engineexpo2010
22, 23, 24 June 2010
Messe Stuttgart, Stuttgart, Germany

The Ricardo low carbon roadmap – The long way to CO_2 reduction

Engine Expo 2010

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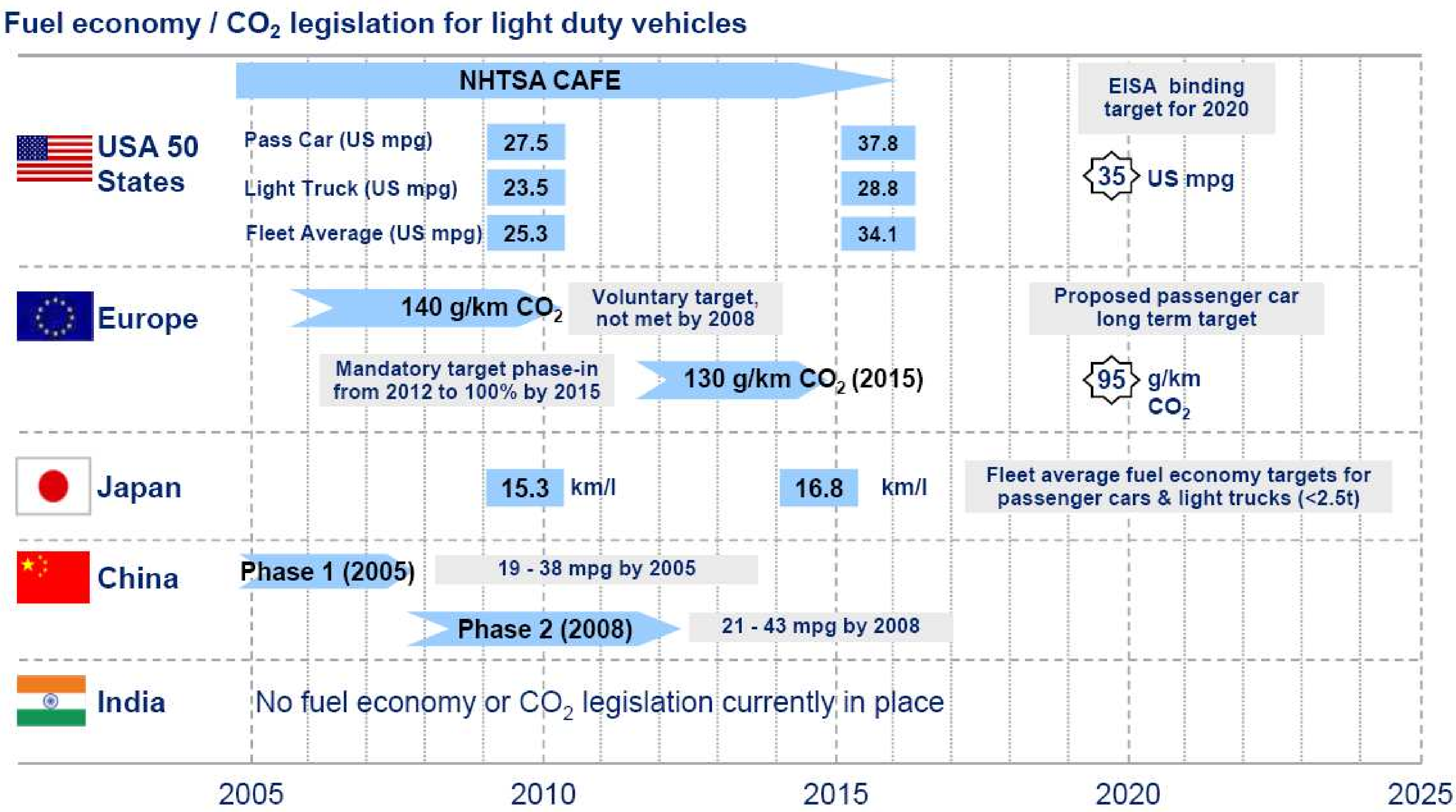
Stuttgart, 23rd June 2010

Contents

- **Background and key issues**
- Methodology
- The Ricardo Low Carbon Roadmap – Technology steps
- Purchase and ownership costs
- Conclusions

Most Countries adopting low carbon targets for road transport, emphasis on energy security and climate change



Source: Ricardo EMLEG database

Current volume-weighted average fleet emissions in Europe per manufacturer and country

Average new car emissions in EU15 (g/km)					
Year	**2008**	**2007**	**2000**	**% ch '08 vs '07**	**% ch '08 vs '00**
Austria	158.1	162.9	168.0	-2.9%	-5.9%
Belgium	147.8	152.8	166.5	-3.3%	-11.2%
Denmark	146.4	159.8	175.7	-8.4%	-16.7%
Finland	162.9	177.3	181.0	-8.1%	-10.0%
France	140.1	149.4	163.6	-6.3%	-14.4%
Germany	164.8	169.5	182.0	-2.8%	-9.5%
Greece	160.8	165.3	180.3	-2.7%	-10.8%
Ireland	156.8	161.6	161.3	-3.0%	-2.8%
Italy	144.7	146.5	155.1	-1.3%	-6.7%
Luxembourg	159.5	165.8	176.7	-3.8%	-9.7%
Netherlands	157.9	164.8	174.2	-4.2%	-9.4%
Portugal	138.2	144.2	169.2	-4.2%	-18.3%
Spain	148.2	153.2	159.2	-3.3%	-6.9%
Sweden	173.9	181.4	200.0	-4.1%	-13.1%
UK	158.2	164.7	185.4	-4.0%	-14.7%
EU15	**153.5**	**158.7**	**172.2**	**-3.3%**	**-10.9%**

Source: SMMT Annual CO2 Report

- Europe's cleanest model was in 2009 the hybrid Toyota Prius, with 95,6 g/km CO_2
- The car manufacturers have reduced the volume-weighted average CO_2 emissions by 7.9 g/km in 2009

Manufacturer	2008	2009
Fiat	133,7	127,8
Toyota	144,9	130,1
Peugeot	138,1	133,6
Renault	142,7	137,5
Citroen	142,4	137,9
Ford	147,8	140,0
Opel / Vauxhall	151,1	148,9
BMW	160,6	150*
Volkswagen	158,8	150,4
Audi	n/a	160,9
Mercedes	185,0	176,4

Source: JATO Dynamics; *Source: BMW

Contents

The study is based on a basic "rule": each development step must be a robust, mass-market step forward

C-segment vehicle (e.g. Ford Focus, Opel Astra, VW Golf)

- Close to the average size for Europe

Each technology step must be

- **Volume product of European relevance**
  - Capable of 5% market within 5 years of introduction
- **A step forward in terms of well-to-wheel carbon emissions**
- **A fully functional vehicle** at its given CO_2 emission
  - Performance, trailer tow capability, passenger & luggage capacity, re-fuel range
- **Validated** wherever possible from real production or prototype vehicles
  - With appropriate corrections for vehicle size
  - And an assumption of small incremental improvement to the state of the art, for products existing further in the future

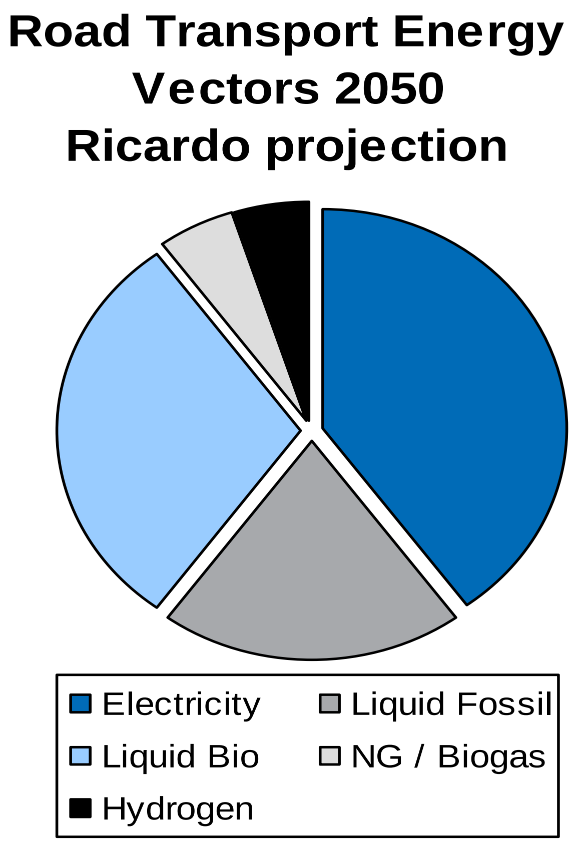
Known "hard points" such as legislation, and more speculative long term forecasts, were used to frame the technology steps

2020 (Driven by CO_2 legislation)

- **130g/km, 95g/km** EU new car fleet
- **Limited segment down-shifting**
  - Perhaps 20%, limited by space needs
  - But more buyers choose a low carbon option WITHIN their segment
- **Significant role for conventional technologies**
  - Diesels remain as best-in-class for CO_2
  - Second generation advanced Gasoline engines could close the gap being cheaper
  - 12 volt start/stop ubiquitous
- **Significant rise in mass-market high-volt electrification** starting to happen
  - 10-20% EV/PHEV/HEV possible
  - But <5% necessary for 130g/km

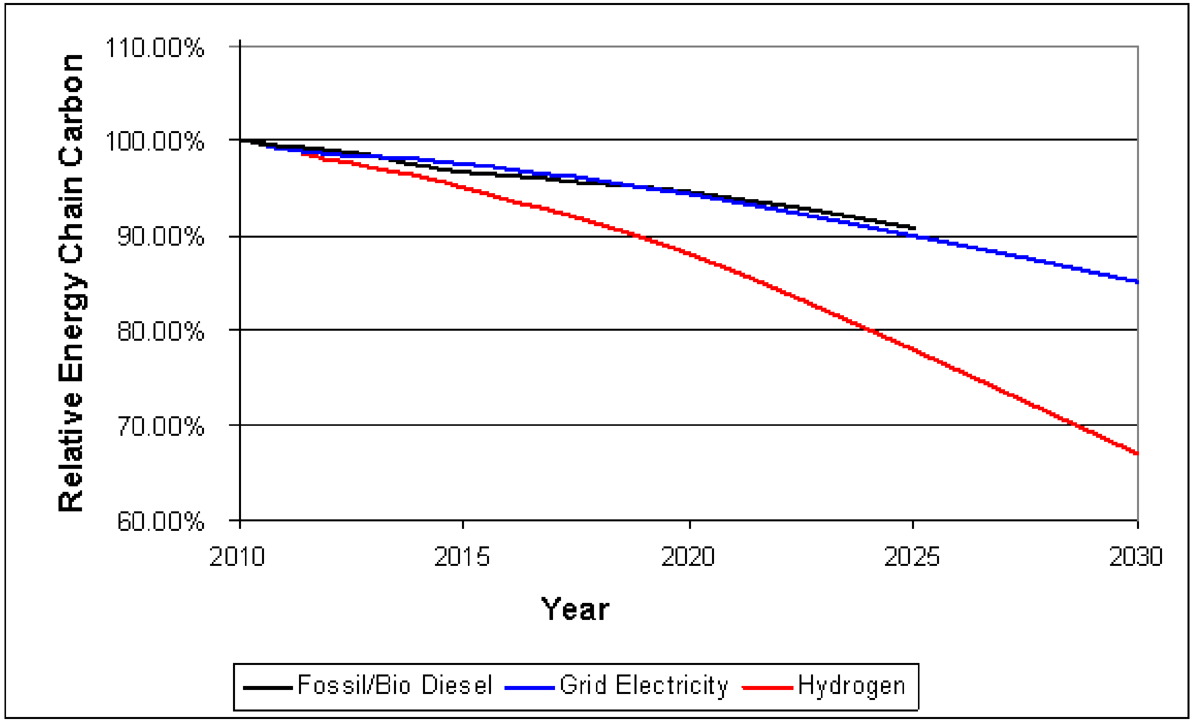
2050 (Speculative, Peak Oil & GHG driven)

- **Substantial shift to new energy vectors, with electricity being dominant**



Aggressive assumptions were made for rising energy prices and greening of energy supplies

- **Fuel price scenario based on $70/bbl** in 2009, rising to $200/bbl in 2025
- **Progressive "greening" of energy vectors**
  - **Diesel** with 1st & 2nd gen bio-fuel, up to 15% (limited by supply and demand from other sectors)
  - **Electricity** in line with EU SET-plan (Average EU-25 mix assumed)
  - **Hydrogen** to extent needed to compete with prior step (result broadly in line with European targets)



Contents

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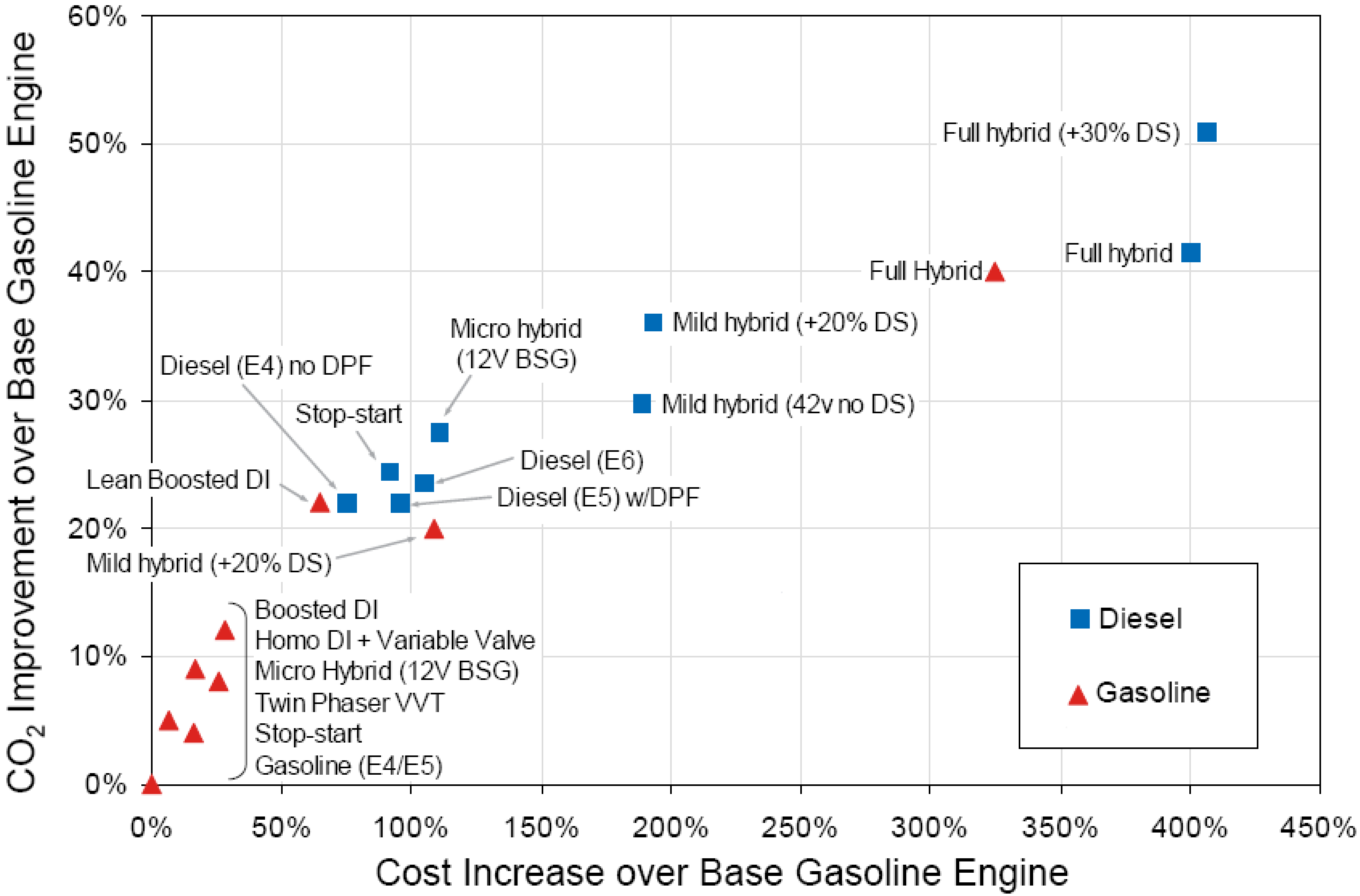
An accelerating pace of incremental improvements to parasitic losses, weight and drag means that <100g/km is possible at 12v

	Technologies	Energy Chain	CO_2 T2W	CO_2 W2W
2010 Step 1: Optimised 12v Diesel with Stop/Start	Start-stop, smart charging & cooling, reduced weight, rolling resistance and aerodynamic drag, optimised calibration	Diesel B5 Gen 1	99g/km	109g/km

2010

- **Baseline: Typical C-segment Diesel economy model - 119g/km T2W, 132g/km W2W**
- **VW Golf, Audi A3, Volvo C30 already achieve 99g/km**
  - All at 12v, with start-stop, smart charging, intelligent cooling, longer gear ratio
- **Ricardo roadmaps targeting 100g/km Gasoline and 85g/km Diesel** (C-segment) for research – low cost 12v or "12+X" systems

Improved Gasoline engines will remain cheaper than current Diesel engines

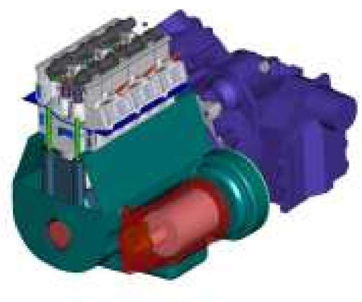


Hybrids will benefit from improvements to 12v vehicles, and from better high voltage systems: giving lower CO2 than seen in the past

		Technologies	Energy Chain	CO_2 T2W	CO_2 W2W
2015	Step 2: 6kW Diesel Mild Hybrid	1.2l engine, 6kW ISG motor, Li-Ion	Diesel B8 Gen 1 & 2	84g/km	90g/km
2020	Step 3: 20kW Diesel Full Hybrid	1.2l engine, DCT 20kW full hybrid	Diesel B12 Gen 1 & 2	69g/km	72g/km

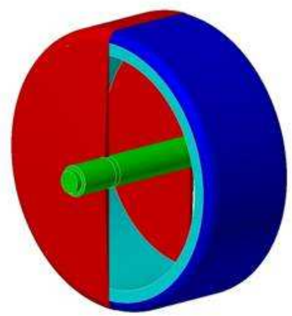
Mild Hybrids: A familiar recipe, but improved – 84g/km at the tailpipe

- Engine downsized to 1.2l 3cyl, same 80kW
- 6kW electrical machine – probably belt drive
- Smart, low loss cooling and lube systems, fast warm-up, 5% lighter car
- “12+X” VRLA + super-capacitor energy storage – or Li-Ion
- In reality, a mix of Diesel (<85g/km) and Gasoline (<100g/km)



Full Hybrids: A mix of solutions suiting the application, ultra low 69g/km

- Same engine, larger 20kW electrical machine clutched to engine and DCT
- Further powertrain and vehicle improvements, another 5% lighter
- Other solutions (e.g. Gasoline-fuelled) will co-exist



Flywheels could be an enabling technology!

Electrification offers an immediate W2W improvement (in urban use at least), but configuration must be tailored to duty cycle

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	Technologies	Energy Chain	CO_2 T2W	CO_2 W2W
2025 Step 4: Plug-in Hybrid, Range Extended EV	20km EV range via enlarged battery	Diesel B15 G2 Elec CO_2 –6%	52g/km	63g/km*

* Assumption: 25% electricity from grid

Electrification: PHEV retains full vehicle functionality, benefits CO_2

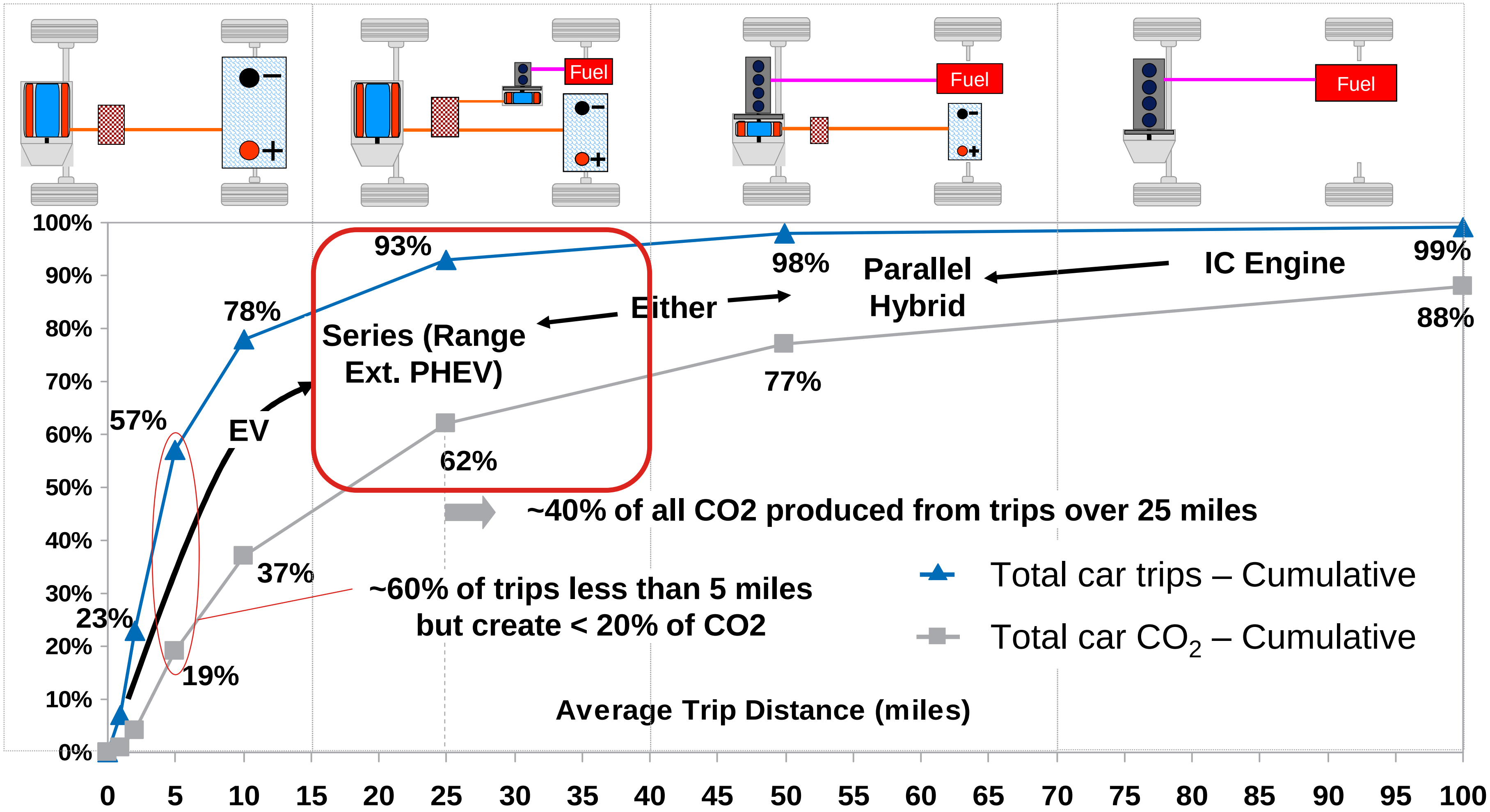
- Vehicle as before, extra 20km EV range at €3-400/kWh
- 406g CO_2/kWh EU grid (ref EU SET-plan) gives urban 44g/km on electricity
- Majority of Full Hybrids may be plug-in by this time
- Most are likely to be cheaper gasoline series drive – but Diesel / Parallel is most efficient and functional “all-rounder”

In earlier stage the introduction of Range Extender will increase the market acceptance of EVs

- Short distances represent conventionally urban trips, which are the natural destination of most of electric cars
- It is possible to resize the expensive battery packs to lower pure electric driving ranges, covering unusual longer trips with a small and cheap combustion engine aimed to recharge the batteries

Electric vehicles limited to city use due to battery size/cost - Range anxiety addressed by Series PHEV – IC/Parallel hybrid for highway

- Most efficient powertrain configuration is a function of application
- EV likely to be more efficient for city use but series electric range extender less efficient than parallel hybrid for highway/motorway travel



GB, 2002/2006 average, *Source: DfT analysis*

Hydrogen remains the most practical non-fossil long-range energy vector, but the PHEV sets a high bar for "green" Hydrogen

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	Technologies	Energy Chain	CO_2 T2W	CO_2 W2W
2030 Step 5: Hydrogen-Electric Plug-in Hybrid	40kW Fuel Cell	Elec CO_2 –15% H_2 CO_2 –30%	0g/km	60g/km*

* Assumption: 25% electricity from grid

Hydrogen: Synergistic long-term PHEV range-extending fuel

- Electricity will still be limited as a long-range fuel
  - Battery mass & cost: 500km range requires a 900kg, €20-30k battery
  - Fast refuelling: circa 300kW required for 10 minute charge, or cumbersome swap system
  - No proven concepts with full C-segment functionality – unlike Hydrogen
- Hydrogen vehicle derived from ICE-based Series-PHEV, with substitution of Fuel Cell (assumption in this study: 25% only electric driving)
- Electricity from 2030 EU grid @ 366g CO_2/kWh, gives urban 39g/km
- 30% "greener" Hydrogen gives 67g/km on NEDC (vs 69 for Diesel HEV)
- Plug-in function reduces dependency on Hydrogen infrastructure
  - Fuelling stations concentrated on highways, trunk routes & transport nodes; re-charging at home, workplace & municipal car parks

The steps show progressive reduction in tailpipe and well-to-wheel CO_2 – and indicate how "green" a Hydrogen supply needs to be

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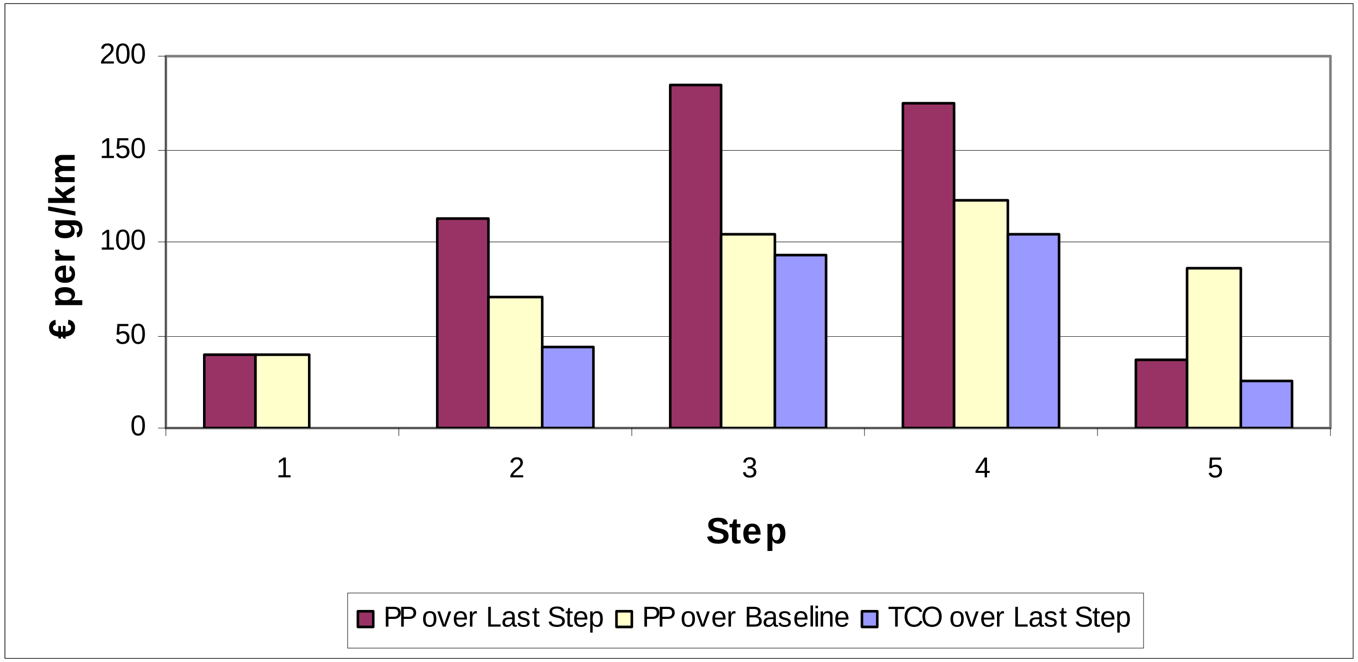
Even with aggressive fuel price and low depreciation, analysis shows rising costs for high voltage and hydrogen systems

- **Purchase price** estimated from bill-of-materials and future component costs
  - Basis 100,000 units p.a.
- **Total Cost of Ownership** includes fuel, depreciation, interest on capital, maintenance

Comments

- **Mild and Full hybrids** show increased cost – though fiscal incentives and fleet-average penalties would tip the case
- **Fuel Cell systems** appear to offer a lower cost increment – but ONLY if un-proven cost-down can be realised



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The evolutionary electrification principle remains valid for mass markets, though disruptive niches will gain in significance

- **Pace and impact of cumulative detail improvements to the conventional ICE has increased**
  - And these can offer mainstream solutions to current legislation
- **Electrification technologies remain expensive, even in a high fuel price scenario**
  - Fiscal incentives can tip the balance in a receptive market
- **The Plug-in Hybrid is a significant step**
  - Offers a step to different types of range-extending powertrain
  - Early stages of market do not require much infrastructure
- **Hydrogen remains a promising long term fuel**
  - But fuel cell cost-down needs to be realised
  - And Hydrogen supply needs to be “greened” as part of integrated energy policy
- **There will be Enablers**
  - Now: Ultra-downsized Gasoline engines competing with Diesel
  - Next: Kinetic (flywheel) hybrids offering half the cost per unit benefit
  - Then: Breakthroughs in electricity or hydrogen storage – or something else?

Contact information

Thank you for your interest

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