

Influence and Importance of Fuel Octane in Future Engine Developments

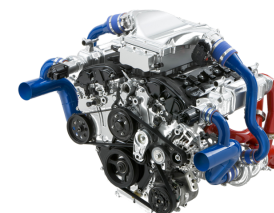
Final project report

Date 5 December 2011
Report RD.11/351705.3
Project C001223

Confidential Renewable Fuels Association

Report by John J. Kasab

Approved Rod Beazley



- Regulatory standards for reduced greenhouse gas emissions and pollutants will require significant changes to light duty vehicles and their powertrains
- Vehicle electrification will be part of the solution, but the vast majority of vehicles sold through 2025 will use gasoline fuelled, spark-ignited (SI) internal combustion engines as the primary form of propulsion
 - Battery-only electric vehicles will only represent a niche market
 - SI engines will appear in both conventional and hybrid vehicles
 - Higher octane fuels would unchain the performance of advanced SI engines technologies
- This report describes the requirements, technologies, and potential configurations for the next 5–15 years

Future powertrain solutions will have a natural thirst for higher octane fuels

- **Challenge or Opportunity...**
- Technology Roadmap
- Technologies Explained
- Conclusions

Ricardo History: ~100yrs on the frontiers!

Advancing powertrain systems technologies through the decades

- In the Beginning: Understanding combustion / continuously improving Fuel Economy ...
- In the Future: Leveraging a "natural thirst" for octane in the quest for 2025 / 54.5mpg regs



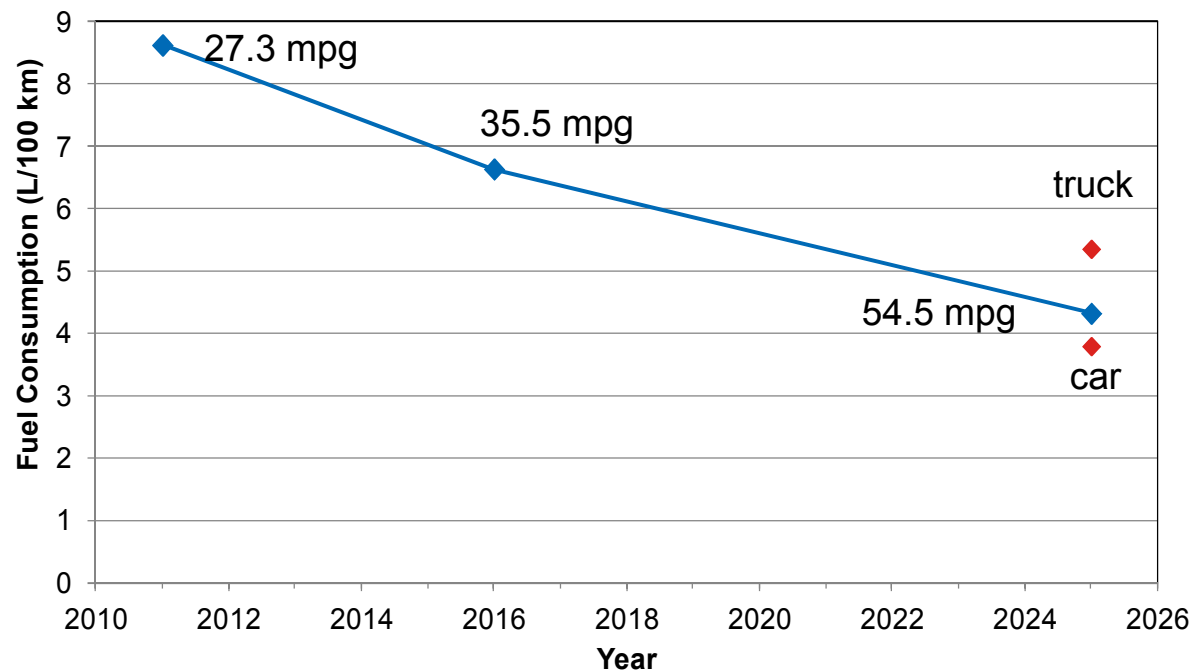
1915 Engine Patents Ltd. Est.	<ul style="list-style-type: none"> • Harry Ricardo formed Engine Patents Ltd, the precursor of today's Ricardo Plc becoming famous for the design of a revolutionary engine which was utilised in tanks, trains and generators
1930 Fundamental Fuel Research	<ul style="list-style-type: none"> • Development of a variable compression engine which was used to quantify the performance of different fuels. <u>This was the forerunner of today's octane rating scale (RON)</u>
1931 Comet Combustion Chamber	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 50 off "Olympic Green Messenger" vehicles co-developed by Chery Automobile and Ricardo

Challenge or Opportunity...

163 g CO₂/mi equivalent to 54.5 mpg fleet average



- New Federal regulations to be released governing light duty vehicle fleet fuel economy and greenhouse gas emissions
 - 54.5 mpg combined fleet average (62.0 for cars, 44.0 for trucks)
 - 50% reduction in new vehicle fuel consumption from 2011 to 2025
- Vehicle electrification will be part of the solution, but the vast majority of vehicles sold through 2025 will still have internal combustion engines in them
 - Both "conventional" powertrain and hybrids



California ARB LEV III Targets Fleet-Average SULEV-Level Emissions Performance from New Vehicles by MY 2022



California Environmental Protection Agency

Air Resources Board



Air Resources Board

Mary D. Nichols, Chairman
9450 Testa Avenue, Suite 4
El Monte, California 91731 www.arb.ca.gov

Linda S. Adams

Secretary for Environmental Protection

Arnold Schwarzenegger

Governor

February 10, 2010

Mail-Out #MSC 10-05

TO: All Interested Parties

SUBJECT: PUBLIC WORKSHOP TO DISCUSS POSSIBLE AMENDMENTS TO CALIFORNIA'S LOW-EMISSION VEHICLE REGULATIONS FOR PASSENGER VEHICLES – LEV III (REVISED)

The Air Resources Board (ARB) is developing a proposal for more stringent emission requirements for new passenger vehicles, to be considered by the Board later this year. A one day workshop to discuss our preliminary thoughts and sources of information upon which to base the proposed standards and procedures is scheduled for March 2nd, 2010, in El Monte, California.

Details of the meeting are as follows:

DATE: March 2nd, 2010

TIME: 9:00 a.m.

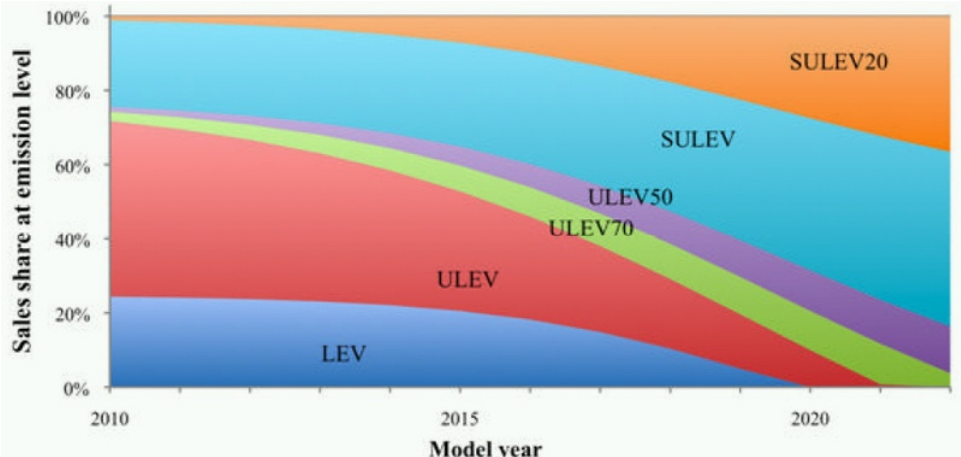
PLACE: California Environmental Protection Agency
Air Resources Board
9530 Telstar Avenue
El Monte, California 91731

ARB staff has developed a draft proposal for criteria emission standards, and is seeking comments and input from stakeholders. The preliminary proposal for the criteria standards can be found in the document "Preliminary Discussion Paper – Amendments to California's Low-Emission Vehicle Regulations for Criteria Pollutants – LEV III." A copy the document may be found at: <http://www.arb.ca.gov/msprog/levprog/leviii/leviii.htm>

The energy challenge facing California is real. Every Californian needs to take immediate action to reduce energy consumption. For a list of simple ways you can reduce demand and cut your energy costs, see our website <http://www.arb.ca.gov>

California Environmental Protection Agency

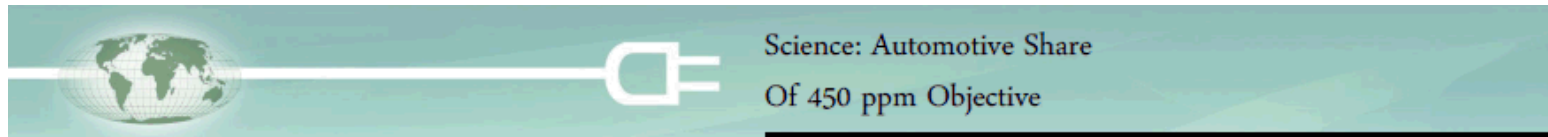
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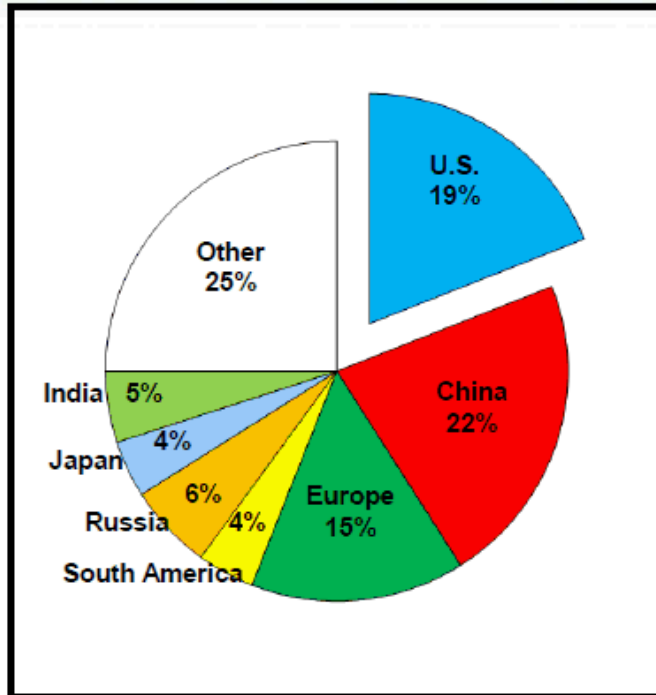
Proposed LEV III NMOG+NO _x Emission Standards				
Category	Existing NMOG standards ^a (g/mi)	Existing NO _x standards ^a (g/mi)	Combined NMOG+NO _x standards (g/mi)	Proposed NMOG+NO _x emission standards ^b (g/mi)
LEV	0.090	0.070	0.160	0.160
ULEV	0.055	0.070	0.125	0.125
ULEV70	–	–	–	0.070
ULEV50	–	–	–	0.050
SULEV	0.020	0.010	0.030	0.030
SULEV20	–	–	–	0.020

^a 120,000-mile durability basis
^b 150,000-mile durability basis.

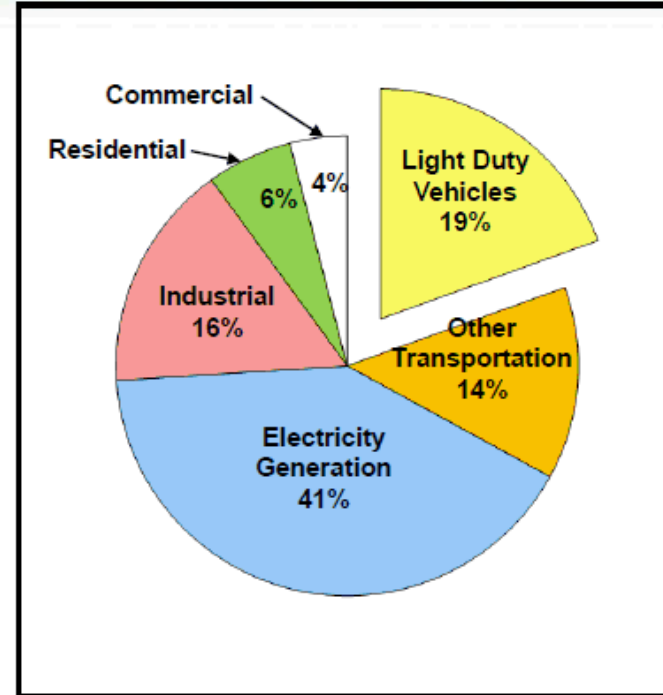
Ford sees focus on CO₂ mitigation driving development



2008 Global CO₂ By Market



2008 U.S. CO₂ By Industry



Achieving the 450 ppm Glidepath Requires A Well-to-Wheel Focus



Slide 13, May 4, 2011

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

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- Challenge or Opportunity...
- **Technology Roadmap**
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Spark-Ignited Engine Technologies Overview

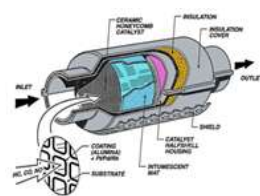
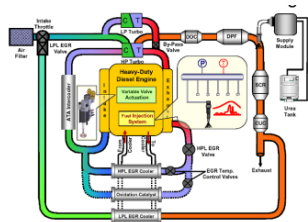
- Gasoline fuelled spark-ignited (SI) engines will remain the dominant powertrain in the US light-duty vehicle market through 2025
 - Used in both conventional and hybrid vehicles
- The primary challenges for SI engines are
 - Reduce CO₂ emissions and achieve fuel economy targets
 - Maintain performance
 - Maintain emissions compliance, especially with California LEV III rules
 - Minimize increases to manufacturing cost
- These challenges will best be met by a range of improvements, from the application of highly-efficient downsized engines through to detailed optimization of components and systems

Potential market scenario for light duty vehicle propulsion systems in 2025

	2010	2025
Gasoline based fuels	92%	74% (25–80%)
Diesel based fuels	6%	6% (5–20%)
HEV	2%	9% (4–15%)
PHEV/EREV	0%	9% (5–25%)
CNG	0%	2% (1–12%)
Fuel Cell	0%	0%

>90% of vehicles in 2025 should still be powered by gasoline or similar fuels, between conventional vehicles, HEV, and PHEV/EREV.

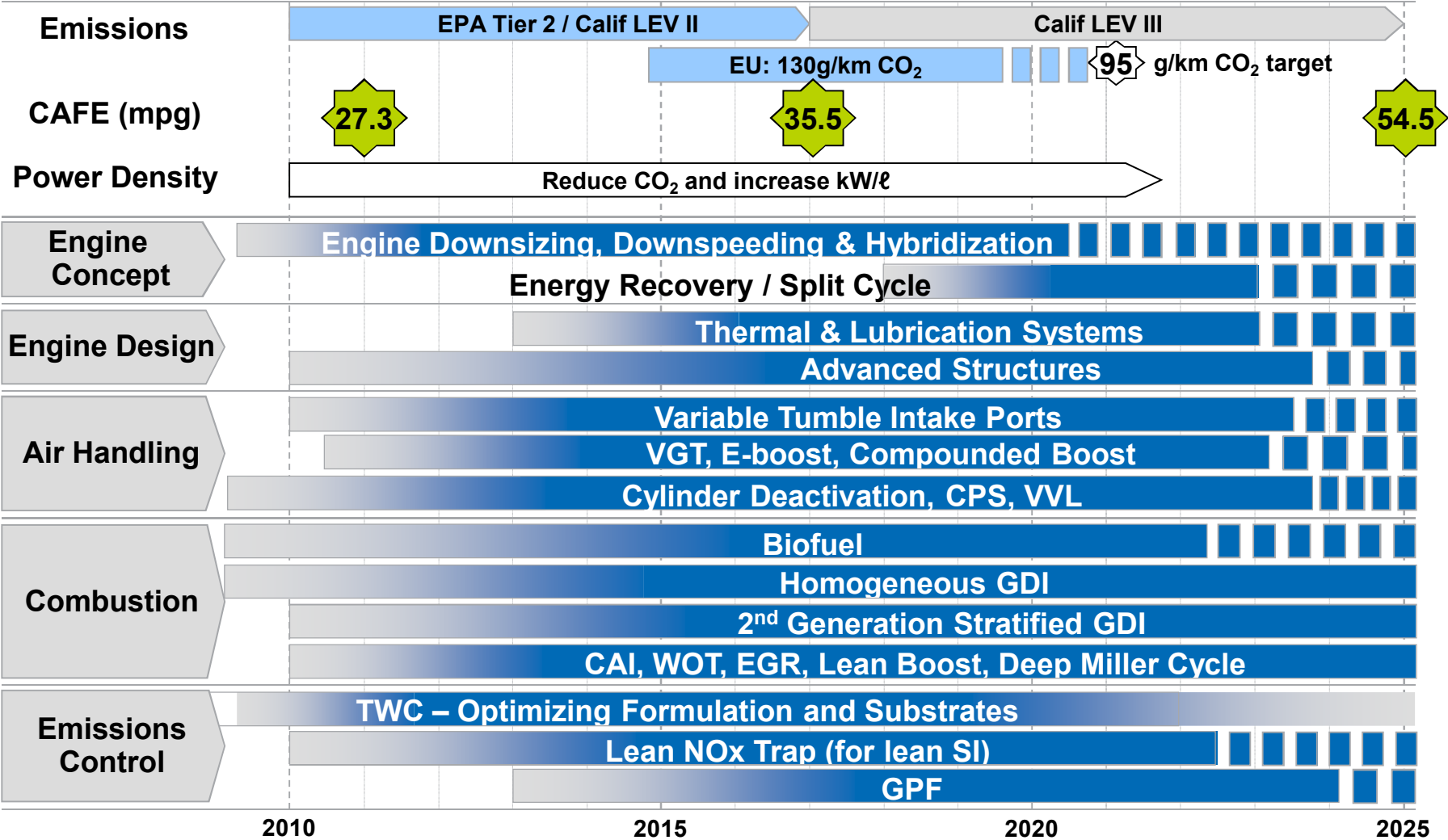
2025 market share was derived from a straw poll of some industry leaders



SI engine development will focus on CO₂ reduction, as emissions will be less challenging, even under LEV III

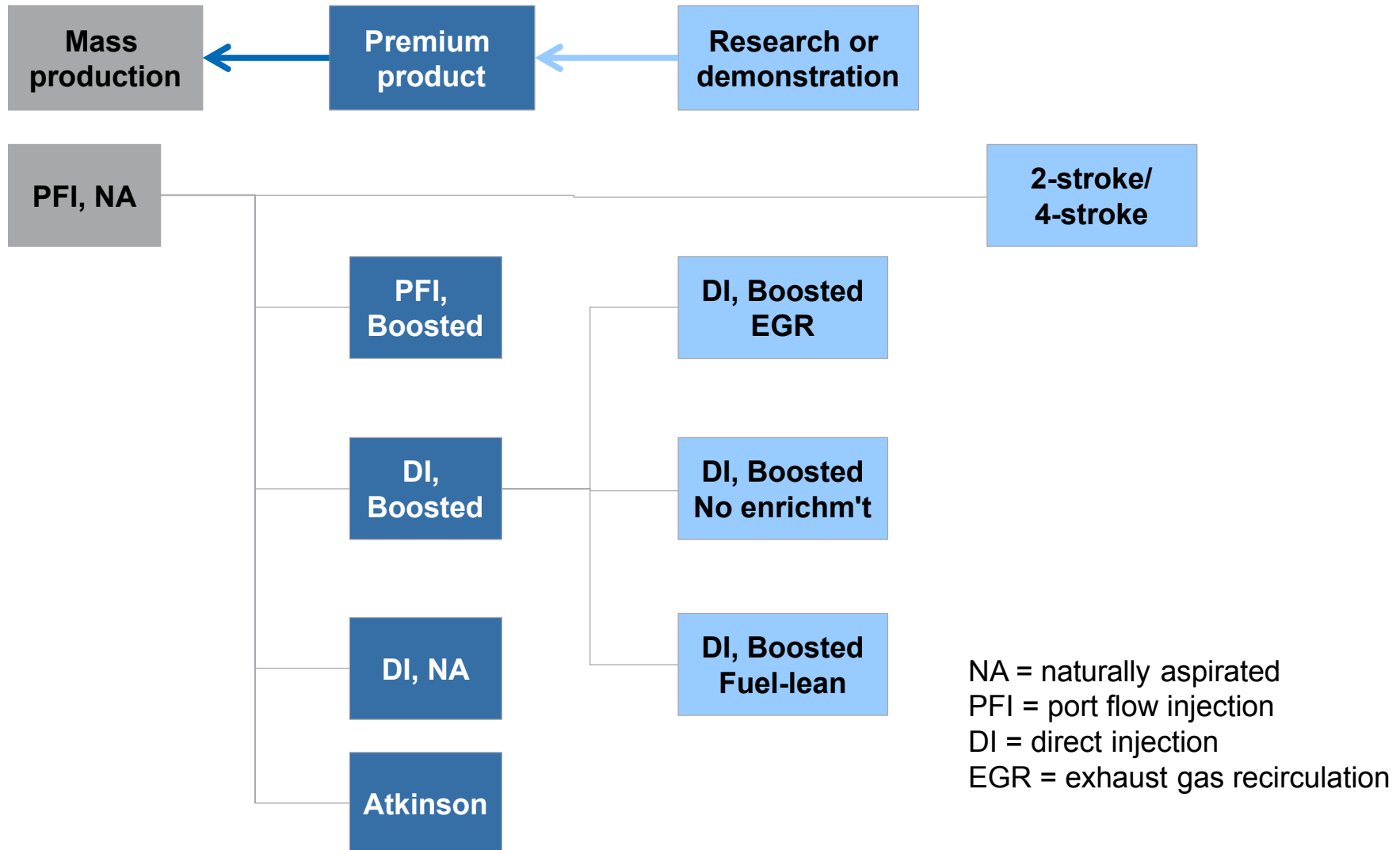


Technology Roadmap for Light Duty Gasoline

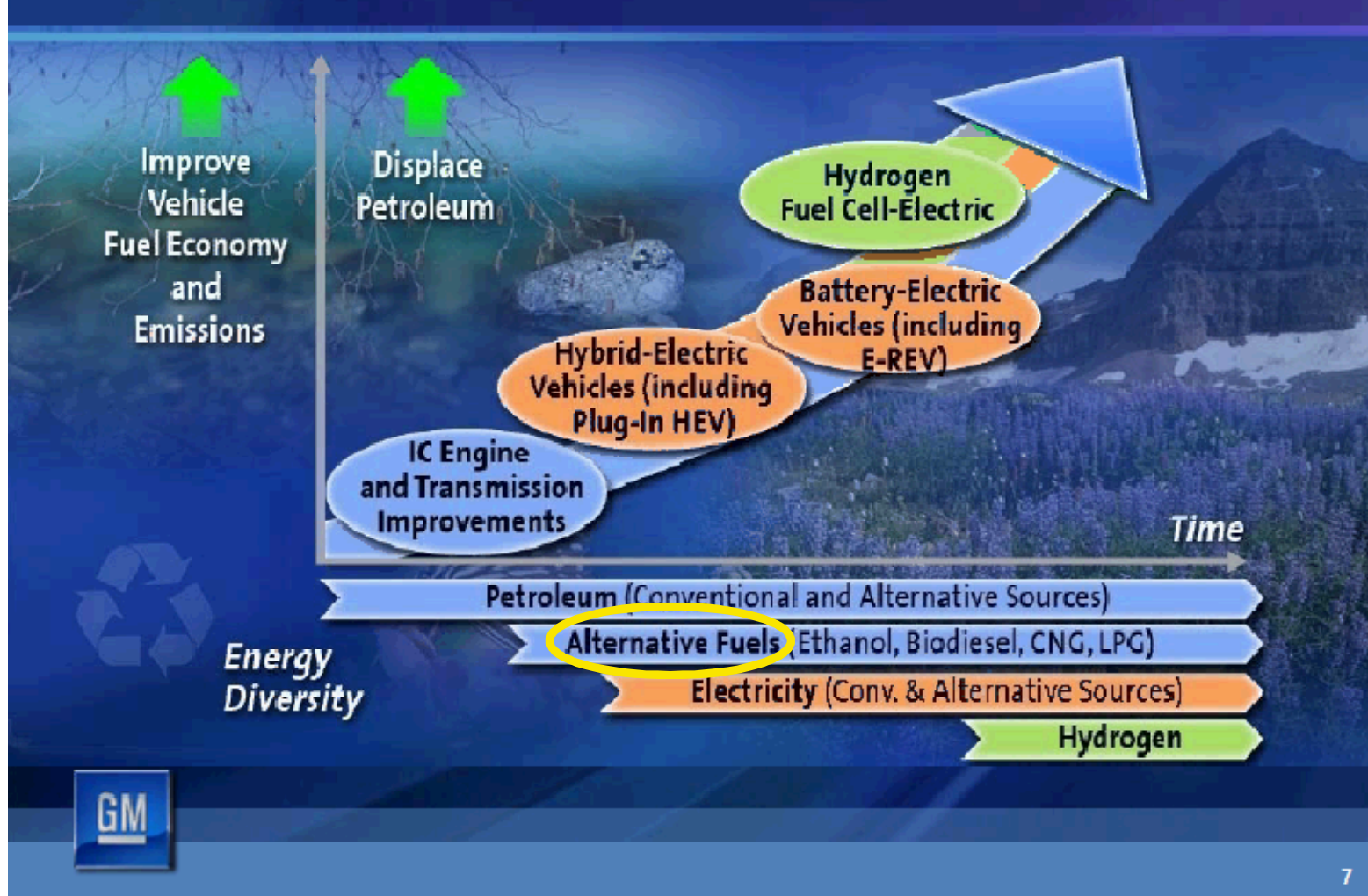


Source: Ricardo Analysis

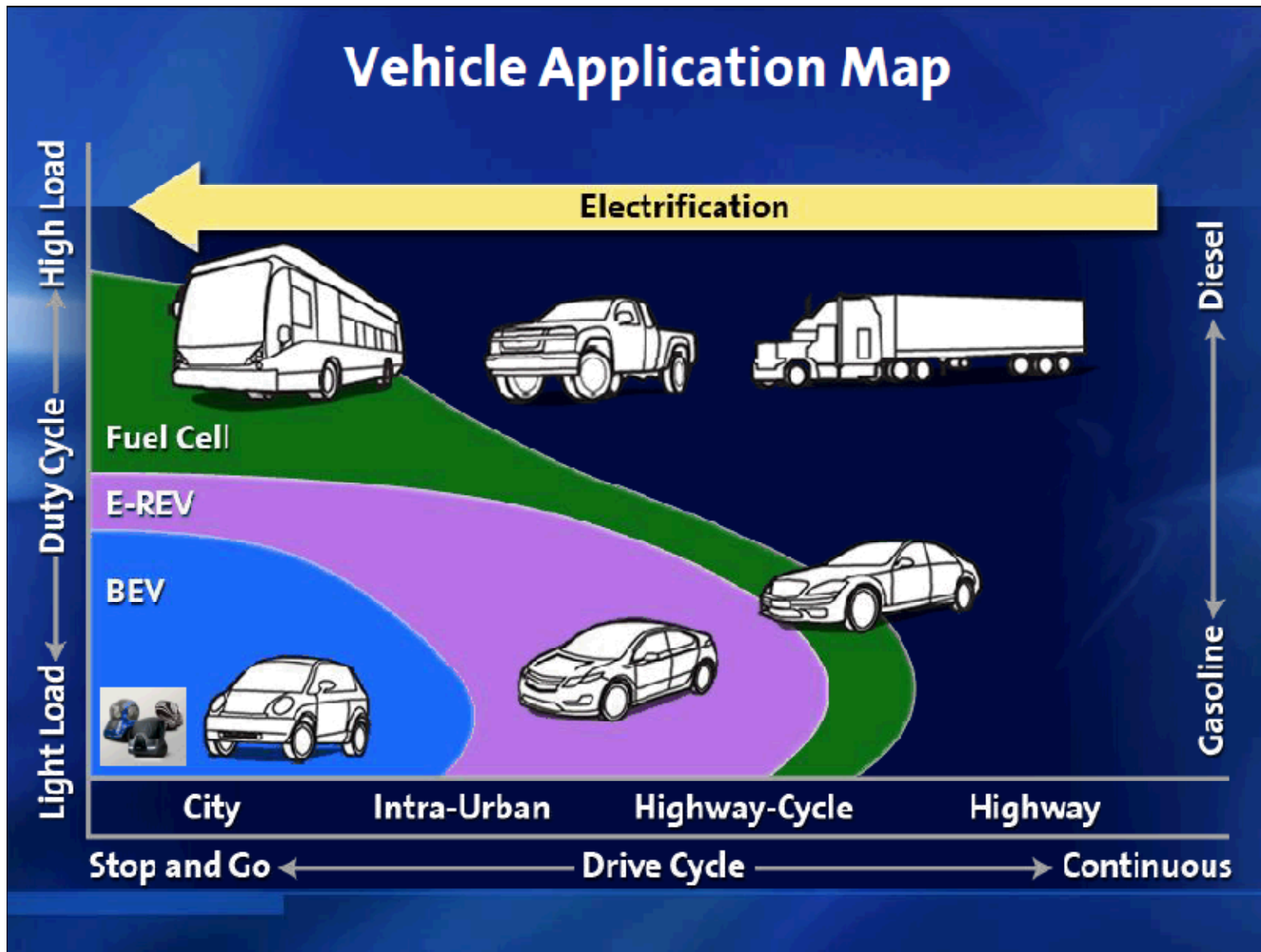
Pathways for SI engine developments for light duty vehicles: Progress from research to premium product to mass market



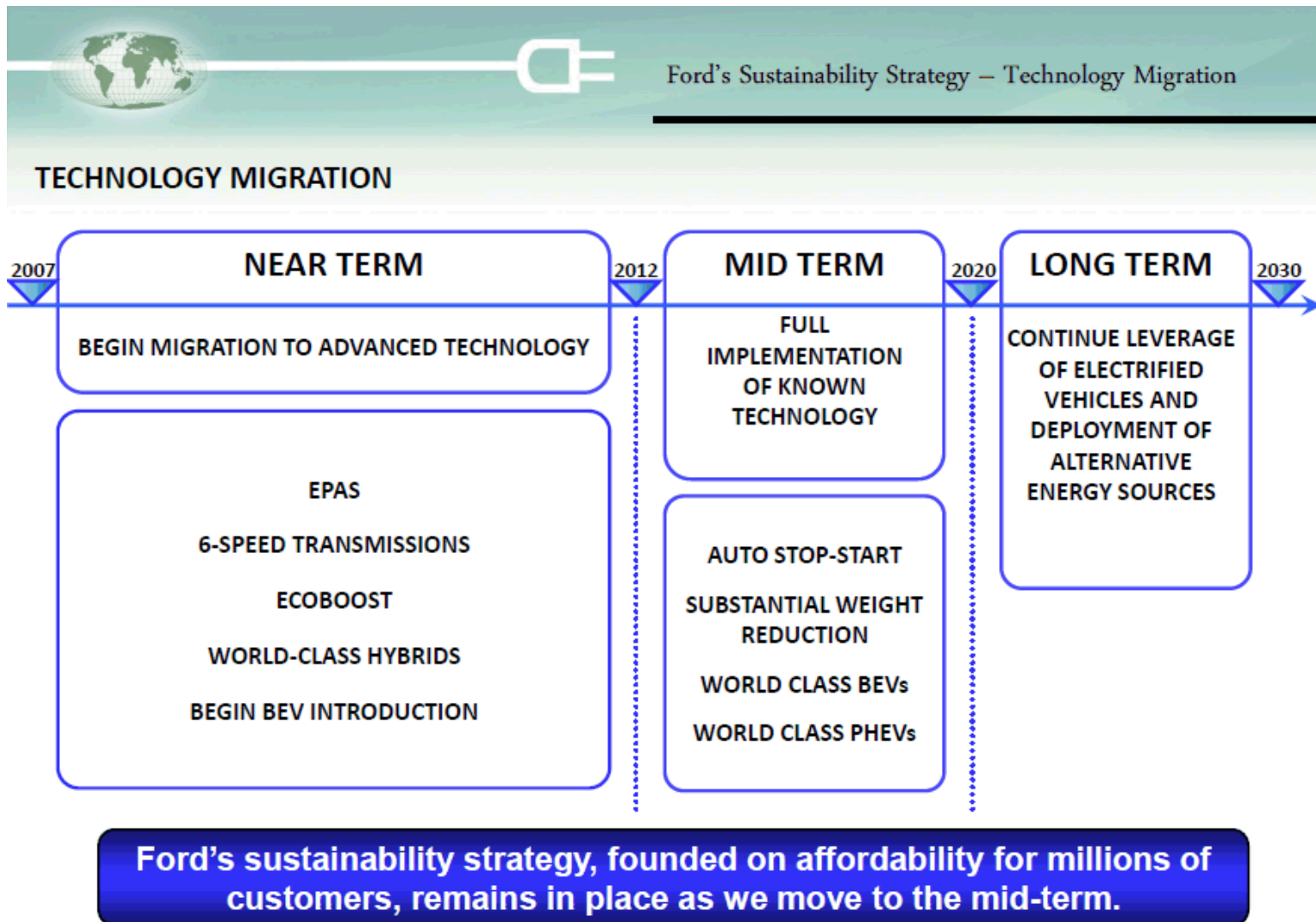
Advanced Propulsion Technology Strategy



General Motors' vision recognizes that the right powertrain depends on the application



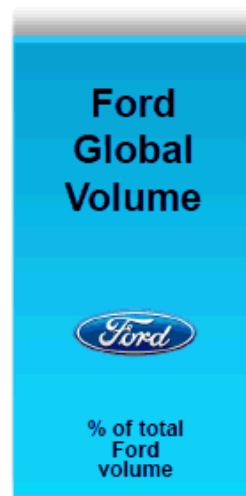
Ford likewise sees a mix of powertrain options in the future...



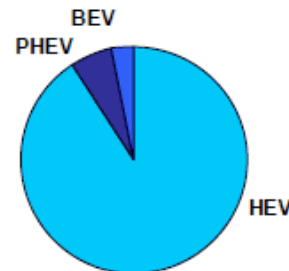
Slide 14, May 4, 2011



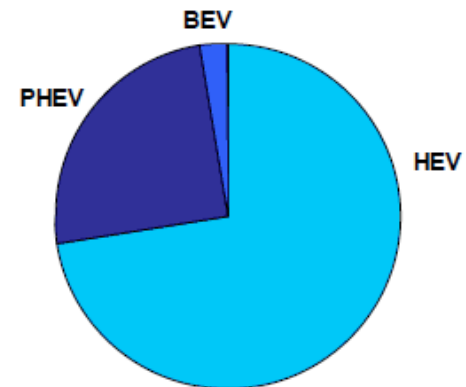
... but even so, Ford only sees a sliver of its global sales not having engines



1%



2-5%



10-25%

- Portfolio Approach = HEV/PHEV/BEV (customer-driven)
- Global Flexibility = Electrify Highest Volume Platforms
- Best Value = HEVs Remain Highest Volume
- Affordability Remains Key = Sharing Common Components



Ford's electrified platform strategy provides global flexibility



Slide 18, May 4, 2011

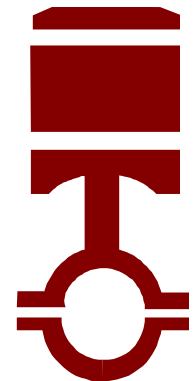
Cost-benefit overview for leading fuel economy improvements shows a mix of options

Technology	Benefit	Cost	Vehicle Manufacturers Using
Advanced Fuels	+	0	n/a
Compression Ratio Increase	+	0	All
Cam Profile Switching	++	\$\$	Honda, Mitsubishi, Porsche, Audi
Active Valvetrain	+++	\$\$\$	Fiat, BMW
Direct Injection Fuel Sys.	++	\$\$	Mitsubishi, Audi, GM, Ford, BMW, etc.
Turbocharging	++	\$\$	Ford, Volvo, GM, Audi, BMW, etc.
Advanced Boosting systems	+++	\$\$\$	None
Exhaust Energy Recovery	+	\$\$\$	Commercial vehicles

- Effects are not simply additive—some synergies are possible, as are conflicts
- Higher fuel octane will facilitate changes to engine compression ratio, direct injection fuel systems, and higher boost pressures.

- Challenge or Opportunity ...
- Technology Roadmap
- **Technologies Explained**
 - **Component technologies**
 - Complete engines
- Conclusions

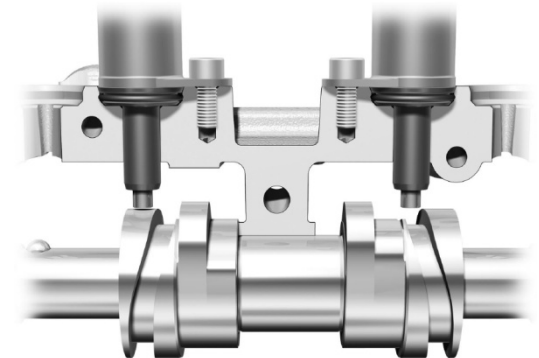
- Increasing the compression ratio for SI engines improves fuel consumption by improving the volumetric and thermal efficiency
 - Fuel energy is more effectively used by the engine
- Higher compression ratios, though, affect engine performance, since the knock limit is reached faster
 - Higher octane fuel increases the range of engine speed and load where autoignition (knock) is not a problem
 - 87 octane fuel limits performance, as engines knock sooner
- CO₂ benefit of 3–5% over drive cycles per higher ratio
 - e.g., increase from 9.5:1 to 10.5:1 compression ratio
- Negligible increases in engine cost



- Increasing the engine's intake air pressure with a compressor increases the torque and power available from a given engine displacement
 - This allows the same power from a smaller engine
 - This reduces pumping work in the engine by shifting engine operation to higher-load operating points
- Several types of boost systems are expected to be available over the timeframe, including
 - Supercharger: the compressor is driven mechanically by the engine
 - Turbocompressor: the compressor is driven by a turbine powered by expanding exhaust gas
 - Two-stage turbocharging: Two turbocompressors in series can provide better response and higher pressures, but for higher cost and complexity
- CO₂ benefit of 5–10% over drive cycles
- 10–15% increase in engine cost

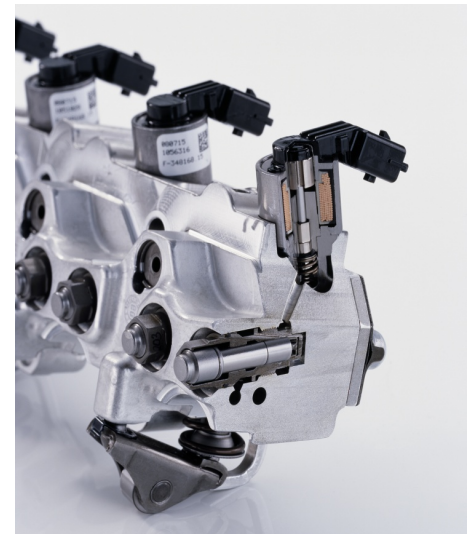


- Cam-profile switching (CPS) systems allow selection between two or three cam profiles by means of a hydraulically-actuated mechanical system
 - CPS systems have been developed by a number of Japanese and European OEMs, such as the Honda VTEC, Mitsubishi MIVEC, Porsche VarioCam and Audi Valvelift (pictured)
- CPS systems can be optimized either to improve low-speed torque, or to improve fuel economy by reducing pumping losses at light load
- CO₂ benefit of 5–7% over drive cycles
- 8–10% increase in engine cost



Camless Valve Actuation

- Fully camless valve actuation systems allow full flexibility for valve lift and valve opening and closing times
 - Fiat MultiAir is the only system in the market currently
- Camless systems can be optimized either to improve low-speed torque, or to improve fuel economy by reducing pumping losses at light load
- CO₂ benefit of 8–10% over drive cycles
- 10–12% increase in engine cost

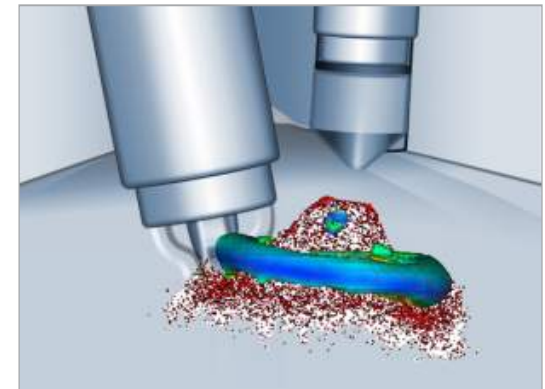


- Homogeneous direct-injection SI engines operate in a very similar manner to port fuel-injected (PFI) engines, except that fuel is injected directly into the cylinder
 - SIDI engines were first introduced in Japan in 1996, and a significant number of new gasoline engines now feature direct injection.
- The application of direct injection produces modest fuel economy benefits, resulting from the ability to apply higher compression ratio.
- CO₂ benefit of ~3% over drive cycles
- 8–10% increase in engine and aftertreatment cost



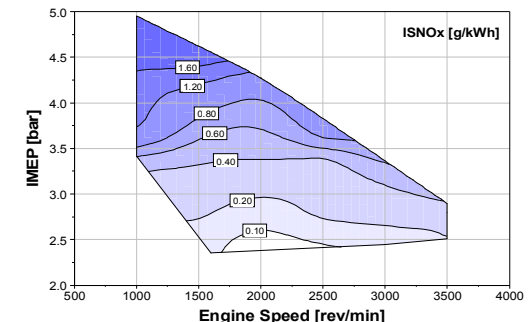
Stratified Charge Direct Injection

- In stratified-charge engines the fuel is injected late in the compression stroke with single or multiple injections. The aim is to produce an overall lean, stratified mixture, with a rich area in the region of the spark plug to enable stable ignition.
- Stratified lean operation allows the SI engine to operate unthrottled, eliminating the majority of pumping losses.
- CO₂ benefit of 8–10% over drive cycles
- 15–25% increase in engine and aftertreatment cost

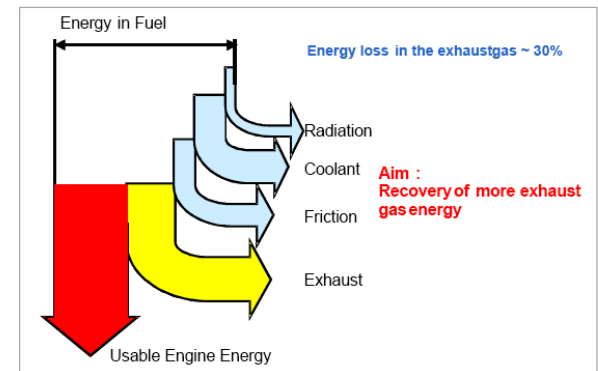


Homogeneous Charge Compression Ignition (HCCI) or Controlled Auto-Ignition (CAI) Combustion

- Homogeneous charge compression ignition (HCCI), also known as controlled auto-ignition (CAI) combustion, is distinct from the conventional SI and CI engine operating modes
 - In the idealized case HCCI/CAI combustion initiates simultaneously at multiple sites within the combustion chamber, and there is little or no flame propagation
- The most likely implementation has dual mode operation
 - HCCI/CAI at part-load
 - SI for high-load, idle and starting
- CO₂ benefit of 2–10% over drive cycles, depending on how the benefits of the constituent technologies are counted
- 20–30% increase in engine and aftertreatment cost



- Exhaust energy recovery encompasses a number of technologies, such as turbo-compounding and thermoelectric devices
 - In turbo-compounding a radial turbine is connected through a mechanical transmission directly to the crankshaft
- Turbines are generally sized to recover energy at high load operation; a variable-speed transmission between engine and turbine can be used to improve the efficient operating range
- Costs: Not established for light-duty vehicles
- CO₂ benefit of 3–5% over drive cycles
- Costs are not established for light-duty vehicles



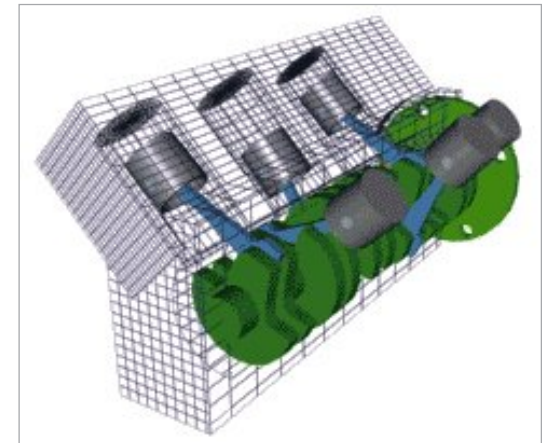
- Wherever possible renewable fuels should operate in a manner identical to conventional fuels, especially gasoline for U.S.
 - Increasing blending of conventional gasoline and biofuels is likely to occur
 - EPA RFS 2 standard mandates increasing use of renewable fuels
- The CO₂ benefits from the use of renewable fuels are complex and disputed
 - Tank-to-wheels fuel economy for biofuels is similar to conventional fuels
 - The higher octane number of ethanol-based fuels may facilitate other technologies
 - Additional CO₂ benefits can be attributed to renewable fuels use if the complete life-cycle is considered (e.g., for cellulosic ethanol)
 - Higher heat of vaporization can improve performance by providing charge cooling effect in cylinder
- There is no significant engine cost associated with the use of single-fuel renewable fuels, although appropriate materials must be applied in the fuel system



- Challenge or Opportunity ...
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 - Component technologies
 - **Complete engines**
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Current (2011) SI Engines

- Current SI engines light-duty vehicles in the US market are a range of naturally-aspirated port fuel-injected (PFI) engines, featuring dual-independent cam phaser (VVT) systems
- Costs: Baseline – powertrain and aftertreatment cost of ~\$1500–\$2000 for standard car segment



Stoichiometric Direct-Injection Turbocharged Engines

- Downsizing replaces a naturally-aspirated engine with a smaller-displacement turbocharged engine, having equivalent torque and power
 - Use direct injection to facilitate higher power density
- Downsizing reduces pumping work by shifting operating points to higher load factors, and can also produce reductions in frictional losses
- CO₂ benefit of 8–10% over drive cycles
- 15–25% increase in engine and aftertreatment cost



Lean Boost Direct-Injection® (LBDI®) Engines

- In the LBDI concept the octane requirement to avoid engine knock is controlled using direct injection and lean operation at full load
- LBDI engines combine the downsizing benefits described on the previous slide with the additional efficiency benefit of homogeneous lean operation at high load
- CO₂ benefit of 20–22% over drive cycles
- 50–60% increase in engine and aftertreatment cost
 - Lean NO_x aftertreatment on US06 (aggressive highway) cycle is expected to be challenging



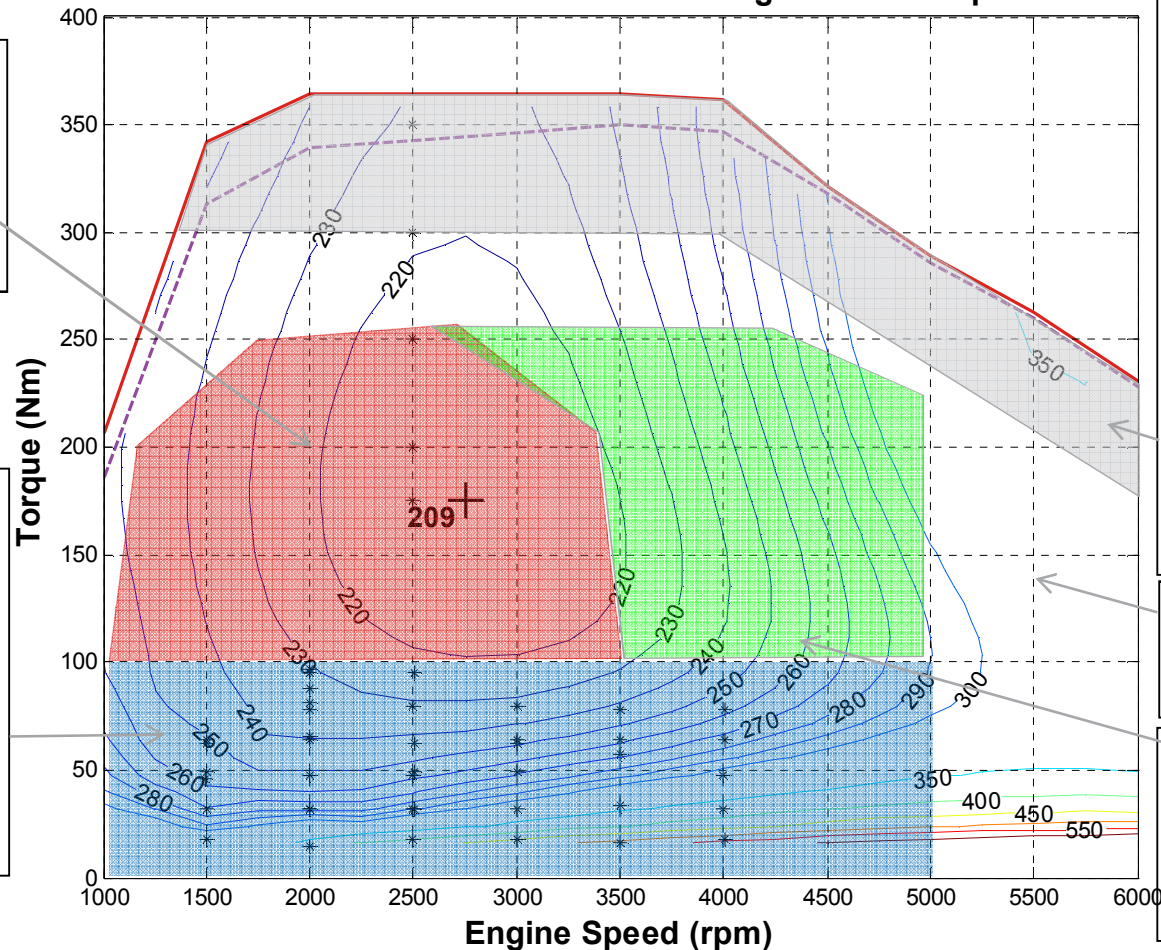
High-Load EGR Engines (EBDI®)

- In the EBDI® concept the octane requirement to avoid engine knock is controlled by EGR dilution at full load
- High-load EGR engines combine the benefits of downsizing described previously with the additional efficiency improvement of EGR dilution at high load
- CO₂ benefit of 15–18% over drive cycles
- 40–45% increase in engine and aftertreatment cost
 - Should be able to use three-way catalyst



EGR and (Un-Optimized) BSFC map for Next Gen engine

2.0L GTDI Stratified Next Gen Engine BSFC Map



Red region:

- WOT boosted region
- Combination of closed spaced late injections and MIVIS strategy
- EGR 0 – 10%

Blue region:

- WOT (effectively) NA stratified region
- All late, close spaced multiple injections
- EGR 10 – 30%, dependant on engine out NOx target
- BSFC further improved since map was generated

Grey region:

- Lambda 1 operating region with multiple injection strategies for knock mitigation
- Assumed 1050 T/C or water cooled exhaust manifold
- Low pressure cooled WOT EGR (5 – 15%) can be used when combined with advanced boosting and increased CR for further efficiency improvements

Clear region:

- Lambda 1 operating region, no EGR required

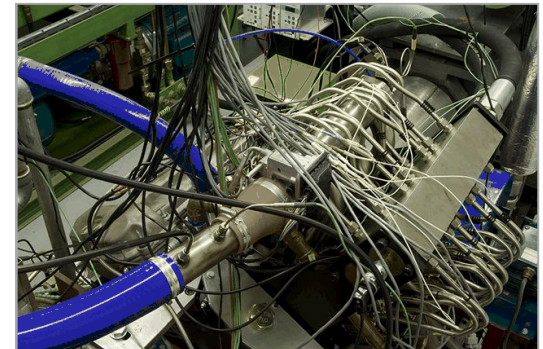
Green region:

- WOT Boosted region
- **MIVIS strategy for best BSFC**
- EGR 0 % as “off-cycle”

- Part load EGR percentage dependant on engine out NOx target vs BSFC penalty
- Recommend use of WOT EGR with advance boosting system (E-Boost/Twin stage) as otherwise detrimental to compressor sizing and thus transient response
- SGDI combustion system and injection strategies to mitigate knock and allow full load lambda 1 engine operation possible when combined with high temperature turbine (1030°C) or water cooled exhaust manifold

Two-Stroke/Four-Stroke (2S-4S) Switching Engines

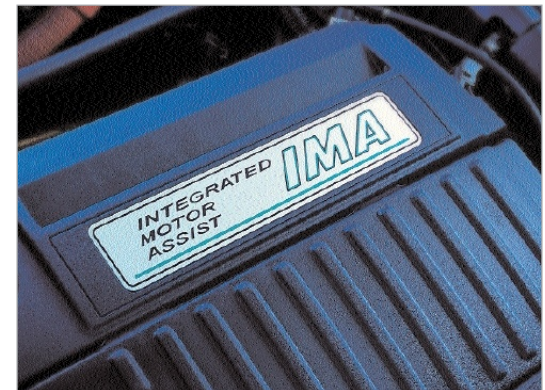
- The vast majority of passenger cars use the four-stroke cycle, but some characteristics of two-stroke engines—especially high specific torque—remain attractive for automotive application
- 2S-4S engines combine a combustion system capable of operating as both two-stroke and four-stroke with advanced valvetrain and boosting systems.
- 2S-4S engines offer the greatest opportunity for engine downsizing, and hence improvement in efficiency
- CO₂ benefit of 25–27% over drive cycles
- 70–80% increase in engine and aftertreatment cost



- Application of stop-start or micro-hybrid concepts requires only very minor changes in base engine architecture. Typically a belt-driven starter-generator is applied in place of a separate starter motor and alternator.
- CO₂ benefit over drive cycles depends on time spent idling
- Base engine costs are largely unchanged for stop-start systems. Additional engineering cost is required to implement the stop-start calibration.
 - Cabin heating or cooling systems will require upgrades to function during engine off



- In hybrid electric vehicle applications the gasoline engine can be optimized for use in the limited modes required by the full hybrid powertrain.
 - Engine technology optimization for hybrid powertrains in infancy. Clear trend towards system level optimization to obtain best overall performance.
 - Hybrid features such as stop-start, CVT operation, electrical launch, and electrical assist provide an opportunity to optimize the engine system in ways not offered by conventional drivelines.
 - Electrical assist offers opportunity to reduce engine size and specific power in hybrid vehicle and use lower specific power or increased BSFC technologies
- CO₂ benefit is a strong function of the hybrid control strategy
- Base engine costs may be slightly reduced for hybrid vehicle applications through the use of lower specification engines.

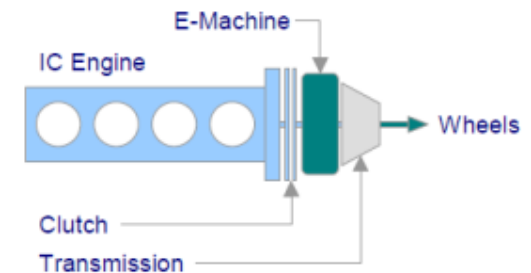


- The stop-start hybrid is the simplest form of hybridization, supporting engine shut-off during idle periods; typically employs enhanced starter motor and limited use of driver comfort features during engine off
 - The stop-start hybrid decreases fuel use by minimizing idling but provides no benefit for highway use or when air conditioning is needed
- Application of stop-start or micro-hybrid concepts requires only very minor changes in base engine architecture. Typically a belt-driven starter-generator is applied in place of a separate starter motor and alternator.
- CO₂ benefit depends on time spent idling (approx. 3–5% benefit)
- Base vehicle costs are largely unchanged for stop-start systems. Additional engineering cost is required to implement the stop-start calibration.
 - Cabin heating or cooling systems will require upgrades to function during engine off

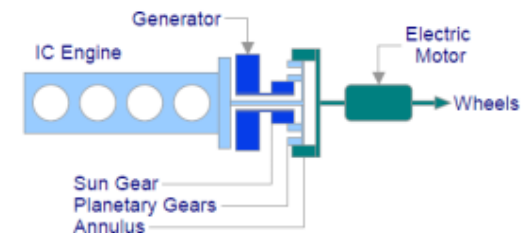


Full Hybrid: P2 Parallel Hybrid

- An electric machine (EM) is placed between the engine and the transmission, typically with a clutch between the engine and EM
 - The EM supports launch assist and regenerative braking
 - P2 Parallel Hybrid provides stop-start, electrical launch, and launch assist driving, all of which facilitate downsizing the engine for better efficiency
- CO₂ benefit of ~20% on city cycles, <5% on highway
- Costs will come from engineering work to implement the system and controls and from added equipment for hybrid powertrain, including electric machine, battery, and controller



- Power split hybrids use an electric machine directly integrated into the transmission, and either provide an additional input parallel to the engine or act as an additional output from the transmission
 - Both configurations permit an electric (only) operating mode.
 - Hybridization provides stop-start, electrical launch, and launch assist driving, all of which facilitate downsizing the engine for better efficiency
- CO₂ benefit of 22–33% on city cycles, modest benefit on highway
- Costs come from added equipment for hybrid powertrain, including electric machine, battery, and controller
 - Input Power Split Hybrids are already in production, including the Toyota Prius and Ford Escape



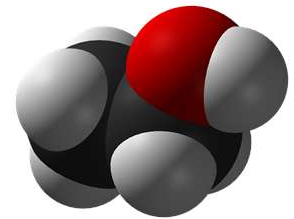
- Challenge or Opportunity ...
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- **Conclusions**

Conclusion: During the next decade internal combustion engines will become significantly more efficient

- Future fleet fuel economy targets in the U.S. will require significant changes in engine technology over the next 10–15 years
- Vehicle electrification will be part of the solution, but the vast majority of vehicles sold in 2025 will use internal combustion engines as the primary form of propulsion
 - Battery-only electric vehicles will only represent a niche market
- Engines will have higher specific power from using technologies such as
 - Direct injection
 - Turbocharging or similar boost systems
 - Higher compression ratios

Conclusion: Higher minimum fuel octane number will facilitate engine technologies

- Octane rating or octane number is a standard measure of the anti-knock properties (i.e. the performance) of a motor or aviation fuel. The higher the octane number, the more compression the fuel can withstand before detonating.
 - Pump octane numbers average the Research Octane Number (RON) and the Motoring Octane Number (MON), which are measured by testing
- Higher fuel octane number moves the knock limit further from normal operation
 - Allows fully stoichiometric operation at high speed and high load
- Higher minimum fuel octane number will facilitate engine technologies such as
 - Direct injection
 - Turbocharging or similar boost systems
 - Higher compression ratios



110 RON

Future powertrain solutions will have a natural thirst for higher octane fuels