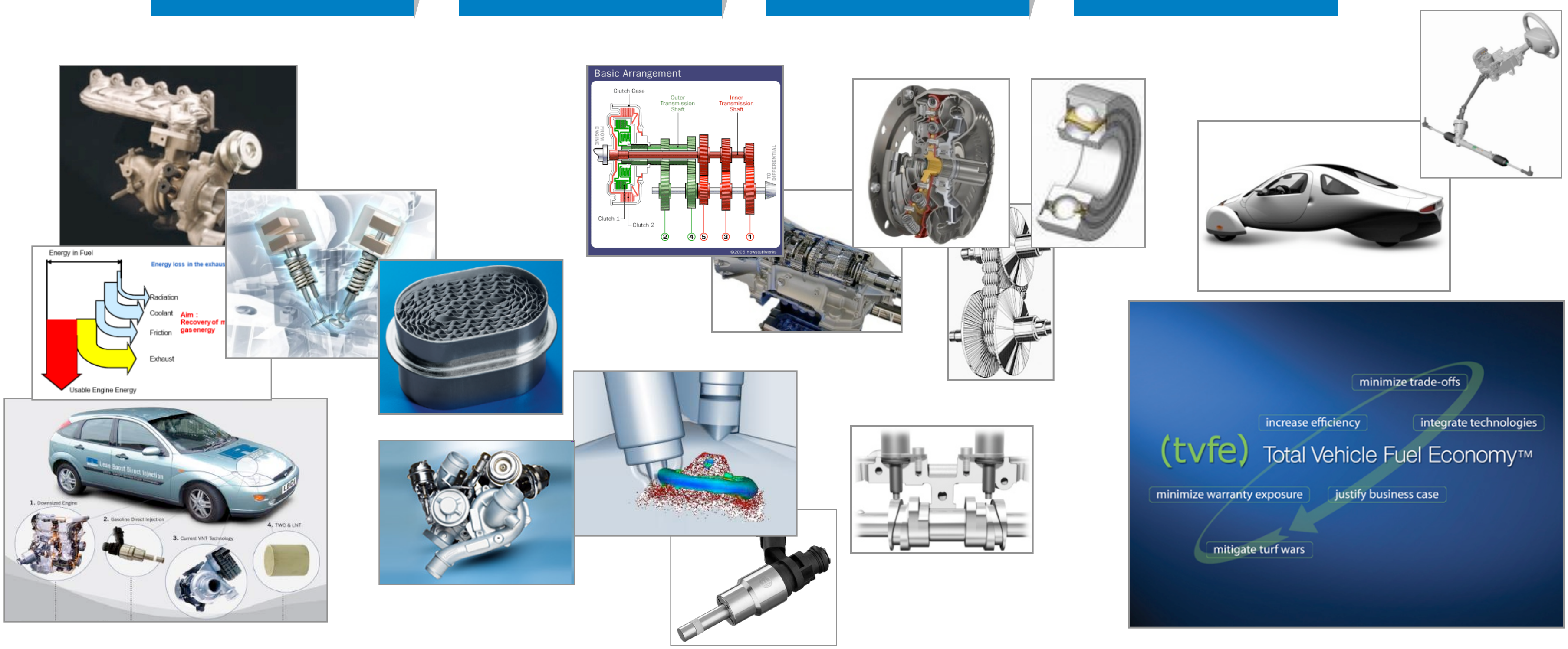
Advisory Committee

California Environmental Protection Agency
Air Resources Board

icct
THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

Ricardo and EPA used an agreed process to evaluate technologies for inclusion in the study design space

Technology Identification → Ricardo Subject Matter Expert Assessment → EPA Review & Technology Discussion → Technology Package Selection



Ricardo, EPA, ICCT, and Calif ARB identified several LDV technologies for further evaluation by Ricardo SMEs

Technology Identification → Ricardo Subject Matter Expert Assessment

- Engine technologies and configurations
  - Fuel injection, boost system, valvetrain, combustion, and controls
- Hybrid powertrain technologies and configurations
- Transmission technologies and configurations
  - Advanced automatics, CVT, DCT, launch devices
  - Transmission technologies
- Vehicle technologies
  - Mass reduction, aerodynamic improvements, rolling resistance, accessories

Gasoline engines focus will be on CO_2 reduction as emission legislation remains less challenging, even under LEV III

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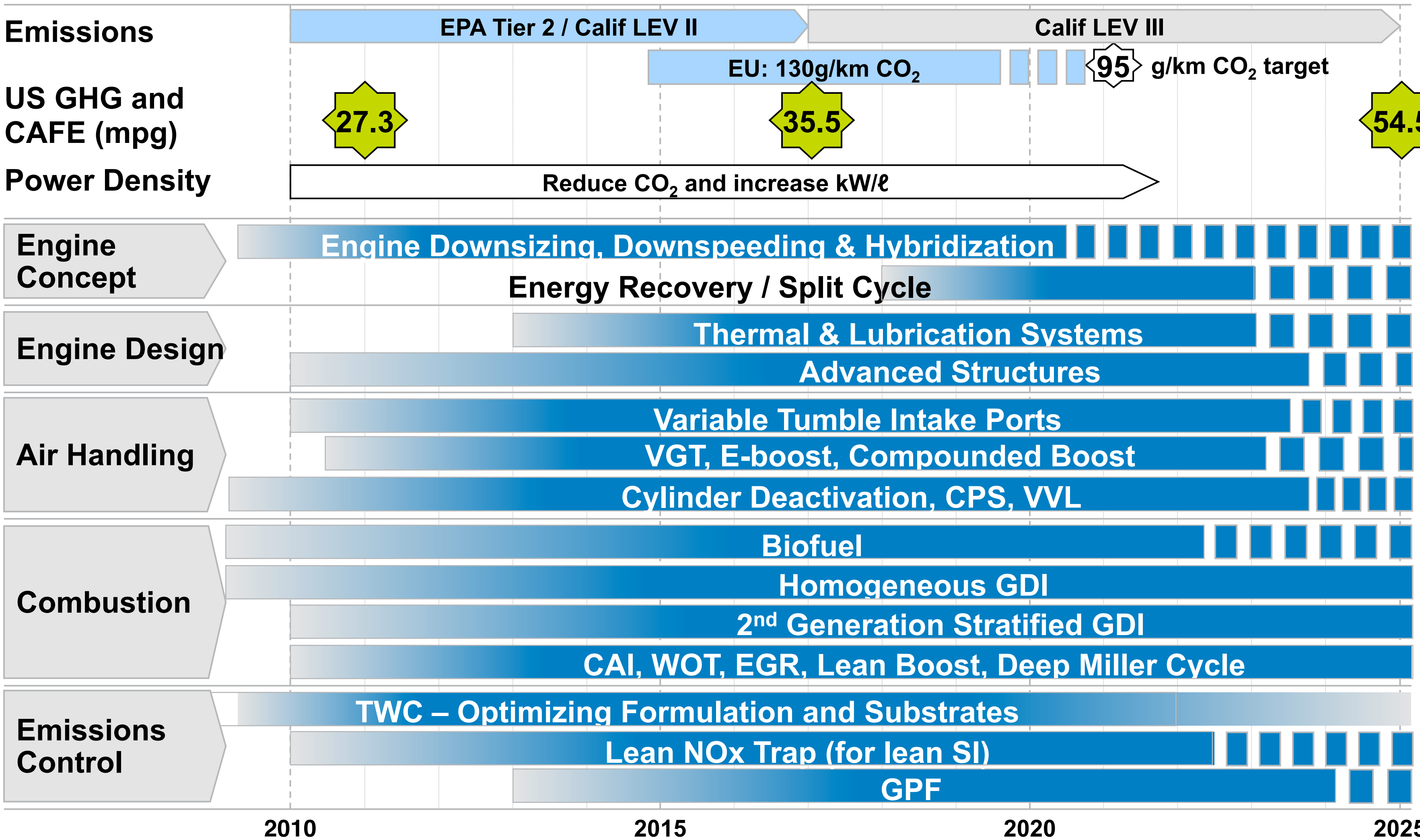
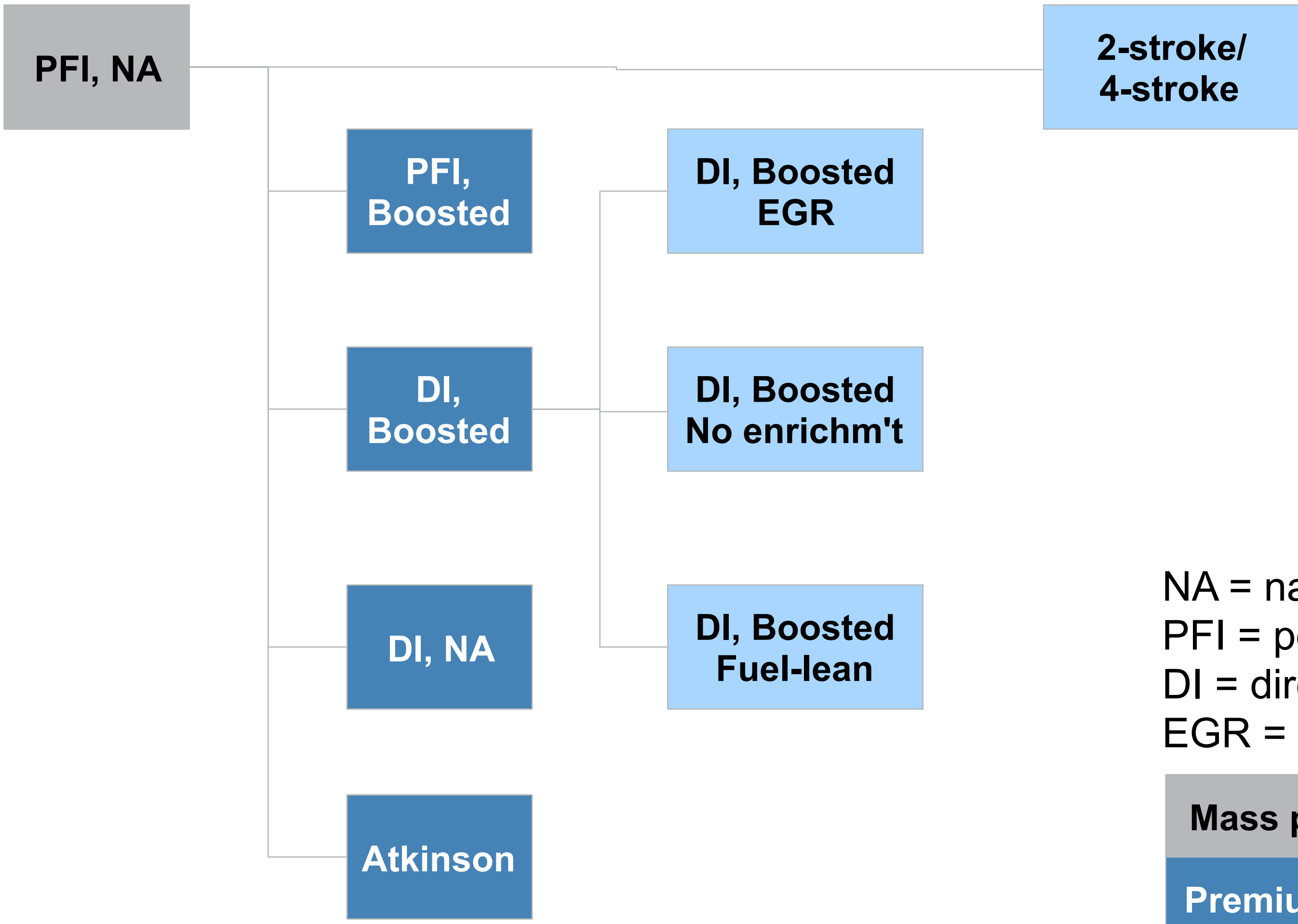
Technology Roadmap for Light Duty Gasoline



Source: Ricardo Analysis "

Pathways for gasoline engine development
Progress from research to premium product to mass market



NA = naturally aspirated
PFI = port flow injection
DI = direct injection
EGR = exhaust gas recirculation

Mass production
Premium product
Research / demo

Source: Ricardo Analysis

Ricardo SME assessment example
Advanced Boosting Technologies

Technology and Status

- **Concept:** Improvements in air handling through a suite of boosting technologies either standalone or in combination
- **Base Functioning:** Provision of higher specific torque and power to enable downsized engines. Technologies include eBoost (e-machine in CHRA or electrical separation by e-Turbine and e-Compressor); supercharging (advances to avoid variable drive); variable nozzle compressor
- **CO_2 Benefit:** 2% (more if engine downsized for equivalent performance)
- **Costs:** Increase in turbocharger air system matching and development time, increased complexity in engine controller. Variable cost of turbocharger doubles plus additional air cooling requirement, sensors and actuators

Ratings of Technology

1 (worst) ↔ 10 (best)

Effectiveness	3
Availability	7
Market Penetration	5
Long-Term Cost Viability	7
Current Maturity	4

Technology Applicability

- Technology applicable to all sectors of diesel application
- Highway benefits – improved transient response from engine allows downsizing. More air allows improved emission performance for NOx and PM control giving leeway for CO_2 reduction.
- City benefits – much improved transient performance allowing downsizing. Operation in more efficient area of turbocharger map gives more noticeable CO_2 benefit in city driving
- In conjunction with enhanced EGR allows for premixed or homogeneous combustion in part load operation for very clean emissions. Design can facilitate the use of pre-TC catalyst for quick aftertreatment light-off

Visualization

Picture: http://honeywellbooster.com

Ricardo SME assessment example
Launch Device: Damp Clutch

Technology and Status

- **Concept:** Similar concept as a wet clutch but only a limited spray is applied to achieve cooling
- **Base Functioning:** Still requires a lubrication system but is more efficient due to controlled environment (less windage and churning)
- **CO_2 Benefit:** Similar benefits as a dry clutch
- **Costs:** **slight increase to** wet clutch

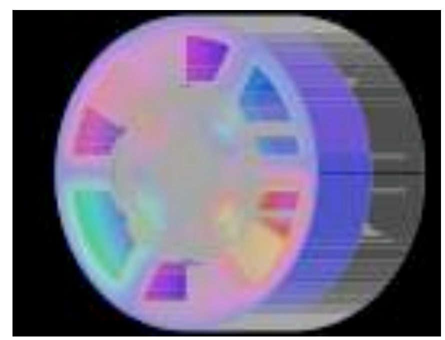
Ratings of Technology

Technology Applicability

- Applicable to most automatic transmissions – best of both worlds, efficiency of a dry clutch matched with the longevity and higher torque capacity of a wet clutch
- As for the other launch devices, the increase in efficiency is applicable mostly to city driving.

*Note: Effectiveness relates to improvement in transmission efficiency

Visualization



Picture: www.cerom.lsu.edu

Ricardo SME assessment example
Aerodynamics: Active

Technology and Status

- **Concept**: Opportunity exists to reduce overall vehicle drag through improved control of drag-affecting features (cooling apertures, ride-height etc). Radiator grill sizing is designed for maximum thermal rejection; at high ambients / high vehicle loads. Most of the time, the majority of vehicles need much less cooling. Thus openings can be significantly reduced, reducing vehicle drag.
- **Base Functioning**: A reduction in C_D has a direct affect on reduction of the force required to enable forward motion. As drag force is dependant on the square of vehicle speed, at higher speeds, the fuel economy gain is increased
- **CO_2 Benefit**: Active cooling aperture control could give an 8-10% vehicle drag reduction. A 10% reduction in drag can give a 2.5% improvement in fuel economy
- **Costs:** Some associated on-cost

Technology Applicability

- The faster the vehicle is required to travel, the greater benefit this is. Most effective where significant freeway travel is required. Suits all powertrain variations
- Has some (small) weight penalty, thus city-only vehicles may be penalized; however, city-only cars could have altered drive-cycles, as unlikely to need to drive up mountains in Death Valley, at GVW
- Potential improvements through cooling system aperture control C_D 0.008 for small and medium cars and 0.03 for large passenger cars and SUVs
- Where available, ride height reduction with increasing speed reduces the effective frontal area, and increases tire coverage

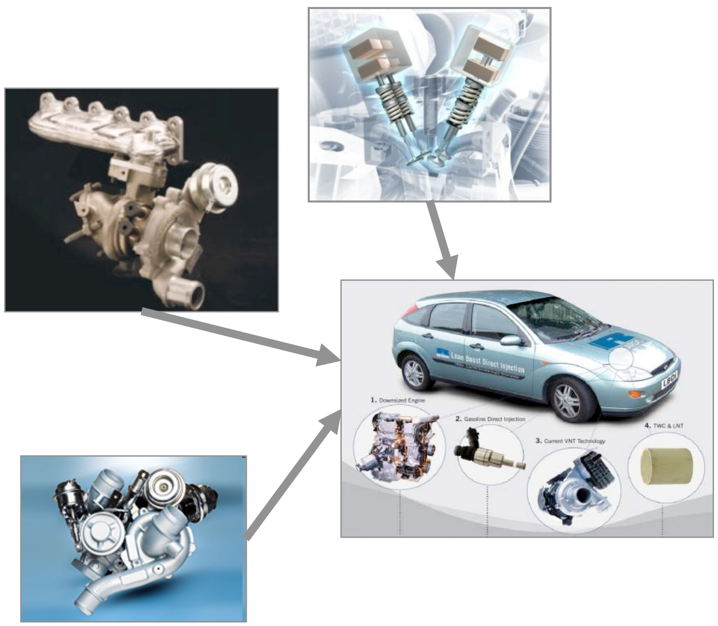
Ratings of Technology

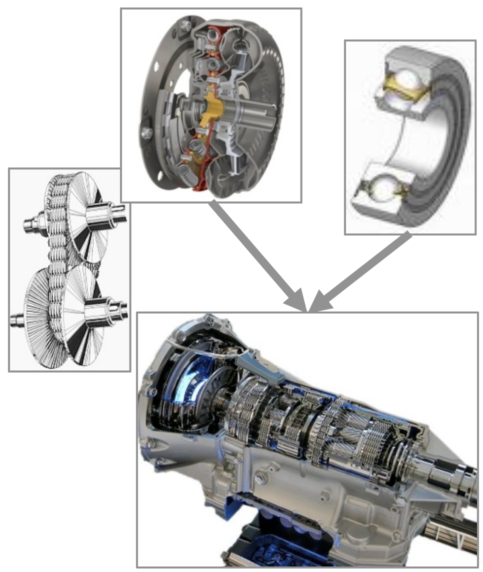
Visualization

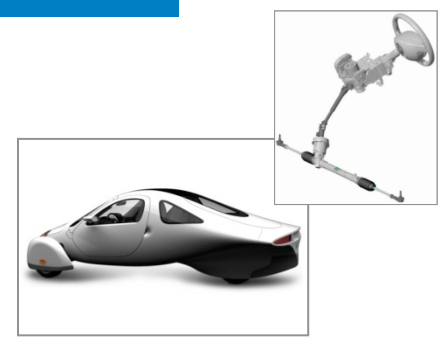
Picture: www.parkviewbmw.com

Ricardo SME assessments were then reviewed, and technology packages developed for further evaluation

Technology Identification → Ricardo Subject Matter Expert Assessment → EPA Review & Technology Discussion → Technology Package Selection

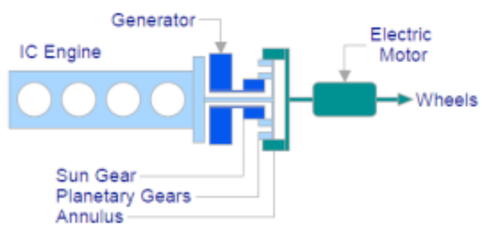


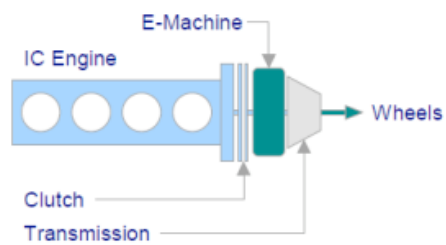




Technology packages in the 2020–2025 Design Space

- Vehicle classes: (EPA study only in blue)
  - B Class (Small Car)
  - C Class
  - D Class (Standard Car)
  - E Class (Full Size Car)
  - Small crossover utility vehicle (Small multi-purpose vehicle)
  - Small N1
  - Large N1 (Large MPV)
  - Light-Duty Truck
  - Light Commercial Vehicle (Light Heavy-Duty Truck)
- Powertrain architectures:
  - Conventional, with stop-start
  - Powersplit hybrid
  - P2 hybrid

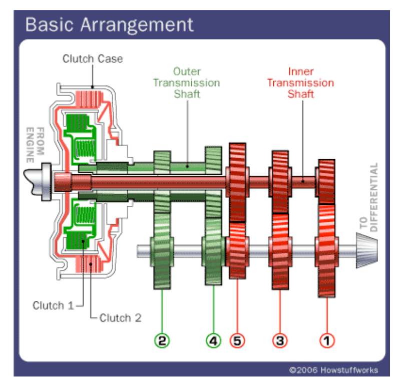




Technology packages in the 2020–2025 Design Space

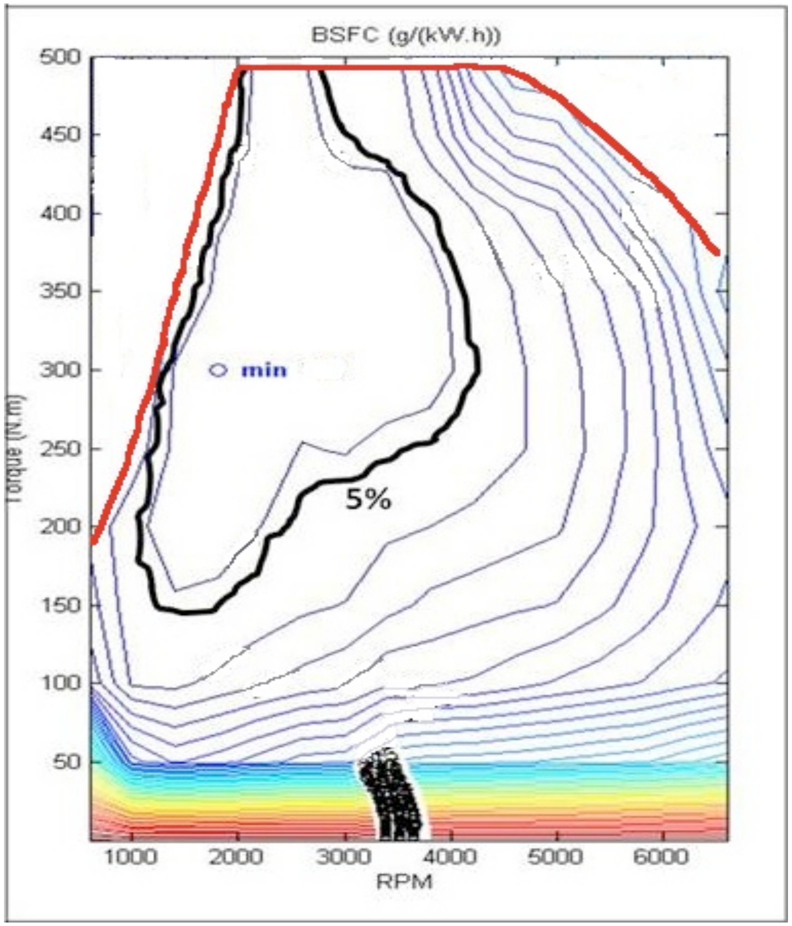
- Engines:
  - Stoichiometric direct-injection turbocharged (SDIT) SI engine
  - Lean-stoichiometric direct-injection turbocharged (LDIT) SI engine
  - EGR direct-injection turbocharged (EDIT) SI engine
  - Atkinson cycle SI engine with cam-profile switching (CPS)
  - Atkinson cycle SI engine with digital valve actuation (DVA)
  - Advanced European Diesel
  - Advanced U.S. Diesel
  - 2010 Baseline SI engines
  - 2010 Baseline Diesel engines

- Transmissions:
  - 2010 baseline six-speed automatic
  - Advanced automatic transmission, eight-speed
  - Dual clutch transmission, eight-speed, dry or wet clutch
  - Powersplit planetary gearbox

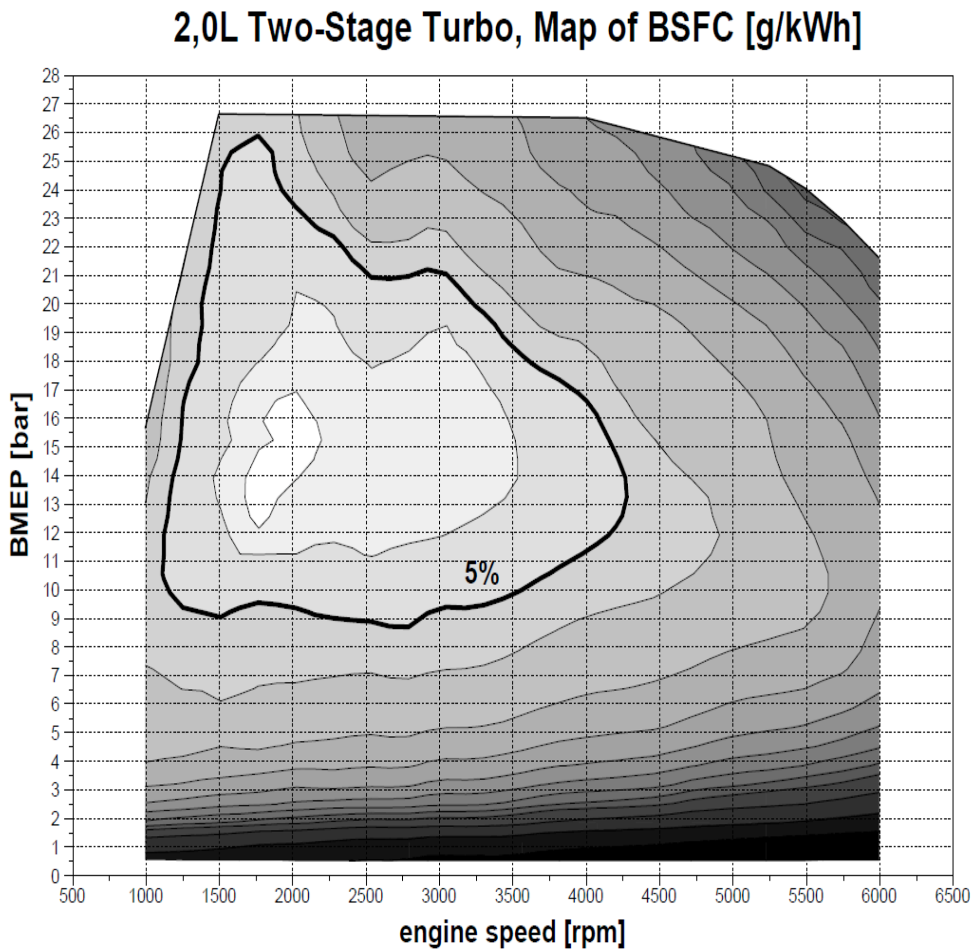


Ricardo developed model inputs for technology packages, e.g., Stoichiometric, Direct Injection Turbocharged Engine

Efficiency map generated by Ricardo for EPA program (left) is based on benchmarking and research data, and compares favorably to research results from 2011 General Motors paper (right) from demonstration engine.



Source: Ricardo Analysis



Source: Schmuck-Soldan, S., A. Königstein, and F. Westin, 2011

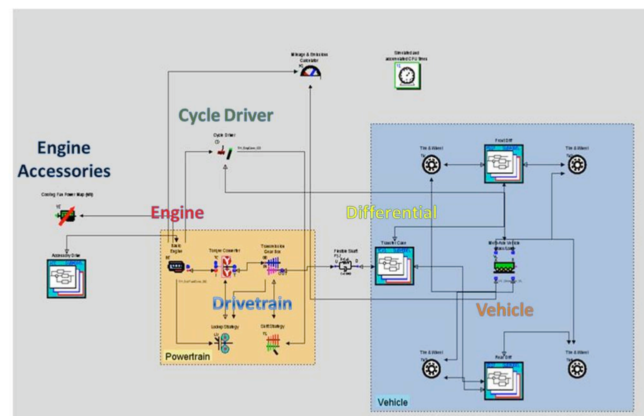
The 2020–2025 Design Space was defined and sampled for simulation results

- The complete design space covered by the EPA and ICCT studies includes
  - 9 light-duty vehicle classes (7 for EPA, 6 for ICCT)
  - 3 powertrain architectures (conventional, Powersplit Hybrid, and P2 Hybrid)
  - 9 engine types (two baseline + seven advanced)
  - 4 transmission types (baseline, advanced automatic, wet & dry DCT)
  - 6 vehicle-level continuous parameters (mass, final drive ratio, aero, etc.)
  - 6 drive cycles (NEDC, FTP, HWFET, US06, JC08, performance)
- With DoE method, needed ≈400,000 simulations to sample the design space

	Hybrid Architecture		Advanced Engine				
Vehicle Class	P2 Hybrid with 2020 DCT	Input Powersplit	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		DoE Range (%) 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

			ced Engine				Advanced Transmission				
Vehicle Class	Baseli 2010 6 Autom	2010 D 6-Spee Transi	Stoich with C	Lean with C	EGR DI Turbo with CPS	2020 Diesel	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

Results from DoE simulations fit to Response Surface Models, which were then implemented into a Data Visualization Tool

RSM were fit using neural nets

Input Factors

- Vehicle class
- Powertrain configuration
- Engine
- Transmission
- Engine displacement
- Final drive ratio
- Rolling resistance
- Aerodynamic drag ($C_d \cdot A$)
- Vehicle mass
- Engine efficiency
- Electric machine size

Output Factors

- Drive cycle fuel economy
  - NEDC, JC08, US06
  - FTP, HWFET, and combined
- Drive cycle CO_2 emissions
  - NEDC, JC08, US06
  - FTP, HWFET, and combined
- Acceleration times
  - 0-10, 0-30, 0-50, 0-60, 0-70 mph
  - 30-50 mph, 50-70 mph
- Top speed on 5% or 10% grade
- Velocity or distance at 1.3 s
- Velocity or distance at 3.0 s

Source: 8pt Dark Grey (R 167, G 169, B 172)

Individual advanced vehicle configurations can be assessed

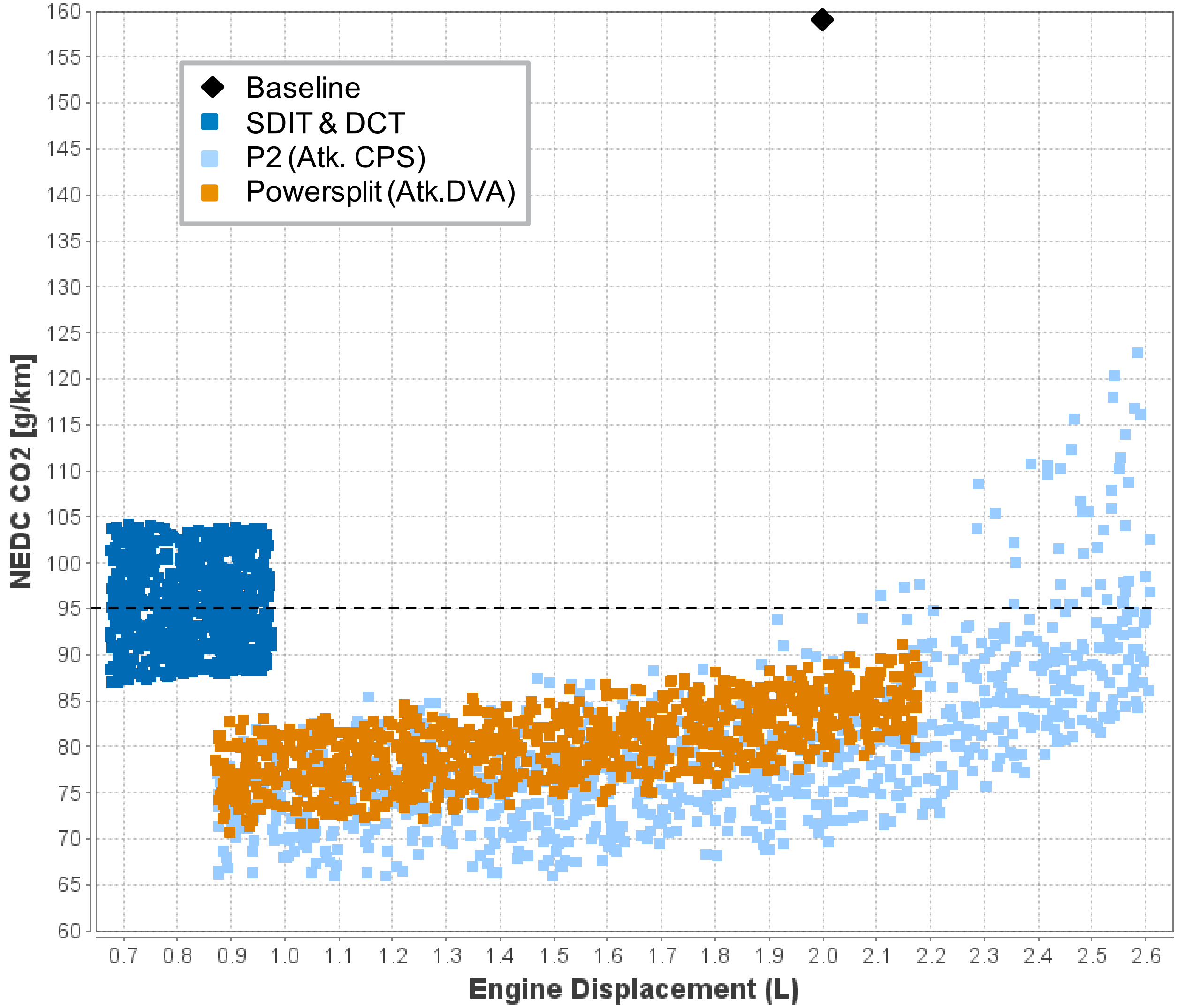
- Various C Class vehicle configurations can achieve similar GHG levels

C Class Vehicle Configuration	Vehicle Mass	Rolling Resist.	Aero. Drag	g CO_2/km on NEDC
Baseline with SI engine	100%	100%	100%	165
Baseline with Diesel engine	100%	100%	100%	124
Stoich DI Turbo + 8-spd DCT	100%	100%	100%	107
	85%	90%	90%	93
	70%	80%	80%	80
Adv EU Diesel + 8-spd DCT	100%	100%	100%	104
	85%	90%	90%	93
	70%	80%	80%	83
Atkinson (CPS) Powersplit Hybrid	100%	100%	100%	96
	85%	90%	90%	86
	70%	80%	80%	77
Atkinson (CPS) P2 Hybrid	100%	100%	100%	81
	85%	90%	90%	71
	70%	80%	80%	62

- All other parameters are at 100% of nominal C Class value

Hybrid and conventional powertrains can lead to similar GHG emissions

Results are for C Class Car, varying powertrain configuration, engine displacement, vehicle mass, and electric machine size (for hybrids). Rolling resistance and $C_d \cdot A$ are 90% of Nominal.



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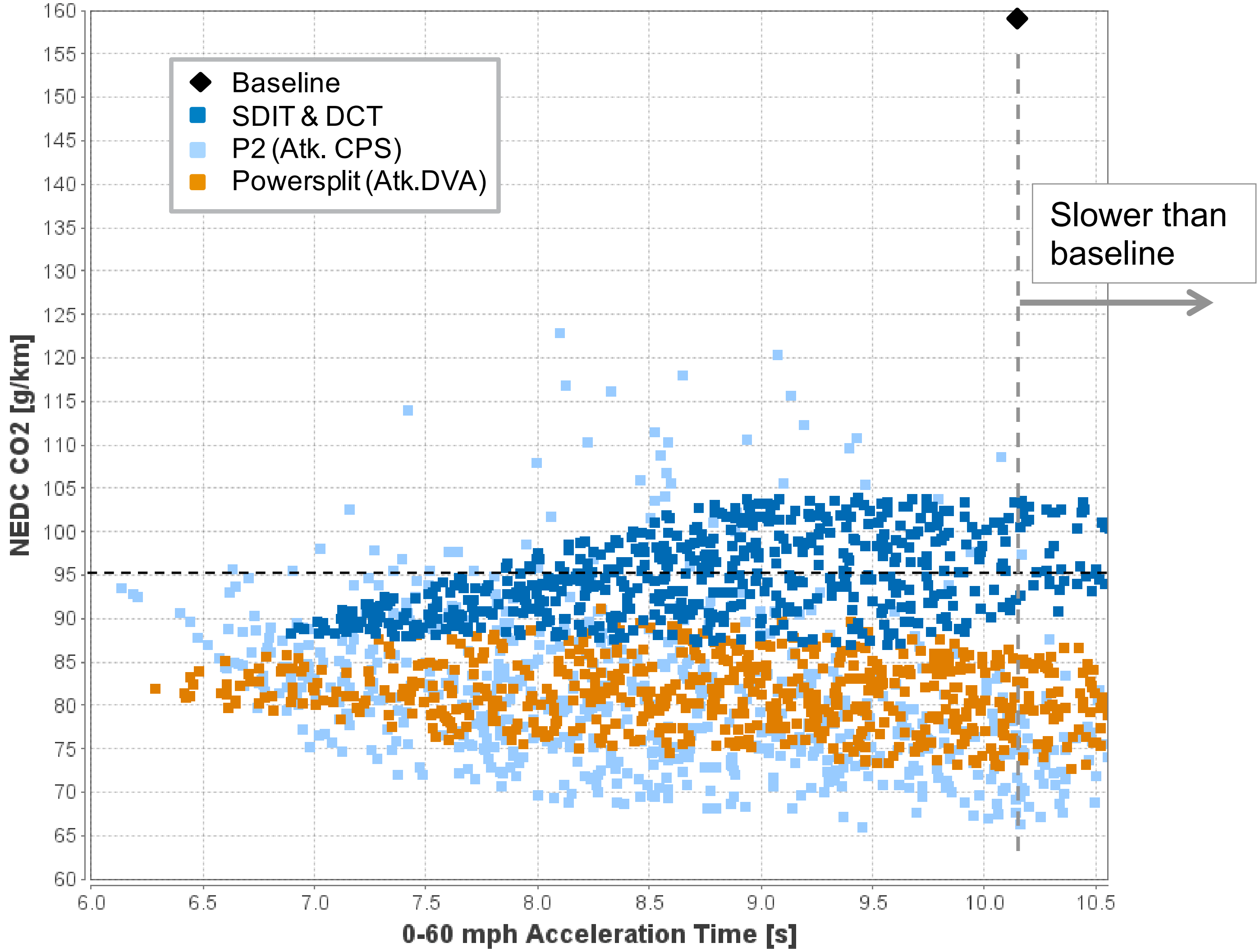

Conclusions – Lower GHG emissions will drive innovation in LDV segments

- Several technology combinations will be pursued in parallel to help meet new GHG emissions
  - Mix will include more than just hybrids
  - Downsized engines and advanced transmissions have a role to play
- Trends and product announcements from the industry are consistent with those predicted by Ricardo for this study
  - E.g., 2012 Ford Escape with downsized engine replacing hybrid option
- With eye on 2016 requirements and knowing that tougher rules are coming in the US, EU, and Japan, manufacturers and suppliers have not been sitting idle
  - Several manufacturers implementing advanced valvetrain designs
  - Several manufacturers implementing turbocharging and direct injection to support downsizing engines
  - Hybridization and electrification of vehicles continues

Thanks for your attention. Questions?

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