An Overview of Hybrid Technologies

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Group Technology Director

Agenda

- Definition of variants
- Modes of operation
- Potential benefits and costs
- Market penetration
- Plug-in hybrid vehicles
- Effective support for R&D

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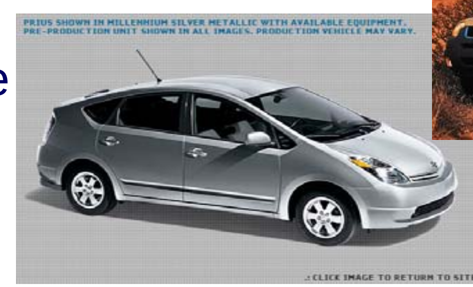
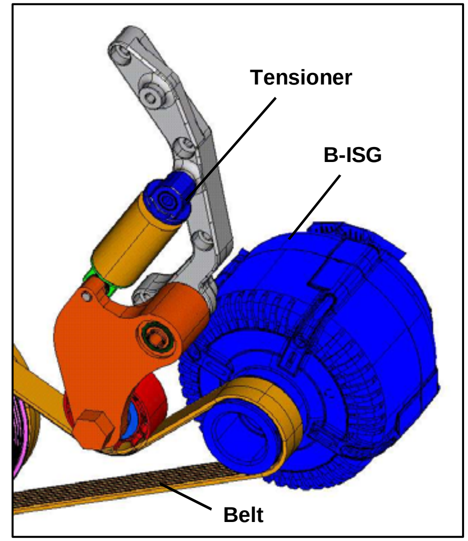
Hybrids combine two power sources, one of which can store energy when the vehicle slows down. Usually these are an IC engine and an electric motor. There are many permutations…

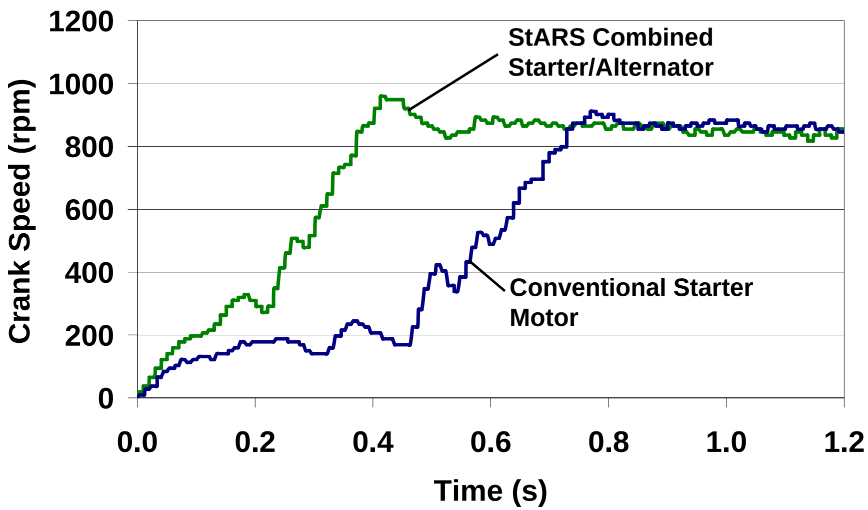
- **Stop / Start and Micro Hybrid**
  - Simplest systems are just automated starter motors; but most are belt-drive starter/alternators
  - Fuel saving: 3-10% - but up to 20% in heavy traffic
  - Best for: Urban delivery vans, Gasoline city cars
  - On Sale: Citroen C3
- **Mild Hybrid**
  - Small motor that supplements engine power, usually used together with a down-sized engine
  - Fuel saving: 20-35% - half or more from down-sizing
  - Best for: Cost-effective Gasoline or Diesel family vehicles with mixed usage
  - On sale: Honda Civic IMA and Accord IMA
- **Full Hybrid**
  - 1 or 2 Electric motors of significant power
  - Many different arrangements of engine & motors
  - Fuel saving: 30-50% - but not at high speed cruise
  - Best For: Family or premium vehicles (inc SUVs) with tendency to urban use
  - On Sale: Toyota Prius, Ford Escape, Lexus RX

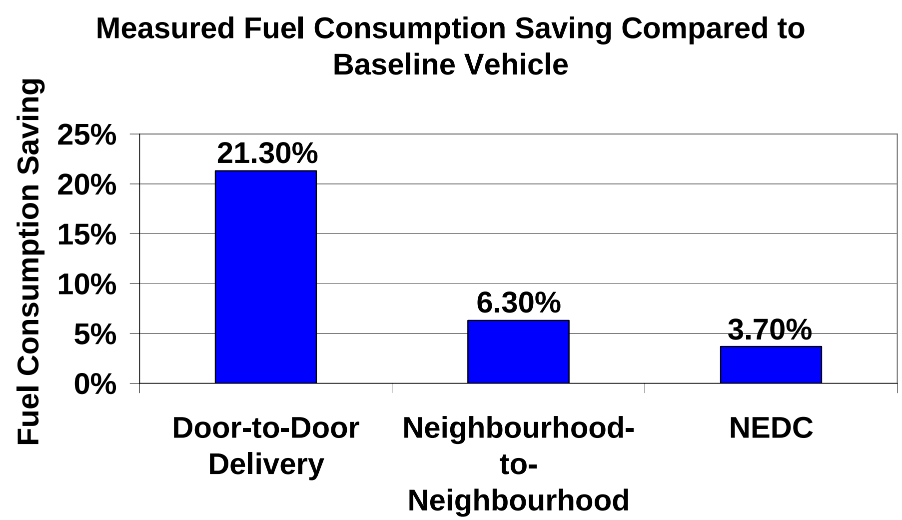


Stop and Start mode enables the prime mover to be shut down when not in use

- Urban driving demands an increased amount of engine idling
  - Running ancillaries (AC, PAS, Alternator, etc.)
  - Normal starter too slow for instantaneous re-start
- Higher power motor allows for almost "seamless" re-starts
- Benefits achieved through engine shut-down when stationary, although requires catalyst to be "lit-off" in order to gain full benefit







Ricardo's HyTrans project, delivered in 2005, illustrates what can be achieved with low cost technology in a micro-hybrid vehicle

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Hybrid | **Diesel Micro-Hybrid Example**

The Program

- **HyTrans was a partnership, including Ricardo, Ford, Valeo and Gates with funding from all partners and from UK Government Energy Savings Trust**
- **Management quality demonstrator vehicle delivering:**
  - Fuel consumption improvement 15-25% over urban delivery cycle
    - But only 4% improvement on the NEDC
  - No reduction in payload
  - Conventional vehicle refuelling with no external electrical charging
- **12 month program**
- **Ricardo were the project leader, with technical responsibilities for:**
  - Concept evaluation,
  - Cost/benefit analysis,
  - Supervisory control strategy implementation,
  - Vehicle build and calibration

Hybrid Technologies

- **Stop/start, regenerative braking and potential for torque assist on 2.0L Diesel**
- **Belt driven 42V Integrated Starter Generator**
- **Gates Electro-Mechanical Drive (hydraulic tensioner system)**
- **Battery: 36V advanced lead acid**
- **DC-DC voltage converter**

Energy Saving Trust

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Ford

Valeo

Gates

A Tomkins Company

- **Results:**
  - Production units scheduled for 2010
  - Significant interest from commercial fleets

Source: Ricardo Research

Ricardo's *i-MoGen* diesel mild-hybrid demonstrator vehicle, an internally funded research program delivered in 2001

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Hybrid | **Diesel Mild-Hybrid Example**

The Program

- **The *i-MoGen* research programme delivered**:
  - <4l/100km fuel economy
  - Vehicle weight neutral to 2.0 litre Astra
  - In gear acceleration in top gear 1 second better than base vehicle
  - 28% Fuel Consumption reduction from donor vehicle
  - 20% from downsized engine, fast warm up and intelligent cooling, 3% from Stop and Go, 5% from regenerative braking
  - Incremental cost <$1000
  - < half Euro IV diesel emissions
- **Used Ricardo Supervisory controller:**
  - Controls FMED, batteries (SOC/SOH), safety strategy, engine & emissions
- **Uses Ricardo's own downsized 1.2l, 4-cyl diesel engine with 100hp and electric DPF aftertreatment**
- **Electrical machine, power electronics & advanced thermal systems from Valeo**
- **Prototype vehicle used for 1200+ test drives & driven for over 20,000 km**

Hybrid Technologies

- **Stop/start, regenerative braking, torque assist & intelligent power management**
- **42V, 6kW Integrated Starter Generator**
- **Battery: 42V NiMH, 17Kg, 9kW**
- **DC-DC voltage converter**
- **42V Ancillaries: Water pump, fans, HVAC (no fan belts or alternator**

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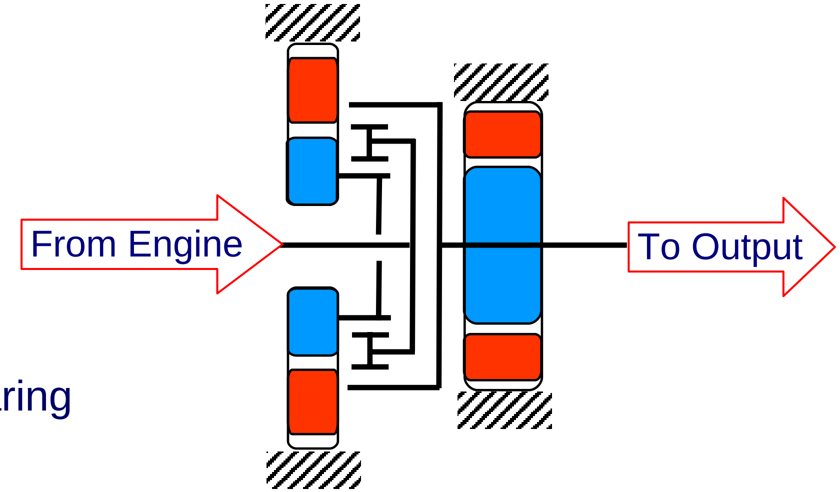
saft

Source: Ricardo Research

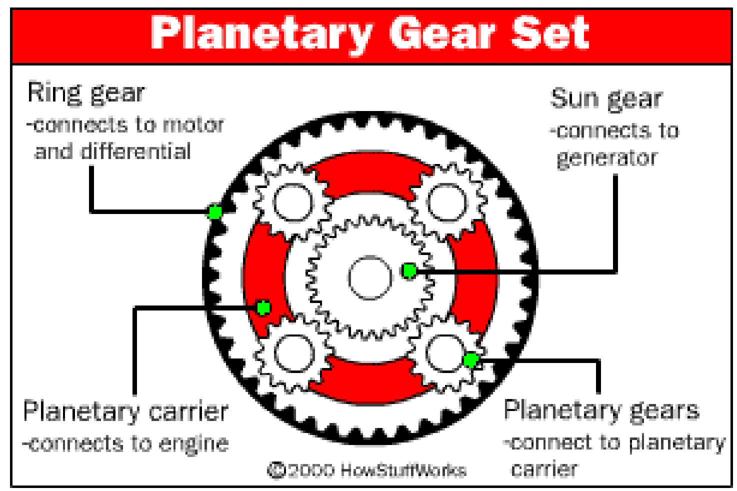
Power-Split – Single epicyclical transmission forms the basis of Toyota approach – requires separate motor & generator

CONCEPT: Twin motor series-parallel hybrid with single epicyclic

- **Method of Operation**
  - Generator attached to Sun
  - Engine attached to Planet Carrier
  - Motor attached to Annulus (output)



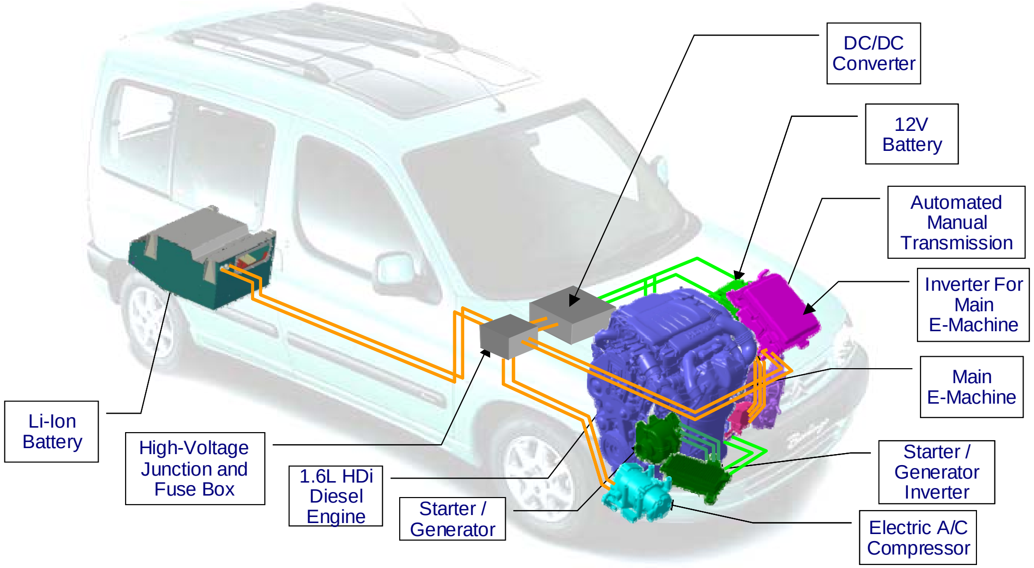
- **Issues**
  - Motor rotates at output speed unless additional gearing is applied between motor and output shaft (Lexus application).
  - Gear ratio controlled by relative speeds (torques) of motor and generator
  - High speed (primarily engine driven) operation inefficient due to requirement for holding torque on generator, but can be improved by incorporation of a brake.
  - Large motor required on output to meet vehicle performance requirements
  - Engine starting torque from EV mode is reacted through driveline – OK for Atkinson cycle gasoline – Not OK for diesel unless decompression device used or power electronics for damping.



Source: HowStuffWorks.com

The Ricardo full hybrid technology demonstrator Efficient-C has successfully delivered 99g/km CO_2

Hybrid | **Diesel Full-Hybrid Example**



VEHICLE	Berlingo Multispace	Efficient-C
Engine	Diesel 1,6L (66kW)	Diesel Full-Hybrid
Performance (with half of maximum payload)		
Maximum speed	158kph / 99mph	171kph / 106mph
0 - 100 km/h (s)	14.8	13.4
0 - 1000 m (s)	36.6	35.5
NEDC Cycle		
Fuel consumption Urban*	6.7 l/100km, 42 mpg	3.7 l/100km, 76 mpg
Fuel savings Urban	reference	45%
Fuel consumption Combined**	5.4 l/100km, 52 mpg	3.75 l/100km, 75 mpg
Fuel savings Combined	reference	30%

* SOC neutral operation in each phase ** SOC neutral over combined cycle

- Collaborative research programme, lead by Ricardo, with PSA Peugeot Citroën and QinetiQ, supported by Energy Saving Trust
- Diesel full hybrid vehicle delivering 99g/km CO_2, 3.75 l/100km, 75 mpg
  - 30% improvement over 1.6 litre diesel baseline
  - With Euro 4 emissions
  - Zero emissions mode 5-10km
  - Uncompromised interior
  - Improved performance

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Agenda

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- ❑ **Modes of operation**
- ❑ Potential benefits and costs
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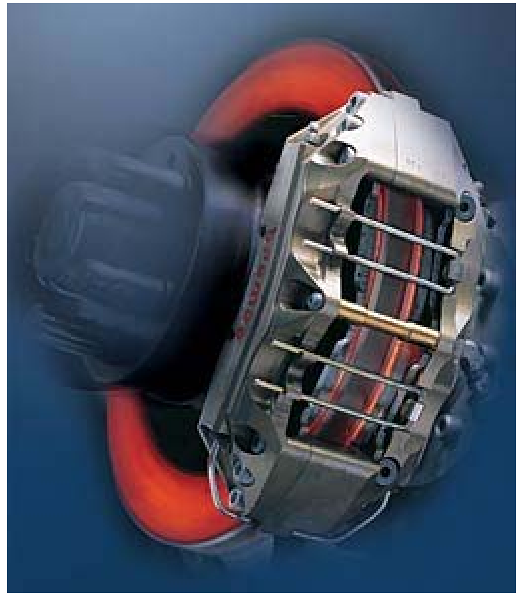
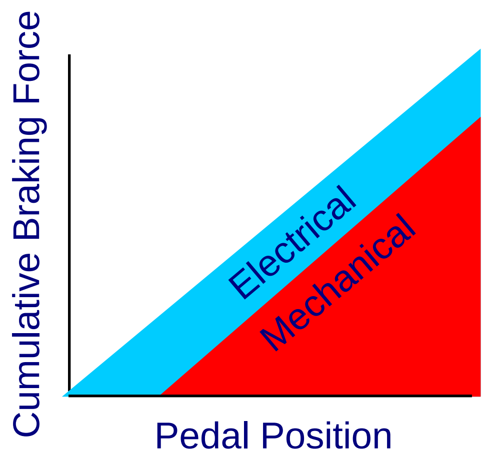
- ❑ Plug-in hybrid vehicles
- ❑ Effective support for R&D

Regenerative braking recovers kinetic energy which would normally be lost though heat under braking

- Typically, during the NEDC drive cycle >25% of fuel energy is “wasted” in braking
- Instead of heat, this energy can be converted to electrical energy and stored in the vehicle’s battery for re-use later
- The vehicle’s foundation brakes are still required to achieve full braking performance
  - Regenerative braking can provide a good proportion of braking effort
  - Transition between electrical braking and mechanical braking is critical
    - Driver confidence
    - Safety
    - Vehicle stability
  - Electro-hydraulic brake systems are the most common way to achieve this but are very expensive

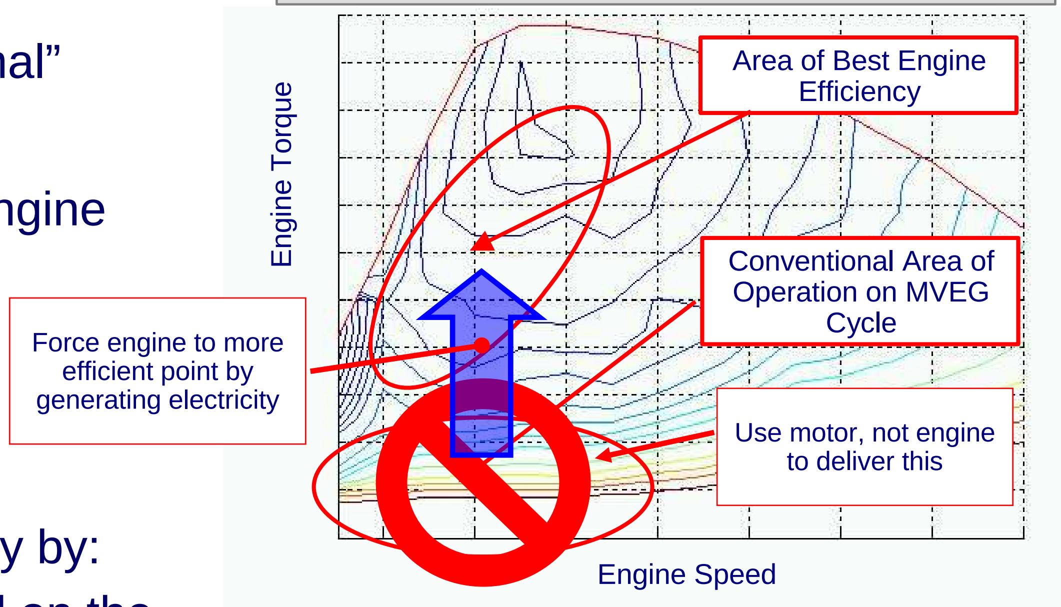




Hybrid systems enable the engine to be operated at the most efficient point resulting in improved fuel consumption

- An engine's efficiency varies widely depending on the speed / load operating range
- Typically efficiency is poor under "normal" driving conditions
- Peak efficiency occurs at around 1/3 engine speed and 2/3 engine load
- A hybrid system improves fuel economy by:
  - Using the motor to increase the load on the engine
  - This improves efficiency but generates surplus power as electricity
  - The electricity is stored in the battery and then used to propel the vehicle

Typical Fuel Efficiency Map
Mid-Sized Diesel Engine



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Given the investment and incremental costs of Hybrid systems, introduction will follow an evolutionary path, building on existing powertrains and architectures

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Powertrain Configuration: Evolution →

IC Engine	Conventional	Conventional	Conventional	Downsized - No FEAD	Downsized - No FEAD	Downsized - Optimised Cycle
Electric Motor	Belt Driven Starter Alternator (14v)	Belt Driven Starter Alternator (42v)	Belt Driven Starter Alternator (42v)	Crankshaft Mounted ISG (42v)	Crankshaft Mounted ISG (100+v)	Remote Mounted (288v) via Transmission
Ancillaries	Conventional	Conventional	Electric	Electric	Electric	Electric
Main Battery	PbA 25kg	PbA (VRLA) 30kg	PbA (VRLA) 30kg	NiMh 20kg	NiMh 40kg	NiMh 60kg
	Stop/Start	Micro Hybrid		Mild Hybrid		Full Hybrid

Capability:

Start/Stop	✓	✓	✓	✓	✓	✓
Regenerative Braking		✓	✓	✓	✓	✓
Intelligent Energy Management			✓	✓	✓	✓
Electric Launch					✓	✓
ZEV Capability						✓

Start / Stop

Benefits:

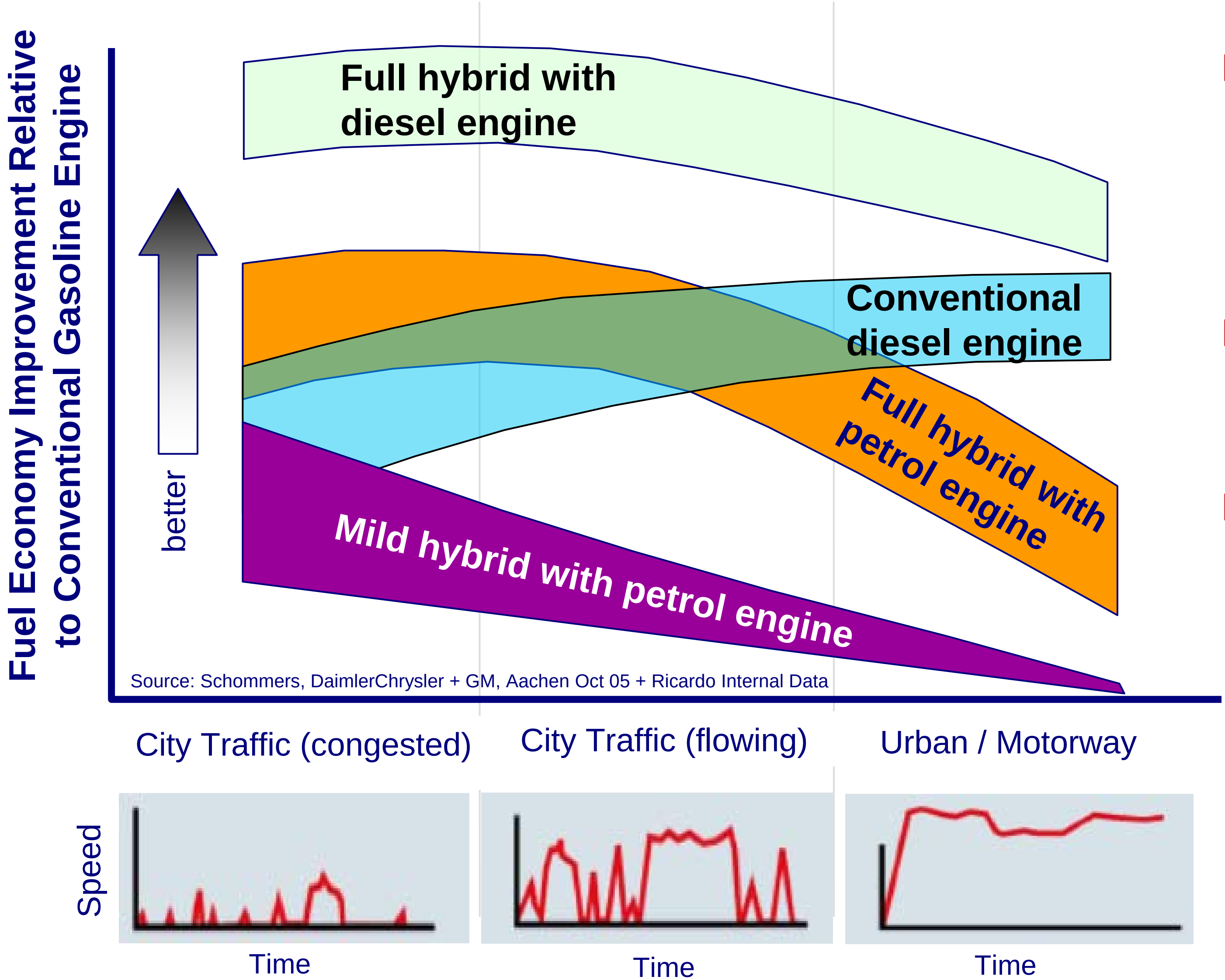
Drive Cycle Fuel Economy	3%	7%	10%	30%	35%	40-50%

Cost →

Additional Cost:

Additional Cost	Low	Moderate	Medium	High

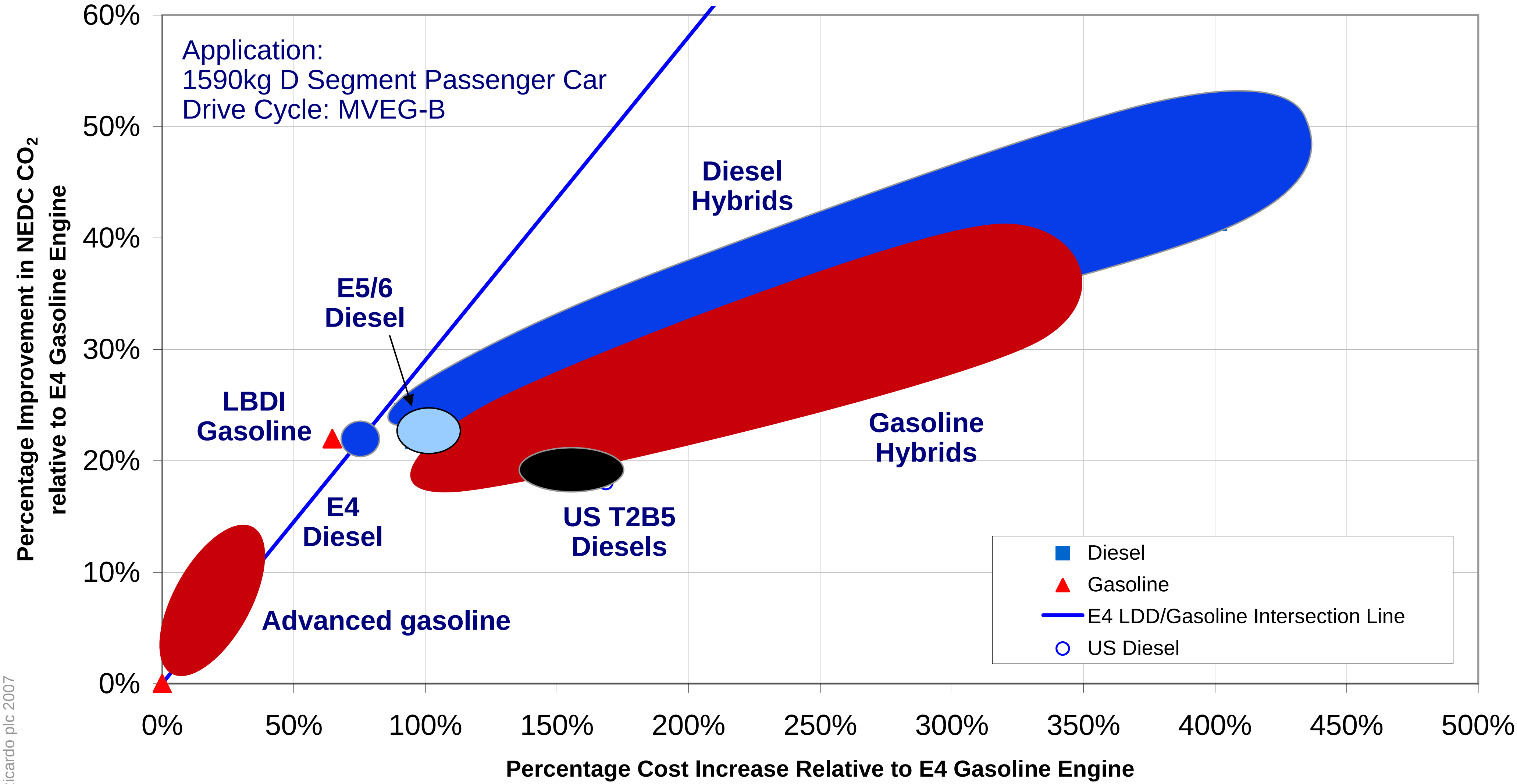
Hybrid Systems - higher fuel economy in congested traffic - diesel more efficient than hybrid gasoline in higher speed free flowing traffic – diesel hybrid best but expensive



- Relative merits of Diesel or Hybrid depend on application and drive pattern
- Stop/start and low speed driving favours Hybrid configuration
- Higher speed operation requires high efficiency combustion and driveline
  - “Electric Transmission” always less efficient than mechanical system

Technologies to reduce CO_2 add cost to the powertrain with hybrid being the most expensive

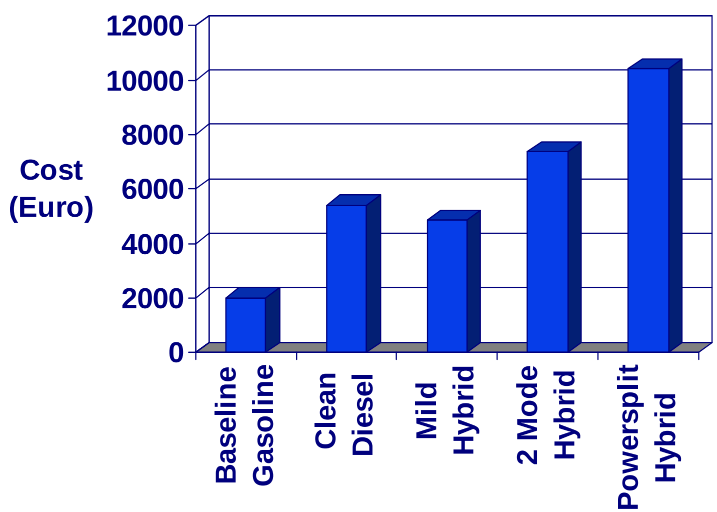
Cost versus Fuel Consumption Improvements for Powertrain Technologies



Source: Ricardo analysis

The cost of a Hybrid powertrain can be up to four times more expensive that the equivalent conventional gasoline engine

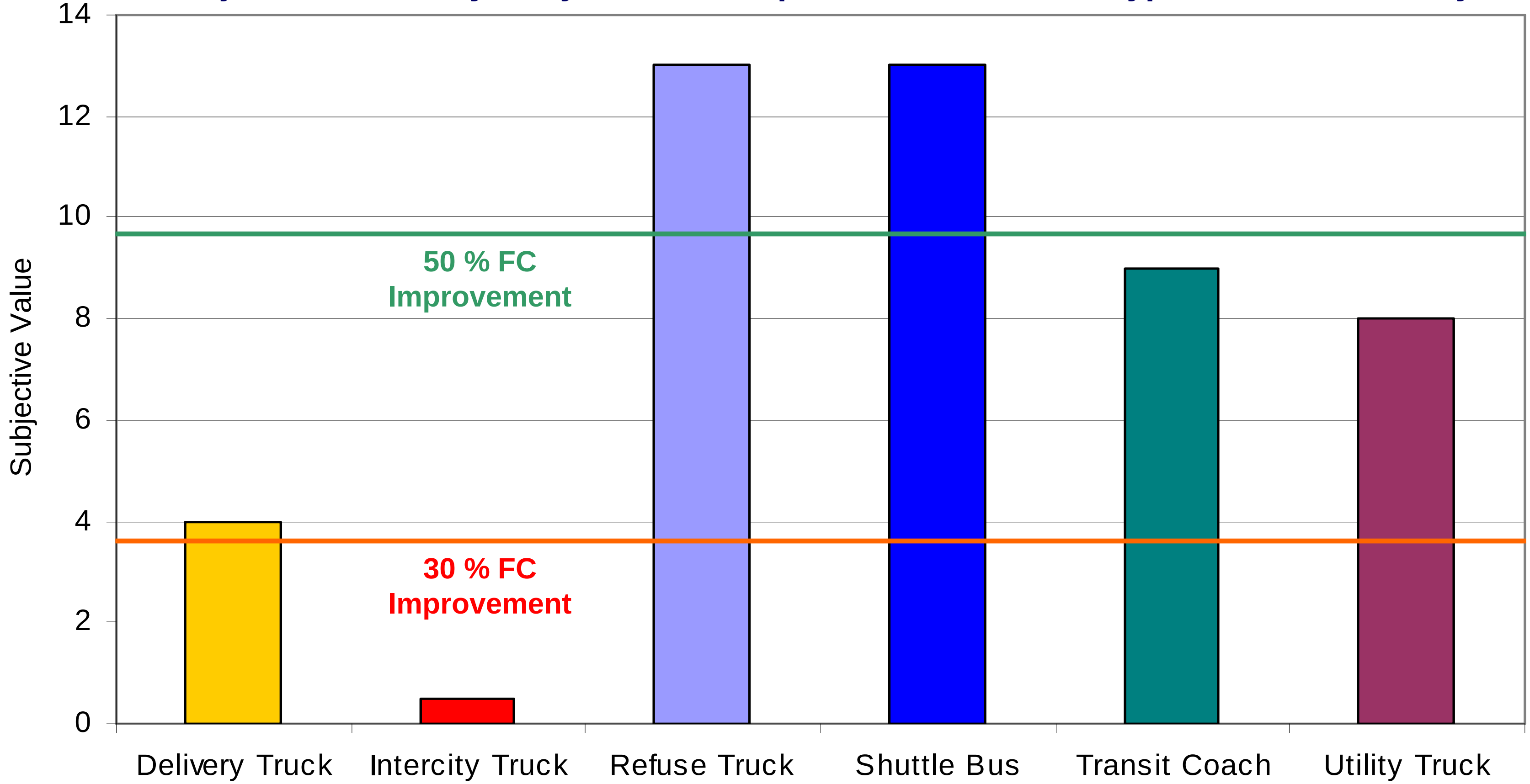
- Cost analysis was based on the US Market
  - Tier 2 – Bin 5 capable
- Vehicle: Crossover SUV
  - Performance: 0-60mph in 7s
  - Top Speed: 250 kph

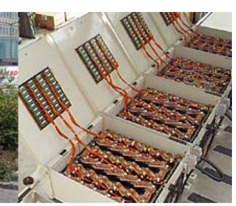


		Baseline Gasoline	Clean Diesel	Mild Hybrid	2 Mode Hybrid	Powersplit Hybrid
Specifications	Engine size (litres)	4.3	4.3	3.9	3.5	3.5
	Engine Power (kW)	210	210	190	170	170
	Configuration	V8	V8	V8	V6	V6
	E-Motor1 (kW)			20	60	150
	E-Motor2 (kW)				60	
	Generator (kW)					100
	Battery Size (kW.h)			2	3	3
Costs (€)	Base Engine	2000	3900	2000	1600	1600
	Aftertreatment/Em Control		1500			
	Motor + Inverter			600	1500	3750
	Generator/Motor2 + Inverter				1500	2500
	Battery Management			150	250	250
	Battery			1200	1800	1800
	DC/DC and cables			250	250	250
	Simplification from auto trans			100	-100	-300
	Cooling system			100	100	100
	Vehicle adaption (steering, vacuum, HVAC)			460	460	460
	Total Cost (€)	**2,000**	**5,400**	**4,860**	**7,360**	**10,410**
	% Increase	**-**	**170%**	**143%**	**268%**	**421%**

The application of hybrid technology can also be extended to an array of commercial vehicle applications with a varying degree of potential

A subjective summary of hybrid vehicle potential based on a typical 8 hour drive cycle





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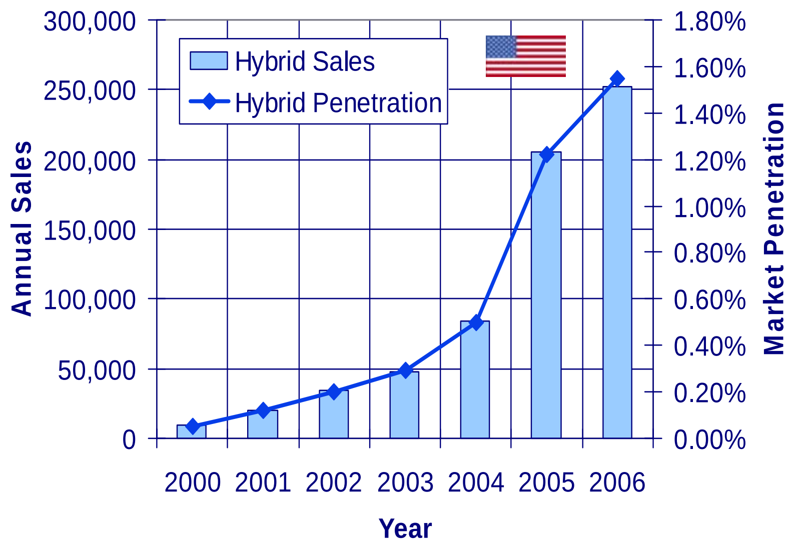
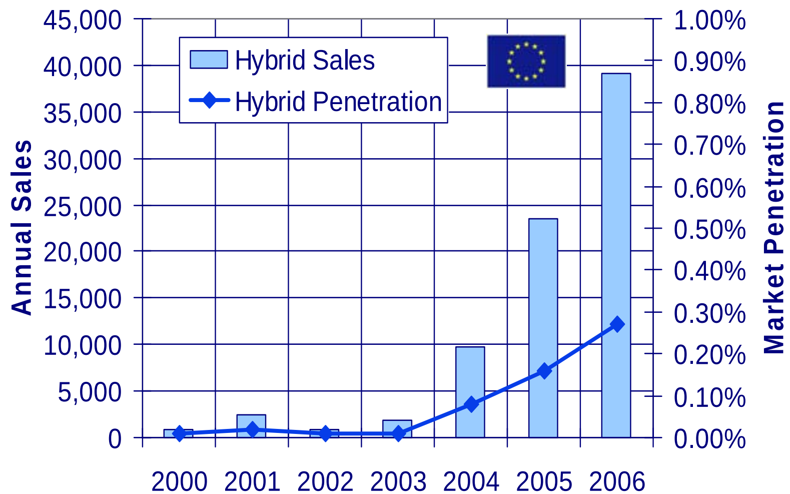
There has been poor early adoption of hybrids in the passenger car market primarily due to the high technology cost



USA

- Recent success can be attributed to:
  - Increase in gasoline fuel prices
  - Concerns over fuel supply security (Iraq)
  - Increased incentivisation
  - Unique marketing success of the Toyota Prius



Western Europe

- Hybrid sales in Western Europe remain very low due to:
  - Consumers having a wide choice of diesel engines across all vehicle segments not just one or two gasoline hybrid models
  - Diesel offering as good fuel economy as hybrid gasoline without the cost premium
  - Diesel offering better fuel economy than hybrid gasoline in suburban / motorway driving conditions

Achievement of proposed EU targets requires high levels of penetration of new technologies

- Analysis of Technology mix required to meet **130g/km CO_2** fleet average target by **2012** - assumes:
  - A steady-state reduction in CO_2 of 2.44% per annum which continues to 2020
  - Consumers continue to buy roughly the same size cars (no vehicle segmentation change)
- EC target of 100g/km CO_2 in the 2020 – 2030 time horizon

EUROPE

Technology required for EU-15 fleet average CO_2 to meet targets

Technology	2004	2008	2012	2020
Diesel	48.9%	55%	58%	65%
Advanced Gasoline	< 10%	28%	30%	35%
Advanced automatic transmission	< 10%	33%	62%	95%
Stop/start hybrid	< 1%	10%	25%	32%
Micro hybrid		5%	10%	12%
Mild hybrid		5%	9%	12%
Parallel (full) hybrid		3%	9%	10%
Fleet average CO_2 g/km	163	143.2	129.0	111.0

- **Ricardo view on 2012 target:**
  - Technology mix required to achieve 130g/km without a change in segmentation will require significant rollout of new gasoline engines and hybridisation. Not enough engineering resource or production infrastructure to achieve this
- **To achieve 100g/km (c. 111g/km via technology) by 2020:**
  - 95% of vehicles will have an advanced automatic transmission
  - 66% of vehicles sold will have some form of hybridisation, of which 40% need to be full-hybrid
  - Note: this analysis does not consider alternative fuels e.g. LPG, CNG or effect of biofuels

Source: Ricardo analysis

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- **Plug-in hybrid vehicles**
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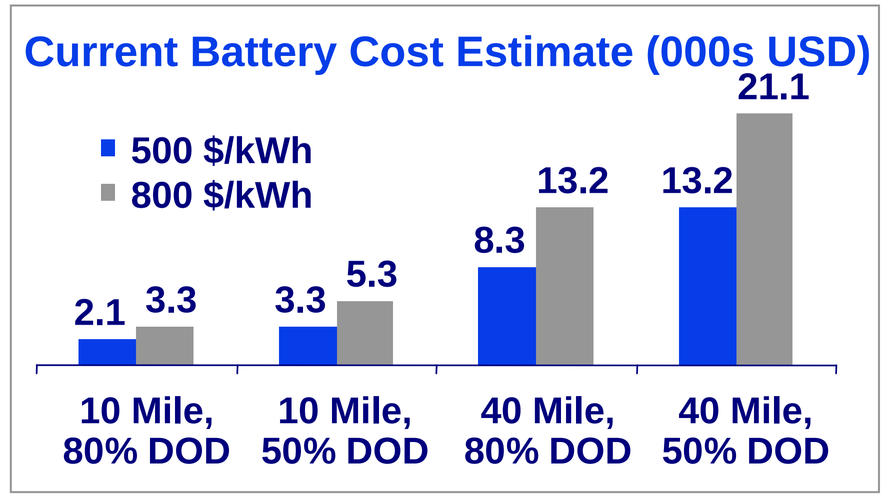
Plug-in hybrids show large potential though high battery costs are currently limiting their financial feasibly

- Plug-in hybrids are any type of Hybrid which can be re-charged from grid
- Plug-in hybrids offer reduced CO_2 when operated on low carbon electricity (e.g. coal with carbon sequestration, renewable or nuclear)
- Significant plug-in interest in the US
  - Potential to reduce dependence on imported oil/petroleum products
  - Electricity supply from domestic fuel sources
- Batteries charged using off-peak electricity
- Battery sized for range of 10-40 miles (15-60 km) - gasoline fuel for longer distances
- Key hurdle is is energy storage technology
  - **Cost:** Currently up to ~$20k US for battery
  - **Size:** Limited package space in pass cars
  - **Durability:** Replacement cost major issue



Note: battery cost is a contentious subject, driven by differing views on materials costs, rate of technical improvement, permissible depth of discharge (DOD), range, etc.

Based on performance and cost criteria Nickel Metal Hydride and Lithium Ion batteries are the best available technologies in the near term

	Energy Storage Device	Energy Density	Power Density	Cost per unit energy	Cost per unit power	Lifetime in full-time hybrid operation	Sized for typical hybrid duty cycle: Mass	Sized for typical hybrid duty cycle: Cost*	Self Discharge	Low temp. performance	Warm-up time	Commercial availability
		Wh/kg	kW/kg	£/kWh	£/kW	Cycles	kg	£	%/month	° C	hours	
NEAR TERM < 2010	Lithium Ion	100 to 150	0.9	400	34	4×10^5	40	900	5	- 30		
NEAR TERM < 2010	NiMH	50 to 80	0.8	270	20	4×10^5	70	900	30	- 8		
NEAR TERM < 2010	Zebra	~90	~0.2			2×10^4					24	
NEAR TERM < 2010	Bipolar Lead Acid			180		1×10^3				- 30		
NEAR TERM < 2010	Super Capacitors	5	2-5	13,000	7	1×10^6	141	12,000	36	- 40		
LONG TERM > 2010	Lithium Ion Polymer	100 to 155	0.1 – 0.3			1×10^6						
LONG TERM > 2010	Cr-F-Li		~ 0.7									

- There are many other battery technologies being researched for the longer term e.g. zinc-bromine, zinc air
- For Zebra the warm-up time is inappropriate for this application and for bipolar lead acid there is a lot of advanced development work underway but it is orders of magnitude short in terms of life cycle
- The remaining options are Lithium Ion, Nickel Metal Hydride (NiMH) and Super Capacitors

* Cell and battery management system (BMS) cost assuming high production volumes (50 – 100,000 units p.a.)

Source: Manufacturer data sheets and papers, Ricardo PowerLink database, Ricardo knowledge & analysis

Energy storage for Hybrid systems – NiMH systems likely to be replaced by new Li-Ion chemistries but still 100x lower energy density than gasoline

Energy Storage Device	Energy Density	Power Density
	Wh/kg	kW/kg
Lithium Ion	<180	0.9
NiMH	<80	0.8
Zebra	~90	~0.2
Bipolar Lead Acid	30	
Super Capacitors	5	<5
Lithium Ion Polymer	100 to 155	0.1 – 0.3
Cr-F-Li		~ 0.7
Flywheel	140	
Air at 20 bar	75	
H2	33,500	
Gasoline	**12,000**	

Nickel Metal Hydride

- High energy and power density
- In widespread use in current hybrid vehicles
- State Of Charge estimation difficult
  - Achieved by integration of current over time
  - Tolerant to overcharge - Integrator reset by “overcharging“ battery periodically

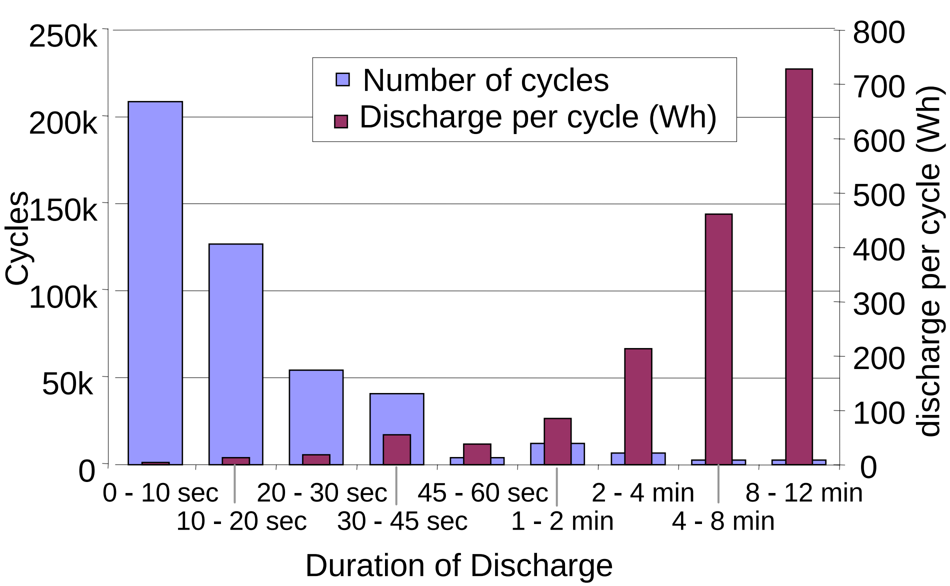
Lithium Ion

- Highest energy and power density
- Cost predicted to equal NiMH circa 2009
- Battery management more complex – cells must be individually controlled
- Not tolerant to overcharge
- Failure mode can be catastrophic
- Open Circuit Voltage (OCV) proportional to State of Charge (SOC) – much easier to estimate

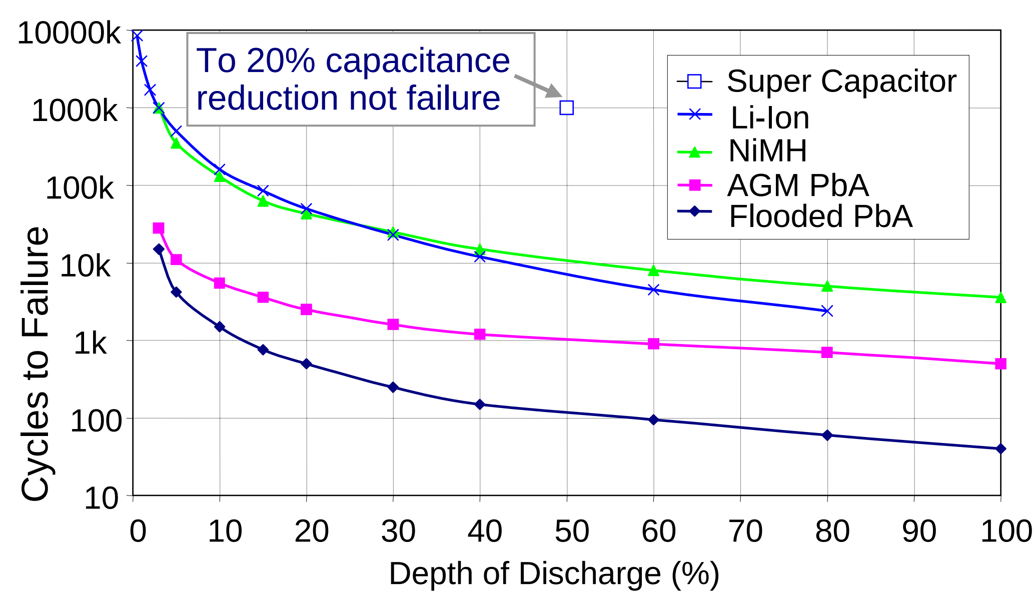
Battery specification (and size) is a balance between in-service life and initial purchase cost

- **Many options available:**
  - Advanced Lead Acid
  - Nickel Metal Hydride
  - Lithium Ion
  - Sodium based batteries
  - Supercapacitors
- **Key factors are:**
  - Power Density
  - Energy Density
  - Cycle Life
  - Cost
- **Typical vehicle life target:**
  - 240,000 km (150,000 miles)
- **Battery cycle life defined from typical driving patterns:**
  - First-order factor in determining battery size
  - Only 10-20% DoD possible to achieve life targets

Discharge cycles for full hybrid



Battery type cycle life



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The automotive innovation process creates capable prototype technologies – Market take up requires a co-ordinated approach

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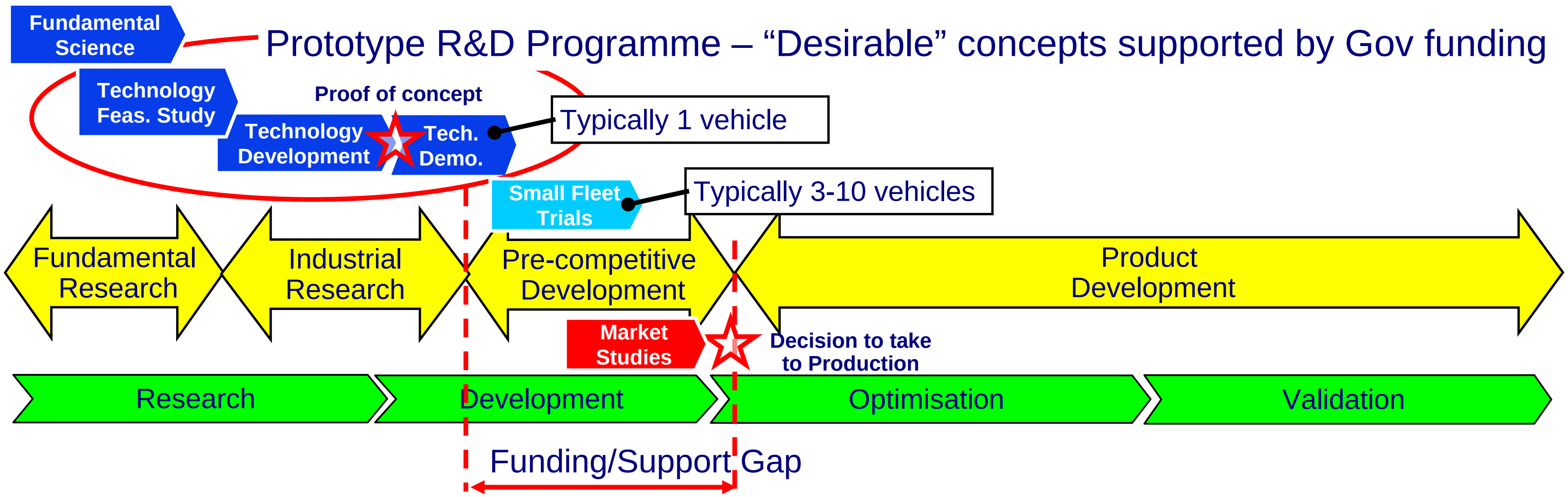
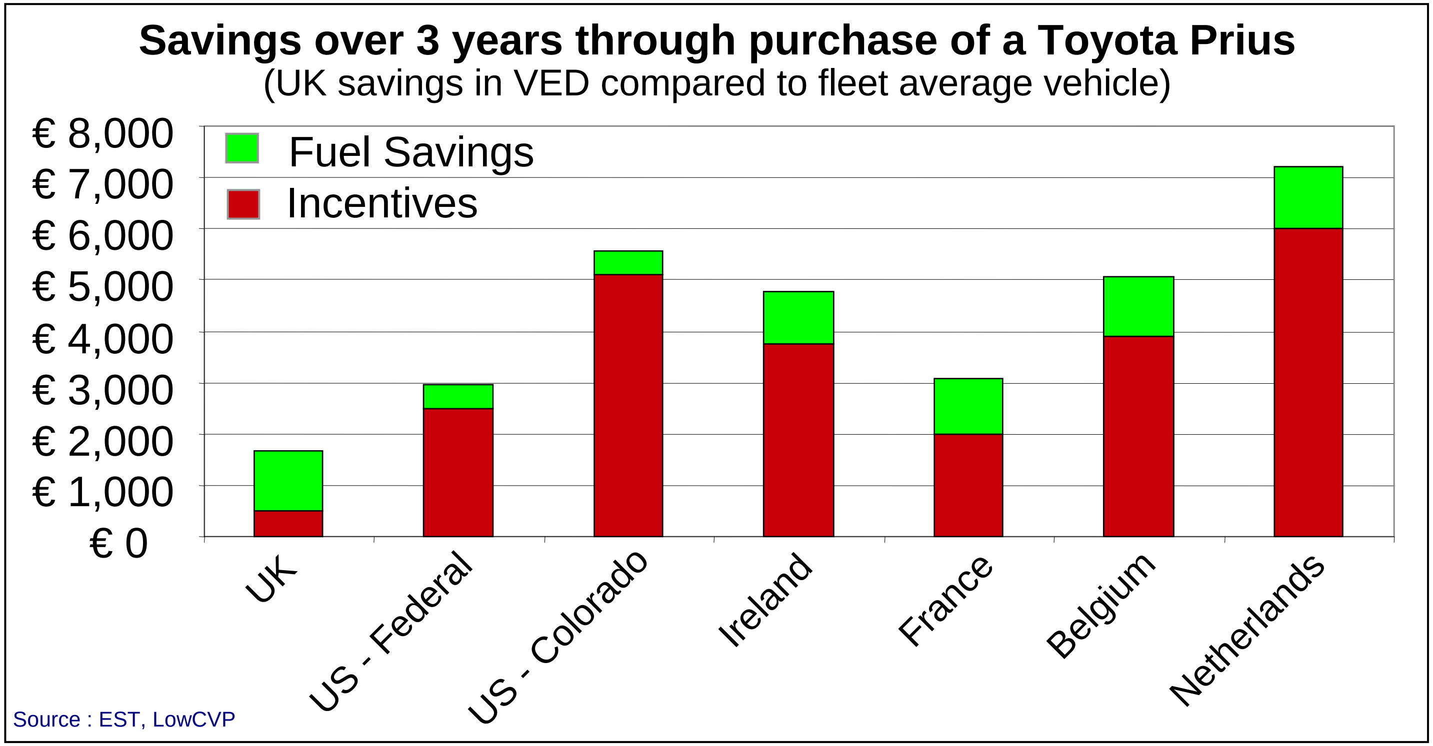
- The innovation process in Automotive Engineering can last up to 5 years…



- However, new technologies only make an impact if they are brought to the market in significant volumes…
  - The decision to take new technologies to production represents vast capital investments and needs robust and supportive market/fleet trial information
  - This is where many environmentally friendly technologies fail to get adequate support as they compete with many shorter term lower risk alternatives
  - Government support for fleet trails/procurement initiatives could close this gap…

Fiscal incentives encourage demand for fuel efficient hybrid vehicles – Market transformation will require more aggressive measures and/or change in consumer attitudes…



- Many countries provide financial incentives to encourage purchase of gasoline hybrid vehicles
- UK incentive scheme recently dropped…
- Many argue that fiscal incentives should be technology neutral

- Market transformation to low carbon vehicles will require either significant consumer fiscal incentives or a “U turn” in consumer attitudes to carbon emissions
- Government must be seen to provide lead in this area through co-ordinated *procurement and use* of low carbon vehicles – promoting UK technology would be key part of this strategy

A fleet of UK designed & built Low Carbon Diesel Hybrid Vehicles would promote Government intent & UK low carbon capability

- Many countries provide financial incentives to encourage purchase of hybrid vehicles – these have recently been withdrawn in the UK with intent to direct resources to improve consumer education and awareness of carbon emissions
- The GCDA has invested in a number of fuel efficient Toyota hybrid vehicles for use by Government ministers and senior officials – whilst this promotes low carbon behaviours, it does very little to promote UK low carbon technologies and products
- The UK DfT via the Energy Savings Trust is supporting research & development in a range of fuel efficient diesel hybrid concepts – some with enhanced driveability – this provides an excellent opportunity to showcase UK based fuel efficient hybrid technologies

- An opportunity exists for Government to procure a small fleet of advanced Ultra-Low-Carbon vehicles engineered and built in the UK. This would demonstrate both UK Government commitment to low carbon vehicles and UK expertise and product capability, whilst promoting brands with strong UK identity