UNIVERSITY OF MICHIGAN
TRANSPORTATION RESEARCH INSTITUTE
Research Advancing Safe and Sustainable Transportation

Automotive Powertrain Technologies through 2016 and 2025

University of Michigan Transportation Research Institute Conference.
Marketing New Powertrain Technologies: Strategies in Transition
February 15, 2012

Mark Kuhn
Ricardo Strategic Consulting

Agenda

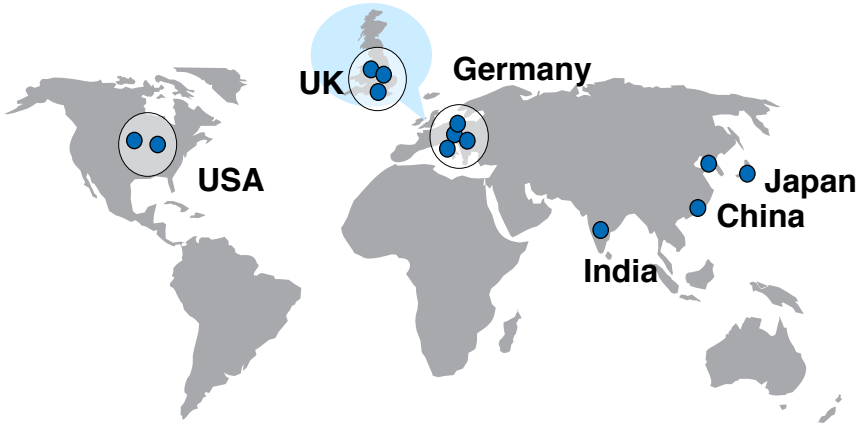
- **Introduction to Ricardo**
- Technology Roadmaps
- Passenger Car Fuel Economy Improvement and Greenhouse Gas Reduction Potential

Ricardo is one of the world's leading automotive consulting companies

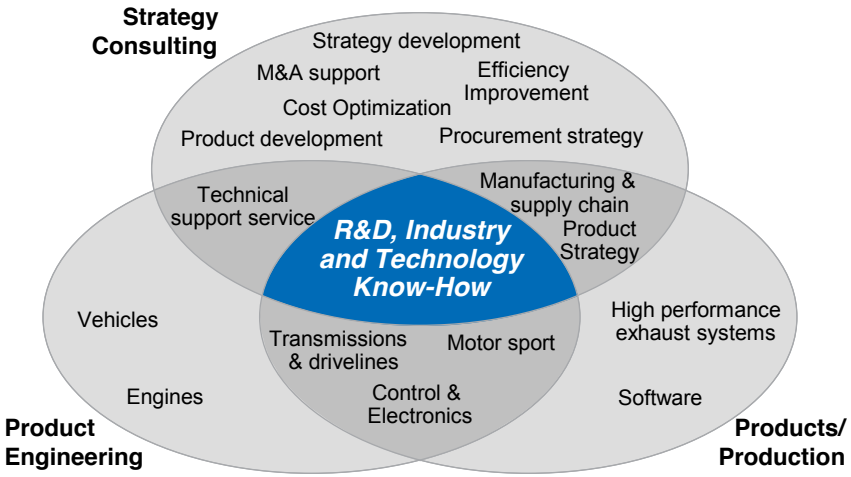
Established Success Factors

- Focused on value-adding services
- Solving key industry issues
- Program delivery as a core competence
- Investment in people and technology
- Critical mass with revenues exceeding $330M and over 1500 people
- Independent and long established (1908)

International Presence



Value-Adding Capabilities



Global Client Base (selection)

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- Introduction to Ricardo
- **Technology Roadmaps**
- Passenger Car Fuel Economy Improvement and 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
  - Trend is now continuing into the commercial vehicle space in US, Japan and Europe

- **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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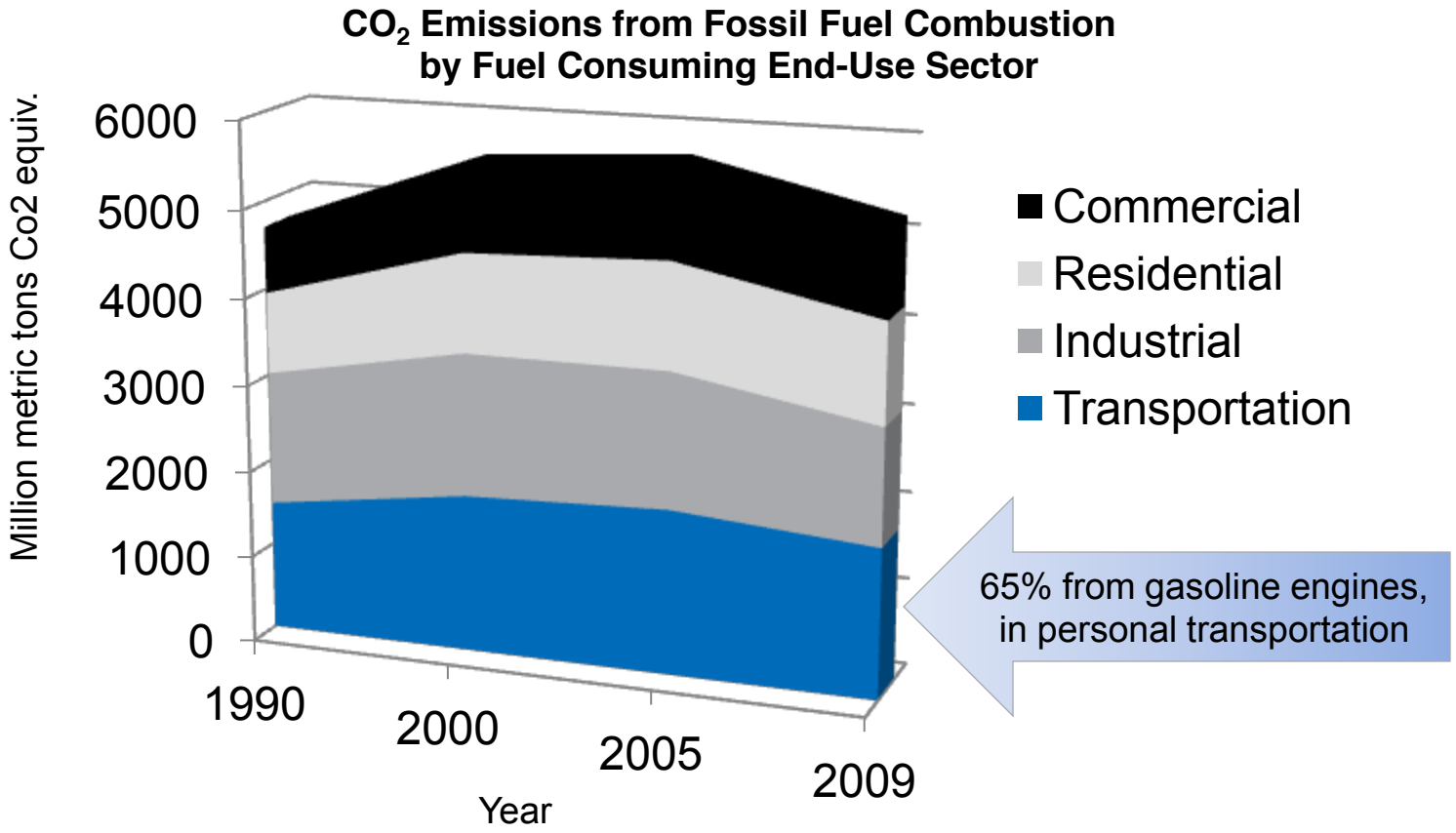
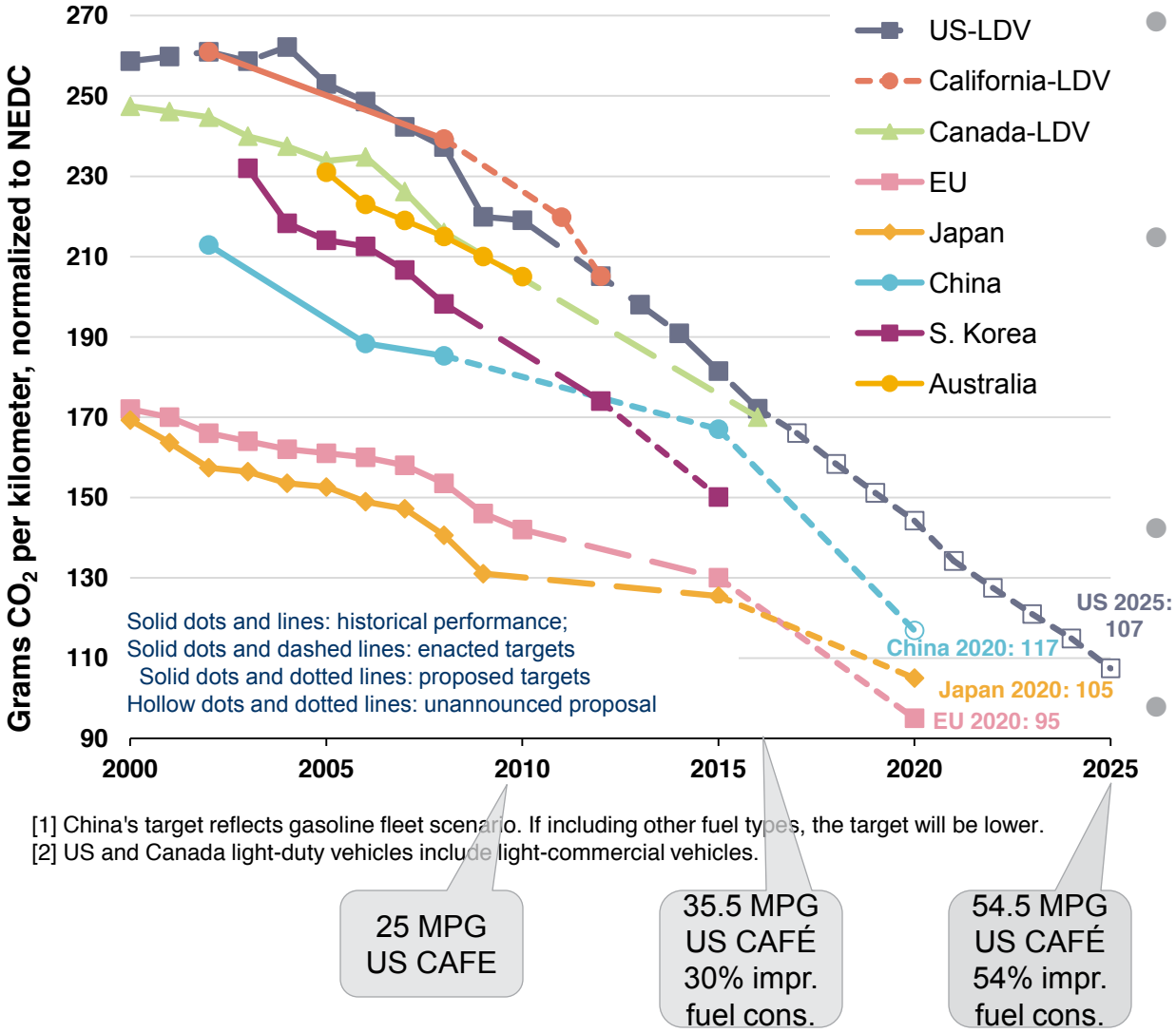
Transportation sector is 33% of total CO_2 contribution. Nearly 65% comes from gasoline engines for personal vehicles



Source: EPA US GHG Inventory 2011 Complete Report http://www.epa.gov/climatechange/emissions/downloads11/US-GHG-Inventory-2011-Complete_Report.pdf

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

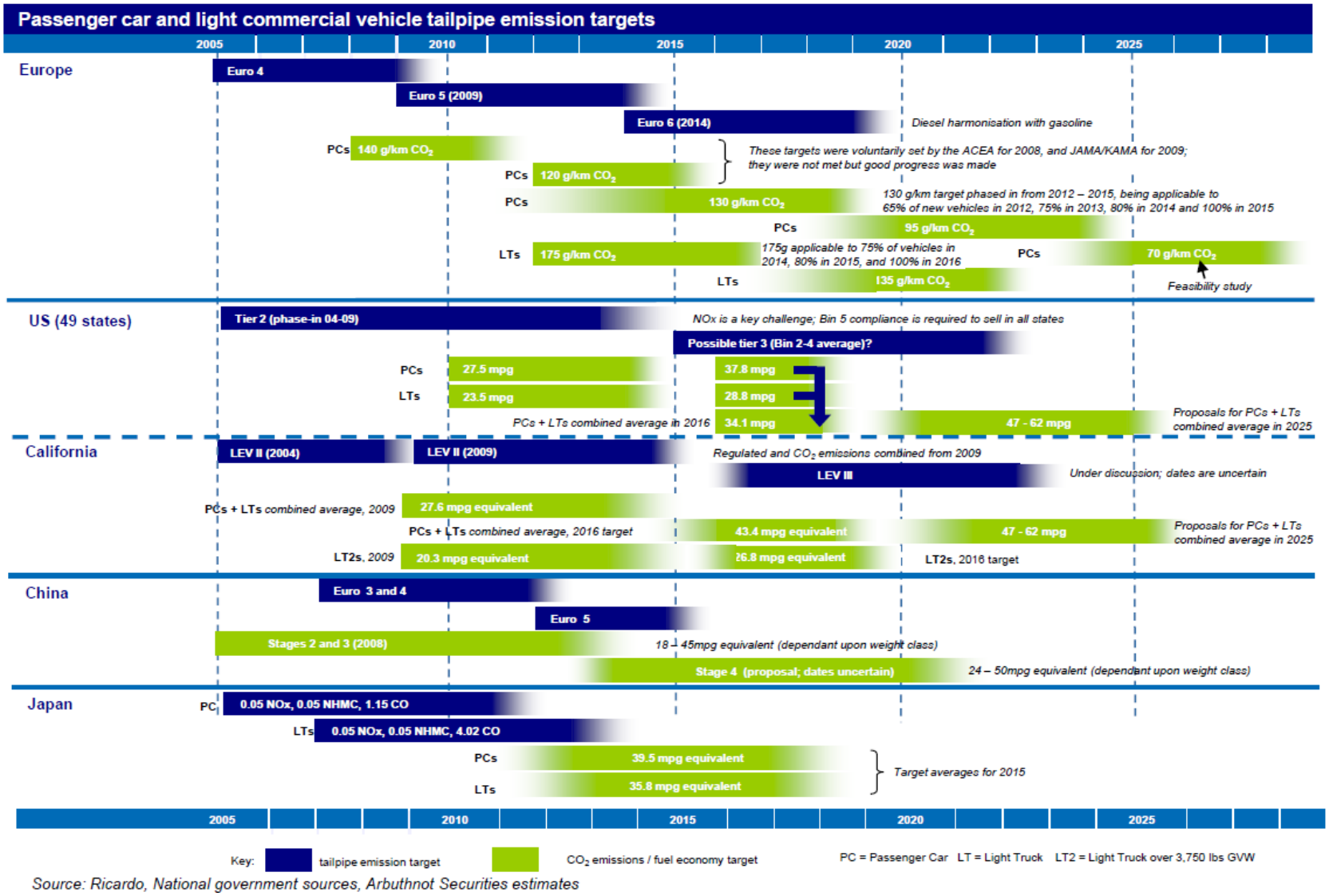


[1] China's target reflects gasoline fleet scenario. If including other fuel types, the target will be lower.
[2] US and Canada light-duty vehicles include light-commercial vehicles.

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

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

Regulation will continue to drive lower toxic emissions with additional fuel economy and CO_2 legislation likely



Source: Ricardo, National government sources, Arbuthnot Securities estimates

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

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

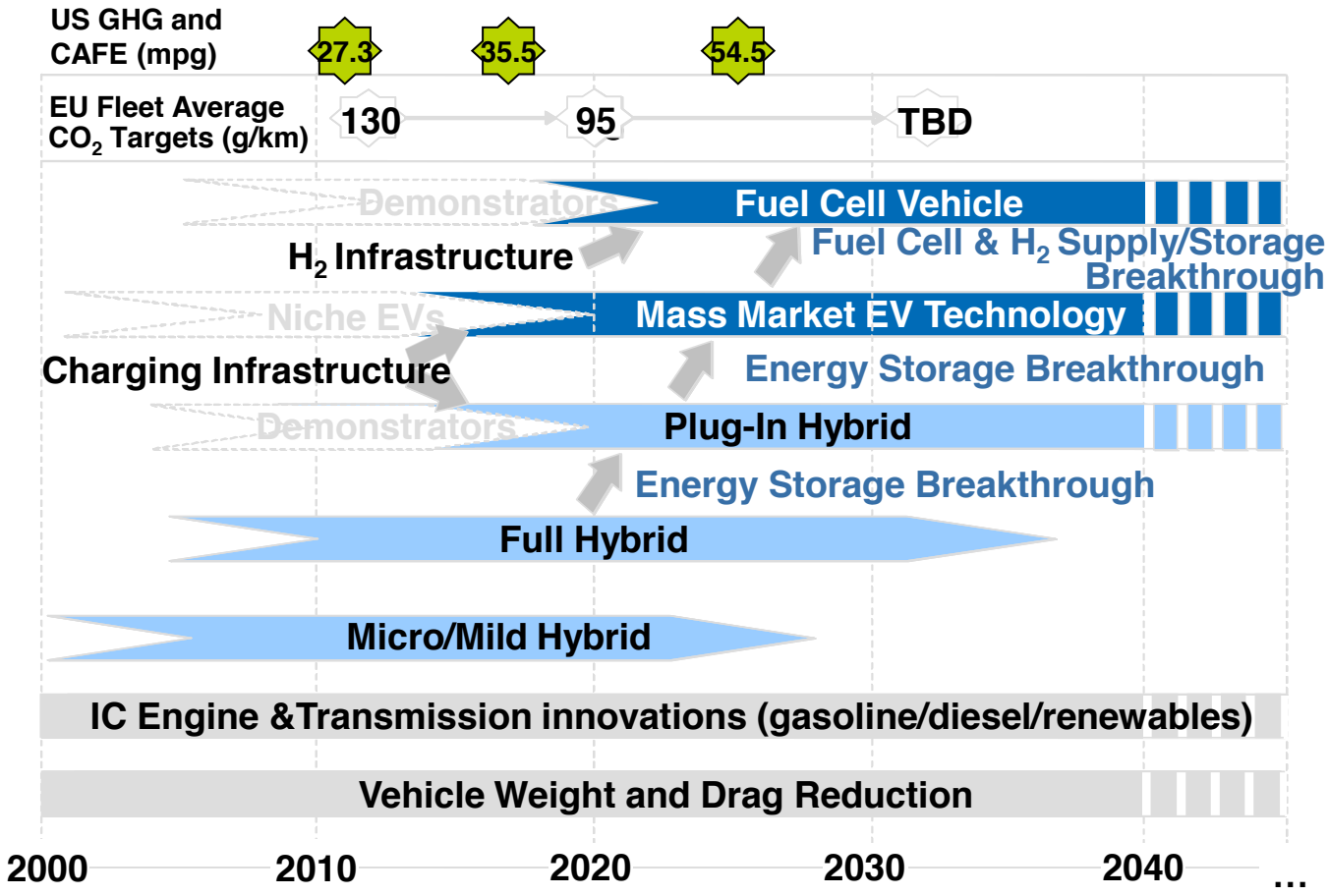
- High Efficiency Advanced Combustion:
  - Lean Stratified SI
  - Low temperature combustion
- Combined turbo/ supercharging systems
- Advanced low carbon fuel formulations
- PHEV's in premium & performance products
- EV's for city vehicles

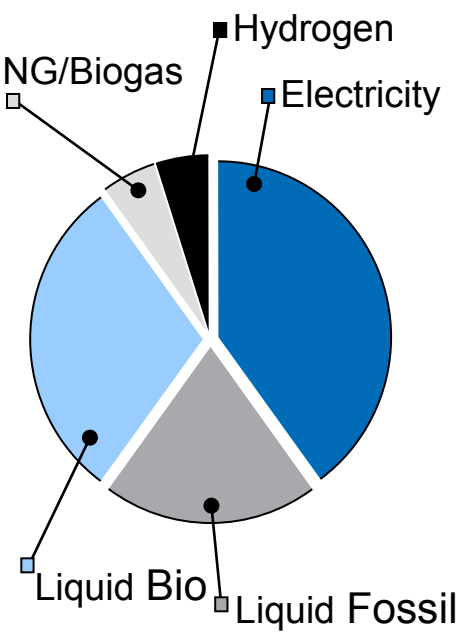
LONG TERM: ~2050

- 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

Mass market roadmap developed by Ricardo shows that range of technologies will be required to meet regulatory targets





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)

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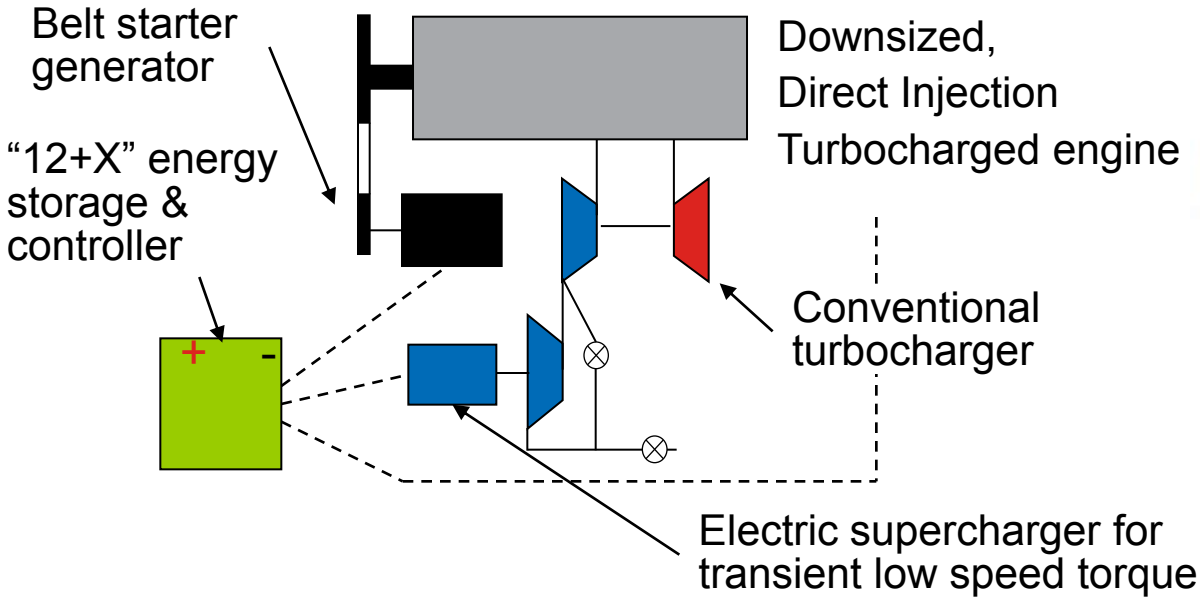
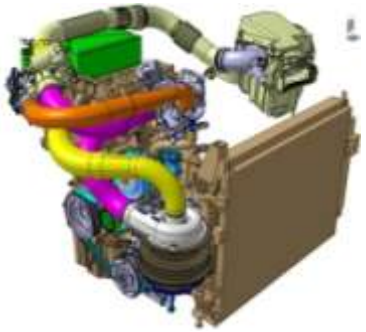
Ricardo HyBoost concept features “Intelligent Electrification” - downsizing, e-Boost & brake energy recovery/stop/start





Fuel Economy Improvement/CO_2 Emissions Reduction:

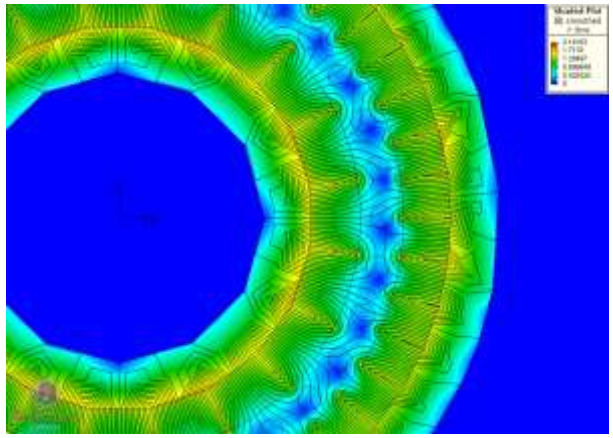
Base vehicle (Ford Focus 2.0 litre Gasoline) 107 kW:	**169g/km**
50% downsized 1 litre, Boosted DI, low friction 105 kW	-25%
Add stop-start and 6kW re-generation during deceleration	-10%
Add cooled EGR and revised turbo match via e-supercharger	-6%
High torque enables taller gear ratios + gearshift advisor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

40% Impr

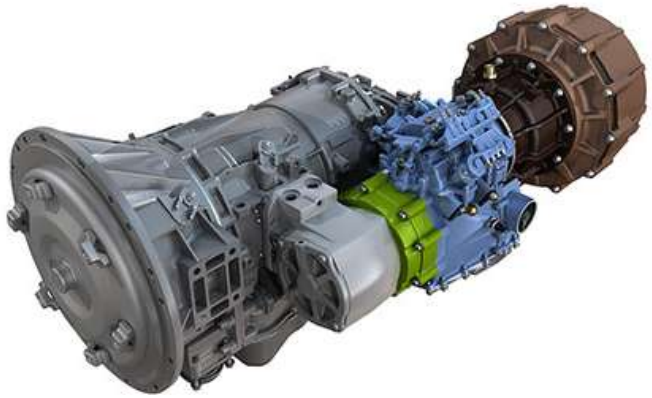
Technology Strategy Board Driving Innovation

Disruptive lower cost hybrid technologies possible via high speed flywheel technology – Ricardo "kinergy"

- Primary USP of Flywheel technology is very high "round trip" energy efficiency
- Project to apply Torotrak & Kinergy® technology on a PSV (Optare bus)
- **Reduces CO_2 emission by around 20 percent** during urban stop-start operation.
- Partners:, Torotrak, Ricardo, Optare, Allison



To eliminate the need for vacuum seals a non-penetrative magnetic coupling system is used to transfer kinetic energy through the housing



Source: Ricardo. Note USP = Unique selling proposition

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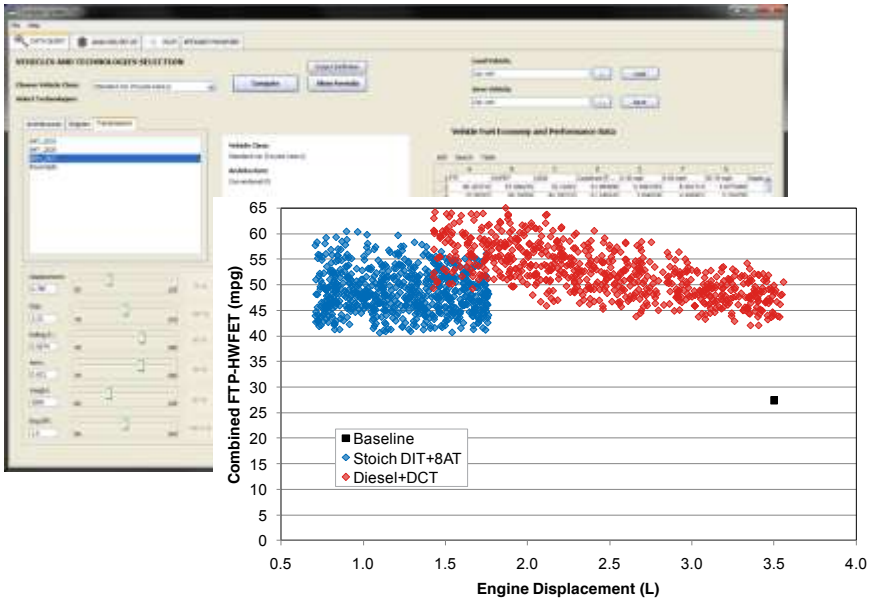
Technical Input to EPA for 2017–2025 Light Duty Vehicle Greenhouse Gas Proposed Rule



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

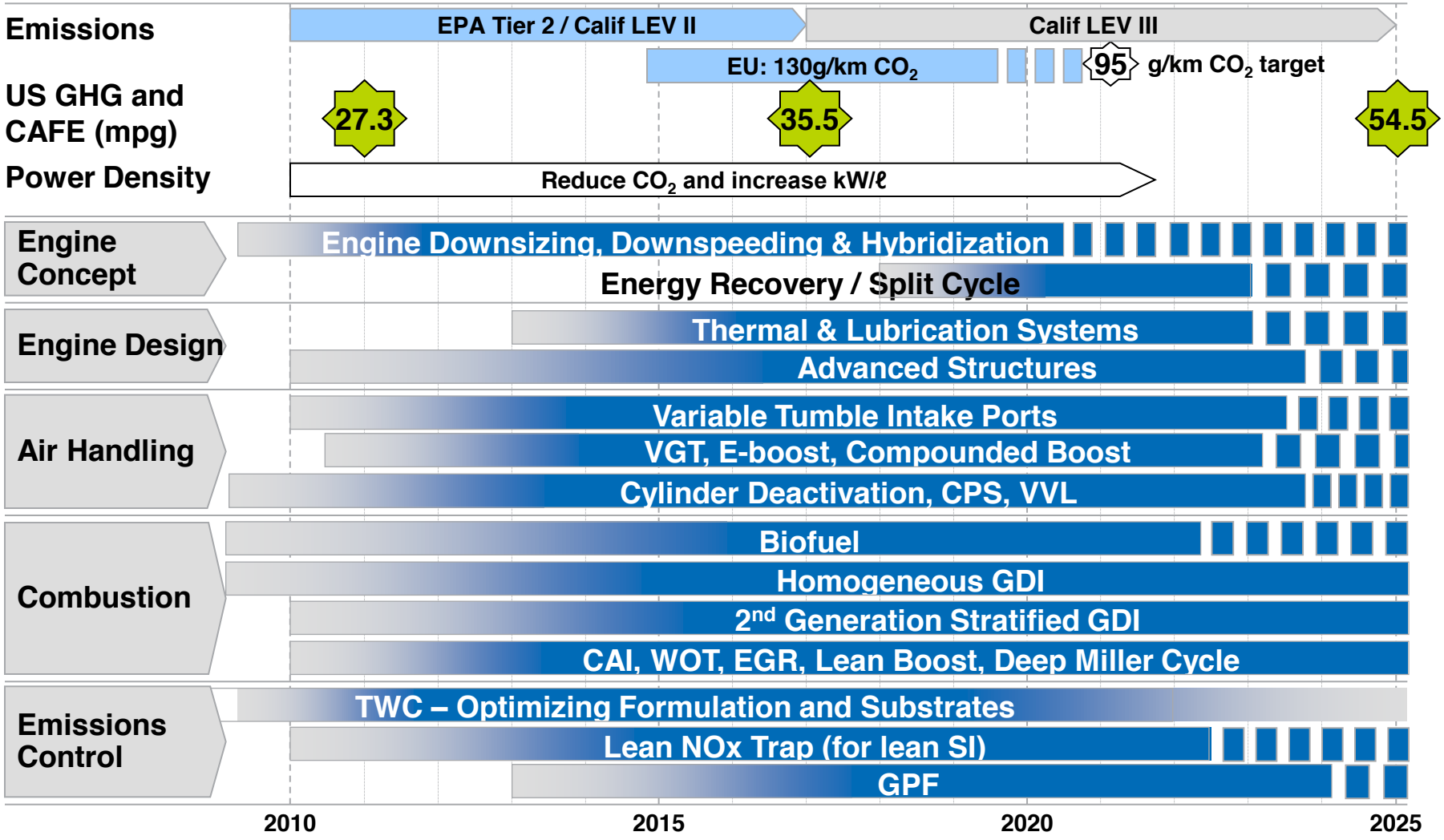
- Broad design space examined hundreds of combinations of technologies, and their synergistic effects
- Predicted MPG reductions of 35% to 62% relative to baseline SI engine
- Technologies included combinations of advanced gasoline, diesel, hybrid, 8 speed transmissions
- Also included weight reduction, aerodynamics and reduced rolling resistance

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

- 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

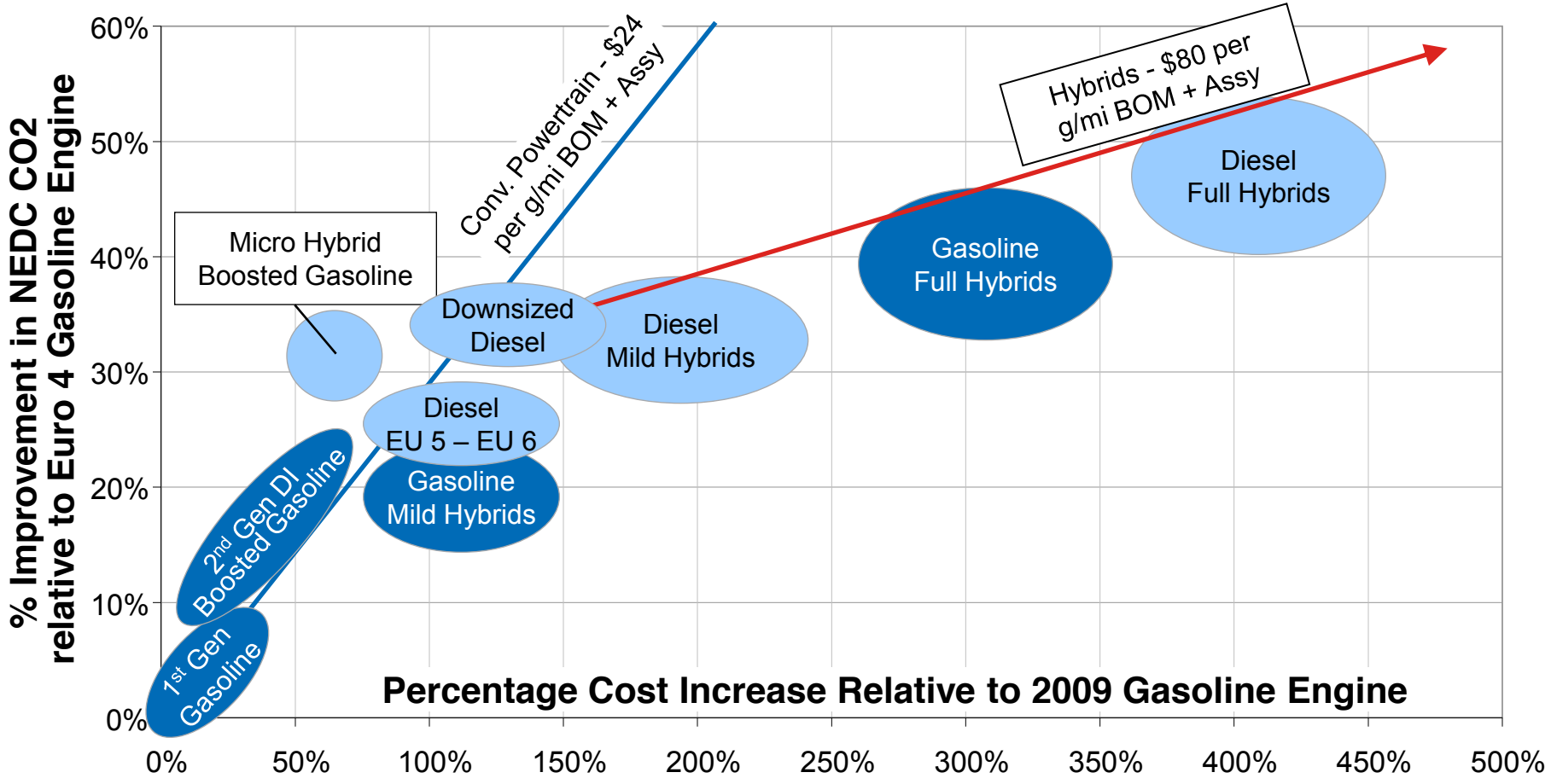
Technology Roadmap for Light Duty Gasoline



Source: Ricardo Analysis. Notes: CPS = camp profile switching, VVL = variable valve lift. GDI = gasoline direct injection. CAI = controlled auto ignition. TWC = 3-way catalyst, GPF = gasoline part. filter

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

Benchmark Passenger Car: - CO_2 Cost Benefit for Powertrain Technologies



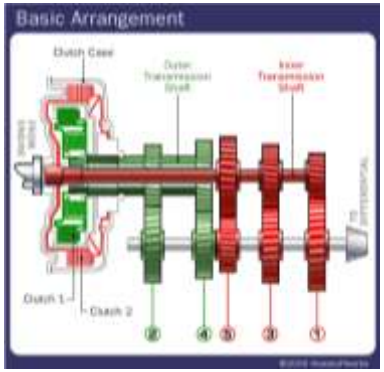
- Consumers buy vehicles – not powertrains – technologies must also compete on image, utility and lifestyle requirements and deliver fundamentally **Good Cars**

Source: Ricardo Analysis. NEDC = New European Drive Cycle

Technology packages in the 2020–2025 Design Space

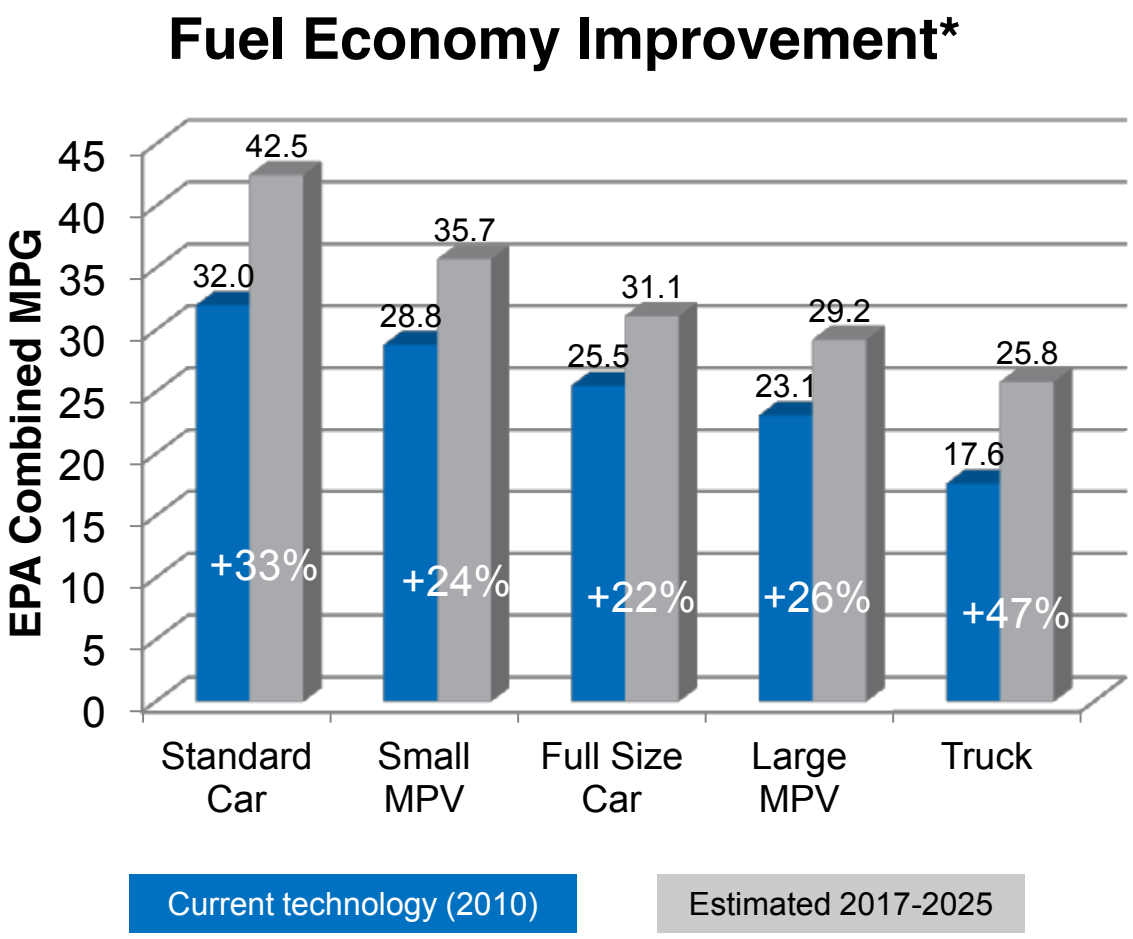
- Engines:
  - Stoichiometric direct-injection turbocharged (SDIT) SI engine
  - Lean-stoichiometric direct-injection turbocharged (LDIT) SI engine
  - EGR direct-injection turbocharged (EDIT) SI engine
  - Atkinson cycle SI engine with cam-profile switching (CPS)
  - Atkinson cycle SI engine with digital 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



Source: Ricardo Analysis.

Fuel economy improvements of 22-47% were predicted for various sized vehicles from standard car to pick-up truck



Technologies included

- Cam phasing
- Variable valve lift
- Gasoline direct injection
- Diesel (for truck)
- Turbocharging
- Dual clutch transmission
- Electric accessories and fast engine warm-up
- Aero drag reduction & low rolling resistance tires
- Final drive ratio
- Oil and friction modifier

*Note 1: 22-47% fuel economy (MPG) improvement = 18-32% fuel consumption (gal/mile) reduction
Note 2: Change from old truck to new std. car reduces fuel consumption by 59%

Source: Ricardo Analysis.

Hybrid and conventional powertrains can lead to similar GHG emissions; improvements from 25% to 62% reduced CO_2

- 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	% Reduction from baseline
Baseline with SI engine	100%	100%	100%	165	
Baseline with Diesel engine	100%	100%	100%	124	25%
Stoich DI Turbo + 8-spd DCT	100%	100%	100%	107	
	85%	90%	90%	93	
	70%	80%	80%	80	52%
Adv EU Diesel + 8-spd DCT	100%	100%	100%	104	
	85%	90%	90%	93	
	70%	80%	80%	83	50%
Atkinson (CPS) Powersplit Hybrid	100%	100%	100%	96	
	85%	90%	90%	86	
	70%	80%	80%	77	53%
Atkinson (CPS) P2 Hybrid	100%	100%	100%	81	
	85%	90%	90%	71	
	70%	80%	80%	62	62%

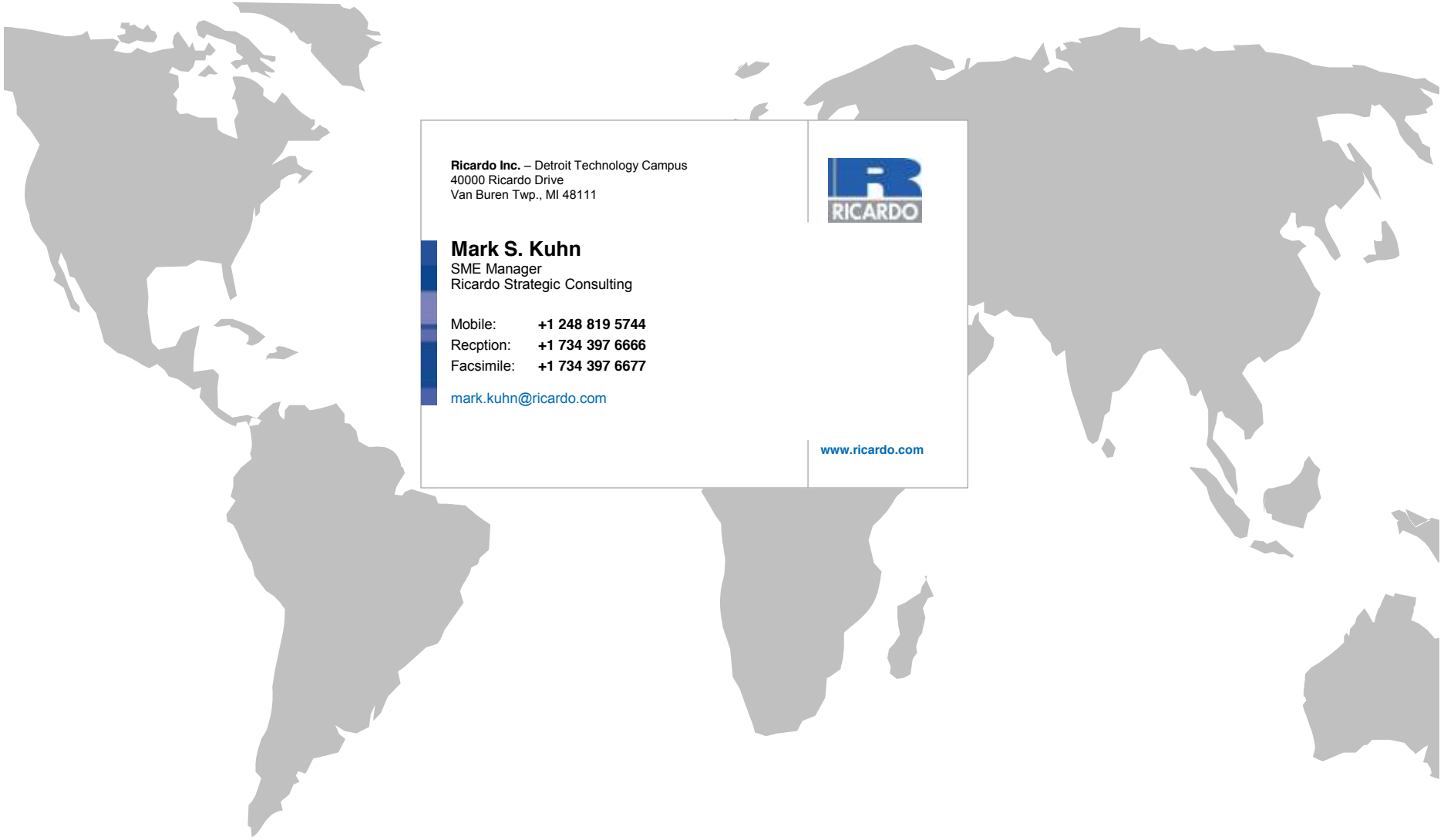
- All other parameters are at 100% of nominal C Class value

Note: CPS = cam profile switching. P2 hybrid = Inline full hybrid, capable of full engine-off operation at any speed

Conclusions – Aggressive fuel consumption and lower GHG standards will drive innovation in passenger car segments

- Several technology combinations will be pursued in parallel to help meet new fuel economy and GHG emissions standards
  - Mix will include more than just hybrids
  - Downsized engines and advanced transmissions have a role to play
  - Continued development in aerodynamics, lightweighting and reduced rolling resistance
- 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

Thank you for your attention…



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