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"CARBON TO HYDROGEN" ROADMAPS FOR PASSENGER CARS: A STUDY FOR THE DEPARTMENT FOR TRANSPORT AND THE DEPARTMENT OF TRADE AND INDUSTRY

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EXECUTIVE SUMMARY

Road transport in Europe accounts for an estimated 20% of total manmade CO_2 emissions, produced by the combustion of fossil fuels. The average car emission has been reducing in the UK, reflecting the EU Voluntary Agreement on new car emissions, supported also by the UK's introduction of graduated CO_2-linked car taxation.

This report looks at options to further reduce CO_2 emissions in passenger cars, by improvements in vehicle technology (such as Hybrids and Fuel Cells) and its interaction with new fuels (such as Hydrogen), from the perspective of the technology in the vehicle itself. Focusing on an illustrative class C/D car, the report discusses the possible evolution from current vehicle technology toward a possible zero CO_2 future, based on sustainably-produced Hydrogen fuel.

Two routes toward this end are examined. A ***"Low Carbon"*** route is based on relatively low-risk, limited cost evolution of current vehicle technology, designed to give progressively lower-carbon performance. Early vehicle types on this route use hybridisation of current, liquid fuelled Internal Combustion engines to achieve maximum CO_2 reduction at relatively low risk. These are followed by further new technologies, aimed at completing the transition towards the Fuel Cell vehicle. A ***"Hydrogen Priority"*** route assumes that policy priority is attached to the early shift towards the use of Hydrogen. The initial vehicle types use Hydrogen in an IC engine, before adopting Fuel Cell technology. Dates are identified in the review for earliest technically feasible development of the vehicle type.

The report focuses on vehicle technology. It does not deal with the prospective cost of Hydrogen, nor with the availability of sustainably-produced Hydrogen. The CO_2 figures for Hydrogen vehicles are for prospective fossil Hydrogen.

For each vehicle type along the routes, estimates have been made of the **"well-to-wheels" CO_2 emissions** (which includes CO_2 produced in supplying the fuel to the vehicle's tank, as well as that emitted in the exhaust); and also the **sale price of each vehicle.** Manufacturing and ownership issues are discussed. Illustrative vehicle types provide for all prospective future safety, air quality emissions, and driver demands.

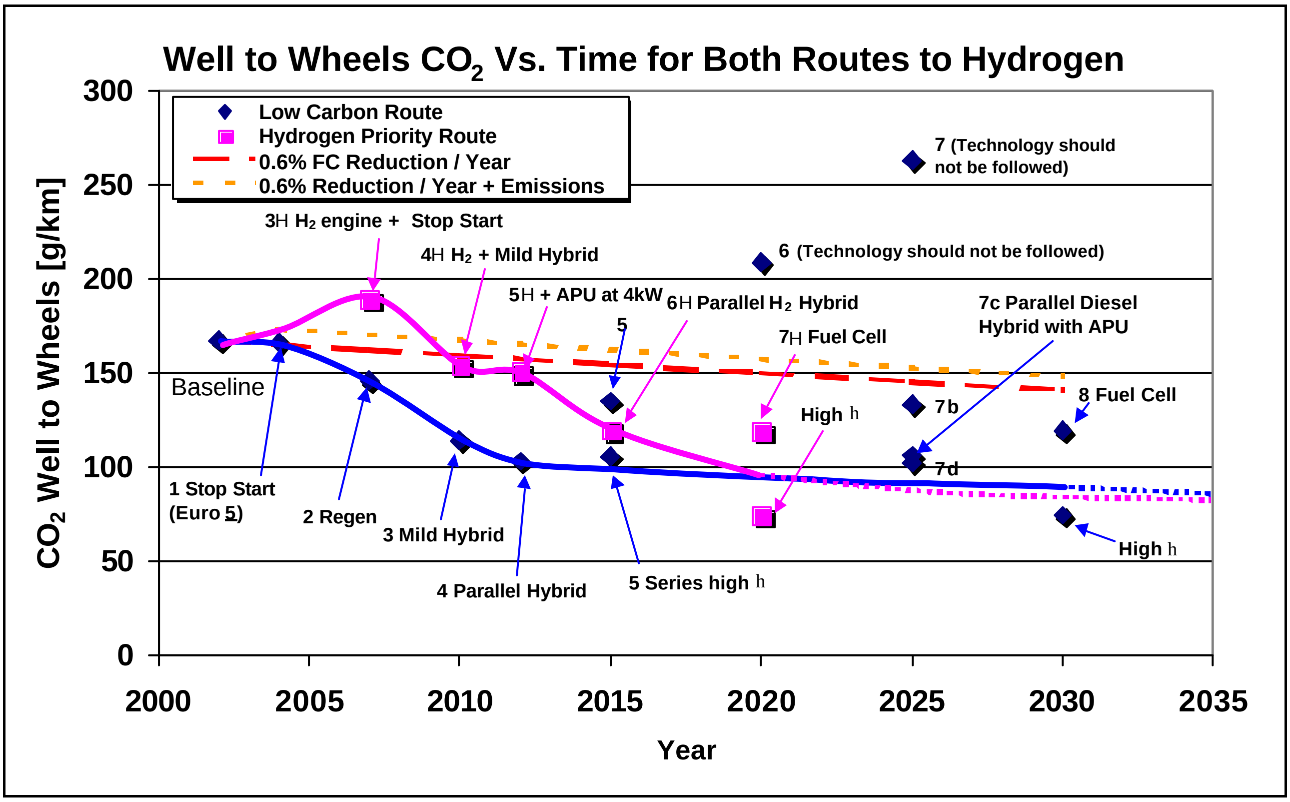
Major Conclusions are:

General

- Risk-managed, step-wise evolution toward sustainable transport is feasible and is likely to be the only approach compatible with the business-model and corporate philosophies of the car industry and the preferences of conservative buyers

- Every step can contribute to the next, in terms of technical know-how and, in many cases, carry-forward hardware. Some hardware will become redundant, but this need not be incompatible with the natural process of product obsolescence

- Every step carries an incremental cost. Although these costs are generally proportionate to benefits, they are high relative to the marginal profitability of the industry and the competitiveness of the marketplace.



Low Carbon Route

- Progressive electrification and Hybridisation offers significant CO_2 benefits regardless of the fuel or its source, at a risk level more manageable than alternatives such as more radical new vehicle technologies or major infrastructure change

- The Low Carbon route (shown by the blue line on the figure above) provides progressively lower CO_2 for best-in-class vehicles over the coming decade, through to 'Step 4' – a Diesel Parallel Hybrid vehicle. This offers a Well-to-Wheels CO_2 figure of 103 g/km (equivalent to a Tank-to-Wheels exhaust CO_2 emission, as currently measured, of 92 g/km). This is 38% lower than the starting point 'Step 0' car (a composite average of current class-leading C/D segment Diesel vehicles), at 167 g/km Well-to-Wheels, and 149 g/km Tank-to-Wheels

- The estimated list-price of the Step 4 vehicle in 2012 is between £17,600 and £18,400 (at 2002 values), compared to £15,300 for Step 0, in return for which a 38% reduction in fuel consumption and CO_2 is estimated over the NEDC test cycle

- A number of technology options exist to move forward toward a Hydrogen fuelled, Fuel Cell vehicle, as shown by blue diamonds 5,6 and 7 in the figure above. But it is not clear that all of these can offer a further reduction in CO_2. Manufacturers may wish to develop and trial these technologies, as part of their development of Fuel

Cell models – but they would probably not want to put these technologies onto the volume market, because there are no worthwhile CO_2, driver or cost benefits

- Beyond the introduction of the Step 4 vehicle, further reductions in fleet average CO_2 are likely to be derived from incremental technology improvement (indicated by the blue line in the figure above) and increasing penetration of these technologies towards 100% of the new car fleet

- Progressive introduction of the Fuel Cell as an Auxiliary Power Unit, starting with luxury vehicles, offers a functionality improvement in terms of onboard power and ZEV range extension, introduces Hydrogen as a dual fuel and can offer CO_2 savings

Hydrogen Priority Route – and Comparison with Low Carbon

- In order to start the transition to Hydrogen use as soon as possible, the Hydrogen Priority route would start with the use of Hydrogen in an IC engine. It would then progress to Fuel Cell technology when this becomes ready for volume production

- The Well-to-Wheels CO_2 emissions of Hydrogen Priority vehicles would initially exceed the time-equivalent Low Carbon route vehicles by up to 30%, mainly because of the less carbon-efficient Well-to-Tank performance of Hydrogen derived from fossil fuels

- The objective of the Hydrogen Priority policy would be to encourage the earlier arrival of Fuel Cell power. After this, the CO_2 performance would improve, with emissions reducing to the point where they equalled the Low Carbon vehicle performance. There is, however, no margin of final CO_2 gain, compared to Low Carbon vehicles, unless the most optimistic targets for future Fuel Cell efficiency are achieved by the introduction of the first vehicles. On this high efficiency assumption, the gain is of the order of 10-20%

- However, the full Fuel Cell vehicle, unlike fossil-fuelled Hybrid vehicles, has the potential to be zero-carbon when renewable Hydrogen is available. Also, Fuel Cell vehicles have near-zero regulated 'tailpipe' emissions (HC, CO, NOx, and Particulate), regardless of the source of Hydrogen. By comparison, an IC-engined Hybrid vehicle may in future be capable of regulated emissions levels 50% or more below the forthcoming "Euro 4 Petrol" standard, but can only be zero-carbon with a Hydrogen-burning IC engine

- The estimated price of the full Fuel Cell vehicle is £18,100 to £21,300 (today's values) if introduced in 2020 (Hydrogen Priority Step 7H), or £17,700 to £20,700 if introduced in 2030 (Low Carbon Step 8). These estimates have a lower degree of confidence than those for the Hybrid vehicle due to the higher risk in bringing the technology to the volume marketplace. This study does not address prospective Hydrogen fuel cost.

UK Expertise and Research

Significant expertise exists in the UK, especially in the fields of Internal Combustion engines and Hybrid vehicle technology, in the form of world-class university and private-sector research organisations as well as the manufacturing base.

The creation of a successful, world class Low Carbon vehicle fleet and technology infrastructure in the UK is likely to require a holistic approach, embracing:

- incentivising the purchase of low carbon vehicles
- promotion of research and development in the UK
- promotion of early product introductions using UK component and vehicle manufacture.

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"CARBON TO HYDROGEN" ROADMAPS FOR PASSENGER CARS: A STUDY FOR THE DEPARTMENT FOR TRANSPORT AND THE DEPARTMENT OF TRADE AND INDUSTRY

1 INTRODUCTION

In recent years, the topic of greenhouse gas (GHG) emissions from road transport has been the subject of much discussion. The primary source of GHG emission from road transport is the gas Carbon Dioxide (CO_2), produced by the combustion of fossil fuels. Road transport in Europe accounts for an estimated 20% of total manmade CO_2 emissions [1][1].

Emission of CO_2 is the inevitable consequence of burning fossil fuels. For a given fuel type, fuel consumption (measured in litres per 100 kilometres, l/100km) is directly proportional to CO_2 emission (measured in grams per kilometre, g/km)[2]. Further information on CO_2 and other vehicle emissions trends are given in Appendix A.

In the UK, there is now pressure toward reduction of CO_2 emissions from a number of sources:

- Company car taxation which incentivises low CO_2 vehicles (Appendix G)
- Fuel taxation which incentivises consumer choice of fuel efficient (hence low CO_2) vehicles
- A voluntary agreement by European manufacturers through their association, ACEA, to achieve a new car fleet average CO_2 emission of 140 g/km by 2008 [2]

These pressures are similar in the rest of Europe and many other parts of the world (Appendix A). There are a number of options for reducing CO_2 emissions from road transport, namely:

- Encourage lower usage of existing road transport technology, i.e. fewer vehicle-miles per year, thereby consuming less fuel
- Encourage new technology that uses existing fuels more efficiently
- Encourage new energy sources which produce less CO_2
- Encourage other measures such as sequestration of CO_2

This report looks at the second and third options from the perspective of the technology in the vehicle itself. Step-by-step routes are proposed as evolutions from current vehicle technology toward a possible zero CO_2 future. In common with many studies of this type, the endpoint of this evolution is assumed to be sustainably produced Hydrogen fuel.

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[1] Numbers in square brackets [ ] indicate references given at the end of the report

[2] This is not the case for miles per gallon (mpg) which has a reciprocal relationship to CO_2 emissions, as explained in Appendix A

The objectives of the study have been to:

- Provide an informed vision of the Technology Roadmap from conventional vehicles to a sustainable mainstream future product
- Investigate a "Low CO_2" and a "Hydrogen priority" route to Hydrogen fuelled road transport
- Quantify the benefits, costs, risks and technology gaps for each step of the two routes
- Quantify the possible CO_2 performance of prospective vehicles along the two routes
- Quantify the possible purchase price of the prospective vehicles, on a mass-production basis

The study does not deal with prospective fuel costs of the vehicles, or the cost of infrastructure change associated with new fuel types.

Information presented in this study is based upon projected performance and cost of technologies that are mostly un-proven in today's vehicles. It is of course impossible to state with confidence that any technology will be feasible at the time of its projected use in production. Key risks that may impact this feasibility are stated.

2 STUDY METHODOLOGY

2.1 Approach

There are many, highly complex studies in the public domain dealing with the topic of future low CO_2 technologies including alternative fuels, Hybrid vehicles, Fuel Cell propulsion, electric vehicles and other concepts, plus the new infrastructure (mainly fuel supply) required to support them [3, 4, 5].

This study does not seek to duplicate that work. Instead, existing data from studies of this type, research results and other sources has been used to identify the likely performance (in terms of CO_2 emissions) and cost to the consumer, of "technology steps" from today's vehicles toward a more sustainable future. The key elements of this study are:

- Maximising use of existing credible information from research prototypes, simulation or analysis either in the public domain or within Ricardo knowledge databases
- Understanding how the "technology baseline" (today's vehicles) will change over time without any major new technology, with regard to CO_2, cost and other factors
- Constructing reasoned step-by-step technology evolutions, in such a way that each step is feasible at the time it is taken
- Analysing CO_2 emissions over the NEDC "Combined" cycle (ECE + EUDC), but noting any likely trends with other driving styles
- Analysing CO_2 emissions in "well to wheels" terms, which embraces the issue of CO_2 produced in the manufacture and distribution of the fuel
- Estimating the on-sale cost of new technologies from information available today, and estimation of how the cost will change due to technical innovation and increasing volume
- Noting other issues such as the impact of new technology on other

emissions, vehicle packaging, ride and handling, refinement, driveability, thermal comfort, safety, reliability, servicing and maintenance, manufacturing and recycling, infrastructure for fuelling and servicing

This study focuses on the passenger car segment, specifically a C/D segment vehicle (such as a Ford Focus or Mondeo), although comment is made on the applicability of the technology to other types of vehicle. Specifically, rules for the candidate study vehicle are:

- Best-in-class CO_2 emissions
- Significant sales volume (taken arbitrarily as 5% or more) for the type of technology used on the vehicle

In today's new car fleet, vehicles with turbocharged, common-rail Diesel engines meet this criterion, whereas low volume vehicles such as the Toyota Prius Hybrid car, do not. At any time, the new car fleet will probably contain a small number of such pioneering vehicles; while their technical significance must be respected, they do not yet have a significant impact on total or average CO_2 emission of the fleet.

2.2 Carbon-to Hydrogen Routes

The automotive industry has a track record of more than a hundred years of technology improvement by gradual evolution. While dubbed "conservative" by some, the evolutionary approach is inevitable in view of:

- Very high cost of introducing new products – typically over £1bn for a new vehicle family
- The need to prepare the dealer / servicing network for any new product or technology
- The need to manufacture any new technology in significant volume in order to be cost-effective
- The risk of a new technology attracting adverse publicity due to poor reliability or unexpected safety or environmental issues

For these reasons the most feasible route for introducing new technology to mainstream production remains an evolutionary one, with new vehicles often being launched with existing (if improved) powertrains (engine, transmission) from a previous model, and new powertrains being launched into existing vehicles. This dictates that any new technology has to have a degree of "backward compatibility". Some vehicles such as the Toyota Prius and Honda Insight (both Hybrid cars with bespoke powertrains and bodies) have bucked this trend, but only at relatively low production volumes and with considerable investment by their manufacturers.

Against this background, two routes toward zero CO_2 transport have been proposed and used as a basis for analysis:

- The "low carbon route" is intended to represent moderate risk at each step, and makes much use of existing technology (in very much improved form)
- The "Hydrogen priority route" represents a scenario whereby Hydrogen fuelled transport is very vigorously promoted, encouraging rapid transition to new technologies

In both cases it is intended that the technology steps presented could meet the criteria of best-in-class CO_2, and 5% or greater sales volume for the technology. For the "Hydrogen priority" route it is likely that a significant increase of investment in research, product development and infrastructure would be required.

2.3 Base Vehicle

2.3.1 2002 Baseline

Current volume production consists of a mix of Petrol (Gasoline) and Diesel engines (at various technology levels) together with a mix of Manual and Automatic transmissions (again, various types). Referring to the rules for candidate study vehicles in section 2.1 above, the "2002 Baseline" should be a vehicle with a turbocharged, direct-injection Diesel engine and 5-speed manual gearbox. This type of vehicle has enjoyed significant growth in the European market, with Diesel accounting for 40% of all new car sales in 2001, although Diesel penetration was only 20% of the UK market. Manual transmissions still occupy over 80% of the market, and deliver lower CO_2 than almost all current automatic types.

Key parameters for an "imaginary" 2002 base vehicle were generated by taking the average of a typical sample of modern Diesel vehicles in the "C" and "D" segments. These segments have dominated vehicle sales in the UK and Europe, and are likely to do so due to the emergence of a wide range of derivatives from C and D segment platforms, such as people-carriers, "soft" 4x4's, coupes, roadsters etc.

C & D Segment - DI European Vehicle Facts									
Platform		**Ford Focus**	**Ford Mondeo**	**Opel Astra**	**Opel Vectra**	**Renault Megane**	**Renault Laguna**	**VW Golf**	**Average**
Engine		**1.8 TDCi**	**2.0 DI**	**2.0 DTI 16V**	**2.0 DTI 16V**	**1.9 dCi**	**1.9 dCi**	**1.9 TDI**	**C+D Class**
Power (kW)		85	85	74	74	77	88	81	81
Weight (kg)		1279	1491	1250	1410	1215	1425	1260	1333
0->100kph (s)		10.8	11.0	12.0	13.0	11.5	10.7	12.6	11.7
Top Speed (km/h)		193	193	188	195	189	200	180	191
Fuel Cons' (L/100km)	Combined	**5.5**	**6**	**5.6**	**6**	**5.2**	**5.5**	**4.9**	**5.5**
	ECE	7.2	8.3	7.5	8.1	6.8	7.7	6.5	7.4
	EUDC	4.5	4.6	4.5	4.8	4.4	4.6	4.1	4.5
Emission level		E3	E3		E3	E3	E3	E3	
Release date		Jul-01	Nov-00	May-00	Feb-01	Oct-01	Mar-01	Dec-99	
Engine FIE technology		2nd Gen CR	2nd Gen CR	HP Rotary Pump	HP Rotary Pump	CR	CR	EUI	
UK retail price (£) - 5dr h/back		£14,320	£16,170	£14,870	£15,515	-	£15,580	£15,480	£15,323

Table 2.1 - C and D Segment – DI Diesel European Vehicle Facts

The data is summarised in Table 2.1 above. The "average" vehicle generated from this data, shown on the right, has a fuel consumption of 5.5 l/100km (equating to a CO_2 emission of **148.8 g/km** – conversion between l/100km, mpg and CO_2 is explained in Appendix A), and a list price of £15,323.

2.3.2 Underlying trends

It is important to recognise that some key attributes of the vehicle will change in the future, sometimes regardless of the level of incentive to reduce CO_2 emissions. The attributes of principal importance are:

- CO_2 emissions of existing technology
- Weight of the vehicle (which can impact CO_2)
- Cost of the vehicle (which impacts the affordability of better technology)

CO_2

The fuel economy / CO_2 emission of vehicles with no "new" technology tends to improve with time, due to:

- New engine and transmission designs which are lighter, have lower friction and warm up more quickly
- Improved "calibration" of engine management systems
- Small improvements in vehicle aerodynamic drag and rolling resistance
- Incremental improvements in every component

A brief study was performed to quantify this effect. Data was taken from:

- Comparison of official fuel consumption / CO_2 figures for new or upgraded vehicles with older models of the same manufacturer and technology specification
- Differences between best (low CO_2) vehicles and worst, older designs in a sample of C-segment cars
- Public domain data from similar studies [3]

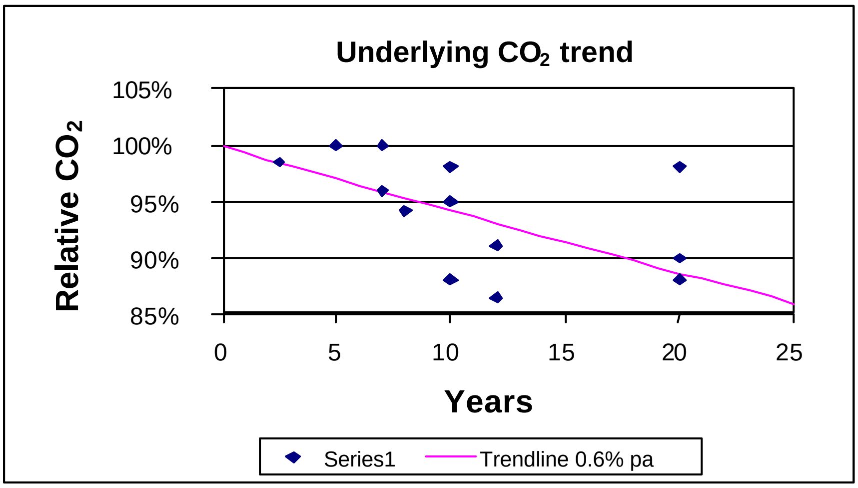


Figure 2.1 - Underlying CO_2 reduction trend

This data is plotted in Figure 2.1 above, in terms of relative CO_2 emission versus the "age gap" of the new versus old technology studied. The trend line shown represents the average reduction in CO_2 emission, of **0.6% per year.** This is very similar to the figure of 0.64% estimated by MIT in their comprehensive new technology study [3]. It is considered likely that a trend of this magnitude can be expected to continue, as many vehicles in production contain major elements (for example floor-pan, cylinder block, transmission) whose basic design can be up to 20 years old. These elements will be replaced in a stepwise manner with state-of-the-art designs.

Weight

The last 20 years has seen a steady, 40% apparent increase in the typical weight of passenger cars, as illustrated for the C-segment in Figure 2.2 below. However, around half of this is due to growth in the size of cars in the segment – for example, the length of a typical B-segment hatchback (Ford Fiesta, VW Polo, Vauxhall Corsa) is similar to the smallest C-segment hatchbacks of 20 years ago. If overall length is used as a guide to a car's "size" (an important criterion for parking, but not the best indicator of interior space), then the true increase is more like 20%.

Many studies assume aggressive weight reductions in the next 20 years [3,4,5]. However, Ricardo believes that this is a high-risk assumption. There are currently a number of conflicting factors in the argument over future weight trends:

- There is currently little evidence of a levelling-off of passenger car weight (Figure 2.2 below)
- Safety and functionality features (Air conditioning, electric seat motors, side impact beams, airbags and sound deadening material) have been responsible for increases in vehicle weight in the past.
- While there will remain a demand for improved safety and comfort, there is a trend for the means by which it is delivered to move from heavy hardware items, towards lighter electronic and software solutions (skid control, drive-by-wire / x-by-wire, telematics, intelligent climate control and active noise cancellation)

Ricardo believes that the net result will be a slowing pace of upward weight pressure, increasingly counterbalanced by innovative low-cost weight reducing technologies. An assumption has been made that:

- Growth in nominal vehicle segments will be ignored – if the vehicle size in segments continues to grow, the sales volumes will shift to lower segments to counterbalance. In practise, popular cars are constrained from getting much larger by traffic and parking considerations, and constrained from getting much smaller by the need for carrying capacity
- Base vehicles (prior to fitting specific new technologies described in this study) will be **weight-neutral (no change) to 2015**, with a reduction of 10% weight between 2015 and 2030

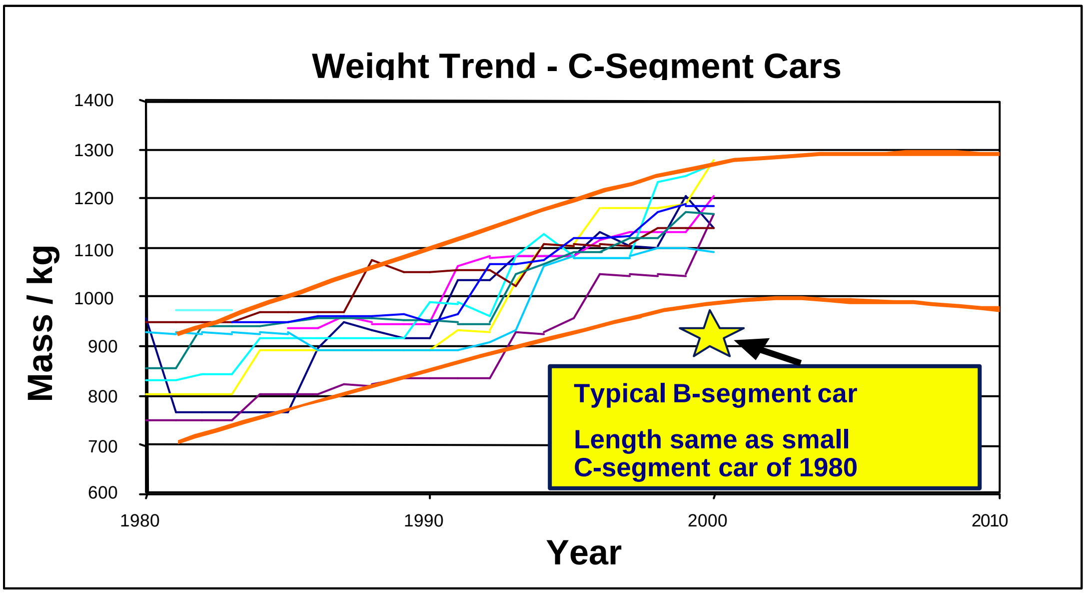


Figure 2.2 - Vehicle weight trends

The significance of weight is as follows:

- Increasing weight has a negative impact on CO_2 emissions. As an approximate guide, analysis of current data for the vehicle fleet suggests that every 1% increase in weight will lead to around 0.5% increase in CO_2 emissions, due to the extra energy needed to accelerate the vehicle in the NEDC test (which involves frequent stopping and starting). However, heavier vehicles in the new car fleet often have superior performance (acceleration, top speed), which may require the use of a powertrain which is less efficient under the conditions of the NEDC test. Hence the true impact of increased weight is typically around half this level. Hybrid vehicles, which store energy when slowing down, may see a smaller impact still (down to around half again, or 0.1-0.3% per 1% weight increase), depending on the technology used
- Large changes in weight may impact the handling, refinement or safety of the vehicle

Cost and List Price

Over last forty years, vehicle prices have remained similar in real terms (the exact comparison depends on whether a retail price index is used, or affordability relative to average income), with major improvements in functionality. These have included:

- Replacement of unassisted, drum brakes by servo-assisted disk brakes, mostly equipped with an ABS system
- Replacement of 3 and 4 speed gearboxes by 5 and 6 speed units
- Replacement of carburettor-fuelled, 2 valve per cylinder engines with no emission control, by 4 valve per cylinder, fuel injected units with emission control, electronic engine management, and a high degree of auto-diagnostic capability
- Introduction of seat belts, crash protection and airbags

- Replacement of the (often optional) heater with a full air-conditioning system
- Replacement of crude suspension systems with sophisticated multi-link independent suspension

This has been enabled by an underlying trend of cost reduction due to:

- Industry consolidation and common platforms, yielding economies of scale (for some components 5-10% cost saving per doubling of volume)
- Improved designs and manufacturing processes requiring less labour, machining, assembly etc
- Improved, lean industrial processes with low stock levels

In order to predict a future underlying trend, it is necessary to understand:

- The likely trend in the cost of manufacturing a vehicle of today's specification
- The incremental cost of other features expected by buyers, which make no direct contribution to CO_2 reduction

At the current time, high competitive pressure and a degree of over-capacity have given rise to aggressive industry cost-cutting targets. Ricardo experience suggests that a cost reduction of 5% per annum is currently typical for a major global manufacturer, whereas in 1998 the figure would have been 2-3%. It would, however, be unrealistic to assume savings of this magnitude will be available on a long term basis, purely to cover the cost of CO_2-reducing technologies:

- Current industry profitability is under such pressure that the future of some manufacturers is far from certain. Manufacturers need to be able to deliver sufficient profit to satisfy shareholders and finance the development of new products – including low CO_2 technologies
- The current pace of industry consolidation, and consequent cost-saving via platform and parts-bin consolidation, cannot continue indefinitely
- Continuing customer demand for extra features as standard equipment will absorb cost savings, as per the example of the last forty years, cited at the start of this section. Looking to the future, side airbags, GPS navigation systems, telematics and smart cruise control are all features that are usually optional today but may become standard by the end of this decade

Public domain data (which is limited on this topic) cites expected vehicle manufacturing cost reductions of up to 30% in the next ten years [4], although some sources suggest that list price will remain similar, probably due to addition of extra features to the standard equipment list [3].

For the purpose of defining an underlying trend for the next 20-30 years, the following scenario is proposed:

- Cost savings for a vehicle of the same specification, requiring no extensive R&D of new technologies, will average around 2-3% per annum - a lower rate than at present, but acknowledging that the potential of consolidation and globalisation is not unlimited, and the industry needs to restore its profitability

- The majority of this saving will be absorbed by vehicle improvements not related to the new low CO_2 technologies, including higher levels of standard equipment, improved safety and refinement, and the cost of the "underlying" CO_2 reduction of 0.6% p.a. described earlier in this section. This appears consistent with what has happened in the past
- R&D costs – typically 5% of a manufacturer's turnover, sometimes up to 10% – will rise due to the pace of introduction of low CO_2 technologies in addition to continuing improvements in other areas (emissions, safety, refinement), but this rise will be paid for by the remainder of the cost saving

For the purpose of cost analysis, it is therefore assumed that a representative list-price can be estimated by **adding the cost of specific new power-train technology** (ratioed to a list price increment) for the purposes of CO_2 reduction or meeting future emissions targets.

The suggestion that what appears to be significant cost savings will be offset by rising costs of R&D and the "standard equipment list" is perhaps controversial. However, today's Diesel vehicle is an interesting case study in this respect, as it represents a low CO_2 technology compared to the Petrol-engined vehicles which are being displaced by them in sales volumes. In this case the higher cost of the Diesel engine (typically 80% higher than an equivalent Petrol unit) is one possible cause of the currently reduced profitability of the industry, despite higher list prices. This indicates that the cost of other CO_2 reducing technologies cannot be absorbed by industry cost saving and consumers.

2.4 Technical Assumptions

2.4.1 Baseline Underlying Trends

The underlying annual trends in base-technology CO_2, weight (and its impact on CO_2) and costs have been used in estimating the incremental effect of every technology step. Implicit in this is the assumption that the forward-projection of these trends is correct. The issues relevant to this assumption are discussed in the preceding sections.

2.4.2 Emissions Legislation

The issue of emissions legislation is of high significance, as emission control devices often have a negative impact on CO_2 emissions. Principal reasons for this are:

- Backpressure (restriction to flow) imposed by placing after-treatment devices such as catalytic converters and particle filters in the exhaust system
- The need to control the engine in such a way as to allow the after-treatment device to function, for example operating a Petrol engine at a perfectly stoichiometric air/fuel ratio for the benefit of a three-way catalyst, rather than the more efficient lean-burn operation
- The need to operate the engine in an unusual, inefficient condition to promote "re-generation" of after-treatment systems. This does not apply to Petrol engines with three-way catalysts, but particle filters and "Lean-NOx" devices often require this type of operation

In the past, the inefficiencies introduced by these issues have been counterbalanced by the inherently more accurate control of the engine via electronic management of fuel-injection and (for Petrol engines) ignition. However, it is possible that the majority of this benefit has now been realised.

Past and future European emission legislation typically follows a five-yearly pattern of change. The assumption has been made, that each technology step will be compliant with legislation pertinent at the time, with any negative impact on CO_2 accounted for.

Any product launched within two years of new forthcoming legislation will tend to comply with that legislation, as the cost of re-engineering the product so soon after launch is hard to justify. Therefore the assumption is made that **each technology step will comply with current legislation, or new legislation which is less than two years away** at the time of introduction.

Year	Diesel	Petrol (+ LPG, CNG, H_2)
2005	"Euro 4" HC + NOx = 0.30 g/km CO = 0.5 g/km NOx = 0.25 g/km Pm = 0.025 g/km	"Euro 4" HC = 0.10 g/km CO = 1.0 g/km NOx = 0.08 g/km Pm = Not Legislated
2008	Assumed "Euro 5" HC = 0.05 g/km CO = 0.5 g/km NOx = 0.15 g/km Pm = 0.0125 g/km	Assumed "Euro 5" HC = 0.05 g/km CO = 0.5 g/km NOx = 0.04 g/km Pm = not legislated
2012	Assumed "Euro 6" HC = 0.05 g/km CO = 0.5 g/km NOx = 0.10 g/km Pm = 0.0125 g/km Pm0.1 Legislated?	No further reductions for HC, CO, NOx Possible Pm legislation?
2016	Assumed "Euro 7" HC = 0.05 g/km CO = 0.5 g/km NOx = 0.07 g/km Pm = 0.008 g/km Pm0.1 = 50% Euro 4 Gasoline vehicle	Pm & Pm0.1 legislated
2020	Assumed Unified legislation for all fuels HC, CO, NOx = 50% Gasoline "Euro 4": HC = 0.05 g/km CO = 0.5 g/km NOx = 0.04 g/km Pm = 0.005 g/km Pm0.1 = 20% Euro 4 Gasoline vehicle	

Table 2.2 - Assumed future emission legislation

In some European countries (including the UK in the case of CO_2-based company car tax for Diesel vehicles), incentives exist for complying with the next step beyond current emission legislation. In recognition of this, the analysis of each step is duplicated for "next step" emission legislation.

The projected timing of emission legislation has been aligned to targets set by the UK Foresight program [6]. It is important to note that this projection represents a re-iteration of these Foresight targets, and is not a recommendation for legislation.

These, and likely trends in emission legislation, are described further in Appendix A, and the assumed timing is given in Table 2.2. As described in Appendix A, it is assumed that during the period under study, the need for continued successive reductions in emission legislation will diminish greatly due to lessening contribution of road transport to poor air quality.

2.4.3 Legislated Test Cycle

The assumption is made that the current NEDC test cycle will continue to be used in its current form. In practise this may not be so, but a consistent measure of CO_2 is required and no universally accepted alternative exists. Factors that may influence future changes to the cycle include:

- The desire to encompass the impacts of more extreme ambient conditions, especially temperature (cold starts, hot soaks)
- The desire to assess a wider range of driving conditions, from heavy traffic to prolonged motorway cruising – and possibly to separate emissions which are most significant in urban areas (for example NOx) from those of global significance (for example CO_2) by using different tests for each
- The desire to assess the impact of using air-conditioning, heating and other vehicle systems

2.4.4 Well to tank characteristics of fuels

CO_2 emission data quoted for vehicles is usually on a "tank to wheels" basis. That is to say, further CO_2 emissions created as a result of extracting, refining, transporting and storing the fuels is disregarded. Appendix B describes issues associated with the various fuel types, and gives information on the "well to tank" CO_2, or efficiency, of the fuels. For convenience this is expressed as percentage efficiency, so that vehicle tank-to-wheels data can be converted to a holistic well-to-wheels figure. The methodology is explained in Appendix B, key data is:

Fuel	Well to Tank %
Petrol (Gasoline)	85.9%
Diesel	89.5%
LPG (Average of Refined & Extracted)	88.5%
Natural Gas (Compressed, 300 bar)	92.5%
Methanol (made from Natural Gas)	65.0%
Hydrogen (made from Natural Gas, compressed 300 bar)	66.0%

Table 2.3 – Well to tank efficiency of various fuels

2.5 Philosophies behind the Low Carbon and Hydrogen Priority Evolutions

2.5.1 Introduction

As discussed, there are rarely major, revolutionary changes in the automotive market. Instead, steady evolution of technology is progressed to improve fuel consumption, emissions and customer enjoyment. However, legislation can significantly affect this, such as emissions legislation forcing the introduction of the exhaust catalyst and so promoting a step change in emissions, in the l970s in the USA, and similarly in the early 1990s in Europe. From then on Petrol and Diesel vehicle emissions legislation has also "evolved" in a series of small steps to allow technology to develop to meet the legislation.

At this point, it is important to understand the criteria which vehicle manufacturers and users consider important. Even with the more aggressive, perhaps "revolutionary" Hydrogen priority route, these criteria require consideration:

For the user:

- Vehicle reliability and safety must never be compromised
- Price premiums for good fuel economy (low CO_2) or emissions are very hard to justify unless counterbalanced by tax incentives or fuel cost savings
- Brand image, performance, refinement and user enjoyment are demanded
- Customers will not adjust to new ways of operating the vehicle or be limited by reduced driving range or luggage space, or limited fuelling infrastructure
- There is a wide variety of usage styles for vehicles, from urban, to high speed motorway, trailer towing etc. New technology must be capable of coping with all of these uses

For the manufacturer:

- Vehicles must be profitable, preferably more so than today due to current poor financial performance in the sector
- Development costs are high due to the enormous complexity of the vehicle's systems (often underestimated by the public and non-experts) and stringent legislation, which limits the degree of risk manufactures can take
- There is an equally costly and deep rooted service and fuelling infrastructure, outside the direct control of the manufacturers themselves, which will govern the pace of new technology introduction

These criteria dictate that technology introduction must be a careful, step-by-step process, which avoids step changes to the way the customer drives, services, fuels or buys the car.

One of the most recent notable examples of this step-by-step evolution is that of the passenger car Diesel engine:

- The evolution from indirect injection to direct injection Diesel engines gave the driver improved performance, economy and durability
- Next came the advanced variable geometry turbocharger which improved performance and allowed engines to become smaller for a given power output, so further improving fuel economy

- Then the “common rail” fuel injection system further revolutionised the Diesel engine, making them comparable to Petrol units for noise, performance and refinement but with significant reduction in CO_2 emissions
- Now, common rail systems are being further refined to bring substantial gains in emissions and refinement

This has happened gradually over about 20 years and with little negative cost impact to the driver but with significant increases in technology complexity and development effort. This has been possible due to gains in computing technology, the increase in Diesel car sales (offering research revenue), emissions legislation (which has added the incentive for improved engine technology) and finally natural market competition.

Against this background, a set of “rules” for each step-by-step route has been developed, as described below:

2.5.2 Low Carbon Route

The Low Carbon route would assume, and be driven by, continuing introduction of increasingly stringent CO_2 targets such as those under the present EU / ACEA Voluntary Agreement on the average CO_2 emissions of new cars [2], together with a continuing development of supporting fiscal measures. An example of this is the UK’s shift to CO_2-related Vehicle Excise Duty and Company Car Taxation. Progress reported by ACEA members indicates a reduction of fleet average CO_2 of around 2% per annum. If 0.6% of this is due to underlying improvement in existing technology (as previously discussed), then the remaining 1.4% per annum is attributable to new technology introduction and changes in the sales mix such as growth of Diesel sales. The latter could in itself be classified as a new technology introduction over the last decade.

Rules for the Low Carbon route are:

- Each technology step must be an incremental development from the previous one, feasible in time-scales, and at moderate risk – meaning that the risk level of new technologies must be acceptable at the time that they are introduced
- The vehicle must be attractive to the customer in terms of its functional attributes (performance, style, practicality, comfort, safety etc) and ease of use (servicing, refuelling) – equal or better than today where possible
- Vehicles must meet the progressively more stringent emission, safety and consumer demands which are likely
- Infrastructure change must be “market force” driven where possible, vehicle technologies must not rely on forced infrastructure change, especially for fuelling
- Manufacturers must be able to sell vehicles with the new technology in significant volumes, profitably – with incentives via taxation or legislation
- The evolution must give genuine reductions in well-to-wheels CO_2 at every step, with no significant negative environmental impacts

2.5.3 Hydrogen Priority Route

The Hydrogen Priority route assumes that priority was attached to promotion of Hydrogen fuelled vehicles to the volume market as aggressively as reasonably possible. Development of new technologies and infrastructure would be vigorously promoted, via substantially increased Government funding for research, low CO_2 vehicle purchase schemes, and supporting infrastructure development, and possibly via further, more demanding legislation. Such a pace of change would require public acceptance of its impact on car-buying choice, car usage, and (possibly) increased taxation to fund the effort required.

Rules for the Hydrogen Priority route are:

- Each technology step must be an incremental development from the previous one, feasible in time-scales, and at a manageable (if higher than the Low Carbon route) level of risk. This means that prioritised research must be capable of reducing the risk level of new technologies to an acceptable level at the time that they are introduced
- Given the above, initial steps must avoid reliance on less well proven or very expensive technology, while later steps will benefit from prioritised research
- The vehicle must be attractive to the customer in terms of its functional attributes (performance, style, practicality, comfort, safety etc) and ease of use (servicing, refuelling), when balanced against strong tax incentives for the new low CO_2 technologies
- Infrastructure change to meet the needs of new vehicle technologies, especially for fuelling, would be supported as necessary by Government, through subsidies and other means
- Manufacturers must be able to sell vehicles with the new technology in significant volumes, profitably – with strong incentives via taxation, subsidies or legislation
- The evolution must seek where possible to give reductions in tank-to-wheels CO_2 at every step, with no significant negative environmental impacts. However, an exception would be on the basis that short-term increases in well-to-wheels CO_2 would be accepted in the interest of the objective of a fast transition to Hydrogen fuelling pending the arrival of zero-CO_2 Hydrogen supply.

The technology developments are described in subsequent chapters. Most of the technologies mentioned in this report are available now, but many are currently far from meeting the market-related criteria (cost, reliability, functionality) above. In simple terms, they need time to mature. Therefore, the introduction dates suggested here relate to an expectation of when the above Rules can be met. Niche vehicles with these technologies will be available before the dates suggested but they will be expensive, bought only by enthusiasts and will have an insignificant impact on lowering carbon fuel usage.

3 LOW CARBON EVOLUTION

This Section describes the Low Carbon Evolution road map (illustrated in Appendix E) indicating the approach, assumptions, pertinent data and the risks associated with each step. In addition, reference is made to Appendix C where key facts and figures are explained in general terms for the new technologies used in each step. Appendix F contains the spreadsheets with the data calculations for each step.

The approach taken to calculate the fuel consumption of each step has been to analyse first how the technologies influence the average power the vehicle uses to drive over the New European Drive Cycle. For example, stop start systems remove the idle section and reduce the engine "on-time" so reducing average cycle power. Regenerative braking recovers power so again reducing average power. Next, the efficiency of the powertrain for generating that average power is calculated and related to the overall fuel consumed over the cycle. Weight and price implications are calculated by analysis of the "add and delete" components including future projections based on published statements and historical improvements.

Please note: The vehicle price calculations include a typical factoring of unit manufacturing costs to on-sale price increment. They DO NOT include an amortisation of the cost of abnormal levels of research, development and investment in manufacturing infrastructure, such as may be required to achieve an abnormal pace of technological change (as opposed to natural replacement of obsolete product). Since such investment would come from many global sources and perhaps also non-automotive industries requiring similar technologies, it is impossible to factor this into vehicle cost.

Also, where a technology has been added to a vehicle (such as a Lean NOx Trap (LNT) or a Diesel particulate filter (DPF) for emission control) these are carried over to the next step unless it is stated that they are removed.

Finally, note that **percentage changes are relative to the previous step** NOT to the baseline vehicle. This approach indicates more clearly if the new step has been beneficial to the parameter in question compared with the previous step.

References are given at each step in the spreadsheets, which are contained in Appendix F.

3.0 Step 0 – The Baseline

Section 2.3 outlines the baseline vehicle, which is an average of typical state-of-the-art C and D class Diesel cars (family sized) which represent the largest sales sector in Europe. The technologies used in this "average" car are:

- 2001 model year
- Modern HSDI Diesel engine with Euro 3 emissions and low combustion noise
- 5 or 6 speed manual transmission
- 12V electrical systems with standard starter, alternator and lead acid battery
- Average cycle CO_2 emissions of 149 g/km (167 g/km CO_2 Well to Wheels) (see Appendix B)
- Average weight of 1333 kg
- Average retail (list) price of £15,323 - actual.

It should be noted that a Petrol engine is an equally valid starting point for the steps that follow, however such vehicles do not meet the "best in class CO_2" criterion if an equivalent Diesel vehicle exists.

The technical data is presented in spreadsheets reproduced in Appendix F at the end of the report. Step 0 shows the data used to generate the baseline vehicle. From this point (taken as 2001) the scenarios are developed in line with the philosophy stated in Section 2.5. The average parameters are modified by the applied technologies with reference to the New European Drive Cycle including the change in CO_2 emission, weight, cost and general characteristics of the vehicle. Two columns are usually shown; the first for the current or near future emissions legislation and the second for the next emissions legislated step. This approach was selected due to the strong influence emissions calibration and technologies have on vehicle CO_2 emissions, weight and cost. In some instances, the improvement in legislated emissions has outweighed the CO_2 improvements offered by the applied technology.

3.1 Step 1 – Stop Start Vehicle - 2004

Engines idling with the vehicle at standstill, such as at traffic lights, waste significant quantities of fuel. Manufactures have introduced a few vehicles over the last twenty years, which shut the engine down when not required and then restart it on a given set of actions by the driver. These were very poorly received and did not achieve worthwhile sales volumes. The principle reasons for this were poor starting refinement (the starter motor was standard technology), reliability issues as the starter system was put under significantly more stress, and the driver acceptance of the delays in the system leading to a lack of confidence the engine would start in time.

Step 1 in the Low Carbon roadmap (Appendix E and F) suggests that this approach will be possible by 2004 in a mass-market vehicle. The key advancements in technology that make this possible are:

- **12V belt driven electrical machines** which replace the starter motor and alternator and, as they are always connected to the engine, are near silent in operation – discussed in Appendix C2 and 3
- **Rapid engine starting** (less than 0.3 seconds is possible) due to high starting torque and engine management and fuel injection systems that can fuel the engine in less than two engine revolutions
- **Proven reliability** through advanced design and analysis of the machine, electronics and the belt drive
- Better understanding and implementation of the **driver to machine interface**

Adoption of this technology to the Diesel engine shows a potential 3.6% improvement over the NEDC drive cycle (and between 7 and 10% for the less efficient Petrol engine depending on its size). However, by 2004, the adoption of the Diesel particulate filter may be desirable for customer acceptance, or even under consideration for legislation by governments in some European cities (as has happened in Tokyo). This is not technically necessary to achieve the Euro 4 Diesel emissions legislation in a vehicle of this weight. Therefore, to present the reasonable worst case scenario, the fuel consumption, weight and cost penalty associated with the filter has been included in the calculations as shown in Appendix F - Step 1.

Overall, a small improvement of 0.4% is possible with a weight and cost penalty of approximately 1.5%. The comments on the spreadsheet state the basis for the calculations.

When the vehicle is taken to the speculated "Euro 5" level, fuel consumption is worsened by 2.6% mostly due to the influence of the NOx reducing device, in this case, a Lean NOx Trap. These systems are described in Section 2.4. It is unlikely that this technology would be brought into production in 2004, but could be offered several years in advance of any legislation if there were tax incentives.

Vehicle weight is not significantly affected by the "stop-start" technology due to the deletion of other components like the traditional starter and alternator. The main increase comes from the aftertreatment. No vehicle specific weight savings are forecast at this time as discussed in Section 2.3. Engine evolution in efficiency and cost is included and are also detailed in Section 2.3.

A 6 speed manual transmission is included as this is becoming a fast growing customer requirement and is well suited to the high torque Diesel engine offering improve refinement during motorway cruising. This has no significant impact on the emissions cycle for CO_2 as the gear change points are pre-described and do not take advantage of the 6th speed. In real world driving, CO_2 improvements are seen. If an automated 6-speed transmission were used then there would be gains over the cycle, however, these are not expected to reach maturity by 2004.

The component costs and the time for development limit the date of introduction for this vehicle. The technologies are available now. The first product launch is expected in 2003, and by 2004 there should be more than three manufactures with products similar to this, although they may be with Petrol engines.

Key Headings Summary for Step 1:

Impacts (relative to step 0):

- Fuel consumption (Well to Wheels g/km CO_2) –0.4% to **166** at Euro 4
- Fuel consumption (Well to Wheels g/km CO_2) +2.6% to **171** at assumed Euro 5
- Weight (kg) +1.46% to **1352** at Euro 4
- Weight (kg) +1.61% to **1354** at assumed Euro 5
- Retail Price (£2002) +1.66% to **15,577** at Euro 4 (estimated range **£15,550 to £15,600**)
- Retail Price (£2002) +3.29% to **15,827** at assumed Euro 5

Technologies:

- Belt alternator starter on 12V standard electrical system
- 6 speed manual transmission
- Diesel particulate Filter for Euro 4 if required
- Lean NOx trap for assumed Euro 5 emissions

Risks:

- Low risk for electrical system except customer acceptance of stop-start of the engine during dwell periods
- Heating and air-conditioning will be inoperative with the engine shut down, which may impede customer acceptance. It is likely that the stop-start function would be inhibited by high heating or cooling demands to address this concern,

this means that the fuel economy benefit will only be seen in moderate climatic conditions. This is less of an issue for the UK than it would be for Sweden or Italy, for example

- Diesel Particulate Filters (DPF) and Lean NOx Traps (LNT) to enable the assumed future legislation to be met, are still the subject of intensive research with associated risk for future use. DPFs can require ash removal (depending on technologies used) as a service item. This is an issue which is independent of the introduction of stop-start

Vehicle Attributes:

- No change

Impact on Manufacture:

- No significant change – detail changes to electrical and belt systems

Impact on Infrastructure:

- No change

Read Across to Other Vehicle Types:

- Technically applicable to all light duty vehicle types (passenger cars, delivery vans), customer acceptance is only issue

Read Across to Other Usage Patterns:

- Greatest benefits in heavily congested conditions. In suburban and motorway use, the only benefit is a small increase in alternator efficiency – negligible effect on CO_2

Degree of Confidence in Analysis:

- High, based on real world experience and engineering programmes

Alternative Technologies:

- Crankshaft mounted devices (more expensive)

3.2 Step 2 – Stop Start + Regenerative braking Vehicle - 2007

Accelerating and braking accounts for more than half of the fuel used in city driving. If the energy wasted during braking were recovered and then used to help accelerate the vehicle (launch assist) in the next cycle, CO_2 emissions could be reduced. The use of a higher voltage than the current 12v systems is a critical technology step which is likely to inhibit earlier introduction of re-generative braking to mass market vehicles. By 2007, these technologies may enter the mass market and are presented in Step 2 of the Low Carbon roadmap (Appendix E and F). *Please note, all the improvements seen in Step 1 are carried over in to Step 2 and so the improvements presented are referenced to Step 1, NOT Step 0 (baseline vehicle).*

The key advancements in technology that make Step 2 possible are:

- **42V belt driven starter/motor/generator** electrical machines which replace the starter motor and alternator and, as they are always connected to the engine, are near silent in operation. At 42V, increased electrical powers are possible making regenerative braking and launch assist worthwhile (Appendix C2 and 3)

- **Valve Regulated Lead Acid (VRLA) battery**, which can be charged and discharged more rapidly and efficiently than the standard flooded cell battery used today. This makes storing the braking energy possible (Appendix C1)
- Slight **engine down sizing** from 2.0 litre to 1.8 litre improves base engine efficiency and is supported by the additional electrical motoring torque now available from the belt driven machine
- **6 speed Dual Clutch Automated Transmission** allows free selection of gears over the drive cycle, is significantly more efficient than a traditional automatic gearbox and changes gear almost imperceptibly. This improves CO_2 emissions by operating the engine at more efficient points than can be achieved by pre-described gear change points of the cycle – and in real world driving, enables the car, not the driver, to choose gear-change strategies for best fuel consumption. This technology also adds to driving pleasure and safety, enabling fast gear-changes operated by steering-wheel paddles (this type of gear-change is also used on other transmission types today). These technologies are discussed in Appendix C6.
- **DC-DC converter** changes the 42V electricity generated from the belt driven electrical machine to 12V for the rest of the car. This approach offers a small efficiency improvement over the drive cycle compared to a traditional alternator.

These technologies improve the Step 1 vehicle by nearly 15% at assumed Euro 5 emissions levels for a small increase in weight. However, the retail price increase of the vehicle is now significant (over 4%). The electrical machine, power electronics and battery increase the price by 1.6% and the transmission by 2.5%. The added functionality, driveability and fuel economy gains would probably mean this could be made acceptable to the customer in an environment where buying a low CO_2 vehicle is incentivised.

When the vehicle is taken to the speculated “Euro 6” emission levels (unlikely to be feasible for 2007, but probably available ahead of the legislation), fuel consumption is worsened by 3% but the concept still offers nearly 12% improvement from Step 1.

Vehicle weight is not significantly affected by these technologies.

Again, these technologies are available however, the cost of the advanced batteries, the advanced motors and proof of robustness are delaying the mass-market introduction.

Key Headings Summary for Step 2:

Impacts: (ALL RELATIVE TO THE PREVIOUS STEP)

- Fuel consumption (Well to Wheels g/kmCO_2) –14.8% to **146** at assumed Euro 5
- Fuel consumption (Well to Wheels g/kmCO_2) –11.8% to **151** at assumed Euro 6
- Weight (kg) +0.48% to **1361** at assumed Euro 5 and Euro 6
- Retail Price (£2002) +4.12% to **16,480** at assumed Euro 5 (estimated range **£16,350 to £16,600**)
- Retail Price (£2002) +4.75% to **16,580** at assumed Euro 6

Technologies beyond Step 1:

- 42V starter/motor/generator – belt driven with dual 42V / 12V electrical architecture system (see appendix C2 and 3)
- VRLA battery (see appendix C1)

- 6 speed automated dual clutch manual transmission
- DC-DC converter

Risks:

- Low for electrical system except customer acceptance of Stop and Start of the engine during dwell periods
- Transmission clutch technologies are highly rated and can be abused if not adequately protected
- Battery needs to be well designed, specified and used with a good battery management system to achieve sufficient life
- Heating / Air Conditioning issues as per Step 1
- Emission control issues as per Step 1

Vehicle Attributes:

- Small increase in functionality from Dual Clutch Transmission

Impact on Manufacture:

- Electrical systems: implementation of 42v systems and VRLA batteries
- Dual Clutch Transmissions are likely to be reasonably compatible with current manual transmission manufacturing infrastructure

Impact on Infrastructure:

- No change

Read Across to Other Vehicle Types:

- Technically applicable to engine sizes below 2 litres with this technology but with larger motor and battery sizes it is applicable to most vehicles. Engine downsizing is applicable to most applications if customers accept owning a smaller engine

Read Across to Other Usage Patterns:

- Greatest benefits in heavily congested conditions. In suburban and motorway use, small increase in powertrain efficiency due to downsizing, leading to perhaps 1-2% reduction in CO_2 relative to steps 0 and 1

Degree of Confidence in Analysis:

- High, based on real world experience and engineering programmes

Alternative Technologies:

- Crankshaft mounted devices (more expensive), cylinder deactivation instead of downsizing to improve engine operating efficiencies

3.3 Step 3 – Stop Start + Regenerative braking + Significant Downsizing in Vehicle - 2010

Engine friction at part load represents wasted energy. This can be remedied by using a smaller engine operating at higher load, so that the friction becomes a smaller part of the engine's work. If the engine is also up-rated by a higher degree of turbocharging, it can still achieve the same peak power output and so give the vehicle the same peak performance. However, downsizing worsens the initial vehicle acceleration from low engine speeds, as the turbo is not able to boost the engine, therefore, assistance is required. For Step 3, the electrical machine provides this assistance, and is up-sized to 10kW. The downsizing and Mild

Hybridisation shown in this concept offers significant gains in fuel efficiency as presented in Step 3 of the Low Carbon roadmap (Appendix E and F). Because this type of system requires a greater degree of re-engineering than the previous steps, its introduction in mass-market vehicles is not likely until circa 2010. *Please note, all the improvements seen in Step 2 are carried over in to Step 3 and so the improvements presented are referenced to Step 2, NOT Step 0 (baseline vehicle).*

The key advancements in technology that make Step 3 possible are:

- **42V Crankshaft Mounted Starter/motor/generator** electrical machine. This will probably have permanent magnets (although induction and switched-reluctance types are feasible) to give high power density and a lightweight system. Provides rapid engine starting, gives over 100Nm torque assistance at low engine speeds. Also, 10kW of regenerative braking which can improve fuel efficiency further (Appendix C2 and 3)
- **Nickel Metal Hydride battery** for good energy and power density, the ability to absorb and give back regenerative energy efficiently and with long battery life (Appendix C1)
- **Highly Downsized engine** to reduce engine friction as a percentage output at part load so significantly improving the part load vehicle fuel economy. Up-rating ensures peak vehicle performance is maintained

These technologies improve the Step 3 vehicle by nearly 22% at Euro 5 emissions levels, with a reduction in weight given by the downsized engine. However, the larger and higher tech electrical machine, power electronics and battery increase the price by 4%. When the vehicle is taken to speculated “Euro 6” emissions legislation (possibly becoming feasible by this time) fuel consumption is worsened by 3% but the concept still offers nearly 19% improvement from Step 2.

As a point of reference, this concept is similar to the Ricardo i-MoGen vehicle that has recently been demonstrated and offers similar levels of CO_2 benefit.

The electrical technologies are not yet cost optimised for this application, especially the battery technologies. One manufacturer has stated that they have developed the technology for this type of vehicle, but will wait for significant volume production by competitors so that the battery cost is significantly reduced.

Key Headings Summary for Step 3:

Impacts: (ALL RELATIVE TO THE PREVIOUS STEP)

- Fuel consumption (Well to Wheels g/kmCO_2) –21.8% to **114** at assumed Euro 5
- Fuel consumption (Well to Wheels g/kmCO_2) –18.8% to **123** at assumed Euro 6
- Weight (kg) –2.09% to **1332** at assumed Euro 5 and Euro 6
- Retail Price (£2002) +4.50% to **17,222** at assumed Euro 5 (estimated range **£17,000 to £17,400**)
- Retail Price (£2002) +5.08% to **17,422** at assumed Euro 6

Technologies beyond Step 2:

- 42V starter/motor/generator – crankshaft mounted, permanent magnet with dual 42V / 12V electrical architecture system
- Nickel Metal Hydride (NiMH) battery
- Highly downsized engine (1.8 litre to 1.2 litre) with ratings over 63kW/litre.

Risks:

- Low incremental risk for the electrical system. Continuing risk of customer acceptance of stop-start of the engine during dwell periods
- Battery needs to be well designed, specified and used with a good battery management system to achieve sufficient life. Replacement is now a cost the owner will not accept (£332). Battery power availability at temperatures below –10°C is poor. This makes engine starting difficult. There are solutions to this available but improved NiMH and Li-Ion battery technology is being developed
- Higher degree of engine down-sizing brings increased (but manageable) risk of poor durability and driveability. It is likely that these issues can be addressed by 2010

Vehicle Attributes:

- Slight change in torque curve shape due to downsized engine and electrical assistance – with good specification, this can be improved from the base engine. Also, the acceleration feel of the vehicle can now be susceptible to the state of charge of the battery and so is variable which can lead to customer acceptance problems. High speed cruising and hill ascent are not affected

Impact on Manufacture:

- High production volumes of NiMH batteries is currently a challenge but this is expected to be solved by 2010
- New generation of down-sized base engines may be required, although existing units from smaller cars may be suitable

Impact on Infrastructure:

- No significant change. Workshop personnel will require training in the new technologies although these are mostly maintenance free

Read Across to Other Vehicle Types:

- Technically applicable to engine sizes below 2 litres with this technology but with larger motor and battery sizes it is applicable to most vehicles. Engine downsizing is applicable to most applications if customers accept owning a smaller engine. Extreme downsizing in the B and sub-B segments may be ineffective due to inherent inefficiency of very small turbochargers and small cylinders – it is more likely that these price-sensitive cars will use non-downsized engines with the same base hardware as the more powerful downsized units

Read Across to Other Usage Patterns:

- Greatest benefits in heavily congested conditions, but even in suburban and motorway use there will be a significant increase in powertrain efficiency due to downsizing, leading to perhaps 5-10% reduction in CO_2 relative to step 2

Degree of Confidence in Analysis:

- High, based on real world experience and engineering programmes

Alternative Technologies:

- Some belt drive systems may offer the power ratings at lower cost as discussed in Appendices C2 and 3. Cylinder deactivation instead of downsizing to improve engine operating efficiencies

- The NiMH battery can be replaced by lead acid batteries (to save cost) and with the addition of "ultra-capacitors" to store the regenerative braking power. However, this requires additional power electronics and the added cost and weight of the ultra-capacitors. Lithium Ion (Li-Ion) battery technology is another promising alternative, currently more costly than NiMH
- These technologies are equally applicable to the Petrol (Gasoline) engine to offer significant fuel savings for markets where the Diesel engine has poor acceptance or low sulphur Diesel fuel is not available.

3.4 Step 4 – Parallel Hybrid in Vehicle - 2012

The Parallel Hybrid has three key abilities: first, to operate the engine at high efficiency and low emissions conditions. Second it can recover as much regenerative energy as possible whilst the vehicle is slowing down and third, to offer a "Zero Emissions" mode capability, i.e., running on electricity alone for inner city areas. The architecture is shown in "Step 4" of the roadmap (Appendix E). These are self-sufficient, grid independent vehicles that do not need electrical charging from a base station. The engine can drive the wheels directly or torque can be "shared" between the engine, a motor, a generator and the wheels to find the optimum operating point at any given road condition. This gives the Parallel Hybrid the potential for significant fuel savings. However, the motor, generator, transmission system, batteries and electronics add greatly to the cost of the vehicle. In the analysis presented here, cost reductions are projected to 2012 to take account of technical and production improvements. Even so, this is still a significantly more expensive technology than the Mild Hybrid variants discussed previously.

The engine chosen is a downsized Diesel engine operating over a limited speed range and as close as possible to its high efficiency areas. Unlike the Mild Hybrid concept, the engine does not have to be significantly up-rated (although there are benefits in doing this, including the ability to sustain high speeds or fully laden hill-climbs) as the electric system can assist the vehicle more substantially during full load accelerations. However, driving style and previous driving history will have a noticeable affect on vehicle performance. For example, the Toyota Prius 0 to 60 mph times vary from 14 to 20 seconds depending on battery state of charge. This can affect the public uptake of these technologies. This situation is improved by increasing battery capacity performance and state of charge control and by increasing the engine rating.

The Parallel Hybrid offers a 16% improvement in CO_2 emissions compared to the Mild Hybrid as presented in Step 4 of the Low Carbon roadmap (Appendix E and F). This is over 38% improvement from the base vehicle for similar performance and considerably lower regulated emissions. Again, this technology requires a greater degree of investment than previous steps, hence introduction to the mass market is not likely until circa 2012. *Please note, all the improvements stated in the spreadsheet for Step 3 are carried over into Step 4 and so the improvements presented are referenced to Step 3, NOT Step 0.*

The key advancements in technology that make Step 4 possible are:

- **High voltage motors, generators and power electronics** enable high power ratings to be achieved efficiently. Over 300V is typical. Permanent magnet machines are usually specified for high efficiency and low weight although for very large motors (over 30kW) induction machines are a viable option due to lower costs. Motor efficiencies between 90 to 95% are possible, however, the whole electrical powertrain involves many components with efficiencies between 90 and 95% (electronics, batteries etc.) and so the overall efficiency cannot match mechanical transmission systems. The total system efficiency gains come from the flexible control these systems offer. (Appendices C2 and 3)

- **Nickel Metal Hydride battery** for good energy and power density, the ability to absorb and give back regenerative energy efficiently and with long battery life. It is expected by this time, Lithium Ion (Li-Ion) batteries, and possibly Ultra-capacitors, will be a competing, cost effective technology which can offer improved specific ratings as detailed in Appendix C1.
- **Highly Downsized Engine** to reduce engine friction as a percentage output at part load so significantly improving the part load vehicle fuel economy. Up-rating ensures peak vehicle performance can be maintained. In the Parallel Hybrid, the engine speed and load is carefully controlled via a flexible transmission system to ensure high operating efficiency. This can lead to the vehicle "sounding strange" as it is driven.
- **Torque Sharing Transmission** is used to allow the engine, motor and generator to operate at their most efficient. These can be epicyclic transmissions, DCT or CVT based designs. They are discussed in Appendix C6.

These technologies improve the Step 4 vehicle by nearly 16% at "Euro 6" emission levels. However weight and especially the retail price increase significantly due to the motor, generator and battery increase in specification.

Date for introduction to the mass market is again linked to the price of the electrical equipment and the battery.

Key Headings Summary for Step 4:

Impacts: (ALL RELATIVE TO THE PREVIOUS STEP)

- Fuel consumption (Well to Wheels g/kmCO_2) –16.0% to **103** at assumed Euro 6
- Fuel consumption (Well to Wheels g/kmCO_2) –14.0% to **105** at assumed Euro 7
- Weight (kg) +5.14% to **1401** at assumed Euro 6 and Euro 7
- Retail Price (£2002) +9.37% to **18,024** at assumed Euro 6 (estimated range **£17,600 to £18,400**)
- Retail Price (£2002) +10.28% to **18,174** at assumed Euro 7

Technologies beyond Step 3:

- High voltage, high power motor and generator (permanent magnet)
- NiMH or Li-Ion battery at high voltage
- Highly downsized engine (1.0 litre) with high ratings (over 63kW/litre), a slightly smaller speed range and lightweight materials.
- Torque sharing transmission

Risks:

- Customer acceptance of a different driving experience. In this evolution, it is expected that the customer will have experienced "engine shut down" but almost random engine noise and silent motion will require some accommodation

- Battery systems are now vital to the life and cost of ownership of the car. It is expected by 2012 that these issues will be understood and production ready for the mass market at reasonable cost. Low temperature operation is still an issue
- Heating and air-conditioning issues remain, but larger battery capacity may enable more effective electric systems

Vehicle Attributes:

- Driveability and noise will be good but variable depending on operating mode and battery state of charge

Impact on Manufacture:

- High volumes of NiMH and Li-Ion batteries are currently difficult to manufacture but this is expected to be solved by 2012
- Torque sharing transmissions and more powerful motors may require a degree of new production facility
- Vehicle platforms will require a higher degree of adaptation especially to accommodate the larger battery. Packaging of the large battery unit may render the technology incompatible with vehicle platforms not originally designed to accept it
- Vehicle build is more complicated, and considerably more engineering effort is required in the design and development phases of the vehicle programme

Impact on Infrastructure:

- Service personnel will require training to a high standard in order to be safe with the dangerous high voltage DC present on the vehicle. However, these systems are mostly maintenance free and would be safely designed and implemented on the vehicle

Read Across to Other Vehicle Types:

- Technically applicable to most vehicle applications, however, the larger the vehicle the greater the price increase

Read Across to Other Usage Patterns:

- Greatest benefits in heavily congested conditions. In suburban and motorway use, a small further increase in powertrain efficiency will be seen due to downsizing, leading to perhaps 2-3% reduction in CO_2 relative to step 3

Degree of Confidence in Analysis:

- High, based on real world experience of production vehicles, engineering programmes and technical publications

Alternative Technologies:

- There are many alternatives to this theme but the core ingredients and approach is as presented here
- This is equally applicable to Petrol (Gasoline) and Diesel engines and offers the building blocks to head towards alternative prime movers such as Fuel Cells

3.5 Step 5 – Series Hybrid (Electric Transmission) Vehicle - 2015

The Series Hybrid has no mechanical connection between the engine and the wheels. This is done electrically. The theoretical improvement over the Parallel Hybrid is that the engine can be operated at exactly its lowest fuel consumption point rather than over a range of conditions as for the Parallel Hybrid. This should offer some fuel efficiency gains. However, the route from engine torque to wheel torque is generally not efficient using today's technologies. Studying Step 5 in the roadmap (Appendix E) it can be seen that energy from the engine goes through the generator, the power electronics, the battery, out the battery, into the power electronics then to the motor and the wheels. This involves a considerable chain of efficiencies as listed below:

Generator efficiency at 13kW	0.875
Power electronics efficiency in	0.960
battery in	0.930
battery out	0.930
Power electronics efficiency out to motor	0.960
Motor efficiency at 7kW	0.875

(The battery efficiencies shown here are the best Li-Ion batteries that are currently known published by the manufacturer SAFT however, NiMH can also approach these levels.)

These efficiencies must be multiplied together to create an overall system efficiencies. Using the data above, this multiplies to 61% system efficiency, compared to 84% system efficiency for a complete mechanical transmission at part load in a traditional vehicle.

This loss in efficiency seriously hinders the case for the Series Hybrid in a passenger car. To its advantage however, it does have the ability to recover more regenerative braking energy and in the analysis presented here, this accounts for a 9% improvement in cycle efficiency.

In the Step 5 spreadsheet shown in Appendix F, the cycle efficiency with today's system efficiencies is shown as 28% worse than the Parallel Hybrid (step 4). Also shown is the required increase in system component efficiencies to total 77% if the Series Hybrid is to match the Parallel Hybrid for overall CO_2. These are broken down below:

Generator efficiency at 13kW	0.960
Power electronics efficiency in	0.960
battery in	0.950
battery out	0.950
Power electronics efficiency out to motor	0.960
Motor efficiency at 7kW	0.960

Principally, the motor and battery efficiencies need to improve considerably for the Series Hybrid to approach the Parallel Hybrid for passenger car use over the NEDC. The required improvements for motors exceed the current trend in improvements using cost effective technologies and so should be considered high risk. However, power electronics and batteries may well exceed these stated efficiencies in the future.

It should be pointed out that for other applications such as busses and coaches that do inner city stop-start driving, the Series Hybrid does offer advantages due to considerable regenerative braking opportunities.

The Series Hybrid does offer the advantage that the prime mover is now disconnected from the wheels and so can be formed from any subsystem. This potentially develops all the motive systems needed for the Fuel Cell vehicle. If the Fuel Cell is, first, more efficient that the Diesel engine and secondly does not produce CO_2 locally then the loss in efficiency of the Series Hybrid powertrain can be initially accepted.

The key advancements in technology for Step 5 are:

- **High voltage motors, generators and power electronics** enable very high power ratings (peak power of 80kW) to be achieved efficiently. Over 300V is typical. Permanent magnet machines are usually specified for high efficiency and low weight although induction and switched reluctance machines are a viable option due to potentially lower costs. Motor efficiencies between 90 to 95% are possible at full load, however, the whole electrical powertrain efficiencies are low. (Appendix C2 and 3)
- **Larger Nickel Metal Hydride or Li-Ion battery** for good energy and power density, the ability to absorb and give back regenerative energy efficiently and with long battery life. It is expected by this time, Lithium Ion (Li-Ion) batteries will be a competing, cost effective technology, which can offer improved specific ratings as detailed in Appendix C1. However, battery efficiency at between 83 and 93% today is a limiting factor for the Series Hybrid

These technologies together worsen the vehicle (relative to the Step 4 Parallel Hybrid) by 28% at assumed “Euro 7” emission levels due to the “electrical transmission” efficiency chain. If technologies improve beyond what the current progress suggests then the Series Hybrid may approach the Parallel Hybrid efficiency gains for passenger cars. Therefore, Step 5 – The Series Hybrid Vehicle may not be a valid step towards the Fuel Cell car. This issue is discussed further in Section 3.9.

Key Headings Summary for Step 5:

Impacts: (ALL RELATIVE TO THE PREVIOUS STEP)

- Fuel consumption (Well to Wheels g/kmCO_2) +28% to **135** at assumed Euro 7
- Fuel consumption (Well to Wheels g/km CO_2) 0% to **94** at assumed Euro 7 (future target efficiencies)
- Weight (kg) +0.83% to **1413** at assumed Euro 7
- Retail Price (£2002) +2.05% to **18,546** at assumed Euro 7 (estimated range **£18,000 to £19,000**)

Technologies beyond Step 4:

- High voltage, high power motor and generator (permanent magnet) at 80kW
- NiMH or Li-Ion battery at high voltage

Risks:

- Customer acceptance of a different driving experience. In this evolution, it is expected that the customer will have experienced “engine shut down” but “constant engine speed” noise and silent motion will require some accommodation.
- Battery systems are now vital to the life and cost of ownership of the car. It is expected by 2015 that these issues will be understood and production ready for the mass market at reasonable cost

- Heating and air conditioning issues are similar to the previous step
- Component efficiencies are likely to hinder the development of this concept with combustion engines burning fossil fuel as the prime mover

Vehicle Attributes:

- Driveability and noise will be good but variable.

Impact on Manufacture:

- The high sales volumes of NiMH and Li-Ion batteries are currently difficult to achieve however, this is expected to be solved by 2015. Vehicle build is more complicated and considerably more engineering effort is required in the design and development phases of the vehicle programme.

  Packaging of the large battery unit and electric drives is likely to render the technology incompatible with vehicle platforms not originally designed to accept it – however, any new platform architecture may have better compatibility with a Fuel Cell drivetrain

Impact on Infrastructure:

- Service personnel will require training to a high standard in order to be safe with the dangerous high voltage DC present on the vehicle. However, these systems are mostly maintenance free and would be safely designed and implemented on the vehicle

Read Across to Other Vehicle Types:

- Technically applicable to most vehicle applications, however, the larger the vehicle the greater the price increase. Larger vehicles, particularly urban trucks and buses, typically experience greater benefits due to the importance of re-generation for these heavy vehicles in stop-start use

Read Across to Other Usage Patterns:

- Greatest benefits in heavily congested conditions. In suburban and motorway use, CO_2 may be worse than Step 4 due to the loss of system efficiency. For the speculated future system efficiencies (total 77% compared to 84% for step 4), an increase in CO_2 of around 11% could be expected in constant-speed cruising. Without these efficiency improvements, the increase would be greater

Degree of Confidence in Analysis:

- Medium, engineering programmes, technical publications and calculations

Alternative Technologies:

- There are many alternatives to this theme but the core ingredients and approach is as presented here.
- This is equally applicable to Petrol and Diesel engines and offers the building blocks to head towards alternative prime movers such as Fuel Cells

3.6 Step 6 – Series Hybrid Vehicle with a Reversible Fuel Cell - 2020

Step 6 takes a developed powertrain from Step 5 and replaces the battery with a reversible Fuel Cell. This approach was chosen as the battery is lacking in terms of specific energy and power density (compared with liquid fuels for example) and the Reversible Fuel Cell (RFC) aims to improve on this. The operation of the RFC is to take in electricity, use to convert water into Hydrogen, which is compressed and stored (as described in Appendix C7). In the other direction, the RFC operates as a Fuel Cell converting Hydrogen into water and electricity. It is claimed that the RFC would offer significantly better specific power and specific energy (Wh/kg) than a battery with good efficiency. The analysis presented in this report indicates otherwise.

The key advancements in technology that make Step 6 possible are:

- **Reversible Fuel Cell** takes the form of a solid oxide Fuel Cell which is up to 70% efficient at part load, a small Hydrogen storage tank for about 90g of Hydrogen, a water storage tank of a few litres and a compressor to compress Hydrogen for storage at about 300 bar. In addition to this, there is an air compressor, heating and insulation systems so the Fuel Cell can operate at about 900°C. These support systems reduce the efficiency of the system. Storing energy equates to about 65% efficiency and giving out energy is about 70% efficient. This does not compare well with a battery that (for Lithium Ion) can exceed 93% in both directions. For this application the system has been sized to store the same energy as the Step 5 vehicle however, the reversible Fuel Cell is able to supply more power than the NiMH batteries in the Step 5 vehicle. This implies that more regenerative braking energy could be stored (as this is very high power for a short time) which could give an improvement in theoretical fuel consumption. However, over the European drive cycle, it is estimated that Step 5 is recovering most of the braking energy that is available so this small potential gain has not been included in this analysis.

This technology impacts the Step 6 vehicle fuel consumption badly at +98%. However the weight reduction promised by the RFC has been achieved, offering a 1.8% vehicle weight saving over a battery system. Cost has been increased by nearly 8%. Overall, this technology is therefore assessed as an inadvisable step in the Low Carbon Road Map unless a breakthrough in efficiency is achieved.

Key Headings Summary for Step 6:

Impacts: (ALL RELATIVE TO THE PREVIOUS STEP)
- Fuel consumption (Well to Wheels g/kmCO_2) +98% to **209** at assumed Euro 7
- Weight (kg) –1.77% to **1388**
- Retail Price (£2002) +7.86% to **20,003** at assumed Euro 7 (estimated range **£18,600 to £22,300**)

Technologies beyond Step 5
- Reversible Fuel Cell to replace the NiMH battery

Risks:
- There maybe delay in the operation of the RFC, as the Fuel Cell has to reach sufficient operating temperature. Customer acceptance of a different driving experience. In this evolution, it is expected that the customer will have

experienced “engine shut down” but “constant engine speed” noise and silent motion will require some accommodation.

- Such a new technology would take significant development to get into production readiness for the mass market at reasonable cost so there is a risk that it would not actually make it
- Component efficiencies so poor compared with the battery that, in this application, it probably is not a legitimate step forward

Vehicle Attributes:

- Driveability and noise will be good but variable but there maybe delay in the initial start-up of the vehicle

Impact on Manufacture:

- RFC would contain significant amounts of precious metals and manufacturing techniques would be advanced, so requiring considerable investment to make mass production a reality. Vehicle build would be more complicated and considerably more engineering effort would be required in the design and development phases of the vehicle programme. Also, sub-systems would be required for the RFC which would differ from “traditional” vehicles

Impact on Infrastructure:

- RFC systems would be new and so service personnel will require training to a high standard in order to be safe with the Hydrogen storage and compressions systems, high voltage DC and high temperature systems present on the vehicle. However, these systems would be mostly maintenance free and would be safely designed and implemented on the vehicle

Read Across to Other Vehicle Types:

- Technically applicable to most vehicle applications, however, the larger the vehicle the greater the price increase
-

Read Across to Other Usage Patterns:

- This type of system should offer greatest benefits in heavily congested conditions, but the poor efficiencies of energy storage and release prevent this benefit from being realised. Constant speed usage (suburban and motorway) similar to Step 5.

Degree of Confidence in Analysis:

- Low to Medium, for cost and weight based on technical publications, theoretical calculations and projection of stated parameters to the year 2020. However, the fundamental efficiencies stated are stated with medium to high confidence.

Alternative Technologies:

- Clearly the battery is still a valid alternative technology to the RFC,depending on the “POWER storage” (ability to store and release energy fast) that is required
- The Ultra Capacitor is a high POWER storage device that would offer improved efficiency and probably specific ratings, especially by 2020. They would also be cheaper

The only advantage of this approach is to get the Fuel Cell technologies into the market place as early as possible. Given the efficiency issues stated in this section, a better approach may be to use the Fuel Cell as an auxiliary power unit helping to power a Series or Parallel Hybrid. This is discussed more in Section 3.7 and 3.9, and is a feature of the proposed Hydrogen Priority route.

3.7 Step 7 – Hydrogen Internal Combustion Engine with Reversible Fuel Cell - 2025

Step 7 replaces the Diesel engine with a Hydrogen burning engine specially designed for the task. The rest of the powertrain is unchanged from Step 6. This IC engine burning Hydrogen is not the clean, "ideal" engine that is sometimes claimed. It suffers NOx emissions and struggles to compete on power density when compared with the current Petrol or Diesel engines. This is described in detail in Appendix C5. However, it does offer zero local CO_2 emissions hence the introduction in this roadmap. Well to Wheels CO_2 is then a matter of origin for the Hydrogen used in the vehicle which would be controllable by the infrastructure management.

The important issue to consider here is the CO_2 produced when making Hydrogen and the powertrain efficiency. For this study, it has been assumed that Hydrogen has been manufactured from Natural Gas. This is currently an abundant fuel and is probably the most efficient feedstock for Hydrogen production by traditional, non-renewable means. However, the conversion process liberates (typically) 8.33kg of CO_2 for every 1 kg of Hydrogen produced. This is calculated from the theoretical chemical reaction which liberates 5.5kg of CO_2 for every 1kg of Hydrogen, multiplied by the Well to Tank efficiency of the process (including leakage and transportation) of 66% efficiency. The "Well to Tank" figure of **8.33kg CO_2 per 1 kg of Hydrogen** has been used throughout this report. (Please see Appendix B for more details on fuels).

The powertrain efficiency is reduced by 9.5% when changing from a downsized Diesel engine to an advanced and downsized Hydrogen engine. This is due to the change in the combustion cycle, as a Hydrogen engine operates using spark ignition and a degree of throttling, as with a Petrol engine. Likely advances in Hydrogen combustion efficiency have been taken into account, as described in Appendix C5. Also, the amount of CO_2 released per unit of energy for Hydrogen (Well to Tank, compared to Diesel (Well to Tank) is worse when the Hydrogen is produced from fossil fuels. These two facts worsen the Well to Wheels efficiency of Step 7 compared to Step 6.

In practise, and as discussed later, it is unlikely that the Series Hybrid and Reversible Fuel Cell technologies (steps 5 and 6) would be implemented. The impact of the switch from Diesel to Hydrogen would be similarly unfavourable for other technology steps. Switching Petrol vehicles to Hydrogen manufactured from Natural Gas may be a better option. Although Hydrogen IC engines are close to being available today in limited volumes, it is unlikely that they would command significant sales volumes until after 2020 unless there is a significant change in infrastructure policy. Such a change of policy is more appropriate to the Hydrogen Priority route.

The key advancements in technology that make Step 7 possible are:

- **Hydrogen burning IC engine** which is similar to the Petrol (Gasoline) engine but with Hydrogen fuelling equipment, higher compression ratio, high energy spark ignition and a high pressure ratio boosting system in an attempt to get power outputs comparable with Petrol engines as discussed in Appendix C.

- **Hydrogen Storage Systems** which have been assumed to be high-pressure gaseous storage at 300bar. This appears to offer good Hydrogen mass stored for a given package weight and volume. Other storage methods as discussed in Appendix C.

This technology worsens the Step 7 vehicle fuel consumption by 26%. Additional weight is added due to the Hydrogen storage even though the Hydrogen engine compared with the Diesel saves weight. The same is true for cost.

Key Headings Summary for Step 7:

Impacts: (ALL RELATIVE TO THE PREVIOUS STEP)

- Fuel consumption (Well to Wheels g/kmCO_2) +26% to **263** at assumed Euro 7
- **Fuel Consumed 2.27kg/100km Hydrogen**
- Weight (kg) +2.88% to **1428**
- Retail Price (£2002) +0.8% to **20,163** at assumed Euro 7 (estimated range **£18,700 to £22,600**)

Technologies beyond Step 6

- IC Engine burning Hydrogen
- Hydrogen Storage System

Risks:

- H_2 IC engine requires complex aftertreatment to remove NOx from lean combustion and also high pressure ratio boosting systems to achieve power density (although probably carried over from Diesel and Petrol engines)
- H_2 storage is costly however the technical risks are now well understood

Vehicle Attributes:

- Similar to Step 6 – the change of torque curve shape between a Diesel and Hydrogen engine is not likely to impact driveability in either a Series or Parallel Hybrid configuration

Impact on Manufacture:

- The vehicle requires storage of Hydrogen as its only fuel, necessitating a large Hydrogen tank. As with the packaging of larger battery types, this may necessitate fundamental changes in vehicle platform design, and may make the vehicle difficult to manufacture alongside liquid-fuelled vehicles based on the same platform
- Manufacture of durable, crash-safe Hydrogen tanks and fuel systems may be an issue
- Otherwise similar to Step 6

Impact on Infrastructure:

- Supply of Hydrogen required – production, distribution, storage, refuelling – as described in Appendices B and C

Read Across to Other Vehicle Types:

- Technically applicable to most vehicle applications, however, the larger the vehicle the greater the price increase. Hydrogen (as opposed to Petrol or Diesel) as a fuel for IC engines does not particularly favour any vehicle type, except that it may be easier to accommodate storage tanks in trucks, buses and larger cars

Read Across to Other Usage Patterns:

- Similar to Step 6

Degree of Confidence in Analysis:

- Low to Medium, for cost and weight based on technical publications, theoretical calculations and projection of stated parameters to the year 2020. However, the fundamental efficiencies stated are stated with medium to high confidence

Alternative Technologies:

- The Hydrogen engine alternative technology is the Fuel Cell as discussed in future steps

This step gets both the Fuel Cell and the Hydrogen fuel into the market place; however, the considerable worsening of the Well to Wheels CO_2 disqualifies this step under the rules proposed for the Low Carbon route. Please see the alternative steps presented in subsequent sections.

3.7b Step 7b – Parallel Hydrogen Hybrid Internal Combustion Engine with NiMH Battery Vehicle - 2020-2025

Steps 5 to 7 all showed worsening CO_2 performance, due to energy transmission and storage issues of Series Hybrids and Reversible Fuel Cells, added to the poor performance of a Hydrogen engine fuelled from non-renewable Hydrogen. Therefore a number of alternative options have been assessed, in order to seek technologies which offer a genuine improvement on the Step 4 Parallel Hybrid.

The first is the Parallel Hydrogen Hybrid with a NiMH battery (Effectively a Step 4 car fuelled by Hydrogen). This was chosen as the Parallel Hybrid is potentially more efficient that the Series Hybrid and the NiMH battery has higher efficiency than the RFC. Only a brief analysis of this Step is given here. Please see Appendix F for the details.

All data is now referenced from STEP 4, as this was the last plausible step in the Low Carbon Route Map.

Key Headings Summary for Step 7b:

Impacts (ALL RELATIVE TO <u>STEP 4</u>):

- Fuel consumption (Well to Wheels g/kmCO_2) +26.3% to **133** at assumed Euro 7
- **Fuel Consumed: 1.60kg/100km Hydrogen**
- Weight (kg) +2.86% to **1441**
- Retail Price (£2002) +0.89% to **18,184** at assumed Euro 7 (estimated range **£17,600 to £18,800**)

Technologies beyond Step 4

- IC Engine burning Hydrogen
- Hydrogen Storage System

Risks:

- H_2 IC engine requires complex aftertreatment to remove NOx from lean combustion and also high pressure ratio boosting systems to achieve power density (although probably carried over from Diesel and Petrol engines)
- H_2 storage is costly however the technical risks are now well understood

Vehicle Attributes:

- Similar to Step 4.

Impact on Manufacture:

- Similar to Step 7 – impact of Hydrogen tank on vehicle platform

Impact on Infrastructure:

- Similar to Step 4 (Hybrids) and 7 (Hydrogen)

Read Across to Other Vehicle Types:

- Technically applicable to most vehicle applications, however, the larger the vehicle the greater the price increase

Read Across to Other Usage Patterns:

- Very similar to Step 4

Degree of Confidence in Analysis:

- High as for Step 4

Alternative Technologies:

- The Hydrogen engine alternative technology is the Fuel Cell as discussed in future steps

This step offers reasonable Well to Wheels efficiency; however, although it is worse than step 4 it does offer the opportunity to use Hydrogen which could come from lower CO_2 sources than natural gas. For example, if 21% of the Hydrogen used to fuel the vehicle came from zero-CO_2 sources, the well-to-wheels CO_2 would be comparable to Step 4.

3.7c Step 7c – Parallel Diesel Hybrid with Hydrogen APU Vehicle - 2020-2025

A Fuel Cell Auxiliary Power Unit (APU) burning Hydrogen now assists the Diesel Parallel Hybrid of Step 4. This may appear to be an undesirable step, as the vehicle now has three power sources (the Diesel engine, the APU and the battery), and two fuels (Hydrogen and Diesel). However, as a stepping-stone technology it has a number of advantages, and a similar approach is successfully demonstrated in the Hydrogen Priority route (section 4):

- Both Hydrogen and the Fuel Cell are brought to market but with minimum risk - if the Fuel Cell failed or Hydrogen were unavailable the vehicle would still function
- The vehicle has dual fuel capability (as per today's Petrol / LPG cars) with high functionality on Diesel, and limited ZEV capability on Hydrogen
- The APU can power heating and air conditioning systems, overcoming one of the major functionality risks of Hybrids

The APU was specified (arbitrarily) to provide half the energy the vehicle required to drive the cycle (which would enable urban use as a ZEV). APU technology in this power range has mostly been developed for stationary applications, hence there is a shortage of public domain information on low weight technologies. This is reflected in a high weight penalty that may prove pessimistic if APU development is re-focused on this application.

Key Headings Summary for Step 7c:

Impacts (ALL RELATIVE TO STEP 4):
- Fuel consumption (Well to Wheels g/kmCO_2) +0.7% to **105** at assumed Euro 7
- Weight (kg) +8.92% to **1526**
- Retail Price (£2002) +5.45% to **19,007** at assumed Euro 7 (estimated range **£18,300 to £19,800**)

Technologies beyond Step 4
- Solid Oxide Fuel Cell APU at 8kW peak power rating (80kg complete system)
- Hydrogen Storage System

Risks:
- Downsized Diesel engine and Parallel Hybrid system as Step 4.
- H_2 storage is costly however the technical risks are now well understood
- Solid Oxide APU operates at high temperature and there may be start-up issues

Vehicle Attributes:
- Should be the same as Step 4 if there are no significant start-up delays for the APU. Ability to power electrical devices including heating and air-conditioning is restored when the engine is shut off, due to the APU. ZEV range significantly extended
- This is now a dual fuel (Diesel and Hydrogen) vehicle, capable of full performance on Diesel, limited urban use on Hydrogen

Impact on Manufacture:
- Same as Steps 4 and 7, major issue being packaging the APU and its Hydrogen tank

Impact on Infrastructure:
- Same as Steps 4 and 7

Read Across to Other Vehicle Types:
- Technically applicable to most vehicle applications, however, the larger the vehicle the greater the price increase. APUs are likely to be most popular in executive and luxury vehicles where they offer power for heating / air conditioning and “mobile office” functionality

Read Across to Other Usage Patterns:
- Similar to Step 4, but with the further benefit of ZEV potential in urban or heavily congested conditions. In suburban and motorway use, the weight of the APU may create a small (1%) CO_2 penalty

Degree of Confidence in Analysis:

- Medium as there are few references for Solid Oxide APUs and they have not received as much development as automotive PEM Fuel Cells

Alternative Technologies:

- Step 6H from the Hydrogen Priority route although the Well to Wheels efficiency is not as high
- Other Fuel Cell technologies including PEM and Alkali

This step offers very similar Well to Wheels efficiency to Step 4, but with a dual-fuel vehicle operating on Diesel (or Petrol) and Hydrogen. This offers interesting ZEV capability and other functionality. Any level of renewable energy used in making Hydrogen will improve the Well to Wheels CO_2 emissions of this vehicle from Step 4.

3.7d Step 7d – Parallel CNG Hybrid with Hydrogen APU Vehicle - 2020-2025

Step 7d develops Step 7c by changing the engine for CNG. This offers a small improvement in “Well to Wheels” CO_2 as the gain in fuel “Well to Tank” efficiency is offset by the slightly worse Diesel to CNG engine efficiency change. If the baseline were a Petrol engine then there would be more substantial gains. The comparisons between Step 7d (CNG + Hydrogen APU) and Step 7c (Diesel + Hydrogen APU) are also reasonably valid for comparing the same two IC engines without the APU (Step 4 vs. CNG Parallel Hybrid). Appendix C10 gives more information on CNG.

Key Headings Summary for Step 7d:

Impacts (ALL RELATIVE TO STEP 4):

- Fuel consumption (Well to Wheels g/kmCO_2) –2.9% to **102** at assumed Euro 7
- Weight (kg) +6.07% to **148**
- Retail Price (£2002) +4.31% to **18,801** at assumed Euro 7 (estimated range **£18,100 to £19,700**)

Technologies beyond Step 4

- CNG engine (similar to Hydrogen or Petrol engine structure)
- Hydrogen Storage
- Solid Oxide Fuel Cell

Risks:

- CNG IC engine requires complex aftertreatment to remove NOx from lean combustion and also high pressure ratio boosting systems to achieve power density (although probably carried over from Diesel and Petrol engines)
- H_2 storage is costly however the technical risks are now well understood
- Solid Oxide APU operates at high temperature and there may be start-up issues

Vehicle Attributes:

- Should be the similar to as Step 4 and 7c if there are no significant start-up delays

Impact on Manufacture:

- Same as Steps 4 and 7c; CNG storage and fuelling systems offer lower manufacturing risk than Hydrogen

Impact on Infrastructure:

- Same as Steps 4 and 7c, except that CNG refuelling would be required

Read Across to Other Vehicle Types:

- As for step 7c - Technically applicable to most vehicle applications, however, the larger the vehicle the greater the price increase

Read Across to Other Usage Patterns:

- Similar to Step 7c

Degree of Confidence in Analysis:

- Medium as there are few references for Solid Oxide APUs and they have not received as much development as automotive PEM Fuel Cells

Alternative Technologies:

- Step 6H from the Hydrogen Priority route although the Well to Wheels efficiency is not as effective

This step offers similar Well to Wheels efficiency as Step 4 but the fuel is now half Hydrogen, half CNG. This means that any level of renewable energy used in making Hydrogen will improve the Well to Wheels CO_2 emissions of this vehicle from Step 4. However, a significant investment in two infrastructures would be required for this vehicle which would have to happen for other reasons for this to be viable. Perhaps, if the CNG engine had progressed as a replacement for the Petrol engine by this time then this may be a valid step forward for the first use of Hydrogen. However, two sets of high-pressure gas storage tanks may be a little bit off-putting to the owner! The technology may be more viable if an APU fuelled directly by CNG were available, however there is no such technology currently known to Ricardo.

3.8 Step 8 – Fuel Cell Vehicle - 2030

Step 8 replaces the IC engine and the reversible Fuel Cell of step 7 (or the technologies of steps 7b,c,d) with a large Fuel Cell as the main vehicle power unit. As shown in Appendix E, this main Fuel Cell has some level of reversibility so minimising the size of the main system battery. It is envisaged that by 2030, these technologies will be ready for the mass market.

The Fuel Cell technologies and issues are described in Appendix C7. A principal supporting technology is the onboard storage of Hydrogen which, although being the lightest, most energy dense fuel available, it also is one of the least compact requiring high pressure or technologically advanced storage approaches. These are explained in Appendix C8.

The key advancements in technology that make Step 8 possible are:

- **Hydrogen “burning” Fuel Cell,** which is assumed to be a Proton Exchange Membrane (PEM) device specifically adapted for automotive use. The power density for the PEM FC has been extrapolated to 2kW/kg just for the Fuel Cell stack. However, 120kg has been added for the supporting systems such as compressors, fuel control systems, control electronics, thermal systems in addition to the weight of the original vehicle cooling systems and also the pipe work and electrical connections needed for the system. The efficiency has been calculated in two ranges: Firstly with a Fuel Cell of 45% efficiency (part load efficiency over NEDC) and secondly at 65% for future efficiency predictions. Also, the latter efficiency has been combined with the improved electrical system efficiencies as discussed in Section 3.5 above for the Series Hybrid. Thus a range of efficiencies and CO_2 emissions has been calculated, with the lower CO_2 representing what may be achieved with very focussed development.

This technology improves on the (albeit poor) Step 7 vehicle considerably, and can offer an improvement over Step 4 (Diesel Parallel Hybrid). As the Fuel Cell generates electricity directly, it automatically offers an efficiency gain over the IC engined Series Hybrid because the mechanically driven generator efficiency is removed. Between 55 and 72% fuel savings are seen (compared to step 7) compared giving Well to Wheels CO_2 figures of 119 to 74 g/km. 2.8% weight is added due to the Fuel Cell system. Cost decrease is possible from Step 7 as the engine, generator and reversible Fuel Cell is removed. More importantly, the best case figures show a worthwhile improvement over Step 4, the Diesel Parallel Hybrid.

Key Headings Summary for Step 8:

Impacts (ALL RELATIVE TO STEP 4):

- Fuel consumption (Well to Wheels g/km CO_2) – 55 to –72% to **119 to 74** (ZEV)
- **Fuel Consumed: 1.43 to 0.89 kg/100km Hydrogen**
- Weight (kg) +2.8 to **1468**
- Retail Price (£2002) +3.9% to **18,730 (estimated range £17,700 to £20,700)**

Technologies beyond Step 7

- PEM Fuel Cell

Risks:

- Fuel cell system has many risks: precious metal content is very high meaning price is volatile, power density is increasing but support systems such as compressors, thermal, control and electrical systems are almost never reported. These represent real challenges to make the system quiet, efficient, cost effective and packageable in a normal vehicle.
- Hydrogen storage as for previous steps.

Vehicle Attributes:

- The noise from the support systems is usually reported as annoying however this is likely to be solved. It would drive as for a Series Hybrid. There may be start-up delay issues depending on the battery mass used to compensate for cell start-up. This is minimised with Hydrogen fuelled Fuel Cells, would be worse with reformer-based systems (which have not been analysed here)

Impact on Manufacture:

- Large quantities of precious metals, Hydrogen fuelling system would require high quality manufacturing techniques to ensure leak free operation. Modularisation (as currently achieved) would have to be replaced by integration to ensure all the sub-systems could be miniaturised to ensure packaging within a normal passenger car powertrain volume
- A Fuel Cell vehicle in significant production volume may be able to share a platform with Step 4 – 7d vehicles, depending on the provision of package space for Hydrogen storage

Impact on Infrastructure:

- Same as Step 7

Read Across to Other Vehicle Types:

- Technically applicable to most vehicle applications, however, the larger the vehicle the greater the price increase. This technology is very similar in principle to that being used now on the pilot fleet of DaimlerChrysler Citaro Fuel Cell buses in various cities

Read Across to Other Usage Patterns:

- Greatest benefits in urban usage, where the excellent part-load efficiency of the Fuel Cell plus a degree of Hybrid functionality (re-generative braking) are theoretically capable of delivering the optimum powertrain. Efficient motorway operation requires a generously sized Fuel Cell (to avoid poor efficiencies near full load) and efficient electrical power transmission

Degree of Confidence in Analysis:

- Low to Medium, for cost and weight based on technical publications, theoretical calculations and projection of stated parameters to the year 2030. However, the fundamental efficiencies stated are medium confidence hence a range being given

Alternative Technologies:

- There are no direct alternatives at this time that can turn Hydrogen directly into electricity without combustion and with such high potential efficiency. However, within the Fuel Cell field, other technologies such as high-temperature solid oxide types may challenge the PEM in this type of application
- Reformers may be used to produce Hydrogen on the vehicle from liquid fuels. This Hydrogen is used to supply the Fuel Cell, giving a Fuel Cell vehicle that operates on liquid fuels. Current demonstration units are mostly fuelled by Methanol, devices using Petrol (Gasoline) are at the laboratory stage. However, the process of fuel reforming is inefficient, and produces CO_2. Reformers are seen as a bridging technology to enable Fuel Cell vehicles to enter the market before the Hydrogen infrastructure is available. However, the Reformer unit adds weight and cost, and may not warm up sufficiently fast for cold start use. The Ricardo view is that Hybrid technology offers an alternative bridge to the Hydrogen / Fuel Cell destination, as demonstrated by the Low Carbon and Hydrogen Priority routes shown here

3.9 Low Carbon Road Map Discussion

Key points

The following general points emerge from the Low Carbon road map:

- By 2012, the Parallel Diesel Hybrid (Step 4) is a significant (38%) step forward for Well to Wheels CO_2 emissions reduction compared to Step 0. Arriving there via Steps 1-3 offers a drumbeat of incremental improvements, each feeding technology into the next and enabling high risk to be avoided. There is a high degree of confidence in the analysis of this point, including the CO_2 performance and prospective consumer cost, based, as it is, on public domain test data, vehicles in production (such as the Honda Insight and Toyota Prius) and Ricardo knowledge of technologies which may be candidates for production

- The CO_2 performance achieved with Step 4 and a Diesel engine is not likely to be improved on directly with Hydrogen or CNG technologies. The Fuel Cell (Step 8) performance exceeds Step 4 only on the high efficiency assumption, and is on a par with Step 4 on a mid-range assumption – see figure 3.1 below

- There is no carbon incentive for a shift to Hydrogen, and no user or global CO_2 benefits, until a high efficiency Fuel Cell vehicle is achieved (estimated here as being more likely to be achieved by 2030, rather than by 2020)

- There is a low to medium degree of confidence in the cost and weight estimates for Steps 5 to 8 (Fuel cell) and a medium degree of confidence in the fundamental efficiencies.

- Steps 5 to 7 could have value to car manufacturers in developing technology towards future Fuel Cell vehicles. But these steps do not improve CO_2 performance (sometimes the reverse), they do not offer material consumer benefits, and they have a higher cost. Companies may develop these models as part of their technical development programmes – but may choose not put them on the market

- Instead, the most attractive route for progress beyond Step 4 appears to be increasing the penetration of this technology from “best in class” (5% of the fleet) toward total saturation. The emergence of Hydrogen Fuel Cell APUs, and use of CNG and Hydrogen IC engines, are possible technologies to act as bridges towards the Fuel Cell vehicle. If the Fuel Cell vehicle does not succeed, all of these technologies are environmentally valid in their own right

Detailed discussion

The first four steps of this evolution are based on known technology that starts to become cost effective, practical and accepted by the market place during this period. These have a relatively small impact on the driving experience, offer improved Well to Wheels efficiency (over 38% improvement to the baseline vehicle by Step 4) and do not significantly affect the existing fuelling infrastructure. Only the vehicle service and maybe vehicle sales would be affected with new technology introduction but this would be relatively easy to manage (as has already been achieved by Toyota and Honda, albeit in lower volume).

Beyond Step 4, the way forward is more complex as the technologies that seem to assist the introduction of the Fuel Cell in the future reduce vehicle efficiency. The Series Hybrid and the reversible Fuel Cell do not offer improvements in vehicle Well to Wheels CO_2 and so are unlikely to be a “natural evolution” even though the technologies will be useful in the future.

Step 7 sees the first introduction of Hydrogen usage by 2025 for motive power, however, this worsens vehicle efficiency due to the Well to Tank efficiency of producing Hydrogen from natural gas and the loss in thermal efficiency of the

Hydrogen engine compared to the Diesel. Therefore, the additional Steps 7b, c, and d were added. Of these, Step 7c, the Diesel Parallel Hybrid with Hydrogen APU providing half of the cycle average power, seems to offer acceptable Well to Wheels efficiency. This burns Hydrogen, so well to wheels CO_2 emission can be influenced by the proportion of Hydrogen from renewable sources and it still uses traditional fuel so would be easier to accept initially in the market place. Also, it introduces the Fuel Cell to the market. However, the Solid Oxide FC technology may not be the technology adopted by the "Step 8" Fuel Cell (assumed to be PEM, although SOFC may be competitive), it would be bulky to package and would require a small Hydrogen storage tank. It may also be possible to run the Fuel Cell APU directly on Diesel by this date without a reformer (using high temperature SOFC technology) – while this would be more convenient, it would remove the dual-fuel functionality of the vehicle and its ability to promote a fledgling Hydrogen infrastructure. The vehicle would also be able to run without Hydrogen albeit at reduced performance so reducing the infrastructure limitations at that date. Finally, it is worth pointing out that there is OEM activity in this field of study today, particularly for the added vehicle functionality the Fuel Cell APU offers. This includes air conditioning when the engine is off, more electrical power for gadgets and (when coupled with a Petrol engine instead of Diesel) higher vehicle fuel efficiencies.

It is difficult to suggest that Step 7c as detailed (Diesel Parallel Hybrid plus Hydrogen APU) could be an attractive technology before 2020-25, due to its (current) high cost and weight. This leaves a large time-gap between 2012 (Step 4) and 2020-25 (Step 7c). In practise it is likely that this period of time will be filled by:

- Developments of the Parallel Hybrid and its components (Diesel or Petrol engine, Motors, Batteries) to improve efficiency
- Increased penetration of Mild and Parallel Hybrid technology towards 100% of the market (the assumption for Step 4 at 2012 is circa 5% penetration)
- Earlier introduction of Hydrogen, Diesel or Petrol APUs at low power levels to provide electrical energy. Then, the APU will burn Hydrogen and then eventually, by 2025, support the motive power of the vehicle. This is slightly closer in route to the Hydrogen Priority road map, which is discussed next.

Step 7d replaces the Diesel engine in 7c with CNG. This fuel has good Well to Tank efficiency and reasonable engine thermal efficiency. However, for such a small gain over the Diesel engine, it is difficult to imagine the infrastructure growing. If CNG is considered a replacement for the Petrol engine then there would be a worthwhile gain. CNG is discussed in Appendix C10.

The impact the Low Carbon road map has had on Well to Wheels CO_2 vs. time is shown in Figure 3.1 below which has been explained above:

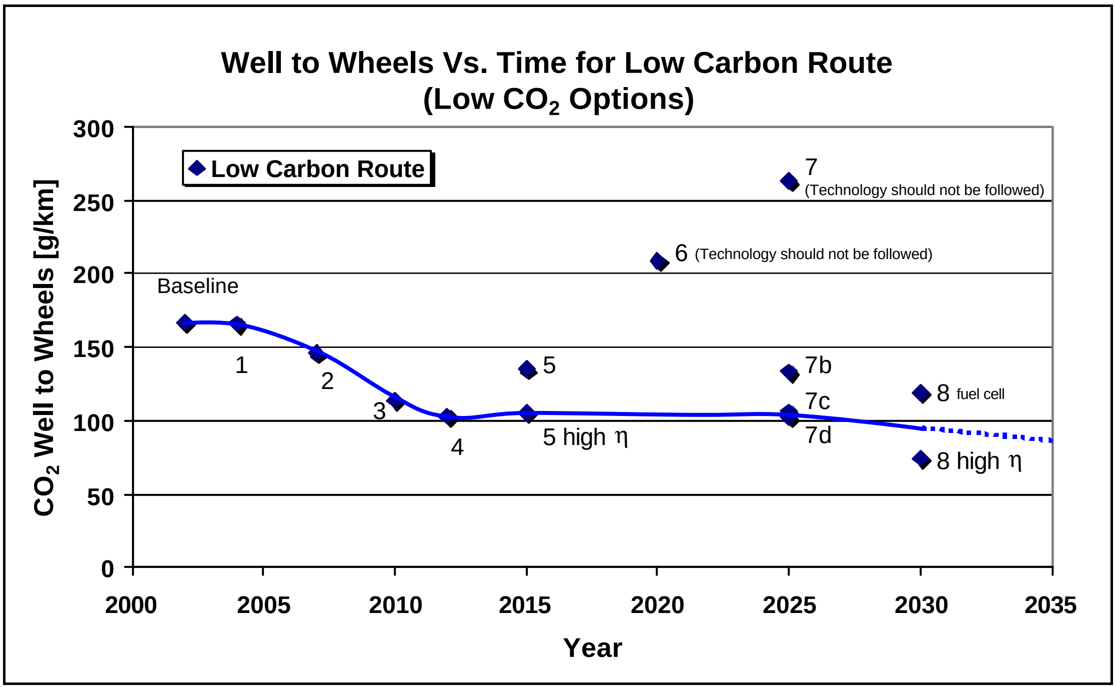


Figure 3.1: Well to Wheels Vs. Time for Low Carbon Route

Figure 3.2 shows the impact the new technologies have had on weight. It can be seen that there is a marked increase at Step 4 where there is a growth in the amount of batteries and electrical machines added to the vehicle. Step 7c adds an APU and a Hydrogen storage tank to Step 4, which explains the large gain in weight there. Finally, the Fuel Cell vehicle deletes quite a lot of heavy technology from Step 4 and 7c resulting in a future vehicle weight of about 1,470kg; 11% heavier than the baseline vehicle.

In this analysis, the increase in weight has not been factored into the fuel consumption calculations. Examination of weight versus fuel economy trends shows that, as a rule, a 10% increase in mass gives rise to a 5% increase in fuel consumption. However, this data includes a number of unwanted effects such as:

- Performance – larger, heavier cars having higher performance engines, often to the detriment of fuel economy)
- Aerodynamic effects – heavier vehicles being physically larger with more frontal area

Removing these factors (for this study, the candidate vehicle keeps constant performance and frontal area) gives less sensitivity to weight perhaps 2-3% increase in fuel consumption per 10% greater weight. Add to this the beneficial effect of regenerative braking (heavily utilised in most of the heavier steps), the impact of weight is further nullified. The greatest error from the “no weight correction” assumption is believed to be less than 3% (for step 7c), which is smaller than other likely errors in forecasting the efficiency of technologies at distant future dates.

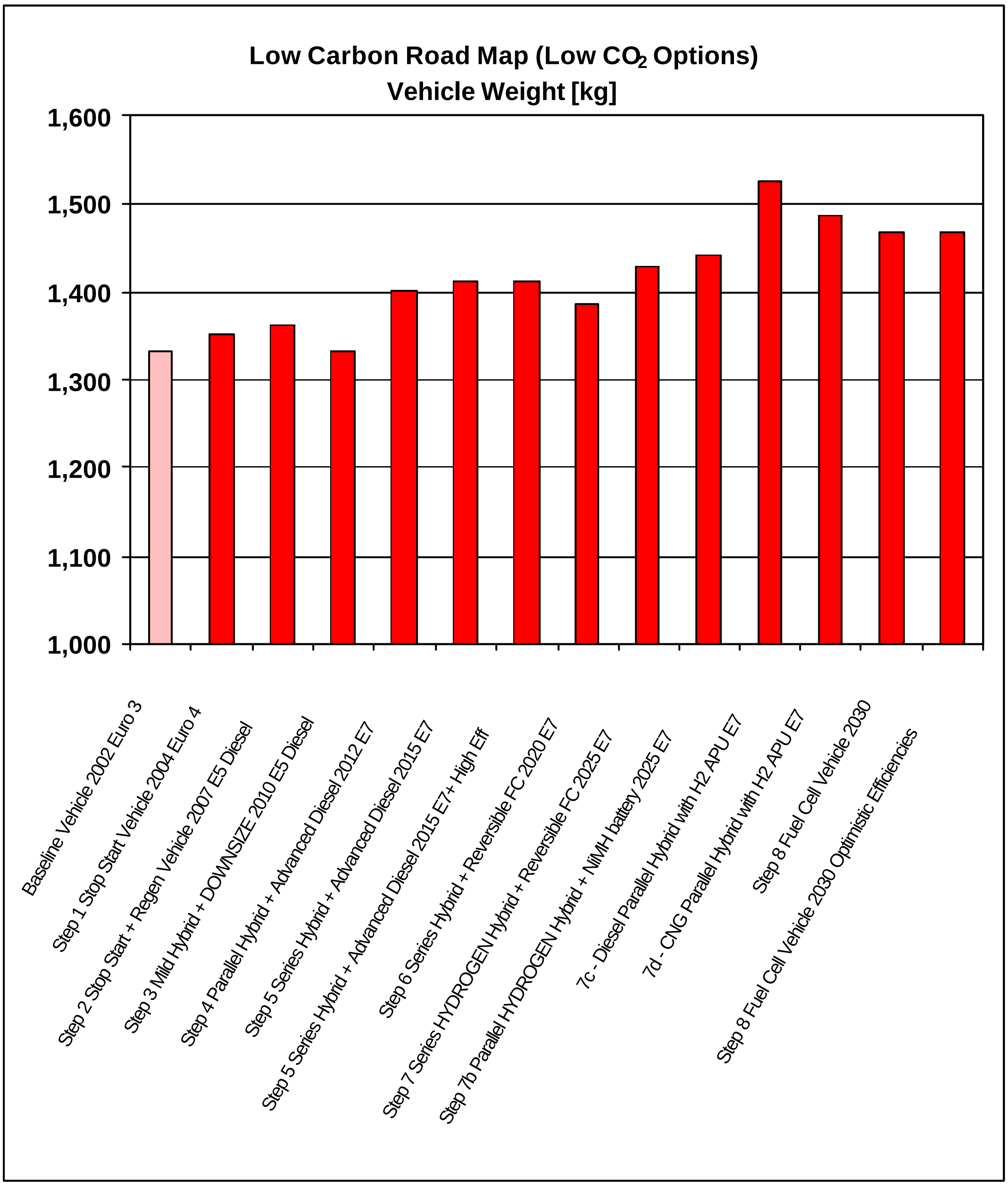


Figure 3.2: Low Carbon Road Map Vehicle Weight vs. Technology Step (Low CO_2 Options NOT Low Emissions Options)

Finally, the retail price is compared with each technology step as shown in Figure 3.3 below for the lowest emissions legislation. There is a high degree of confidence in costs up to Step 5. Thereafter, there is low to medium degree of confidence, relating to the costs of Fuel Cell units and Hydrogen storage tanks:

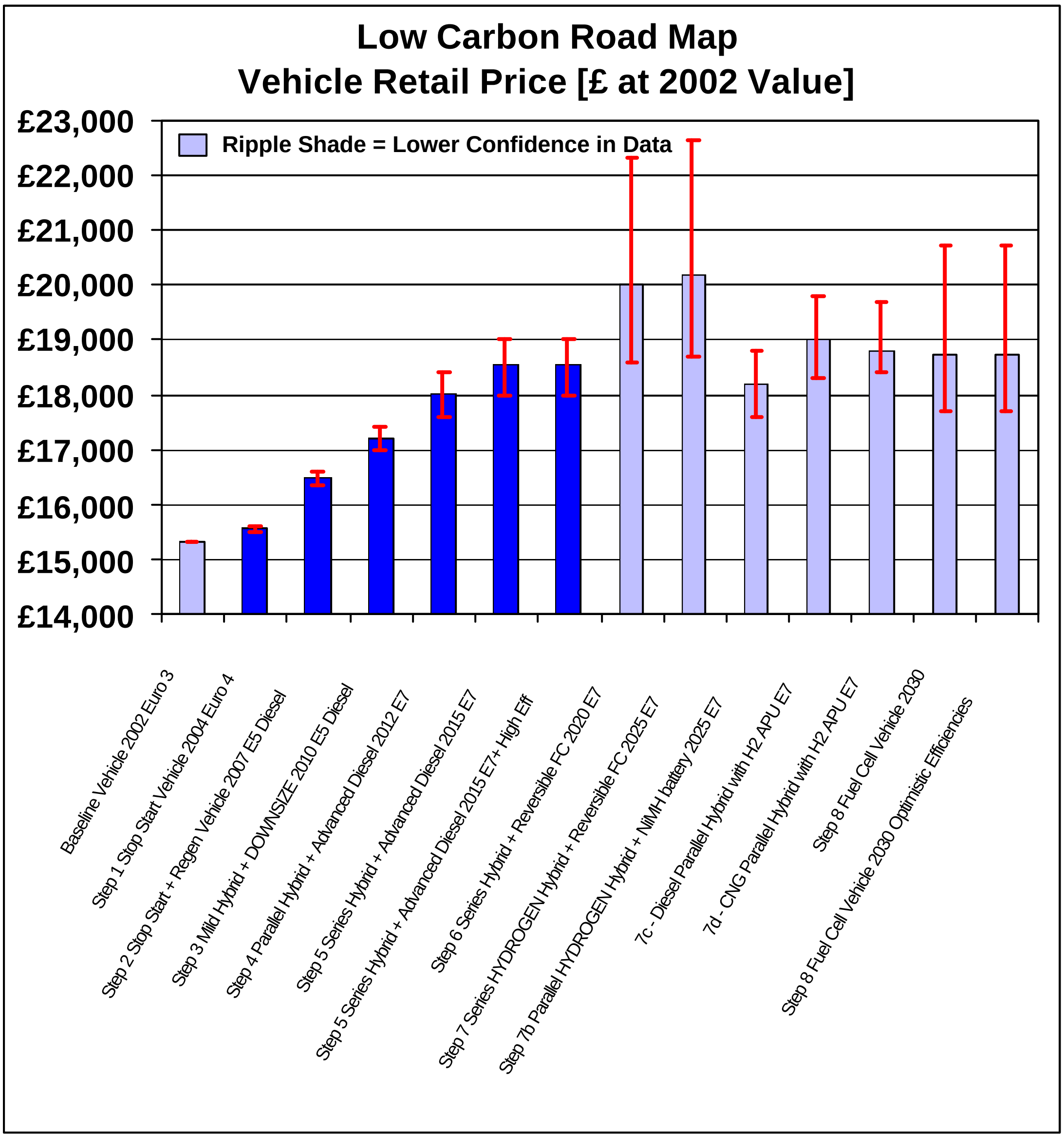


Figure 3.3: Low Carbon Road Map Vehicle Retail Price vs. Technology Step (Low CO_2 Options NOT Low Emissions Options)

This indicates initially that improvements in CO_2 are linked to corresponding price increases until the reversible Fuel Cell is used. If Steps 6 and 7 are ignored then it can be seen that the cost may actually reduce going from Step 7c to the Fuel Cell vehicle due to the deletion of expensive (and heavy) technologies in Step 7 such as the generator, the Diesel engine and transmission. This gives the opportunity for the mass-produced Fuel Cell vehicle to be a reality.

The key risks (some of which constitute technology gaps) that are present in the Low Carbon road map are:

- Battery technologies for cost, low temperature operation, efficiency and life
- Resolution of health concerns relating to Diesel particulate emissions, and public acceptance thereof
- Customer acceptance of stop-start operation and its implication for heating and air-conditioning

- Customer acceptance of Hybrid vehicle driving characteristics, such as the different relationship between engine sound and vehicle speed
- Ability to accommodate successive steps into existing vehicle platforms which are likely to be shared with more conventional vehicles

Beyond 2020, the following risks also arise for Hydrogen and Fuel Cell applications:

- Need for an infrastructure for Hydrogen, which is complex and expensive
- Future Fuel Cell cost effective manufacture including the cost and availability of precious metals used in the Fuel Cell stack (as either an APU or main power unit)
- Cost and space effective, safe Hydrogen storage
- Improvements in the efficiencies of the supporting systems such as the motors, electronics, thermal and fuelling systems
- Customer acceptance of fuel-cell operating noise quality
- Customer acceptance of high-pressure gas storage
- Acceptance of compressed gases by car-parks, Channel Tunnel and other amenities which currently limit their use

These risks are being addressed by development programs by OEMs, suppliers and to some extent governments around the world. It is expected that, with focussed engineering effort, they can be addressed within the timescales suggested. It is worth noting that a Step 4 vehicle with a Petrol engine, the Toyota Prius, exists today.

Government incentives are discussed in Appendix G and UK involvement in these technologies is covered in Appendix D.

3.10 Alternative Technology Developments for the Low Carbon Road Map

There are a number of alternative technologies that are likely to be significant in the realisation of the Low Carbon evolution:

- Use of Petrol engines
- New developments in Engines and ancillary technologies
- Transmissions (Appendix C6)
- Electrical systems (Appendices C1,2 and 3) and alternatives

3.10.1 Petrol Engines

Diesel engines have now captured 40% of the European market, and many predictions indicate that this figure will rise to over 50% by the end of the decade. However, the refining process by which crude oil is turned into pump fuels dictates that, with current refining technology, indefinite rises in the penetration of Diesel passenger cars may be unsustainable. Added to this, Diesel passenger cars have yet to prove successful in major markets outside Europe.

Petrol engine technology is therefore highly valid in the context of a global Low Carbon evolution. The key Hybridisation technologies described are equally applicable to Petrol engines, with similar relative benefits. Indeed it is possible that identical components (especially batteries and power electronics) could be used for both Petrol and Diesel variants.

Petrol engines with current technology cannot equal the Diesel in terms of CO_2. However it is possible that a Petrol Hybrid could become seen as a mainstream alternative to a non-Hybrid Diesel engine, offering similar CO_2 and cost. Currently the Diesel engine is the cheaper option, but cost reduction of Hybrid technology due to rising volume, combined with the possible rising cost of Diesel emission control, could bring the two technologies closer. In practise a mix of the two is likely, driven by manufacturing logistics and customer preference.

3.10.2 Developments in Engine and Ancillary Technology

Numerous developments in engine technology are likely to be seen over the period of the Low Carbon evolution. These include:

- **Downsizing**, to enable reduced CO_2 from lower weight and friction and higher thermal efficiency. This is a technology that is equally applicable to Petrol or Diesel engines, and is usually achieved by **turbocharging** or **supercharging.** Downsized engines tend to suffer poor driveability due to “turbo-lag”, and Hybridisation (as per Steps 2-3) is a means of addressing this. **Electrically assisted boosting**, where electric power is used to overcome turbo-lag, is another technology likely to be successful in the next decade
- **Compact, light weight construction** is a means of countering the bulk and weight of Hybrid systems. Increasing use of aluminium alloys, plastics and specialised coatings are current trends which are likely to continue
- **Variable Valve Actuation** is a promising new technology for Petrol engines, enabling typically 8% fuel economy improvement by elimination of the throttle. The BMW “Valvetronic” engine manufactured at Hams Hall, UK uses this technology. **Cylinder Disablement** (“Displacement on Demand”) is a cost-effective system that is most applicable to six and eight cylinder engines. After 2010, **cam-less** engines using electro-magnetic or electro-hydraulic valve actuation could become a production reality – this technology is currently at demonstration stage
- **Gasoline Direct Injection** is an alternative improving technology for Petrol engines. In lean-burn form it offers a similar 8% typical fuel consumption improvement, but requires use of a Lean NOx Trap (LNT) and low sulphur fuel. Mitsubishi, Peugeot, VW and others have this technology in production. Next generation products include turbocharging and **Lean Boosted DI**, the latter offering CO_2 approaching that of the Diesel engine. It is likely that all but the smallest, cheapest Petrol engines will use either VVA or GDI by circa 2015
- **Clean combustion** is a goal being pursued for all engine types. The most promising technology, known as Homogeneous Charge Compression Ignition (**HCCI**), or Controlled Auto Ignition (**CAI**), is at the laboratory stage and potentially offers low NOx and Particulate emissions. Application to Petrol engines is likely to require both Direct Injection and VVA. For Diesel engines, the next generation of **Piezo-Electric Common Rail Injector** is a key enabler
- **Electric ancillaries**, including water pumps, brake booster pumps, power steering and air conditioning replace the conventional belt-driven systems. The advantages are greater control flexibility, the ability to package the items more efficiently, and the ability to run them from battery power with the engine stopped. This latter advantage is a good fit with Hybridisation, because it enables **climate control** systems to run (within battery

capabilities) during **stop-start**. The availability of electricity from the Hybrid system is also an important enabler. However, there are alternative technologies which retain belt-drive, including **variable speed** ancillary drives, and the use of the integrated starter-alternator to drive **a de-clutched belt** and its ancillaries with the engine stopped (as on the Japanese-market Toyota Crown THS-M)

3.10.3 Transmission Technologies

Apart from the addition of extra speeds and a few (albeit important) design details, conventional manual and automatic transmissions have changed little for almost 50 years. However, this situation is likely to change rapidly over the period of the Low Carbon evolution. These technologies are described more fully in appendix C6, highlights are:

- **Continuously Variable Transmissions** (CVT) have been in use for over twenty years but are now becoming suited to larger vehicles. They offer superior fuel economy (by circa 10%) to a conventional automatic transmission, and with the benefit of the latest control technology they offer a good driving experience. The Toyota Prius uses a CVT transmission, it is an option on the Honda Insight (but on the latter, the manual version has better fuel economy). **Infinitely Variable Transmissions** (IVT) are similar technology with greater ratio range and ability to handle high torque, and the British Torotrak is one example
- **Automated Manual Transmissions** (AMT) aim to offer the mechanical efficiency of a manual gearbox, but with the convenience of an Automatic, and the ability to take gear selection away from the driver for better fuel economy. For this latter reason an AMT is used on the most economical "3l/100km" VW Lupo. These devices operate by robotising the clutch and gear-shift of a conventional device – relatively simple to execute but driver acceptance is poor due to interruption of drive outside their control. The **Dual Clutch Transmission** (DCT) overcomes this, at higher cost, and has the potential to deliver automatic-transmission functionality with fuel economy perhaps better than the Manual unit. DCT and CVT transmissions appear to offer good market potential for Step 1-4 of the Low Carbon evolution

3.10.4 Electrical Systems and their Alternatives

There are many variations in the detail of possible future electrical system technology, as described in Appendix C1-C3, highlights being:

- Motor type: Induction, Permanent Magnet, and Switched Reluctance
- Voltage level: 42v, High Voltage
- Semiconductor technology: MOSFET, IGBT
- Battery type: Lead Acid, Nickel Metal Hydride, Lithium-Ion, Ultra capacitor

It is likely that more than one of each set of options will become successful, due to the ownership of differing intellectual property by competing suppliers. The choice of technology (within competing sets of technologies that offer similar capability) does not have a major impact on the cost or CO_2 benefits described in the Low Carbon evolution.

Of greatest significance is the issue of batteries and energy storage. Critical factors for the technology that emerges as successful are:

- Durability
- Cost
- Operability over a wide range of temperatures
- Ability to accept high charge / discharge rates
- Low weight and small, flexible package size

Many alternatives to the battery as an energy store have been proposed (Appendix C). Of these, **hydraulic launch assist** is currently attracting the most interest. This technology uses a small hydraulic pump/motor to store and release energy from a hydraulic pressure accumulator, thus achieving the functionality of Steps 2-3. Some sources claim lower cost (yet to be convincingly proven), but this technology does not offer a way forward to further Hybridisation, does not help to enable the Fuel Cell vehicle, and does not offer added electrical functionality. Production of this type of system is a promising possibility but as it does not fit with an evolutionary route it has not been studied further here.

4 HYDROGEN PRIORITY EVOLUTION

As described in Appendix E, any policy decision to pursue a Hydrogen Priority route is unlikely to influence the technology sold in vehicles until at least 2008, therefore, this is the starting point for the first Hydrogen-burning vehicle. It is expected that the Hydrogen would be produced from Natural Gas at this time. Looking at the *Low Carbon* route map, it can be seen that by 2008, the Step 2 vehicle would become the baseline for the Hydrogen Priority road map. This is the starting point taken for the subsequent analysis and the next Hydrogen Priority scenario is called Step 3H.

4.1 Step 3H – Hydrogen IC engine with Stop Start + Regenerative Braking - 2008

Although Fuel Cell vehicles using Hydrogen as a fuel will be on sale from 2003-4, these will be sold in very low volumes (initially a few tens of vehicles) and at a high loss to the manufacturer, in order to gain field experience. The business case for these vehicles is not comparable to the Toyota Prius and Honda Insight Hybrids, which are now approaching the point of manufacturing break-even, and constituted a far lower risk at time of introduction.

Therefore the Hydrogen Priority evolution is likely to start with a Hydrogen IC engine. The Hydrogen engine operates like a Petrol (Gasoline) engine using spark ignition. However, the differences in combustion requirements of Hydrogen limit the power output of the engine so a high degree of turbocharging is required, as described in Appendix C5, to obtain comparable engine ratings. This limits the ultimate downsizing potential for the Hydrogen burning engine and so it is probably best seen as an interim technology to allow the use of Hydrogen in transportation at the minimum cost rather than a high efficiency powertrain. NOx emissions are also a considerable problem that requires the use of expensive Lean NOx Traps as previously described.

Step 3H replaces the Diesel engine used in Step 2 of the low carbon route with a Hydrogen engine of the same power output. The stop-start and launch functions are used to minimise fuel consumption and so reduce Well to Wheels CO_2 emissions.

The key advancements in technology are as for Step 2 (Low Carbon) with the addition of:

- **Hydrogen burning IC engine** which is similar to the Petrol engine but with Hydrogen fuelling equipment, higher compression ratio, high energy spark ignition and a high pressure ratio boosting system in an attempt to get power outputs comparable with Petrol engines as discussed in Appendix C
- **Hydrogen Storage Systems** which have been assumed to be high-pressure gaseous storage at 300bar. This appears to offer good Hydrogen mass stored for a given package weight and volume. At this time it is likely that Hydrogen would be stored as a second fuel in a dial-fuel system. Other storage methods as discussed in Appendix C

This technology worsens the Step 3H well-to-wheels CO_2 by 29.5% compared with the Step 2 Low Carbon vehicle due to the poorer Well to Tank efficiency for Hydrogen and the lower thermal efficiency of the Hydrogen engine compared with the Diesel engine of Step 2. Additional weight is added due to the Hydrogen storage even though the Hydrogen engine compared with the Diesel saves weight. The same is true for cost.

Key Headings Summary for Step 3H:

Impacts (relative to Step 2):

- Fuel consumption (Well to Wheels g/kmCO_2) +29.5% to **189** at assumed Euro 5
- **Fuel Consumed: 2.27kg/100km Hydrogen**
- Weight (kg) +2.88% to **1411**
- Retail Price (£2002) +0.8% to **16,586** at Euro 5 (estimated range **£16,400 to £16,800**)

Technologies beyond Step 2 (Low Carbon)

- IC Engine burning Hydrogen
- Hydrogen Storage System

Risks:

- Hydrogen IC engine requires complex aftertreatment to remove NOx from lean combustion and also high pressure ratio boosting systems to achieve power density (although probably carried over from Diesel and Petrol engines)
- Hydrogen storage is costly however the technical risks are now well understood

Vehicle Attributes:

- Will be similar to Step 2 (LC) if the engine is specified correctly. Stop-start will be the same, however, engine noise will probably be lower for Step 3H. For dual-fuel conversions the Hydrogen tank would intrude significantly on luggage space and may prevent the use of folding rear seats to enable carrying of large loads

Impact on Manufacture:

- Same as Step 7, however as this step is proposed considerably earlier, the need for a bespoke platform architecture to accommodate a Hydrogen tank would be a major issue. Because of this, initial vehicles are likely to be dual-fuel with limited Hydrogen range

Impact on Infrastructure:

- A significant Hydrogen infrastructure would have to be available, especially for a Hydrogen-only vehicle, a factor that could limit sales unless addressed. Also, a “standard” for Hydrogen storage and refuelling would have to be in place, otherwise many different types of refuelling systems would have to be made available, which is costly and so unlikely to offer growth. Also, refuelling is no longer a “DIY” job. It is expected that for safety reasons this would have to be fully automated adding further to the cost of infrastructure introduction.

Read Across to Other Vehicle Types:

- Technically applicable to most vehicle applications, however, the larger the vehicle the greater the price increase to maintain the vehicle range due to Hydrogen storage cost issues.

Read Across to Other Usage Patterns:

- As per the equivalent Low Carbon step 2

Degree of Confidence in Analysis:

- Medium, for cost and weight based on technical publications, theoretical calculations and projection of stated parameters. However, the fundamental efficiencies stated are stated with high confidence.

Alternative Technologies:

- The Hydrogen engine alternative technology is the Fuel Cell as discussed in future steps
- Liquid Hydrogen storage is a significant alternative technology

This step forces the use of Hydrogen fuel into the market place with a vehicle that to own would be similar to a conventional vehicle; however, the considerable worsening of the Well to Wheels CO_2 indicates that its adoption is only logical as part of a long-term strategy. For this reason, it is only viable in a forced Priority type road map.

4.2 Step 4H – Hydrogen IC Engine Mild Hybrid Vehicle - 2010

This vehicle is developed as from Step 2 low carbon to Step 3 low carbon by the addition of increased electrical system capability and downsized engine technology. The use of a spark ignited Hydrogen engine (downsized) and Hydrogen storage remain.

The key advancements in technology from Step 3H that make Step 4H possible are:

- **42V Crankshaft Mounted Starter/motor/generator** electrical machine will probably have permanent magnets to give high power density and a light weight system, rapid engine starting and give over 100Nm torque assistance at low engine speeds. Also, 10kW of regenerative braking which can improve fuel efficiency further
- **Nickel Metal Hydride battery** for good energy and power density, the ability to absorb and give back regenerative energy efficiently and with long battery life
- **Highly Downsized engine** to reduce engine friction as a percentage output at part load so significantly improving the part load vehicle fuel economy. Up-rating ensures peak vehicle performance is maintained

These technologies improve the Step 4H vehicle by 18.5% at Euro 5 emissions levels from Step 3H with a 1.3% reduction in weight given by the downsized engine. However the larger and higher tech electrical machine, power electronics and battery increase the price by 4.5%.

Key Headings Summary for Step 4H:

Impacts (relative to Step 3H):

- Fuel consumption (Well to Wheels g/kmCO_2) –18.5% to **154** at assumed Euro 5
- **Fuel Consumed: 1.85kg/100km Hydrogen**
- Weight ([kg]) –1.28% to **1393** at assumed Euro 5
- Retail Price ([£2002]) +4.47% to **17,328** at assumed Euro 5 (estimated range **£17,000 to £17,600**)

Technologies beyond Step 3H:

- 42V starter/motor/generator – crankshaft mounted, permanent magnet with dual 42V / 12V electrical architecture system
- NiMH battery
- Highly downsized Hydrogen engine (1.8 litre to 1.2 litre) with ratings over 63 kW/litre

Risks beyond Step 3H:

- As per Low Carbon step 3

Vehicle Attributes beyond Step 3H:

- Similar to Low Carbon step 3. Slight change in torque curve shape due to downsized engine and electrical assistance – with good specification, this can be improved from the base engine. Also, the acceleration feel of the vehicle can now be susceptible to the state of charge of the battery and so is variable which can lead to customer acceptance problems.

Impact on Manufacture beyond Step 3H:

- As per Low Carbon step 3, and step 2H. Key issues are the impact of Hydrogen storage on vehicle architecture, and NiMH battery manufacture

Impact on Infrastructure beyond Step 3H:

- Issues relating to the availability of Hydrogen fuel will become more important if Hydrogen-only vehicles are beginning to emerge
- Workshop personnel will require training in the new technologies although these are mostly maintenance free

Read Across to Other Vehicle Types:

- Technically applicable to engine sizes below 2 litres with this technology but with larger motor and battery sizes it is applicable to most vehicles. Engine downsizing is applicable to most applications if customers accept owning a smaller engine

Read Across to Other Usage Patterns:

- As per the equivalent Low Carbon step 3

Degree of Confidence in Analysis:

- High from Step 3H to 4H, based on real world experience and engineering programmes in the Hybrid vehicle area

Alternative Technologies:

- Some belt drive systems may offer the power ratings at lower cost. Cylinder deactivation instead of downsizing to improve engine operating efficiencies
- The NiMH battery can be replaced by lead acid batteries (to save cost) and with the addition of “ultra-capacitors” to store the regenerative braking power. However, this requires additional power electronics and the added cost and weight of the ultra-capacitors

4.3 Step 5H – Hydrogen IC Engine Mild Hybrid Vehicle with small APU - 2012

An auxiliary power unit (APU) is added to this vehicle for two reasons; first to allow the use of Hydrogen Fuel Cell in a non-sensitive way and secondly to reduce the Well to Wheels CO_2 impact of the vehicle. This makes sense in this type of vehicle where there is a Hydrogen store already for the IC engine, provided that the package space is available and cost can be justified. The APU has been configured to generate the electrical loads that are present during a drive cycle which are typically 750W. This power has therefore been subtracted from the engine average load. Step 4H already provides efficient electricity generation so most of the savings come from the good efficiency of the APU at generating electricity (40% overall) rather than replacing a poor efficiency alternator.

The key advancements in technology from Step 4H that make Step 5H possible are:

- **Hydrogen Burning APU** would probably be a self-contained unit consisting of a solid oxide Fuel Cell and the necessary thermal and control systems. It would be used to provide 750W over the drive cycle and so remove this average load from the engine. As this is not a particularly integrated technology with the vehicle at this stage there is an efficiency and weight penalty at this date.

This technology improves the Step 5H vehicle by 2.3% at Euro 6 emissions levels with nearly a 3% increase in weight caused by the APU system. Cost is increased by 2.3%.

Key Headings Summary for Step 5H:

Impacts (relative to Step 4H):

- Fuel consumption (Well to Wheels g/kmCO_2) –2.3% to **151** at assumed Euro 6
- **Fuel Consumed: 1.81kg/100km Hydrogen**
- Weight (kg) +2.87% to **1433**
- Retail Price (£2002) +2.31% to **17,728** (estimated range **£17,400 to £18,200**)

Technologies beyond Step 4H:

- 4kW Solid Oxide APU operating continuously at 750W over the drive cycle

Risks beyond Step 4H:

- The solid oxide Fuel Cell operates at high temperatures and would constitute a crash risk that would need careful engineering. The device is expected to be reliable as there are few moving parts.

Vehicle Attributes beyond Step 4H:

- No change in driving attributes however there would be considerably more electrical power available in the vehicle giving added functionality to the driver such as a fully functioning office, and climate control with the engine shut down (although 750W is not sufficient for peak loads). APUs are being pursued by large vehicle manufacturers now for this reason (but not as a supplement to engine power as proposed here). The APU would intrude upon luggage space.

Impact on Manufacture beyond Step 4H:

- There are large quantities of precious metals in Fuel Cells, an issue which would require consideration for mass production volumes
- Accommodation of a Hydrogen tank and an APU without serious intrusion on luggage space would probably require significant re-design of the vehicle platform. This will be hard to justify if conventional Petrol and Diesel variants are co-produced on the same platform

Impact on Infrastructure beyond Step 4H:

- Workshop technicians would require training for APU technologies
- Hydrogen infrastructure has to be abundant by this step as functionality depends on it – dual fuel plus APU is likely to be unacceptable for luggage space

Read Across to Other Vehicle Types:

- Technically applicable to all sizes but most likely to appear in classes D and above to provide mobile office type power availability

Read Across to Other Usage Patterns:

- As per the equivalent Low Carbon step 3, but the APU functionality is at its best in heavy urban traffic

Degree of Confidence in Analysis:

- Medium as there are limited references for this technology in this application

Alternative Technologies:

- Other internal or external combustion engines can provide this role however, the Fuel Cell APU is unique to be able to generate electricity directly from fuel and so offers efficiency benefits

4.4 Step 6H – Hydrogen IC engine Parallel Hybrid Vehicle with 8kW APU - 2015

Step 5H is developed to Step 6H by increasing the power of the APU to 8kW and using it to supply half the motive power for the vehicle (2.85kW). The powertrain is also upgraded to a Parallel Hybrid (as per Low Carbon step 4) burning Hydrogen in a downsized engine. This is similar in concept to the Step 4 Low Carbon vehicle. The objective of this step is to considerably improve the fuel efficiency and to increase the Fuel Cell contribution to the vehicle motive power.

The key advancements in technology from Step 5H that make Step 6H possible are:

- **Hydrogen Burning APU at 8kW** which would probably be a self-contained unit consisting of a solid oxide Fuel Cell and the necessary thermal and control systems. It would be used to provide 2.85kW electrical power over the drive cycle, which is used via the Hybrid electric drivetrain. (Note, being an 8kW unit it could in fact power the vehicle completely, but the efficiency of this type of device decreases dramatically at high load)
- **Parallel Hybrid**, as per Low Carbon step 4, enabling the driveline to benefit from a high degree of electrical input

This technology improves the Step 6H vehicle by 20.6% at assumed Euro 7 emissions levels with an 8.3% increase in weight caused by the Parallel Hybrid and increased size APU system. Cost is increased by 10.64%. It is interesting to compare these figures to the Low Carbon Step 3-4 transition, which used the same Hybrid technologies (without the APU) and reduced CO_2 by 16%

Key Headings Summary for Step 6H:

Impacts (relative to Step 5H):

- Fuel consumption (Well to Wheels g/kmCO_2) –20.6% to **120** at assumed Euro 7
- **Fuel Consumed: 1.43kg/100km Hydrogen**
- Weight (kg) +8.3% to **1552**
- Retail Price (£2002) +10.64% to **19,173** (estimated range **£18,400 to £20,300**)

Technologies beyond Step 5H:
- 8kW Solid Oxide APU operating on average at 2.85W over the drive cycle
- Parallel Hybrid system as for Step 4 Low Carbon

Risks beyond Step 5H:
- The solid oxide Fuel Cell is now a more critical part of the drivetrain and so reliability has to be assured
- Hybridisation risks as per Low Carbon Step 4

Vehicle Attributes beyond Step 5H:
- As for Step 4LC however, there may be start-up issues with the APU

Impact on Manufacture beyond Step 5H:
- There are large quantities of precious metals in Fuel Cells, an issue which would require consideration for mass production volumes
- For a powertrain of this specification, it is unlikely that a conventional vehicle platform designed without this application in mind would be feasible. If this vehicle co-exists with conventional Petrol or Diesel vehicles it is possible that these would be to the Low Carbon Step 4 (Parallel Hybrid) specification, hence the packaging of the powertrain and battery would be accommodated, but the Hydrogen tank and APU would present a serious challenge

Impact on Infrastructure beyond Step 5H:
- Workshop technicians would require training for APU technologies but this has no change on the existing Hydrogen infrastructure requirements. Parallel Hybrid issues as for Step 4LC
- For customer acceptance of this type of vehicle, which is unlikely to have space for dual fuel storage, a full Hydrogen infrastructure is essential

Read Across to Other Vehicle Types:
- Technically applicable to all sizes but most likely to appear in classes D and above to provide mobile office type power availability

Read Across to Other Usage Patterns:
- Likely to be at its best in urban and stop-start use – under these conditions the IC engine is unlikely to run. However there will be small benefits even in motorway use provided that the APU is not operated in its least efficient full-load condition too frequently

Degree of Confidence in Analysis:
- Medium, as there are limited references for this technology in this application

Alternative Technologies:

- Other internal or external combustion engines can provide this role however, the Fuel Cell APU is unique to be able to generate electricity directly from fuel and so offers efficiency benefits

4.5 Step 7H – Fuel Cell Vehicle - 2020

Step 7H replaces the IC engine and the APU with a large Fuel Cell as the main vehicle power unit. It is, in effect, the Low Carbon Step 8 vehicle delivered ten years earlier. As shown in Appendix E, this main Fuel Cell has some level of reversibility so minimising the size of the main system battery. It is envisaged that by 2020, these technologies will be ready for the mass market given that the adoption of a Hydrogen Priority policy will have led governments to offer significant incentives. By this stage it is possible that the infrastructure exists for Hydrogen from sources that generally improve the CO_2 balance for transport. The data given here assumes that the Hydrogen has been produced from natural gas. This step is some ten years earlier than has been assumed achievable via the Low Carbon natural evolution route.

The Fuel Cell technologies and issues are described in Appendix C7.

The key advancements in technology that make Step 7H possible are:

Hydrogen "burning" Fuel Cell, as for Low Carbon Step 8

This technology improves on the Step 6H vehicle only slightly if today's efficiencies are used but significantly if future optimistic efficiencies for the "Series" type powertrain and Fuel Cell are used. As the Fuel Cell generates electricity directly, it automatically offers an efficiency gain over the Series Hybrid with IC engine and generator. Weight is saved due to the deletion of the engine, the transmission, the generator and the APU.

Key Headings Summary for Step 7H:

Impacts (relative to Step 6H):

- Fuel consumption (Well to Wheels g/kmCO_2) – 0.3 to –38% to **119 to 74** (ZEV)
- **Fuel Consumed: 1.43 to 0.89kg/100km Hydrogen**
- Weight (kg) –6.12 to **1457**
- Retail Price (£2002) +0.72% to **19,312 (estimated range £18,100 to £21,300)**

Technologies beyond Step 6H

- PEM Fuel Cell for automotive use

Risks:

- Fuel cell system has many risks: precious metal content is very high meaning price is volatile, power density is increasing but support systems such as compressors, thermal, control and electrical systems are almost never reported. These represent real challenges to make a system which is quiet, efficient, cost effective and packageable in a normal vehicle
- Hydrogen storage as for previous steps

Vehicle Attributes:

- The noise from the support systems is usually reported as annoying however this is likely to be solved. It would drive as for a Series Hybrid. There may be start-up delay issues depending on the battery mass used to compensate for cell start-up. This is minimised with Hydrogen fuelled Fuel Cells

Impact on Manufacture:

- Large quantities of precious metals, Hydrogen fuelling system would require high quality manufacturing techniques to ensure leak free operation. Modularisation (as currently achieved) would have to be replaced by integration to ensure all the sub-systems could be miniaturised to ensure packaging within a normal passenger car powertrain volume
- Vehicle architecture would need to be compatible with Fuel Cell package

Impact on Infrastructure:

- Same as Step 6H due to Hydrogen fuelling

Read Across to Other Vehicle Types:

- Technically applicable to most vehicle applications, however, the larger the vehicle the greater the price increase

Read Across to Other Usage Patterns:

- As per the equivalent Low Carbon step 8

Degree of Confidence in Analysis:

- Low to Medium, for cost and weight based on technical publications, theoretical calculations and projection of stated parameters to the year 2020. However, the fundamental efficiencies stated are medium confidence hence a range being given

Alternative Technologies:

- There are no direct alternatives at this time that can turn Hydrogen directly into electricity without combustion and with such high potential efficiency
- The choice between PEM, SOFC and other Fuel Cell types offers alternative technology routes, as per Low Carbon step 8

4.6 Hydrogen Priority Road Map Discussion

Hydrogen Priority has been implemented by bringing forward technologies that can begin the use of Hydrogen in the passenger car as soon as possible, even if the Well to Wheels efficiencies are not competitive with traditional fuels. This requires government action to promote significant sales (and for cost effective manufacture) to be possible. In Figure 4.1 is shown the Well to Wheels CO_2 vs. Time for each of the Hydrogen Priority steps.

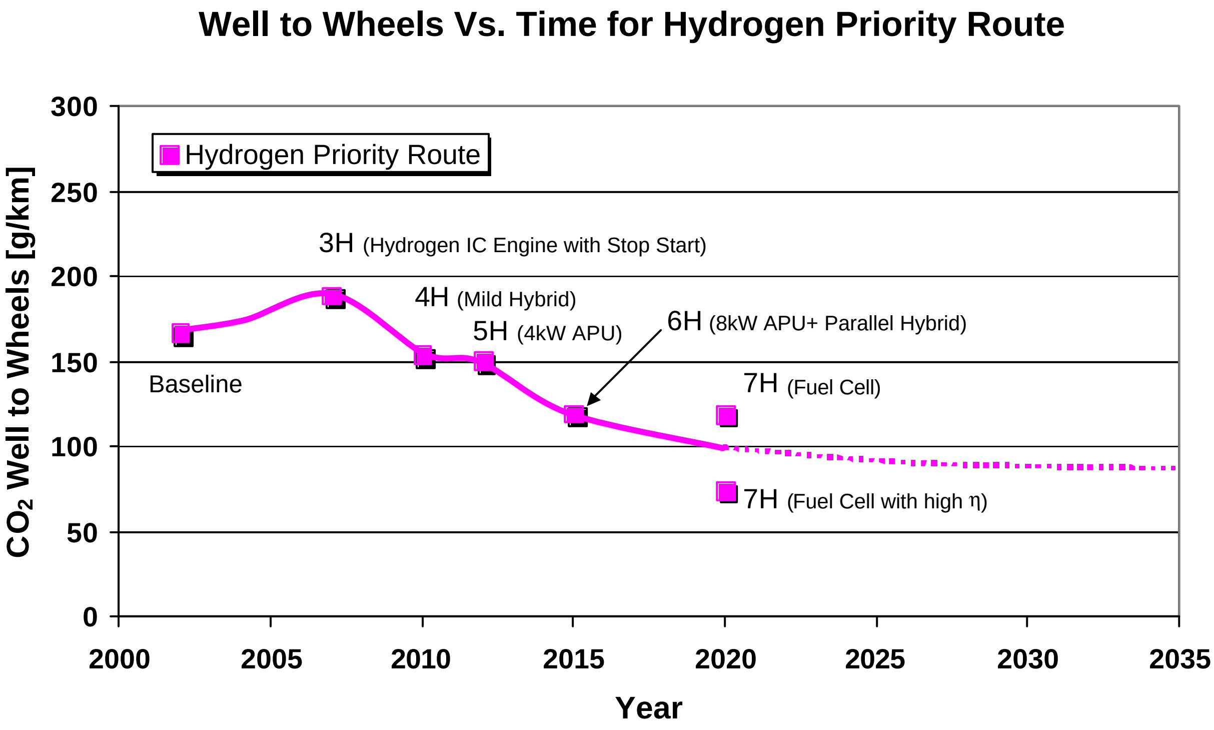


Figure 4.1: Well to Wheels CO_2 Vs. Time for Hydrogen Priority Route

It can be seen that the first step (3H) represents a worsening of Well to Wheel CO_2 by 13% from the baseline vehicle. This is improved considerably by Step 4H with downsizing and Mild Hybridisation but Step 5H (the addition of a Fuel Cell APU) does little to improve the CO_2 emissions. However, Step 5H does introduce the Fuel Cell as early as possible and in a non-critical way. If the APU fails in this vehicle, the driver could still get home. It also offers added functionality to the vehicle in the form of electrical power (for a mobile office as an example) independent of the IC engine.

Step 6H adds Parallel Hybridisation and 50% of the vehicle power provided by a larger Fuel Cell APU. This is a significant step forward and requires good reliability of the Fuel Cell systems. This paves the way for the Fuel Cell vehicle by 2020 by developing sub-systems, Hydrogen storage, the power electronics, motors and driver acceptance. It is assumed that throughout this route, the Hydrogen infrastructure has been developing strongly. By Step 7H in 2020, the Fuel Cell vehicle is ready for introduction to the market and, as shown, there is a range of efficiencies that could be possible. From 2020 onwards, it is expected that significant developments will occur to improve power density and lower fuel consumption.

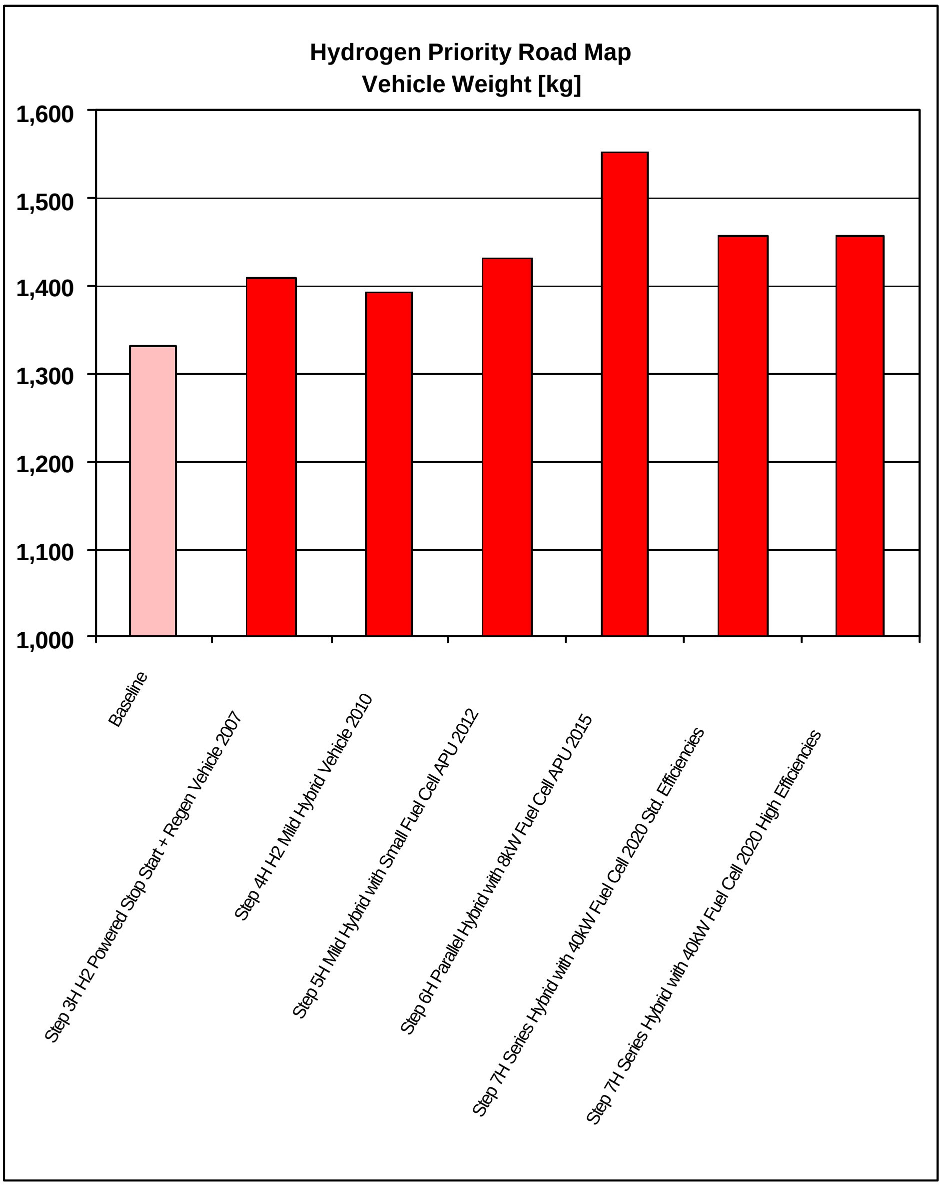


Figure 4.2: Hydrogen Priority Route Weight

The weight of steps 3H to 5H is kept under control by the engine downsizing making up for the increase in electrical systems. The main increase in weight of these steps over the baseline is the Hydrogen storage of about 90kg. Step 6H increases due to the Parallel Hybrid systems added and the increase in the APU power output. The drop in weight going to Step 7H is due to the deletion of the engine, generator, transmission and APU. Even so, weight reduction will have to be a major objective for the Fuel Cell vehicle of the far future.

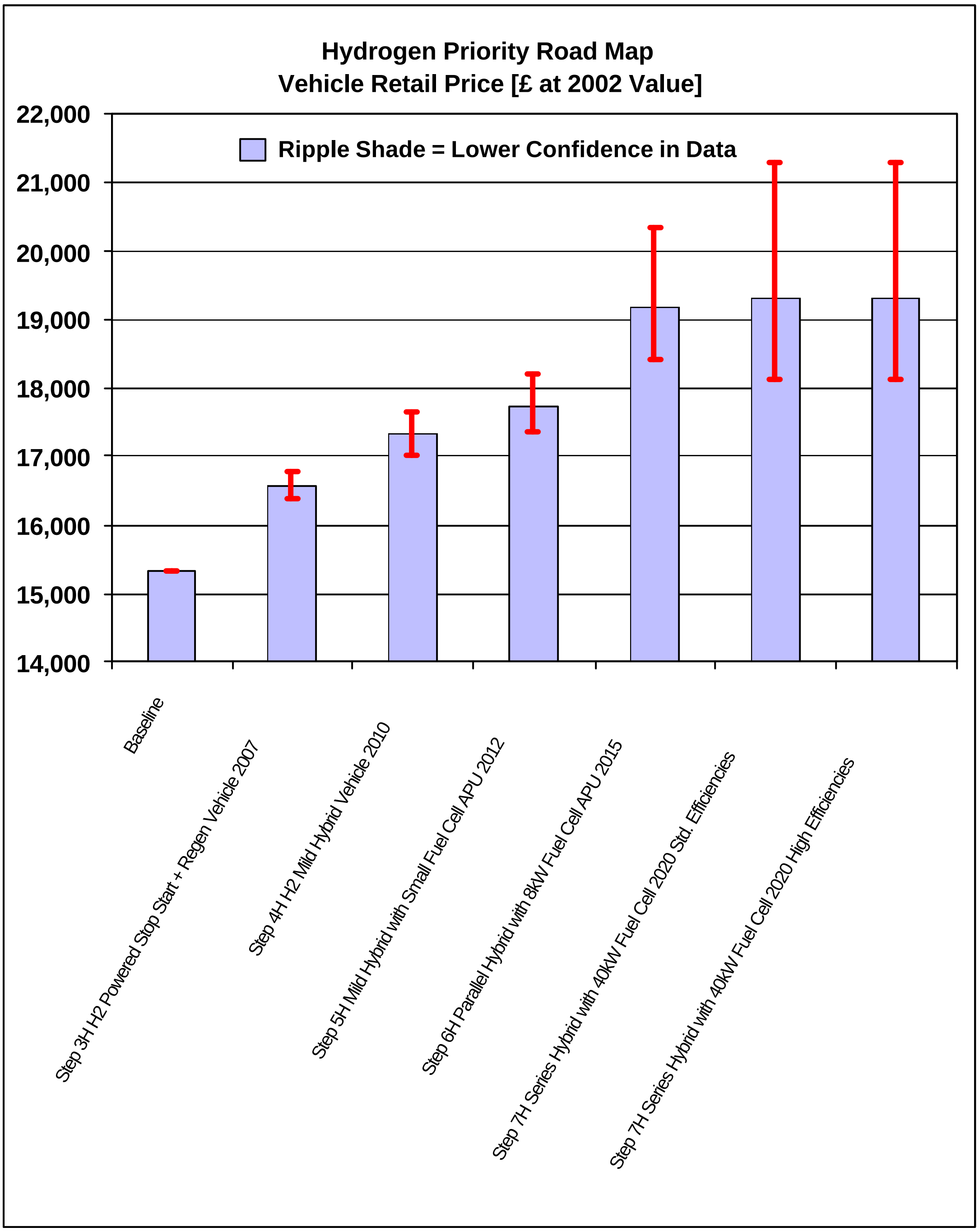


Figure 4.3: Hydrogen Priority Route Price

All cost estimates are subject to low to medium confidence, due to uncertainty about cost of Fuel Cell units and Hydrogen storage tanks.

The retail price increase is as expected for steps 3H to 5H but the sharp increase to 6H is caused by the growth in APU size and the Parallel Hybridisation technologies added. Step 7H does not increase price significantly due to the deletion of technologies (as for weight) and also due to the projection that, by this time, productionised PEM Fuel Cells will be cheaper per unit power output than the solid oxide systems used for the APU.

The road map that is suggested here develops a number of technologies that are replaced not long after introduction such as the Hydrogen IC engine and the Fuel Cell APU. It is interesting to note that in the history of the automotive industry, this is a common occurrence and is often as a result of the need to achieve results quickly and with what technology is available. An example is the advanced carburettor systems developed in the late 80's for emissions control that were replaced by fuel injection systems a few years later. Therefore, it is realistic to suggest that the industry can develop the IC Hydrogen engine even though the Fuel Cell appears likely to replace it in the future. It may also have life in other forms such as in vehicles that are too cheap to cover the cost or too small to package the initial Fuel Cell systems.

It can also be questioned if it is worthwhile developing the interim steps of the Hydrogen Priority road map rather than just pushing the Fuel Cell Step 8 development, omitting Steps 3H to 6H. This would be a high-risk strategy for the following reasons:

- The CO_2 benefits offered by each step would be lost and so cumulatively, there would be missed opportunities for considerable global CO_2 reduction
- OEM's cannot ignore the middle ground by investing all their R & D budget in one, high risk future technology, especially as most of the technologies being developed could actually be used in the interim steps so paying back their development earlier
- If technologies are bought forward, the initial price would be prohibitive unless sold at a loss, so limiting the sales volume potential. This would result in slow growth for these technologies, minimising the impact made on CO_2 reduction. Also, infrastructural growth would almost certainly limit sales
- Customer acceptance of considerably new technologies that changed the driving experience are hard to impose on large sectors of the community, further slowing the uptake of the new technologies. Resale values also need consideration. Toyota Prius and Honda Insight vehicle resale values are not the best in the UK market

Whilst it is possible to introduce new technologies early such as Toyota did with the Prius Parallel Hybrid vehicle in 1997 (and manufactures are aiming to do with the first Fuel Cell cars), these are not mass market vehicles. They offer the manufactures the opportunity to learn about the market and the technologies whilst working on cost reduction and improvement prior to mass-market penetration.

These vehicles are sold or leased at considerable loss initially and bought mostly by enthusiasts. They have insignificant impact on global CO_2. The Prius was possible because it did not require an infrastructure change. A Fuel Cell vehicle that did not reform Petrol or Diesel (which is inefficient) would require infrastructure change and so couldn't follow that model. The step by step approach (supported or not) is probably the most likely route to cost effective mass-market penetration of Hydrogen powered vehicles.

The key risks (some of which are technology gaps) associated with the Hydrogen Priority road map are shown below:

- Accelerated Infrastructure growth for Hydrogen, which is complex and expensive

- Accelerated Fuel Cell cost effective manufacture including the cost and availability of precious metals used in the Fuel Cell stack
- Cost and space effective, safe Hydrogen storage
- Improvements in the efficiencies of the supporting systems such as the motors, electronics, batteries, thermal and fuelling systems reaching sufficient levels in time for the 2020 introduction date of an efficient Fuel Cell vehicle
- Customer acceptance of high-pressure gas storage and the limitations for travel this currently imposes such as currently on cross-channel train services
- The need to accommodate significantly different powertrain and fuel storage systems in the vehicle, without increasing the cost of engineering and manufacturing new platforms to an unacceptable level

At present, apart from the huge cost of infrastructure development and vehicle product development required to support it, there are no technical reasons to conclude that the Hydrogen Priority road map could not be successful.

The fleet average impact for this road map of technologies is discussed in Section 5, Government incentives are discussed in Appendix G and UK involvement in these technologies is covered in Appendix D.

4.7 Alternative Technology Developments over the Hydrogen Priority Road Map

The Hydrogen Priority road map features the use of the Hydrogen engine. These engines will be new to market and so there are no easily identifiable alternatives to this key technology that retain the use of Hydrogen. The issues concerning Hydrogen engines are discussed in Appendix C5.

The APU technology that has been suggested is discussed in Appendix C7 and Hydrogen storage in Appendix C8.

Many of the alternative technology developments discussed for the Low Carbon route (section 3.9), are equally applicable here, specifically those relating to engines and Hybridisation.

Alternative Fuel Cell technologies are available – in this analysis, calculations have been based on Solid Oxide (SOFC) types for APUs, and Proton Exchange Membrane (PEM) types for a Fuel Cell prime mover, simply because this is where most data is available. In principle both technologies compete for both applications, along with other types such as the Alkali Fuel Cell.

If its efficiency as a reversible energy store can be improved, the reversible Fuel Cell is as applicable here as it is on the Low Carbon route, serving as a combined APU and “battery”. However, such major improvements are required that it is unlikely to be a useable technology before the end of the Hydrogen Priority evolution.

It is also important to consider alternatives to Hydrogen and the Fuel Cell as the ultimate destination. Renewably synthesised liquid fuels have been proposed, while effective CO_2 sequestering could significantly extend the useful life of crude oil and natural gas reserves.

5 DISCUSSION AND CONCLUSIONS

The two routes, Low Carbon and Hydrogen Priority, from current best-in-class low CO_2 vehicle technology, towards a suggested ultimate goal of a Hydrogen-fuelled, Fuel Cell vehicle, have been analysed side-by-side in terms of their impact on well-to-wheels CO_2, projected vehicle price, and practical issues relating to manufacture and ownership.

5.1 Comparison of Routes

The impact these two approaches have on Well to Wheels CO_2 emissions vs. their earliest achievable introduction date as class-leading vehicles is shown in Figure 5.1.

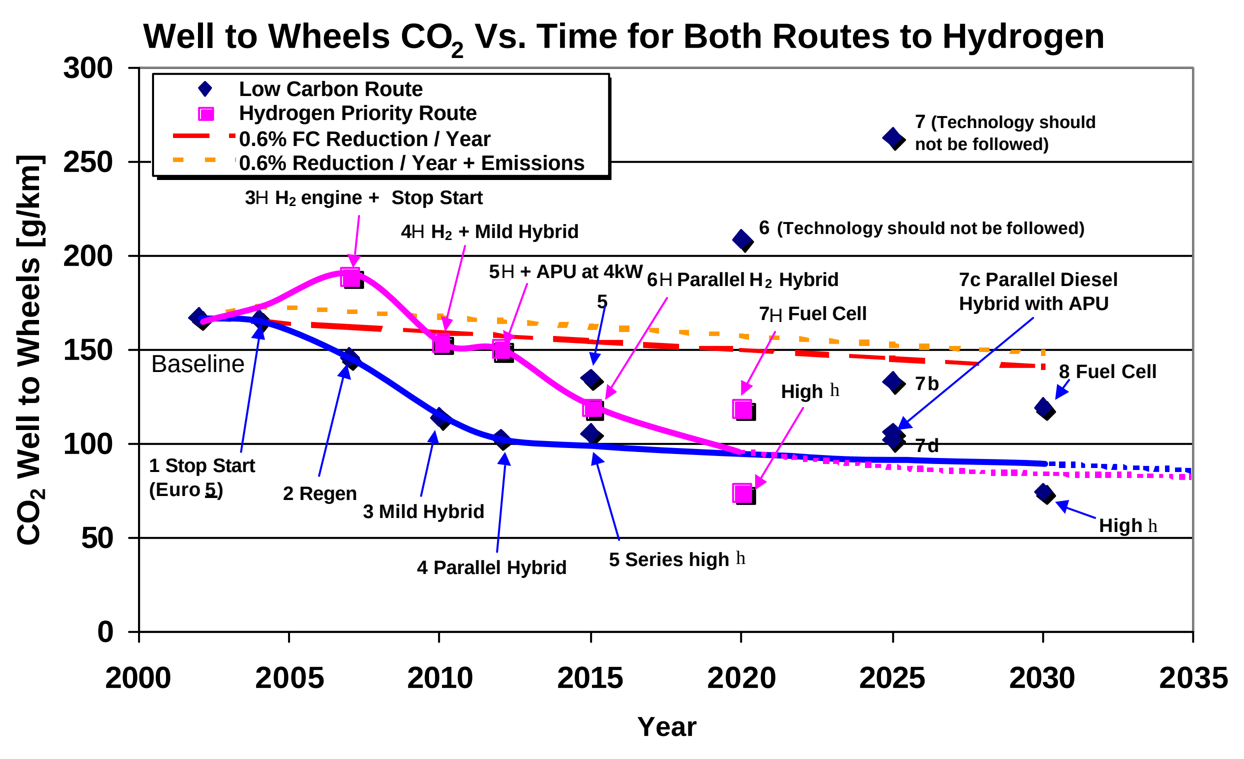


Figure 5.1: Well to Wheels CO_2 Vs. Time for the Low Carbon and Hydrogen Priority Road Maps (Low CO_2 Options)

This illustrates clearly the difference in impact of the two routes. In summary, through to and beyond the Low Carbon Step 4 stage, the Low Carbon vehicle offers well-to wheels CO_2 which is some 30% lower than the Hydrogen Priority vehicle. In practise, it is unlikely that any of the Low Carbon Steps beyond Step 4 would be adopted until the Step 8 Fuel Cell vehicle (Step 7c, Fuel Cell APU, being a possible exception). However, it is possible that these technologies may serve as part of manufacturers' development towards their Fuel Cell vehicles. The Step 4 vehicles would continue as the marketed vehicle, with the normal year-by-year refinement in performance (blue line) and increasing market penetration. The well-to-wheel emission performance of Hydrogen Priority vehicles would similarly improve and would in due course match, but not go beyond, the performance of the Low Carbon vehicles.

On the other hand, the full Fuel Cell vehicle Step 8, in common with all the Hydrogen Priority IC engined vehicles, has the additional potential to become completely zero-carbon when renewably produced Hydrogen becomes available. Fuel Cell vehicles also have zero tailpipe emissions, unlike Low Carbon vehicles, though the air quality emissions built into Step 4 vehicles are 50% or more lower than current Euro 4 Petrol standards.

Also shown is the standard 0.6% reduction in fuel consumption which occurs “naturally” through engineering improvements year on year but with no new technology added to the vehicle. In addition, the worsening in fuel consumption incurred through meeting the emissions legislation required at the year of vehicle introduction is shown. This is mostly concentrated in the first few steps of the line.

5.2 Discussion - Low Carbon Route

The Low Carbon route (see Appendix E) develops currently emerging technologies such as stop start, engine downsizing, Mild Hybridisation and Parallel Hybrids so that, by Step 4, Well to Wheels CO_2 of the best-in-class vehicle has been reduced by 38% compared to Step 0. This evolution is likely to happen naturally in any event, though at a slower pace, given a correct level of incentive, by OEMs and suppliers seeking technical improvements, by customers demanding lower fuel consumption without sacrificing performance, and with the help of continuing fiscal incentives for low-carbon vehicles. This evolution is already underway in advanced engineering programmes, with only the most conservative OEMs holding back from developing such technologies. The highest risk is the cost of batteries, motors and power electronics and the technical capability of current battery technologies. However, as demonstrated by the continuing rise in sales volumes of Japanese Hybrid vehicles in the global market, this will not always be the case.

Beyond the Parallel Diesel Hybrid, the technological improvements set out in Steps 5 to 7 could be useful for manufacturers to explore and trial as part of their development of full Fuel Cell vehicles. But they do not seem likely candidates for marketing, because the carbon performance is no better, and in some cases worse, there are no significant consumer benefits, and the cost is higher. For example, Steps 5 (the Series Hybrid) and 6 (Reversible Fuel Cell) are both less promising than some would claim in a passenger car application. Considerable improvement in motors, generators, power electronics, batteries and reversible Fuel Cell technology would be required before they can match the Parallel Hybrid system efficiencies. However, these technologies are all beneficial for the Fuel Cell vehicle and it is thought possible that the required improvements could be approached in time for the Step 8 Fuel Cell vehicle to reach mass production in 2030.

Once Step 4 vehicles were introduced, the usual year-by–year efficiency improvements and cost reductions can be expected.

However, it could also be useful, in the period between Step 4 and the full Step 8 Fuel Cell vehicle, for manufacturers to adopt more limited technology improvements. These would form a bridge between the rising market penetration of the Step 4 Diesel (and Petrol) Hybrids and the arrival of the totally Hydrogen-dependent Fuel Cell vehicle. In particular, the Hydrogen powered Fuel Cell APU (Step 7c) is a promising technology, although its cost and bulk must not be underestimated. This would start to develop the Hydrogen infrastructure in a non-critical way, and also promote the Fuel Cell as discussed in Section 3.7c and presented in Appendix F, while adding to vehicle functionality by providing efficient onboard power even when stationary. OEMs and suppliers are indeed working on this technology for onboard power, although there is no evidence of development of APUs as a secondary power source for motion. It is likely that this technology will appear first in luxurious vehicles and then filter downward.

It is also worth noting the significance of the Petrol engine (or indeed LPG, CNG or other fuels) which would benefit by a similar amount (perhaps greater for stop/start) while suffering lower cost and efficiency penalties for possible future emissions compliance. Petrol vehicles will not be best-in-class for CO_2, but a Petrol Hybrid may offer a competitive alternative to a conventional Diesel vehicle once rising production volumes enable lower costs.

In conclusion, this analysis suggests that the optimum Low Carbon route can be summarised as:

- Promotion of stepwise introduction of Mild and Parallel Hybrids as best-in-class vehicles between the present day and Step 4;
- Promotion of these low-carbon technologies on a mass-market basis, with a view to 100% coverage of the car fleet by 2020-25.
- Development and trialling of the use of APU technology fuelled by Hydrogen to create dual-fuel vehicles capable of operating as extended range ZEVs with limited performance, but not dependent on Hydrogen at every filling station
- Parallel development of enabling technologies for Fuel Cell vehicles, such as efficient motors and batteries, PEM, SOFC and other Fuel Cell devices, which will spin off into these mainstream Hybrid and APU vehicles
- Consideration of the role of Natural Gas as a transition fuel in the event that it becomes impossible or undesirable to move towards sustainable Hydrogen in the timeframe suggested or, if the supply of crude oil becomes compromised by diminishing reserves or political instability

5.3 Hydrogen Priority Route

The Hydrogen Priority route would require development of the Hydrogen burning IC engine. This is feasible, and both Ford and BMW are active in this field. Key risks are power density from the engine and NOx emissions caused by burning Hydrogen lean in air. These problems are expected to be overcome (with suitably incentivised research) resulting in a cost effective and efficient engine.

Developing the Fuel Cell as an APU appears feasible as there are active programmes now and there are drivers for their use in the near future (mobile office, engine-off climate control). However, there is little evidence of the development of intermediate-sized automotive APUs with a load sharing (vehicle drive) function, and reducing the weight, size and cost of these units is essential. The full Fuel Cell vehicle (Step 7H) is also approaching technical feasibility, however, it is the cost effective manufacture and the real world issues such as start-up delay, noise, operation in extreme ambient temperatures and robustness that require significant effort. This technology could be feasible as a product by 2020 only if OEM research incentives and customer purchase incentives are offered.

The Hydrogen Priority route is also shown in Figure 5.1 where easy comparison with the Low Carbon route can be made. The worsening of the Well to Wheels CO_2 going to Step 3H on the Hydrogen Priority route indicates immediately that if such a move were to be selected it would need to be viewed as beneficial to long-term strategy.

It does not necessarily follow that the whole vehicle fleet would shift to higher CO_2 emissions. Over the period of the Hydrogen Priority evolution, it is highly unlikely that Hydrogen would wholly displace liquid fuels. In fact, even with vigorous promotion, it is likely to be a minority fuel even in 2020 due to the scale of current investment in the production of liquid fuels and the vehicles that use them.

Even if the Hydrogen Priority policy were adopted, it is likely that manufacturers would want to adopt Hybridisation for the generality of non-Hydrogen vehicles, as per the Low Carbon route. It should be noted that the two Routes are an excellent fit in this respect. Provided that the penetration of the Hybrid evolution remained ahead of the rise in non-renewable Hydrogen usage, a decreasing well-to-wheels CO_2 average for the new car fleet would remain feasible. However this would not be the case if research effort and manufacturing effort were diverted away from Hybrid technology towards Hydrogen.

The Hydrogen Priority route also brings forward the Fuel Cell vehicle, via the availability of Hydrogen, and technology incubation in the APU. However, it should be noted that there is no margin of CO_2 gain from the Fuel Cell car, compared to Hybrid vehicles, on the mid-range of Fuel Cell efficiency assumptions. And even on the high efficiency assumption, the margin of gain is not more than 10-20% (until zero-carbon Hydrogen is available).

It should be borne in mind, however, that IC engines and Hybrid technology could make further efficiency advances beyond those projected in this review. It is also possible that battery technology can overcome the present technology blockages, and became an effective carrier of electric energy for mainstream car transport thus performing the same functions and benefits of a Fuel Cell vehicle, without the cost and complications of Hydrogen storage.

Also, it should be noted that many alternatives to Hydrogen have been suggested as long-term sustainable solutions. Liquid fuels may be manufactured sustainably from biomass, or possibly from industrial processes (powered by renewable or nuclear energy) which “mimic nature” in combining atmospheric Carbon with water to produce Hydrocarbon fuels. In the medium term, sequestration of CO_2 is seen by some as an enabler to allow continued use of crude oil and gas reserves.

Thus for all these reasons, one cannot assume that the Fuel Cell car, notwithstanding today's best knowledge, will necessarily prove to be the optimal transport 'final solution'. Technology advances can change the landscape.

For the Hydrogen Priority route, the government-inspired action may be focussed on infrastructure (production and distribution), research into the new technologies in the vehicle (from suppliers and OEMs), and education (of both drivers and the servicing industry). Whilst it is not the purpose of this report to state how this should be done, it is clear that significant funding will be required if Hydrogen is to be made widely available in the marketplace. The key issues in this process are discussed in

Appendices B8 and C9 but primarily it is the production, transporting and refilling processes that need standards to be developed from which robust solutions can be generated. This process is underway in many countries.

A full analysis of the financial implications of this approach is beyond the scope of this study. A possible approach would be to:

- Assess the desired penetration rate of Hydrogen vehicles
- Determine the infrastructure coverage (which depends on whether the vehicles are pure Hydrogen vehicles, or dual fuel)
- Determine the quantities of Hydrogen required
- Analyse the Hydrogen production and distribution process, to establish a cost for the fuel at the forecourt
- Consider likely price of the vehicle, fuel purchase and other operating costs, to calculate the incentives required for the driver to buy the vehicle

Such a study would benefit from co-operation with industry representatives from energy supply and vehicle manufacture. It is highly likely that existing industry collaborative bodies within Europe and the rest of the world are engaged in this type of analysis.

Whichever of these energy approaches is chosen, it is likely that energy-efficient vehicles will be desirable. The Low Carbon technologies, principally Hybridisation, provide efficient vehicles regardless of the origin of the fuel. The Hydrogen Priority route does not offer an advance over the Low Carbon route on this basis.

5.4 Infrastructure and Alternative Fuels

Appendix C8 presents issues associated with the Hydrogen infrastructure. It is clear that progress needs to be made to agree a standard for Hydrogen storage and fuelling methods. Also, the most cost-effective means for transporting fuel within the infrastructure must be agreed. This has begun with the European Integrated Hydrogen Project, Phase II, which should end in January 2004. The cost of such an infrastructure should not be forgotten. It has been estimated that to install 2000 Hydrogen stations in Germany by 2010 will cost around 5 billion Euros.

Alternative fuels that can offer Well to Wheels CO_2 improvements are discussed in this report body and in Appendix B. It has been shown that compressed natural gas is not a particularly effective replacement fuel for the Diesel engine but for the Petrol (Gasoline) engine, it should offer some advantages. Therefore, it may be possible to consider CNG as a stepping stone technology towards the Hydrogen-fuelled vehicle. It develops a similar infrastructure, it conditions the public to accept alternative fuels and potentially assists reducing global CO_2 emissions.

5.5 Evolution versus Step Change

From certain quarters it has been suggested that, since the Hydrogen Fuel Cell is seen as the ultimate goal, this should be the focus of all effort, both in terms of research and in changing customer preferences.

This is over-simple. The following points should be borne in mind.

- Radical change is so much against the philosophy of the industry, and seen as so harmful to its financial viability, that it is unlikely to be considered acceptable or supported by the industry
- Radical change is also regarded with suspicion by car-buyers, who will see it as likely to lead to reduced reliability, difficult maintenance, high depreciation, and the risk that the technology will not "catch on", hence exacerbating these issues. Customer acceptance of considerably new technologies that changed the driving experience are hard to impose on large sectors of the community, further slowing the uptake of the new technologies
- The feed-forward of technology from one evolutionary step to the next, combined with natural product obsolescence, means that the development of stepping-stone technologies such as Mild and Parallel Hybrids, IC Hydrogen engines, etc. can be achieved in a manner compatible with industry practise. Also this can be achieved without "wasted effort", even though the Fuel Cell is seen as being destined to replace them in the distant future
- Investment in one, high risk future technology whose viability is heavily dependent on Hydrogen becoming the fuel of choice, would be seen as unacceptable policy. Investment in more flexible, incremental steps provides a greater chance of short and long term success with earlier pay-back in terms of CO_2 reduction or product sales
- If there are no evolutionary steps from now until the Fuel Cell vehicle then the CO_2 benefits offered by each step would be lost and so cumulatively, there would be missed opportunities for considerable near term global CO_2 reduction
- If more radical technologies are bought forward, the initial price would be prohibitive unless sold at a loss, so limiting the sales volume potential. This would result in slow growth for these technologies, minimising the impact made on CO_2 reduction. Infrastructural growth would also almost certainly limit sales

5.6 Conclusions

The two routes toward mass-produced Hydrogen fuelled, Fuel Cell vehicles have been studied. Although many detailed issues are raised by this analysis, major conclusions are:

- Risk-managed, step-wise evolution toward sustainable transport is feasible, and is likely to be the only approach compatible with the business-model and corporate philosophies of the car industry and the preferences of conservative buyers
- Every step can contribute to the next, in terms of technical know-how and, in many cases, carry-forward hardware. Some hardware will become redundant, but this need not be incompatible with the natural process of product obsolescence
- Every step carries an incremental cost. Although these costs are generally proportionate to benefits, they are high relative to the marginal profitability of the industry and the competitiveness of the marketplace
- Progressive electrification and Hybridisation offers significant CO_2 benefits regardless of the fuel or its source, at a risk level more manageable than alternatives such as more radical new vehicle technologies or major infrastructure change

- Progressive introduction of the Fuel Cell as an Auxiliary Power Unit, starting with luxury vehicles, offers a functionality improvement in terms of onboard power and ZEV range extension, introduces Hydrogen as a dual fuel and can offer CO_2 savings

As demonstrated in Appendix D, there appears to be significant world-class strength in the UK engineering base, especially in the fields of Hybrid systems, Control & Electronics, and advanced Internal Combustion engines and Transmissions. Promotion of this expertise via research could be a key element in the successful introduction of low CO_2 vehicles. This analysis suggests that the following research themes would be beneficial:

Near term:

- Improvements to Hybrid systems and Batteries, especially those that lead to lower cost and extended battery temperature range
- Improvements to the IC engine, especially quantifying and addressing health concerns (for example Particulate emissions and NOx), and enabling lighter, compact, cheaper units with improved efficiency
- Improvements to other vehicle systems including transmissions, and climate-control compatible with stop-start

Medium Term:

- Further Hybrid system improvements especially energy-dense batteries or alternative devices, and better motor/generator and other system efficiencies
- Hydrogen IC engine technology with equivalent power density to liquid fuels, and acceptable NOx control
- Hydrogen storage and distribution technology, both on and off vehicle
- Compact, low cost Fuel Cell APUs

Long term:

- Fuel cell vehicle systems for low cost, robustness and pleasant driving experience
- Sustainable energy including Hydrogen, liquid fuels and sequestration, and the corresponding infrastructure and vehicle technologies
- Alternatives to the Fuel Cell, including very advanced IC engines with energy recovery from waste heat
- Potential for technology crossover from biotechnology, nanotechnology and other areas

APPENDIX A: CURRENT STATUS OF MARKET & FUTURE CO_2 / EMISSIONS DRIVERS

A1 Types of Emissions

A1.1 CO_2

It is important to differentiate between CO_2 and other vehicle emissions. Emission of CO_2 and water are the inevitable result of extracting energy from Hydrocarbon fuels, including Petrol, Diesel, LPG, Natural Gas, Methanol, Ethanol and other types. It is generally believed harmless to human and other life, unless present in such high quantities as to significantly reduce the availability of Oxygen. CO_2 is a “greenhouse gas”, that is, its presence in the atmosphere may cause climate change via “global warming”.

For a given fuel type, the quantity of CO_2 produced is directly proportional to fuel consumption, and can be calculated by the following relationship:

$$CO_2 \text{ (g/km)} = \text{Fuel Consumption (l/100km)} \times K$$

The constant K takes the following values:

Fuel	Minimum	Maximum	**Average**
Petrol	23.79	24.06	**23.95**
Diesel	26.32	29.22	**27.07**

Table A1.1 - Fuel consumption to CO_2 correlation factors

These values are calculated from a homologation database of vehicle fuel consumption and CO_2 emissions. The small variation in the value of K for each fuel type is believed to be due to differences in the properties (chiefly density) of the fuel used for homologation. Likewise, Diesel has a higher value of K than Petrol because of its greater density – that is, a litre of Diesel is heavier than a litre of Petrol, so combusting it will create more CO_2

In the UK market, the more traditional “miles per gallon” (mpg) measure is often used for fuel consumption. This has a “reciprocal” relationship to both the l/100km figure, and CO_2 emissions:

$$\text{Fuel Consumption (l/100km)} = 282.481 / \text{Fuel Consumption (mpg)}$$

It is important to remember this when comparing claims for improvement in fuel consumption. For example, a technology, which reduces the fuel consumption (measured in litres per 100km) by 50%, will:

- Reduce CO_2 emissions by 50%
- Increase the “mpg” figure by 100%

Because of potential for confusion, all data presented here relates to CO_2 emissions, or fuel consumption measured in l/100km.

A1.2 Other Emissions

Other emissions are, in simple terms, the result of "imperfections" in the combustion process. All are considered in some way harmful to health if present in sufficient quantity. Legislation governing the quantity of these other emissions has been in place in Europe for over a decade, with incremental reductions in the quantities permitted. These emissions are:

CO	Carbon Monoxide
HC	Hydrocarbons
NOx	Oxides of Nitrogen
Pm	Particulate matter

The quantity of these emissions produced is not directly proportional to the amount of fuel burned, as other factors have a far greater influence, namely:

- The specification of the engine's combustion system – fuel/air mixing, the ratio of air to fuel, and the completeness and temperature of burning in the cylinder
- The specification of "after-treatment" devices – catalytic converters, particulate traps etc – fitted to the vehicle
- Vehicle related factors such as its weight (which determines how hard the engine must work to move it), gear ratios, nature of usage, etc

A2 Expected trends in CO_2 emissions

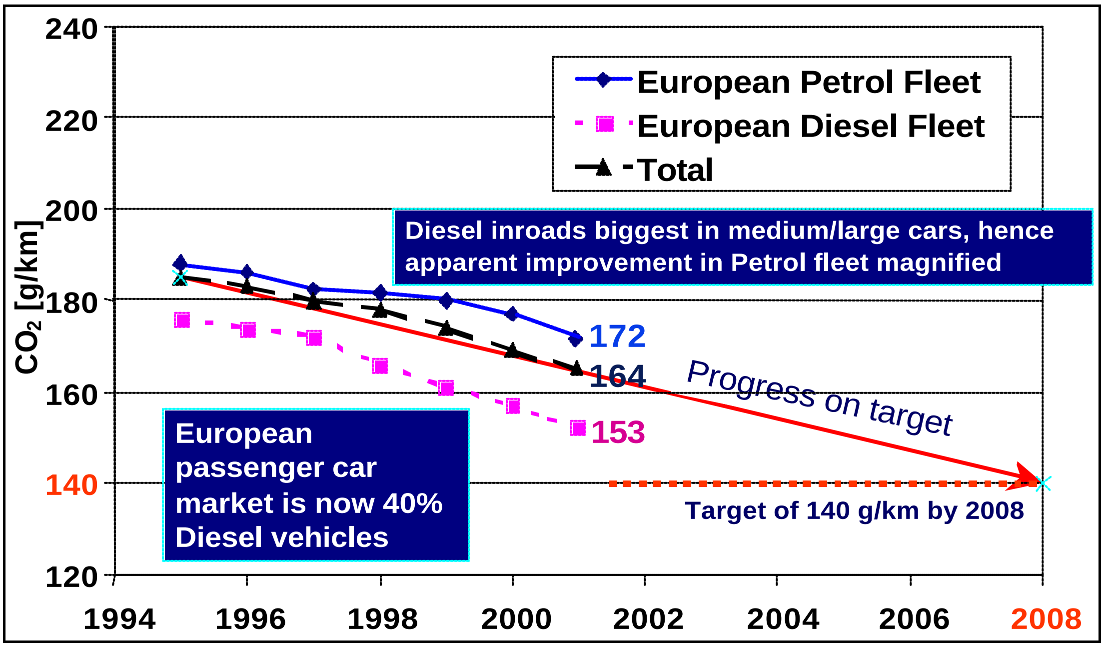
In recent years, the topic of greenhouse gas (GHG) emissions from road transport has been the subject of much discussion. The primary source of GHG emission from road transport is the gas Carbon Dioxide (CO_2), produced by the combustion of fossil fuels. Road transport in Europe accounts for an estimated 20% of total manmade CO_2 emissions [1].

In the past, the only incentive for reduction of CO_2 emissions has been the cost of fuel. While UK and other European fuel taxation has historically been higher than in the rest of the world, other factors such as the more pressing need to direct technological innovation towards complying with emission legislation, and the growing wealth of the population, has led to greater ownership and use of road vehicles, and a consequent rise in total CO_2 produced by road transport.

In the past decade, reduction in CO_2 and other GHG emissions has become subject to the Kyoto Protocol and local legislation aimed at meeting Kyoto obligations. In the UK and Europe, this takes the form of:

- UK company car taxation which incentivises low CO_2 vehicles
- Fuel taxation which incentivises consumer choice of fuel efficient (hence low CO_2) vehicles
- A voluntary agreement by European manufacturers through their association, ACEA, to achieve a new car fleet average CO_2 emission of 140 g/km by 2008 [2]

ACEA members have made significant progress towards meeting the 140g/km target. Shown below, significant improvements in both Petrol and Diesel vehicle averages have resulted in a whole fleet average, which appears close to being “on track” for the required reduction.



Diesel inroads biggest in medium/large cars, hence apparent improvement in Petrol fleet magnified

European passenger car market is now 40% Diesel vehicles

Figure A2.1 - ACEA CO_2 data (source Ref 2)

Significant factors are:

- Over the period shown, Direct Injection Diesel engines have replaced Indirect Injection types which were significantly less efficient. The reduction in Diesel vehicle CO_2 is due mainly to this factor
- Total Diesel penetration has also grown, from less than 30%, to 40% in 2001 (in the UK, Diesel sales remain at only 20%). This shift has had a favourable impact on the fleet average
- Diesel penetration has been very high for larger vehicles, with some manufacturers reporting penetration of up to 80% for some markets in the “E” segment (luxury car). This means that the “average” Petrol car is now a smaller vehicle. The ACEA data does not give enough information to isolate this trend, but it is probably as significant as advances in Petrol engine technology itself.

The pressure for lower CO_2 emissions is becoming similar in many other parts of the world, although Europe appears to be leading the trend. Of significant note are:

- Political discussion in both California and Canada, indicating commitment to CO_2 reduction. Targets and timescales are not yet known, but if these commitments are confirmed they will have an impact toward the end of the decade.
- A variety of local initiatives in other nations, specifically in the Asia / Pacific region

In the USA, legislation for reduction in fuel consumption has existed for some time in the form of the Corporate Average Fuel Economy (CAFÉ) scheme. The CAFÉ figure is calculated as a new car fleet average, but with a sophisticated system of "credits" for selling zero or near zero emission vehicles. However in terms of reducing CO_2 emissions the CAFÉ scheme has been criticised for three reasons:

- The legislated limits have been static for most of the past decade, and recent political debate suggests that they will remain so until the end of this decade (Figure A2.2 below)
- The legislation has a separate, less demanding category for "trucks" – meaning pick-ups, 4x4 sport-utility vehicles (SUVs), and vans. These have risen in popularity and now account for nearly half of all private vehicle sales in the USA (Figure A2.2 below)
- The scale of fines for failure to achieve the target CAFÉ figures is such that paying the fine is considered cheaper than developing new technology, especially for lower sales volumes. While the indigenous US manufacturers generally meet the limits, imported brands usually do not

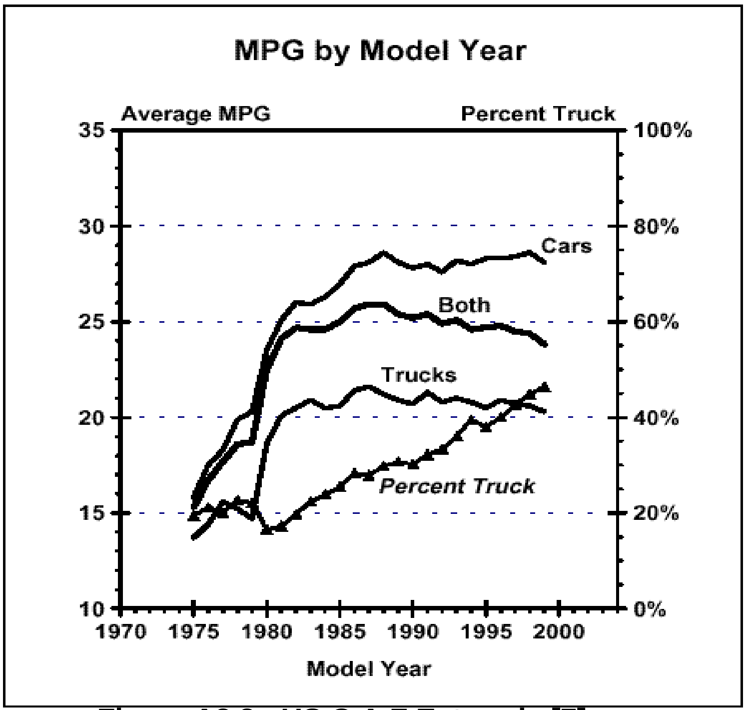


Figure A2.2 - US C.A.F.E. trends [7]

Due to the strong influence of politics, it is impossible to predict a far-future trend for new car fleet average CO_2. However a possible scenario, which appears reasonably compatible with the proposed Low Carbon route, can be indicated by:

- The ACEA target of 140g/km by 2008
- A second, suggested ACEA target of 120 g/km by 2012
- The UK Foresight target of "10% reduction on 90 g/km" by 2020 [6]
- Other public domain targets – specifically those stated by the German ministry of traffic [8] and environment agency UBA [9]

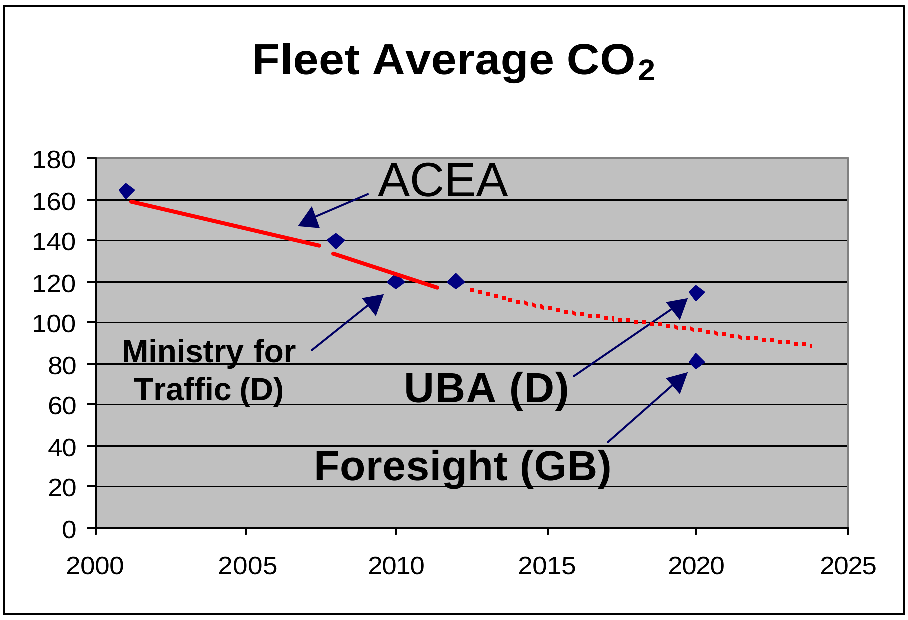


Figure A2.3 - Possible CO_2 (g/km) Reduction Scenario

This information is shown in Figure A2.3 above, and indicates a continuing downward trend, to below 100g/km by 2020.

The equivalent trend for other types of vehicle – delivery vans, buses and trucks – deserves mention. Currently, operating costs are considered sufficient incentive for technologies that reduce CO_2 emission. However, it is entirely possible that similar incentives and agreements to those for passenger cars could be brought into effect over the next decade. The most significant near-term CO_2 reductions can be expected in vehicles with stop/start duty cycles – delivery vans and buses – where in principle, technologies such as Hybridisation can have a similar impact to that for passenger cars on the NEDC test. Larger, long distance trucks are reliant on improvements in steady-state efficiency only, and are likely to see less reduction in CO_2 until alternative, low or zero CO_2 fuels become widely used.

A3 Expected trends in other emissions

The introduction of emission legislation over the past decade is already impacting significantly on the total emissions from road transport, and is expected to continue to do so. The data shown in Figure A3.1 is from the Auto-Oil II project [1], and predicts reductions in all the legislated emission types to less than 20% of 1990 levels by 2020, despite significant traffic growth.

The implication of this is that, while there will probably remain a need to address certain emission issues, there will be a diminishing return from continuing lowering of permitted emission levels. In view of the negative impact of emission control equipment on fuel economy and CO_2 (described in section 2.4.2), it is important that future emission targets are based on objective understanding of the impact of these emissions on human health and the environment.

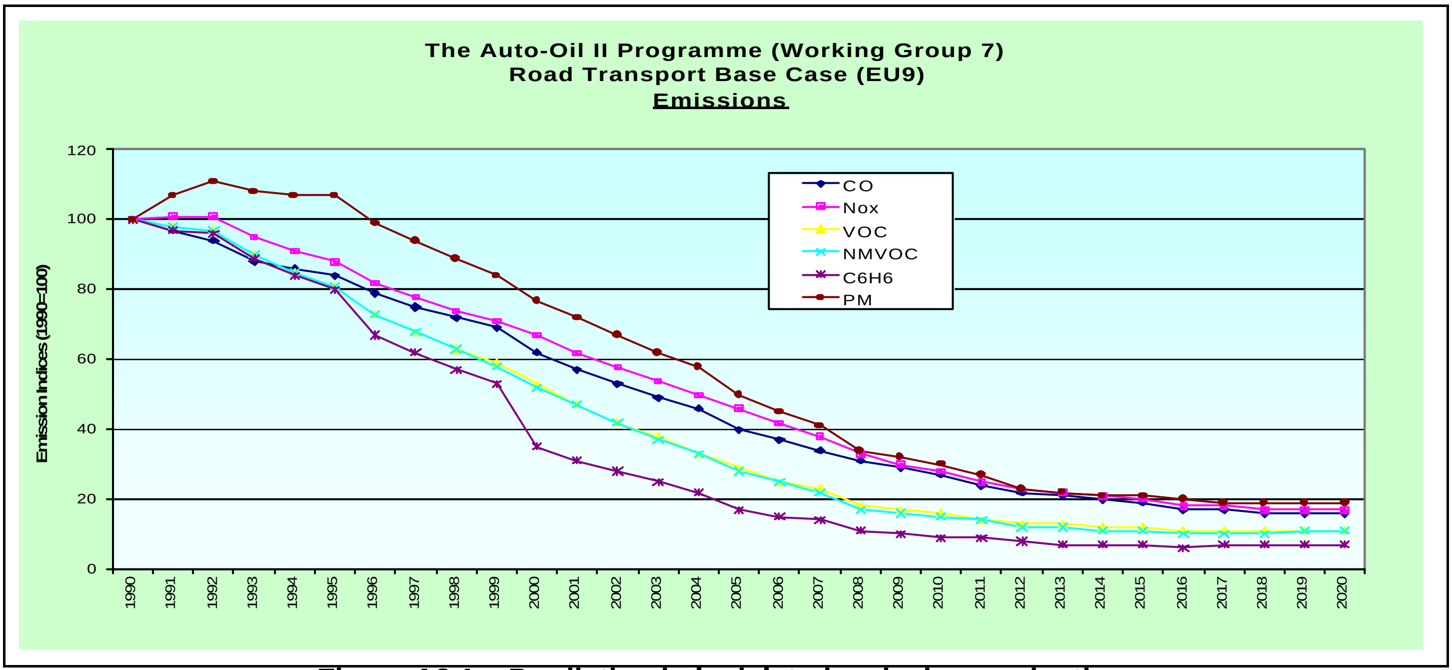


Figure A3.1 - Prediction in legislated emissions reduction

Similar trends are projected for the UK [10], these predictions also indicate:

- A greater reduction in NOx from cars than trucks over the period 1990-2010, suggesting that NOx legislation for trucks will continue to become more stringent after a plateau has been reached for cars
- A short term growth in Pm from Diesel cars over the same period (due to growth in numbers), but this issue being addressed thereafter

For the purposes of this study, the emission targets used in the UK Foresight Vehicle initiative [6] have been used as a guide to likely future legislation. This has necessitated the creation of arbitrary intermediate steps, on a similar 3-5 year increment to that used for past and proposed future legislation.

The Foresight targets for passenger cars apply to all fuel types, and are are:

- Emissions of HC, CO and NOx to be half the forthcoming “Euro 4 Petrol” level (Euro 4 legislation comes into effect in 2005)
- Emission of Pm to be 20% of the forthcoming “Euro 4 Diesel” level
- Emission of Pm0.1 (Particulate with a diameter below 0.1 micron) to be less than 20% of that emitted by a typical “Euro 4” Petrol vehicle

Achievement of these targets will be challenging. Key areas of difficulty will be:

- Technology to measure such low levels of emissions, both for development and certification, and in the annual “MoT” test
- Effective control of very fine particles, some of which may pass through filtration devices
- Control of NOx without excessive penalty to fuel consumption and CO_2
- Escalating cost of emission control equipment, in addition to the cost of low CO_2 technology

APPENDIX B: FUELS AND THEIR SUPPLY

B1 INTRODUCTION

The focus of this study is primarily the technology on the vehicle itself, not the infrastructure which provides the fuel. However, there are some key issues related to fuel supply, which may impact the introduction of new technologies in the following ways:

- Availability of the fuel in sufficient quantities to enable rising penetration of the technology which uses it
- Requirements for fuel properties which enable the new technology to realise its full benefit
- Impact of the process of supplying the fuel to the vehicle, on the "well to wheels" CO_2 emission of the technology

The following sections contain a description of the "well to wheels" methodology, and an overview of other issues relevant to each fuel type.

B2 WELL-TO-WHEELS METHODOLOGY

Before the fuel is used in the vehicle, there are a number of processes that may result in the production of CO_2:

For conventional fuels these are:

- **Extraction:** energy required to operate oil drilling rigs etc
- **Refining:** energy required to operate the refining equipment
- **Storage:** energy required to operate storage facilities at the refinery, oil terminal, depots and filling station
- **Transport:** energy required to move the crude oil or refined fuel from the wellhead, to the oil terminal, the refinery, the distribution depot, and finally the to the filling station and into the car's fuel tank

For alternative fuels, other processes can be relevant:

- **Conversion** from a base fuel, for example the process of making Methanol or Hydrogen from Natural Gas
- **Compression** of gaseous fuels to storage pressure, or **refrigeration to a liquid**. For Hydrogen this alone is a significant factor, sometimes requiring over 10% of the energy in the base fuel to accomplish
- **Leakage** of compressed fuels, or **boil-off** of liquefied fuels. Again this is a significant issue for Hydrogen as its small molecule size makes leakage easy, and its low boiling point makes some evaporation inevitable if it is stored as a liquid

These effects are usually expresses as a "well-to-tank efficiency", that is, the percentage of the original energy contained in the raw energy source (crude oil, for example), which is still contained in the fuel when it reaches the vehicle's fuel tank.

To calculate a “well-to-wheels” CO_2 figure, it is then assumed that the energy “lost” in the process of getting the fuel to the tank, produces the same amount of CO_2 per unit energy as would the burning of the remaining fuel. In practise, the processes of extraction, any number of energy sources may power refining and transport, from coal (which would create more CO_2 per unit energy) to nuclear or renewable (which would produce none). However, it is likely that the major energy sources are crude oil based both to operate the refinery (using the abundantly available crude oil on site) and for transport (using marine or road transport grade Diesel). Hence for conventional liquid or gaseous fuels (Petrol, Diesel, LPG, CNG) this assumption is reasonable. For Hydrogen or Methanol manufactured from Natural Gas, it has been assumed that the process of conversion would be fuelled by natural gas.

The well-to-wheels CO_2 is then calculated as:

Well-to-wheels CO_2 = tank-to-wheels CO_2 / well-to-tank % efficiency

Well-to-tank data is generally well documented in literature, and the values used here are mostly derived from a previous Ricardo study [B1]. For commonly used fuels such as Petrol (Gasoline), Diesel, Natural Gas and LPG, there is good consensus on well-to-tank values [B2, B3]. For proposed future fuels such as methanol and Hydrogen, there is less historical data but typical published values have been assumed [B3, B4]. Here, it is assumed that natural gas is used as the raw material for production of these future fuels.

The data used (as shown in section 2.4 of the main report) is:

Fuel	Well to Tank %
Petrol (Gasoline)	85.9%
Diesel	89.2%
LPG (Average of Refined & Extracted)	88.5%
Natural Gas (Compressed, 300 bar)	92.5%
Methanol (made from Natural Gas)	65.0%
Hydrogen (made from Natural Gas, compressed 300 bar)	66.0%

In the case of Hydrogen, a further calculation is required based on the quantity of carbon dioxide released when the natural gas is converted to Hydrogen and Oxygen:

CH_4	+	H_2O	=	CO_2	+	$3H_2$
Methane (Nat gas)		Water		Carbon Dioxide		Hydrogen fuel

The net effect is that, assuming a best-efficiency process, 22 g of CO_2 is produced per mega Joule of energy in the Hydrogen in the fuel tank. Other sources quote this as being up to 36 g / MJ [B5], other manufacturing processes such as electrolysis from grid electricity made by coal-fired power being less efficient in CO_2 terms.

B3 PETROL AND DIESEL

Issues relating to the use of these fuels in conventional IC engines are well documented elsewhere and have not been considered further here. Known reserves (depending on the source of information) are usually stated as at least 30-

50 years, and it is often said within the oil industry that this figure has not changed much over the last half century. There is growing recognition that this situation will not continue indefinitely, but it is considered likely that there will be sufficient of these fuels available in the UK and European marketplaces to sustain the technology scenarios proposed here.

Key future issues are:

- **Low Sulphur fuel** for Lean NOx aftertreatment
- **Zero Sulphur fuel** for fuel-cell reformers
- **Designer fuels** for new combustion systems

The Hybridisation of the IC engine has little direct impact on these issues, however fuel-cell technologies which run on Petrol or Diesel via a reformer or directly, may be impacted.

B3.1 Low Sulphur Fuel

Low sulphur fuel is required for robust operation of "Lean NOx trap" (LNT) exhaust aftertreatment technology. This is currently favoured technology for passenger car Diesel engines, and is likely to be required for heavier Euro 4 vehicles and more universally at a speculated next stage (dubbed "Euro 5" – for the vehicle in this study, LNT is introduced at this stage). It may also see use in some truck applications, although the "Selective catalytic reduction" (SCR) system, which uses a small Urea tank to treat the exhaust, may prevail in this market. LNT technology is also necessary on lean-burning Petrol (Gasoline) engines such as direct injection ("GDI") and lean-boosted (LBDI) types (Appendix C).

The introduction this decade of 10ppm fuel appears sufficient for these emission controls needs. It has been suggested that, with 10ppm Sulphur in the fuel, sulphur levels in the lubricating oil start to become of similar significance in terms of after-treatment issues.

In markets where LNT technology is used, it is likely that all fuel will become low-sulphur.

B3.2 Zero Sulphur Fuel

Fuel cells and their reformers are highly intolerant to fuel impurities, including Sulphur. It is likely that any Fuel Cell vehicle, or conventional vehicle with a liquid-fuel APU, will require zero-sulphur fuel. While being technically achievable, this type of fuel is likely to cost more, hence there may arise a situation where both fuels co-exist. As with the introduction of unleaded Petrol, this necessitates more complex fuel pumps and the need to prevent the wrong fuel being used.

B3.3 Designer Fuels

Much research is currently being directed at a new type of low-emission combustion. This is known as "HCCI" (Homogeneous Charge, Compression Ignition) or "CAI" (Controlled Auto-Ignition). It is a principle that can be applied to both Petrol and Diesel engines, although the details of its execution differ slightly.

HCCI (see also Appendix C) aims to achieve reduced NOx with improved fuel economy, as it lowers the peak temperature of combustion without lengthening the overall burn period. In both Petrol and Diesel applications, an essentially pre-mixed mixture of fuel and air spontaneously ignites at a variety of sites. Thus it is different from either conventional Petrol (spark ignited) or Diesel (diffusional burn) combustion. It therefore follows that a fuel with different properties to either Petrol or Diesel may be the optimum for this type of combustion. It has even been suggested that Petrol and Diesel technology will converge to a single engine type with a single new fuel.

However, against this idealised picture lie two factors:

- HCCI is only effective over a part of the operating envelope of the engine, over the rest of it, conventional fuel properties remain relevant
- HCCI products will need to be sold alongside conventional ones, hence the need for a new fuel type is an undesirable trait

This issue is unlikely to impact on the technologies considered in this study, and it is likely that any HCCI product will rely on conventional fuels until at least 2020.

B4 LPG

Liquefied Petroleum Gas (LPG) has gained a niche following in the UK and other markets due to favourable fuel taxation and subsidised conversions. LPG vehicles are universally dual-fuel conversions of existing Petrol vehicles, and hence suffer a small loss of power and a compromise to luggage space for the fuel tank (often fitted as a toroidal unit in place of the spare wheel).

A more efficient LPG vehicle could be produced with a bespoke combustion system, however this is very unlikely to happen, because:

- In the short term, the market is unlikely to accept an LPG-only vehicle in sufficient volume to justify it, and
- In the longer term, other fuels and technologies offer lower CO_2

Today’s LPG vehicles tend to produce well-to-wheels CO_2 levels in between those of Petrol and Diesel [B1].

Some operators of tunnels, ferries and car parks do not allow LPG vehicles on safety grounds. It is not known whether this is a real risk, the product of fear of new technology, or the result of malfunctioning poor-quality after-market conversions causing past incidents.

B5 NATURAL GAS

Natural Gas, either as Compressed (CNG) or Liquefied (LNG), is considered attractive by some as a transport fuel because:

- It is reasonably compatible with current IC engine technology, either as a dual-fuel vehicle or a bespoke design
- It has a low Carbon to Hydrogen ratio, hence lower CO_2 emissions
- Known reserves are estimated as being sufficient for upto 300 years, and are reasonably well spread around the globe

CNG passenger vehicles are popular in Latin America, but less so in Europe (Italy having the largest market). Production vehicles tend to be conversions of Petrol cars, and show no CO_2 advantage over Diesel engines [B1]. However, an optimised unit could offer CO_2 levels of 5% or more lower than today's Diesel units. CNG is seen by some as a practical transition fuel to Hydrogen as it can offer competitive well-to-wheels CO_2, and it prepares the compressed-gas infrastructure and vehicle technologies without the leakage and very poor storage density issues of Hydrogen. It is also becoming a popular fuel for depot-fuelled buses in emission-sensitive areas such as California, and for stationary IC engines.

Natural Gas is lighter than air, and will rise if it escapes. This is a cause of concern in tunnels and underground car parks, and prohibition of CNG / LNG vehicles in such places could be a barrier to its uptake.

B6 METHANOL

Methanol is usually manufactured from Natural Gas, although it can also be derived from bio-mass. One of the prime reasons for recent interest in the fuel is its ability to be converted to Hydrogen in the reformer of a fuel-cell vehicle. Methanol has been labelled "the ideal Hydrogen carrier" as it is a liquid fuel with all the handling advantages that this implies. It is also compatible with IC engines, most readily so when blended with Petrol.

However, Methanol is toxic, and can be absorbed by groundwater if it leaks from storage tanks. It burns with an invisible flame, and is corrosive, requiring a higher specification of materials for pipes, tanks, pumps and fuel injectors compared to Petrol or Diesel. The process of manufacture from Natural Gas is not very efficient, hence well-to-wheels performance is poor.

As a long term fuel, Methanol may have the most to offer as a "Hydrogen carrier" as part of a closed-carbon cycle, whereby sequestered CO_2 is used to manufacture Methanol using renewable energy. Such processes have been described to Ricardo but are still very much at the laboratory stage, and their efficiency is unknown.

B7 ETHANOL AND BIO-FUELS

Bio-mass (plant material) may be used to manufacture fuels by:

- Fermentation, to produce alcohol (ethanol), which is often blended with Petrol
- Extraction of oils (Sunflower, Rapeseed), that are then processed to produce Diesel-type fuels

These are, effectively, renewable fuels which produce no net CO_2, provided that all the processes used to produce them (for example, farm tractors) use only these fuels. It is unlikely that such fuels can completely replace crude-oil derived fuels, due to the land required. However, they have a highly relevant place in fuel blends for Petrol or Diesel IC engines, and (if they are manufactured with no input of CO_2-producing fuel) will reduce the well to wheels CO_2 of these technologies in proportion to the energy value of the amount used.

B8 HYDROGEN

Hydrogen may be manufactured by:

- Processing of Natural Gas, Bio-Ethanol and other hydrocarbons
- Electrolysis using grid electricity

The manufacture of Hydrogen will therefore produce CO_2 (as discussed in section B2 above) unless it is made from bio-fuels using only bio-fuel to power the process, or from electricity derived from Nuclear power or renewables.

Hydrogen is easy to see as the ideal fuel, as the (idealised) combustion process produces only water vapour. However its use in vehicle applications presents many real-world issues:

- Well-to-wheels performance of non-renewable Hydrogen is inferior to Petrol and Diesel engines due to the inefficiency of manufacturing and distribution processes
- Real-world use in an IC engine leads to NOx emissions. For the most efficient, lean-burn engine types this requires the use of a Lean NOx Trap (LNT), which is difficult to re-generate in the absence of unburned hydrocarbons (Appendix C)
- Storage requires either a high-pressure tank, or liquefaction (or a number of laboratory stage technologies discussed in Appendix C). Compressing or liquefying the Hydrogen requires a large amount of energy, sometimes over 10% of the total energy in the fuel
- Liquid Hydrogen tanks can be shaped to fit the vehicle, but require costly high efficiency thermal insulation, and are prone to fuel boil-off losses (Appendix C)
- Liquid Hydrogen would cause severe “burning” in case of contact with skin. This necessitates robotized filling stations and extra collision precautions (Appendix C)
- Compressed Hydrogen tanks must be cylindrical or spherical to withstand high pressures (300 – 1000 bar), hence packaging in existing vehicle architectures is difficult, and the tanks are costly to manufacture
- Due to its small molecule size, Hydrogen has a high tendency to leak
- Hydrogen is lighter than air, hence similar issues to CNG would exist with respect to underground parking, tunnels etc

- Hydrogen is (perhaps incorrectly) associated by the public with the Hindenburg airship disaster (although recent research indicates that the highly flammable mix of Iron Oxide and powdered Aluminium used to paint the airship's canvas skin was more likely to have been responsible)

Because of the number of options for making Hydrogen (either short-term or sustainably), its status as an ideal long-term future fuel appears reasonable. However the considerable engineering effort required implementing it in a useable volume-market vehicle should not be underestimated. In addition to the manufacture, distribution and re-fuelling infrastructure, it would require fundamental re-engineering of the vehicle platform to accommodate Hydrogen storage. The engineering of Hydrogen fuelled IC engines or even Fuel Cells may be seen by some as being easier to deal with than these issues.

APPENDIX C: TECHNOLOGY BUILDING BLOCKS

C1 Hybrid Vehicle Battery Technology

Batteries are central to the success of Hybrid Vehicles (HEVs) and present the largest challenges both technically and commercially. Although a few production HEVs with advanced batteries have been introduced in the market, no current battery technology has demonstrated an economical, acceptable combination of power, energy efficiency, and life cycle for high-volume production vehicles.

Desirable attributes of high-power batteries for HEV applications are:

- Energy density – A higher energy density results in a battery that is lighter but can still store the same amount of charge
- Power density – The torque assist and regenerative braking functionality of Hybrid vehicles implies that the battery must be able to rapidly provide/store energy to/from the electric machines
- Operating temperature – The battery must be able to operate in all climatic conditions
- Charge retention – The life of the charged battery if left unused (finite as the charge leaks from the cell)
- Memory effect – The reduction in charge capacity as a result of charging the battery before it was completely discharged (caused by chemical reactions occurring within the cell)
- Cycle life – This is the number of charge-discharge cycles that the battery can withstand before charge capacity becomes too small and the battery needs replacing

Lead acid

Lead acid batteries, used currently in many electric vehicles, are potentially usable in Hybrid applications. Lead acid batteries can be designed to provide high power and are inexpensive, safe, and reliable. A recycling infrastructure is in place for them. But low specific energy, poor cold temperature performance, and short cycle life are still impediments to their use. Advanced high-power lead acid batteries are being developed for HEV applications, in particular valve-regulated lead-acid (VRLA) battery, a more advanced, heavy-duty version of today’s conventional lead-acid battery. It is the most economically feasible at this time but it has less power and a shorter life than advanced batteries.

Nickel Metal hydride

Nickel-metal hydride batteries, used routinely in computer and medical equipment, offer reasonable specific energy and specific power capabilities. Their components are recyclable, but a recycling structure is not yet in place. Nickel-metal hydride batteries have a much longer life cycle than lead acid batteries and are completely safe. These batteries have been used successfully in production EVs and recently in low-volume production HEVs (Toyota Prius and Honda Insight). The main challenges with nickel-metal hydride batteries are their high cost, high self-discharge, heat generation at high temperatures, and low temperature operation.

Lithium-ion

The lithium ion batteries are rapidly penetrating into laptop and cell-phone markets because of their high specific energy. They also have high specific power, high energy efficiency, good high-temperature performance, and low self-discharge. Components of lithium ion batteries could also be recycled. These characteristics make lithium ion batteries suitable for HEV applications. However, to make them commercially viable, further development is needed, including improvement in cycle life and acceptable cost.

Figures C1.1 and C1.2 present a projection over the next 20 years of battery specific energy and cost, the battery's most critical factors for technology acceptance, for the three major technologies considered for Hybrid vehicle use.

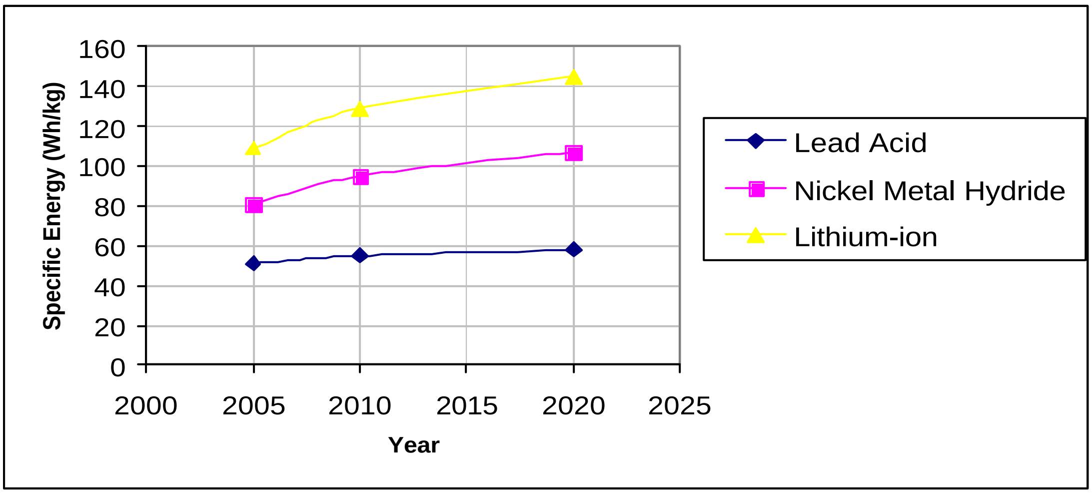


Figure C1.1 - Predictions of battery specific energy over the next 20 years [11]

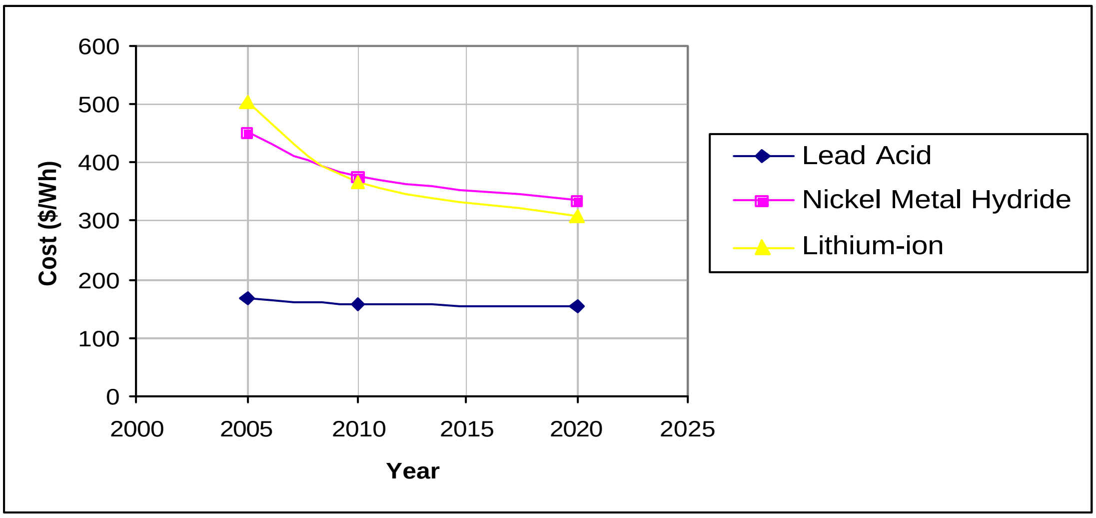


Figure C1.2 - Predictions of battery cost over the next 20 years [11]

Due to their low cost, lead-acid batteries are likely to lead the sales over the next five years. Beyond that, their limitations in terms of power density will see their gradual replacement by Nickel Metal Hydride batteries, which offer a much improved response to power pulses required for torque assist and regenerative breaking. By 2010, Lithium-ion batteries will provide a lighter alternative to Nickel Metal Hydride batteries, as well as improved performance at low temperature. These two types of battery are likely to share the battery market place over the following decade, leading to Lithium-ion becoming the prime product by 2020 [11].

Alternative technology

Ultra-capacitors (UC) may play some part in determining the success of Hybrid vehicles. Named because of their much greater charge capacity than standard capacitors, they can increase battery life by buffering the electrical demand on the battery, and the rapid discharge facility can be used for improved vehicle acceleration. However, they do not allow large energy level storage and so cannot be used to provide continuous power to the vehicle. The power demanded by the drivetrain during a transient cycle is characterised by short duration, high amplitude peaks that may require the battery to be larger than the size required to satisfy the average demand. The UC would allow the battery pack to be reduced in size as it satisfies these transient peaks and it prolongs the life of the battery by minimising peak loading on the battery.

C2 Electric Machine Technology

A standard (non-Hybrid) vehicle uses two different electric motor technologies [12]:

- A permanent magnet direct current (DC) motor for engine start (“starter motor”), which provides high torque to crank the internal combustion engine during engine start-up operation
- An induction alternating current (AC) motor (“alternator”) for battery recharging purposes. These motors’ current generation increases with speed and are therefore well suited when used with ratios of 1:2 to 1:3 between the engine and the motor

Starter motors are only used at engine start-up hence their efficiency has a relatively low impact on the vehicle fuel consumption. However, during the time required to achieve stable combustion (typically one second), a large amount of undesirable emissions from incomplete combustion can be produced.

Current 12V alternators are today reaching the limits of their capabilities. The vehicle electric power demand has increased from a few hundred watts 10 years ago, to 1-1.5kW today. Induced high currents in a 12V systems are responsible for high efficiency losses and require the use of bulky and heavy electrical cables. With the vehicle electric power demand forecasted to reach up to 4kW by the end of the decade on C-D segment cars [13], the need for switching to a higher system voltage is clearly defined.

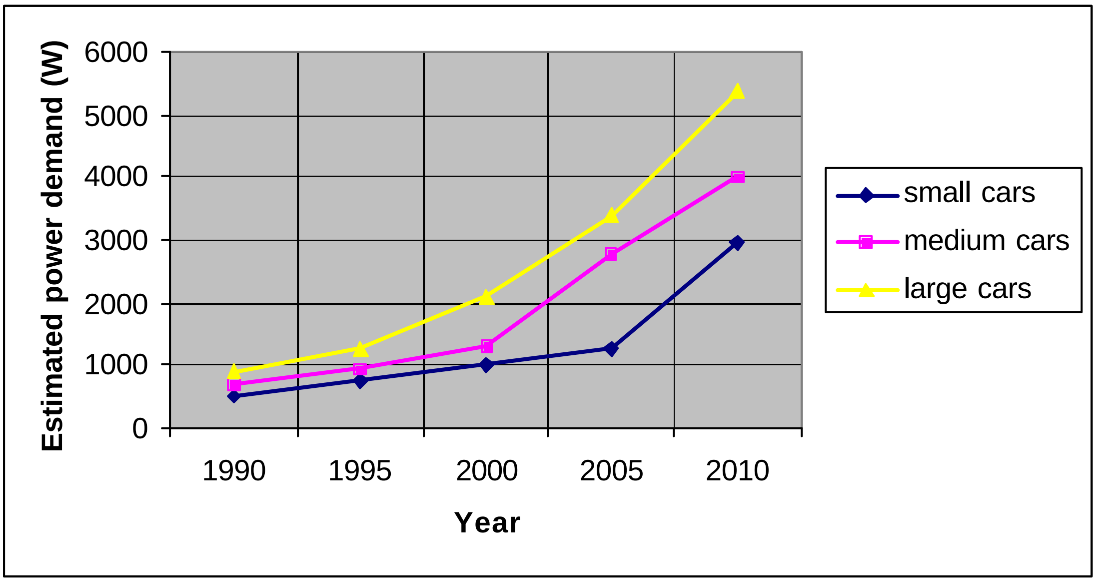


Figure C2.1 - Global Trend of Electrical Power Demand

Integrated Starter-Alternators

The switch to 42V systems is now in motion, together with the use of improved starter-motor and alternator technologies (design optimisation [14]), also made possible thanks to the recent advances in control and electronics technologies. New high power microprocessors, semiconductors and transistors largely contributed to enhanced electronics technologies and have allowed the integration of starter-motor and alternator functionalities into a combined single unit. This unit, linked to the powertrain via a reinforced front-end belt, allows engine start in less than half a second [15]. It benefits from current generation peak efficiency improvements of up to 10% [14] (compared with 50 to 60% for conventional alternators), and is able to recover braking energy to recharge the vehicle battery pack. Stop/start capabilities then become a possibility, further increasing fuel economy in urban driving conditions. Also, the emergence of reinforced belts rated to up to 10kW will allow a launch assist functionality to be implemented.

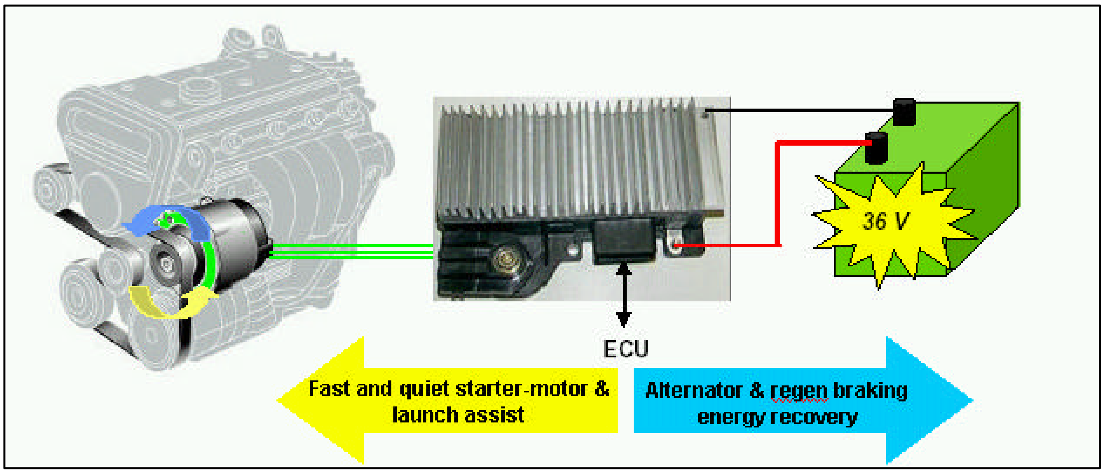


Figure C2.2 - Belt driven 42V Starter-Motor Alternator

The next step will see the relocation of a similar machine directly onto the powertrain, between the flywheel and the transmission clutch. This will provide better packaging, the deletion of the front-end belt, and the possibility to use electric motors of greater power outputs. With the addition of a second clutch to disconnect the motor from the IC engine, this will potentially add ZEV functionality to the vehicle.

Figure C2.3 - Crankshaft mounted Switched Reluctance Motor / Generator

In terms of electric motor technology, there are still some uncertainties as to which technology will dominate the market in the years to come. Brushless DC (BLDC) permanent magnet provide the best peak efficiency (90 to 95%) and weight characteristics, but are the most expensive options. This is mainly driven by magnet cost, which, as a long established and optimised technology, is unlikely to see major cost reductions over the next years. This indeed applies to electrical machines in general, which have been developed and optimised for over a hundred years, hence no major breakthroughs are likely to dramatically reduce cost, weight nor increase efficiency. Most of the machine components are fully recyclable.

As a general rule, machine cost will remain proportional to weight and efficiency, and will only see a slight decrease as production volumes ramp up over the years. Switched reluctance (SR) motors are a good candidate for future applications, as they offer a good compromise on cost, weight, efficiency and robustness.

C3 Power Electronics Technology [1g]

Continuing developments in power electronics allow the full advantage of the developments in motor and battery technology to be realised. Modern automotive microprocessors, "embedded" within the various vehicle subsystems can execute large quantities of calculations in real time, allowing rapid and sophisticated control of the engine (and electric motor, in the case of an electric or Hybrid electric vehicle) and the peripheral systems (such as braking, suspension and steering). Historically these systems have been controlled and actuated by electromechanical, mechanical, hydraulic and pneumatic systems, with each system requiring engine-mounted gear-driven or belt-driven pumps or generators as the prime power source. The performance of these systems has been improved steadily over the decades (efficiency, response time, mass, etc) but the potential offered by modern processor-based control systems is significantly greater. With the constant drive for improvements in fuel economy and emissions, there is now a commercial case for the replacement of the older systems with their superior, electronic equivalents. This ranges from the simple replacement of small pumps and fans to the gradual evolution of the propulsion unit from Petrol to Fuel Cell and beyond.

In most cases, power electronics is the enabling technology that enables the power of the embedded processors to be applied to these new applications. The term applies to electronic circuits where electrical power is switched or converted, usually under the control of a microprocessor. Where the electrical power is used to control peripheral devices such as motors and actuators, purely electronic control of systems such as engines and Hybrid drivetrains becomes possible.

Examples of power electronics in automotive applications:

Present and future examples of power electronics include:

- Electric or electro-hydraulic power steering (EPS / EHPS).
- Speed or position controller for small motors (for windows, seats, ventilation, etc).
- Variable speed control of electric engine cooling fans and pumps.
- Integrated Starter Alternator (ISA) - an efficient, high power generator that replaces both the conventional starter and alternator.
- DC-DC converter (replaces the alternator on electric vehicles and vehicles with ISAs).
- Electromagnetic valve (EMV) drive – replaces the camshafts and cam drive belt.
- Hybrid vehicle or electric vehicle motor drive - replaces or augments the engine, using electrical power to drive the vehicle.
- Electric heating, ventilation and air conditioning (HVAC).
- Steer-by-wire (electric-only steering with no direct mechanical connection).
- Brake-by-wire (electric-only brakes with no direct hydraulic connection).

Why power electronics?

Compared to the traditional engine-driven electromechanical, mechanical, hydraulic and pneumatic systems, appropriate applications of power electronics can deliver a variety of benefits:

- **Improved efficiency.** The parasitic load presented to the engine to achieve the required functionality can be significantly lower than that presented by the equivalent traditional solutions. Ultimately this is seen as a saving in fuel consumption. As the power electronics solution can be optimised for operation independent of the engine speed, the efficiencies of associated motors and actuators is often superior, too
- **Reduced mass.** The mass of a power electronics subsystem is usually considerably lower than the equivalent traditional mechanical solution. This results in reduced vehicle mass, with knock-on benefits in terms of fuel consumption
- **Improved precision and refinement.** By the use of modern embedded processors in these applications, much more precise and rapid control of the system is possible than would be possible using the more traditional methods. (Conversely, it is this very capability that is driving power electronics through the vehicle). Additional interaction with neighbouring

systems is now possible (such as between the engine, gearbox, braking and suspension controllers).

- **Reduced cost.** As the usage of new technology increases, the initial costs become more commercially attractive, particularly when balanced against increasingly stringent legislation and customer expectations. In some cases the like-for-like cost of a given system may increase when it is replaced by the equivalent power electronic system. However, this increased marginal cost may be offset by lifetime savings (through improvements in fuel consumption, emissions, etc) or by improvements in vehicle refinement.

What are the trends in power electronics?

- Advances in electronic device technology and processing power look set to continue steadily past the horizon of this study. These improvements promise year-on-year improvements in the performance / cost ratio, leading to broader application
- More efficient, higher temperature components are being developed that require less cooling and can be applied more comprehensively across the vehicle. The knock-on benefits include lower mass, improved fuel consumption and lower pricing (due to higher device usage leading to economies of scale)
- At a vehicle level, the trend is towards vehicles where traditional functions are replaced by their electrical equivalents. We will soon see IC engined vehicles that are totally devoid of the traditional belt-driven and gear-driven ancillaries. Steer-by-wire, brake-by-wire and electric heating, ventilation and air conditioning (HVAC) will soon become commonplace

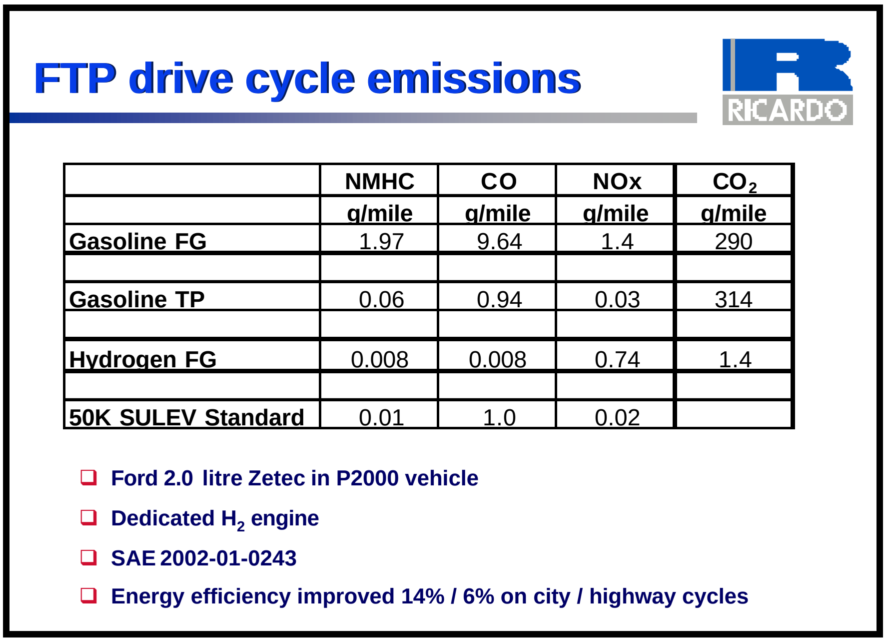
C4 Conventional Internal Combustion Engine Technology

Please see Section 3.10 above for this section. (Added to main text for clarity of reading.)

C5 Hydrogen Powered Internal Combustion Engine Technology

The modifications required to adapt a conventional Petrol (Gasoline) fuelled SI engine to operation on Hydrogen are well understood and outlined below.

The power and torque output of a naturally aspirated Hydrogen engine are 40-50 % less than for the same engine operated on Petrol (Gasoline) [2a]. A torque curve from Ford 2.0 litre Zetec 16 valve dedicated Hydrogen engine is shown in Figure C5.4. Boosting (turbo-charging or supercharging) can restore power and torque. For the same swept volume engine in a C/D class vehicle, thermal efficiency over the NEDC drive cycle will be around 14% better than for Petrol (Gasoline). HC and CO emissions would be low enough to meet Euro 4 or 5 without aftertreatment. NOx emissions would be around 0.5 g/km, requiring an LNT or other lean NOx aftertreatment system, delivering around 90% conversion for Euro 4 engineering targets and around 95% for Euro 5 engineering targets. These values for efficiency and emissions are based on the Ford P2000 vehicle results over the FTP drive cycle shown in Figure C5.1 [3a]. Table C5.1 shows a comparison of US FTP city drive cycle fuel consumption for the Hydrogen fuelled IC engine version of the Ford P2000 car with other advanced variants.



FTP drive cycle emissions

	NMHC	CO	NOx	CO_2
	g/mile	g/mile	g/mile	g/mile
Gasoline FG	1.97	9.64	1.4	290
Gasoline TP	0.06	0.94	0.03	314
Hydrogen FG	0.008	0.008	0.74	1.4
50K SULEV Standard	0.01	1.0	0.02	

- Ford 2.0 litre Zetec in P2000 vehicle
- Dedicated H_2 engine
- SAE 2002-01-0243
- Energy efficiency improved 14% / 6% on city / highway cycles

Figure C5.1 - Ford P2000 demonstration vehicle results

	Fuel Consumption (mile per US gal)
Gasoline fuelled IC engine	27.5
Hydrogen fuelled IC engine	31.4 (gasoline equivalent energy)
Hydrogen fuelled Fuel Cell	56.5 (gasoline equivalent energy)
Diesel with conventional powertrain	63
Diesel with Hybrid powertrain	80 (TARGET)

Table C5.1 - Ford P2000 demonstration vehicle results

Combustion

Table C5.2 compares key properties for Hydrogen and Gasoline relevant to combustion in a spark ignition engine. With a high research octane number (RON) of over 130, conventional knock is not an issue, allowing compression ratios up to around 14.5:1 for a dedicated Hydrogen engine. However, the low minimum ignition energy of Hydrogen leads to difficulties in preventing pre-ignition from hot sources in the combustion chamber. Pre-ignition limits usable air/fuel ratio to leaner than stoichiometric and therefore limits power and torque of naturally aspirated Hydrogen engines. Examples of pre-ignition events are shown in Figure C5.5. In converting an existing Gasoline engine to operate on Hydrogen, a number of measures would be required to reduce the tendency for pre-ignition:

- improved combustion chamber cooling
- calibration for reduced trapped residuals
- improved oil control
- low Hydrogen injection temperature (available with liquid Hydrogen storage)

Inlet manifold backfire has also been widely reported on experimental Hydrogen engines operating on a pre-mixed charge. However both BMW and Ford have reported no problems using sequential port injection. Figure C5.6 shows the injector installation on the BMW V12 Hydrogen engine [1a]. Direct injection would give least risk of manifold backfire, but does not appear to be essential for a successful engine.

In – cylinder emission control is only required for NOx. The measures used are:

- external EGR
- low Hydrogen injection temperature (available with liquid Hydrogen storage)

Property	Gasoline	Hydrogen
Lower calorific value (MJ/kg)	44.4	120
Octane number (RON)	95	130
Minimum ignition energy (MJ)	0.25	0.02
Adiabatic flame temperature (K)	2270	2384
Laminar flame speed (m/s)	0.3	1.9
Stoichiometric AFR	14.5	34.3

Table C5.2 - Hydrogen Fuel Properties

Engine Modifications

As well as improvements to cooling and oil control, other important areas for conversion to Hydrogen would include:

- addition of boosting system or re-engineering of existing boosting system
- fuel injectors
- spark plug and ignition system
- piston
- crankcase ventilation system
- check of engine structure for anticipated maximum cylinder pressure
- electrical equipment (elimination of potential ignition sources)
- ECU, sensors, actuators and calibration
- exhaust aftertreatment (engineering of LNT system)

Development of the first generation of volume production engines would require increased design, development and calibration resources compared to a new variant of a Gasoline engine family, but the introduction of subsequent Hydrogen engines would require comparable resources to Gasoline fuelled engines. Operation on Hydrogen has no fundamental implications for cost, durability and recyclability of the engine. There would be a cost penalty due to the introduction of an LNT and addition or upgrade of the boosting system.

Future Developments and Key Risks

A number of areas require further R&D to reduce technical risk associated with Hydrogen fuelled IC engines.

Boosting systems will be a key technology for future Hydrogen fuelled engines. Practical demonstration vehicles are required to address issues of:

- air management and transient response
- combustion
- control strategy for optimum driveability low engine-out NOx.

Assessment of the cost and benefits of applying direct injection to an automotive Hydrogen engine.

Application of a lean NOx trap (LNT) to a Hydrogen fuelled IC engine is a major risk area. The challenge is dealing with regeneration. Due to combustion limitations, it is unlikely that the engine can be run rich enough to regenerate the LNT. Post injection of Hydrogen, followed by post combustion, will provide excess Hydrogen for regeneration, but there is a risk of an exhaust explosion.

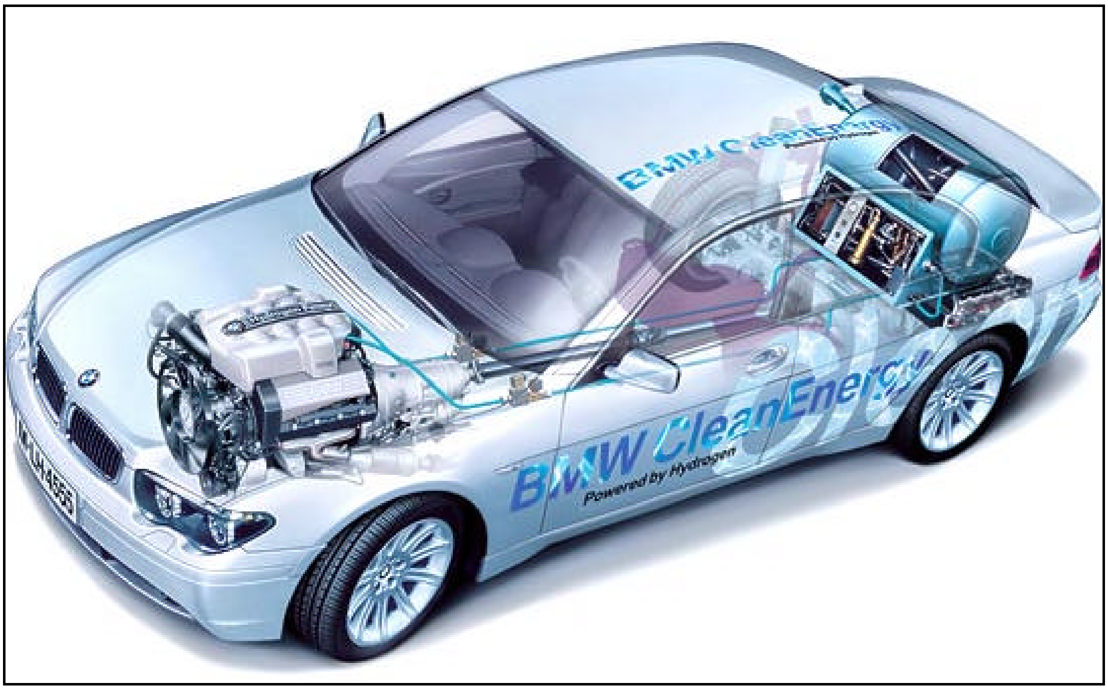
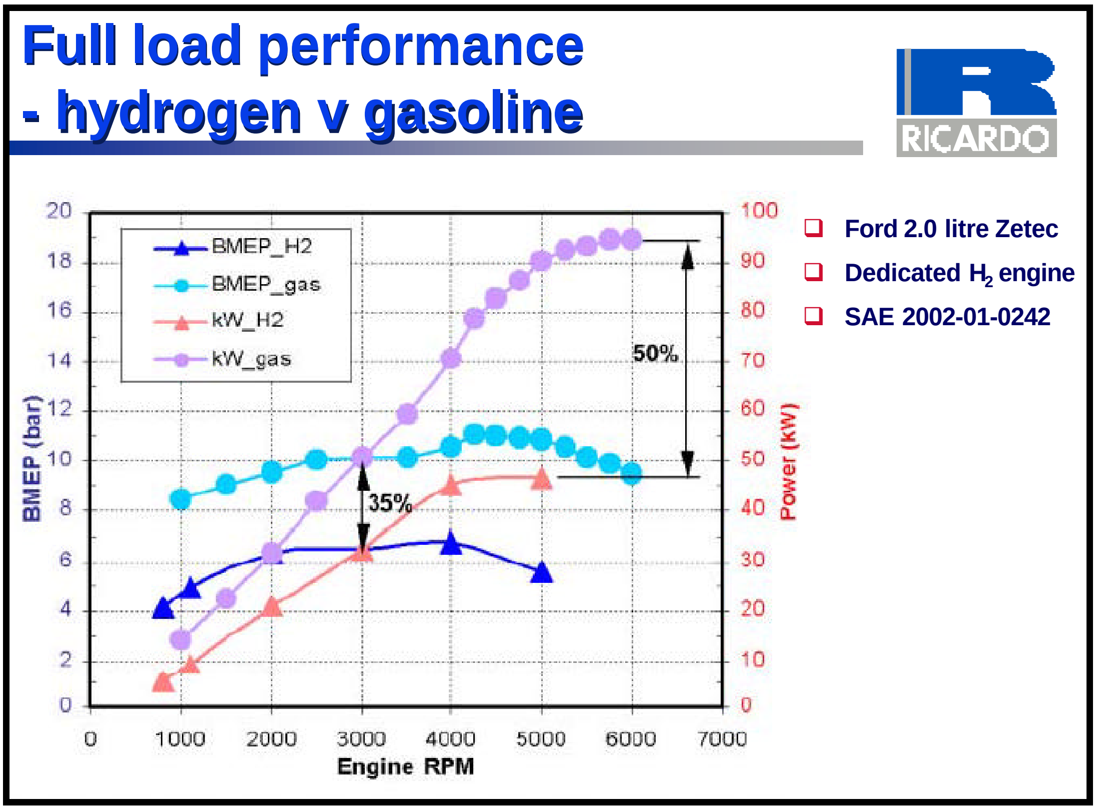


Figure C5.2 - BMW 745h Hydrogen IC Engine Demonstrator

Figure C5.3 - Ford P2000 Hydrogen IC Engine Demonstrator



Full load performance
- hydrogen v gasoline

- Ford 2.0 litre Zetec
- Dedicated H_2 engine
- SAE 2002-01-0242

Figure C5.4 - Full load performance - naturally aspirated – Hydrogen versus Gasoline

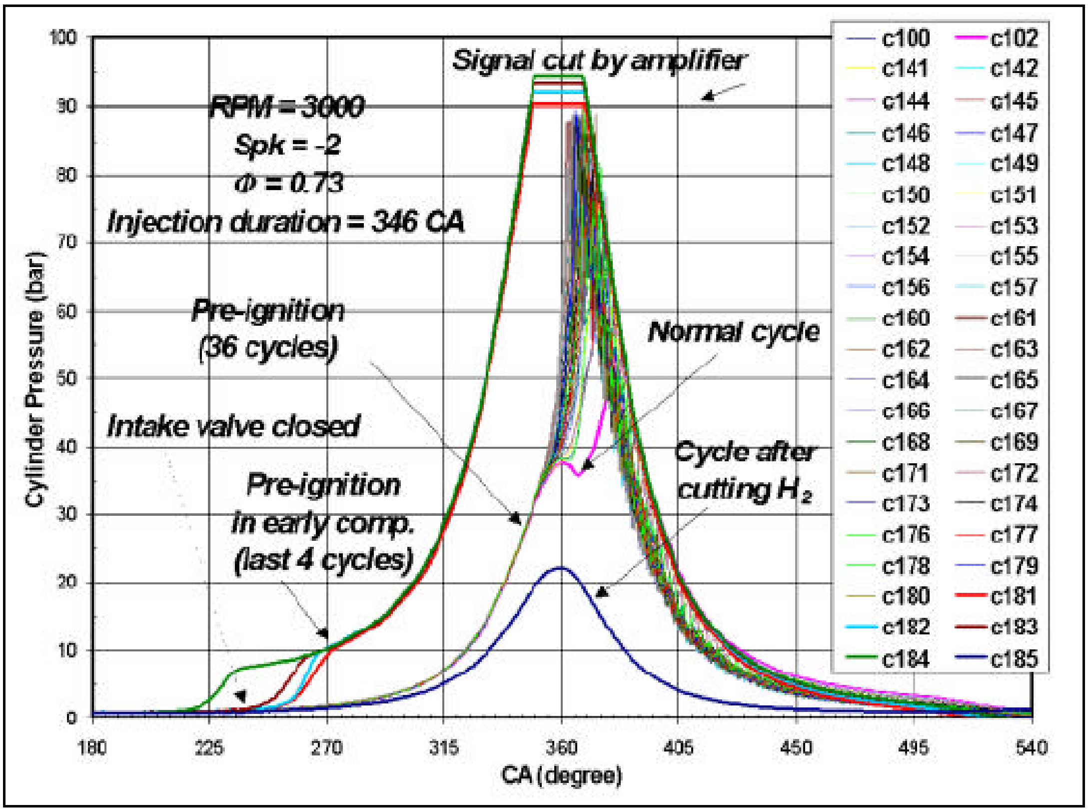
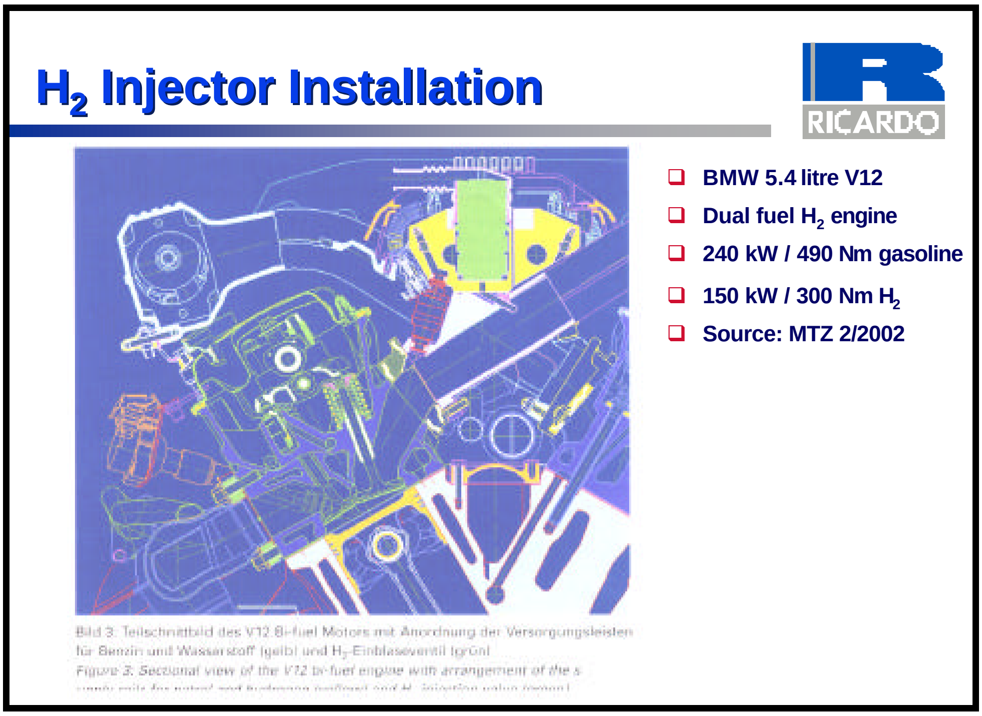


Figure C5.5 - Pre-Ignition events with Hydrogen fuel [2a]



H_2 Injector Installation

- ❑ BMW 5.4 litre V12
- ❑ Dual fuel H_2 engine
- ❑ 240 kW / 490 Nm gasoline
- ❑ 150 kW / 300 Nm H_2
- ❑ Source: MTZ 2/2002

Bild 3: Teilschnittbild des V12 Bi-fuel Motors mit Anordnung der Versorgungsleisten für Benzin und Wasserstoff (gelb) und H_2-Einblaseventil (grün)
Figure 3: Sectional view of the V12 bi-fuel engine with arrangement of the s

Figure C5.6 - Hydrogen injector installation in BMW V12

C6 Transmission Technology

Manual transmissions

Five speed manual transmission is the standard type of gearbox for cars in Europe, and is controlled by the driver through the gear lever and the use of the clutch. This type of transmission has the highest efficiency of all existing systems, about 95% to 97% at high load, and is also the cheapest: US $450 to $550 per unit, depending on volumes [1b, 2b].

Figure C6.1 - Example of five speed manual transverse installed transmission

Fuel economy figures on the emissions cycle are governed by standardised shift-points for manual transmissions, whereas automatic transmissions are allowed to shift gears when dictated by their control strategy. This means that real-life economy comparisons can differ from NEDC test results. Then the driver has full control on the ratio choice and therefore of the engine speed and load, which may lead to run the engine in poor fuel efficiency areas and thus to a poor fuel economy – or vice-versa.

However, even though five speed manual transmissions technology is well proven and well known, there is still room for improvement which could increase the mechanical efficiency by up to 0.5% in the short term future [3b].

The number of speeds has grown from four to five in the past years, with certain sports cars using six speeds. The demand for shorter overall length in the engine compartment leads to three-shaft transmissions, which, compared with two-shaft transmissions are larger and usually more expensive - the latter being more of a problem in price-sensitive vehicle segments. Today, six-speed manual transmissions for front-transverse drivelines are still fairly rare, and some sources suggest only limited growth in demand for this configuration [4b].

A six speed manual transmission is about $80 to $160 more expensive than a five speed manual one [1b] and current production vehicles for which both options are available do not show any significant fuel economy improvement with a six speed gearbox [5b]. This may be due to the way the European emissions cycle is driven with a six speed transmission: the sixth ratio is only used for a short portion of the extra-urban part, having as a consequence only a small impact on the overall fuel consumption. The mechanical efficiency of a six-speed manual transmission can also be up to 1 - 2% lower than for five-speed manual transmissions [1b].

Automatic transmissions

Almost standard equipment in the US, this self-shifting gearbox uses a torque converter to smooth the changes. It is slowly growing from four-five to six speeds in Europe.

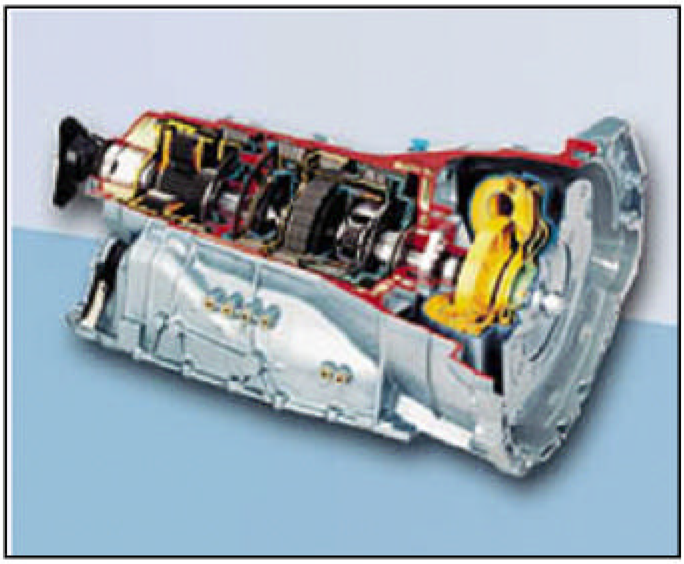


Figure C6.2 - 6 speed automatic transmission

However, for the purpose of CO_2 reduction this type of transmission is not a good candidate as it is more expensive ($1000 to $1200) [1b, 2b], it weighs more (30 to 40kg extra) [6b, 7b] and has a much poorer fuel economy than a manual transmission. Current production vehicles of the C/D segments equipped with a Diesel engine and a five speed automatic gearbox show fuel consumption figures up to 24% higher than the same models equipped with a five-speed manual transmission [5b].

Future technology seems to lead to lighter units, as proven by the new six speed automatic transmissions on the market [7b] and the next products could have an improved fuel economy by up to 7% [8b]. But this is still far from what manual transmissions can achieve.

Continuously Variable Transmissions (CVT)

There are many different concepts based on the same focus: getting away from the limited number of ratios offered by conventional planetary transmissions (even if the number of ratios increases for them) and being able to change ratio more quickly and smoothly. Therefore CVT's are based on radically different technology.

The first category of CVT's vary ratios by means of a variator, with axial repositioning of a conically shaped pair of discs between which a chain or a belt transfers torque. So far the limited torque capacity of this type of CVT's has restricted their application to small vehicles with low power engines but recent developments have demonstrated significant progress which could lead the application of this type of transmissions to Diesel engines in the near future.

The efficiency of CVT's is around 92% depending on the type of belt or chain they use [1b, 9b] but this is a maximum values at high load and high reduction ratio. This value can drop dramatically at lower load and reduction ratio. Mid term developments could raise the overall efficiency to 95% [1b].

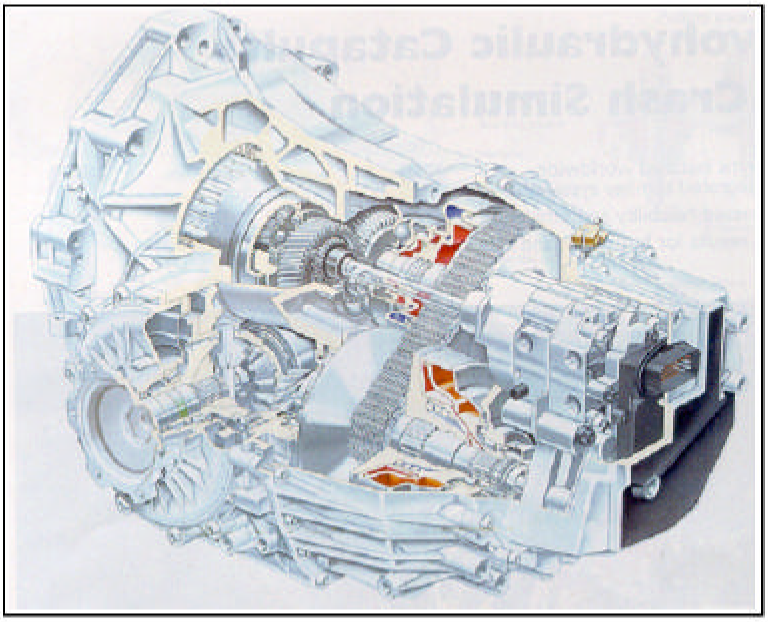


Figure C6.3 - Continuously Variable Transmission

However the theory behind CVT's is that they should allow the engine to work in fuel efficient areas by continuously adapting the transmission ratio function of the driver's demand, thus reducing the overall fuel consumption. But this requires quite a radical change in engine design as engines and their controllers are currently developed to be able to operate in a very large speed and load range and to respond quickly to transients. But to take full advantage of CVT's capabilities, engines need to be redesigned to operate over smaller speed ranges and spend more time operating in the resulting expanded emissions and fuel economy sweet spots.

Therefore current production vehicles equipped with CVT's applied to non specifically designed engines generally produce fuel consumption values higher than with a five speed manual transmission for the same vehicles: up to 18% increase (Gasoline engines; currently no Diesel application). Only one application demonstrates a small fuel consumption decrease by 1.2% [5b].

Literature gives potential fuel savings of up to 3.5% on the European emissions cycle with current belt CVT technology [10b].

CVT's are about the same price as automatic transmissions, from $1100 to $1200 per unit [1b, 11b], and weigh about twice as much as a manual transmission [6b]. Their very specific way of operating – and its consequences on engine speed – can be disturbing for drivers used to conventional transmissions and can be a barrier to market penetration.

The toroidal transmissions are another type of CVT's, even if strictly speaking they are called Infinitely Variable Transmissions (IVT's). They are based on a simple arrangement of input/output discs and variable angle rollers that run between them, without the need for the CVT belt. Unlike other CVT's they are able to run all the way seamlessly between forward and reverse gears without the need for a clutch even if the vehicle is stationary.

The British company Torotrak developed and patented the system and continue to develop it for a number of car and gearbox makers around the world.

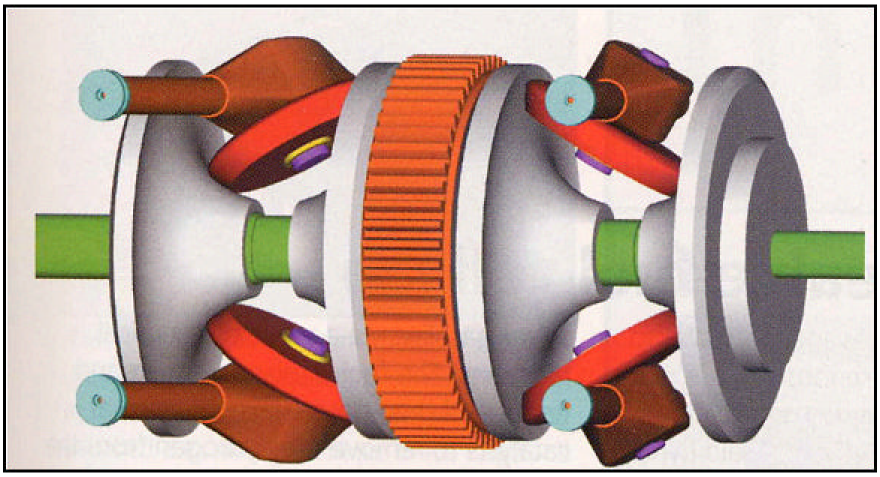


Figure C6.4 - Cross section of an initial stage of a toroidal-type transmission

The efficiency of this device is around 91% and could be increased to about 93% by mid term developments [3b]. It can transmit high torque but there are still some issues concerning durability and use in extreme climatic conditions [6b, 13b]. It is also cumbersome, weighs around 100kg and is expensive to produce [6b]. Only very marginal applications are currently on the market.

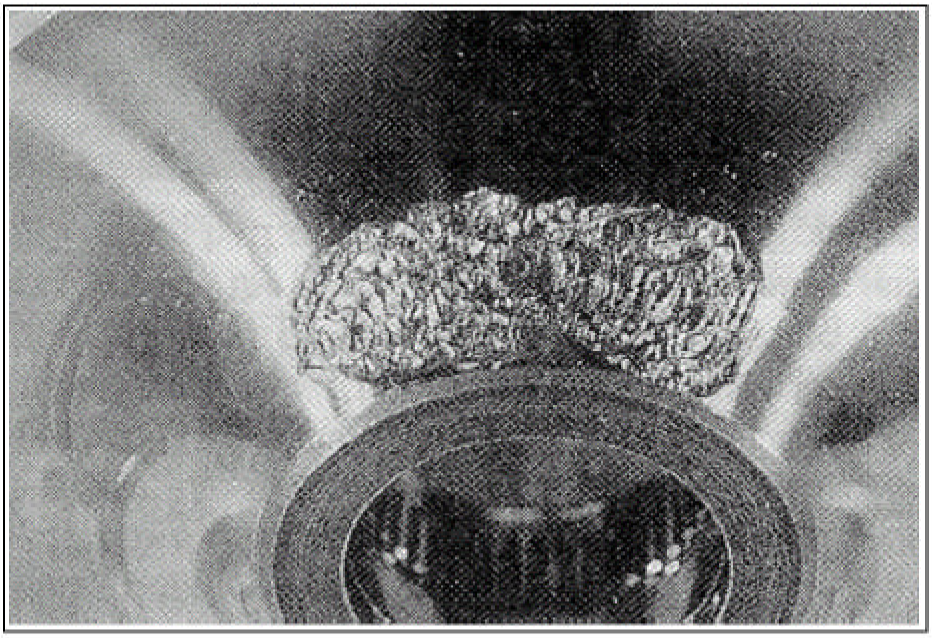


Figure C6.5 - Wear on a toroidal transmission

Automated Manual Transmissions (AMT's)

Automated manual transmissions of the first generation (AMT1) use a standard manual gearbox, with an "add on" that allows automated actuation of the clutch and of the gear selection/engagement. The automation can either be electrically or hydraulically powered and usually the transmission is able to work either on a fully automatic mode (no input from the driver apart from the accelerator pedal one) or on a manual mode where the driver can ask for up-shifts or down-shifts via buttons for instance on the steering wheel or a lever.

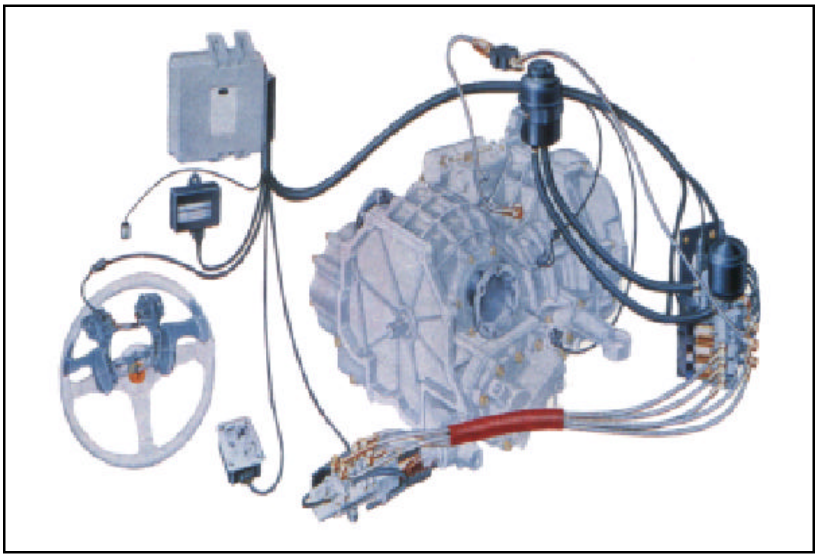


Figure C6.6 - Automated Manual Transmission, first generation

The efficiency of these devices is around 92 to 95% [1b]: the mechanical efficiency is actually higher, similar to the one of a conventional manual transmission but the automation causes some losses. The total weight of the system is not much greater than for a manual transmission (about 10% more) [4b] and thanks to a better management of the gear changes the fuel economy should be improved: some sources claim by up to 10% in fully automatic mode [6b]. For some current production vehicles the gain on fuel economy is around 5% [5b]. The cost of the system is around $110 to $160 higher than for a conventional manual transmission [1b].

However, the system does not only present advantages: the hydraulic units can leak whereas the electric ones are slow to operate the gear shifts. And because of the use of a conventional clutch, the torque interruption during the shift – when the clutch is open - can be badly perceived by the driver whose expectations in terms of shift quality are greater than with a normal manual transmission.

As for the first problems, the introduction of 42V systems should solve them. Hydraulic systems are then likely to be abandoned and more powerful electric devices could be used thanks to the higher available voltage. No more leaks and faster shifts, but still torque interruption [14b].

The solution to this dilemma could be found in the second generation of automated transmissions (AMT2's), as well known as Dual Clutch Transmissions (DCT's). According to many specialists, this could be the transmission of the future [1b, 15b, 16b].

The DCT is based on a conventional transmission. It consists of two, linked layshaft transmissions with two power paths: one for even, the other for odd gear numbers. When it is time to shift, the clutch on the driven path disengages as the clutch on the other path engages. By overlapping the operation of the slipping clutches it is possible to have continuous power delivery to the wheels, which greatly helps the feeling of shift speed and quality.

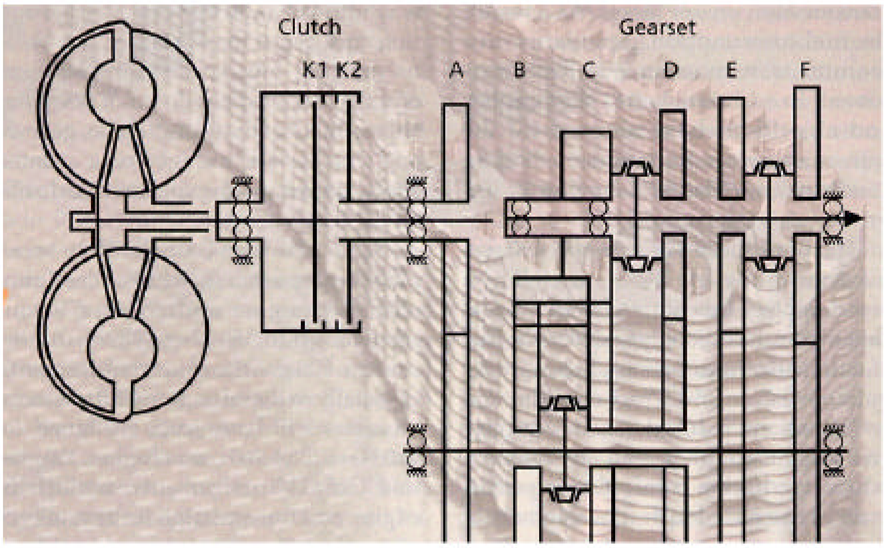


Figure C6.7 - Dual clutch transmission

The efficiency of this type of system is around 89% to 93% [1b] and its cost between $850 and $900 [2b]. The fuel economy is about 1% worse than AMT1's due to the presence of the two clutches [16b]. Technical developments on transmission fluid, friction material and clutch slip control are still required for widespread applications. The only characteristic of this system that may restrict its popularity could be its limited ability to skip gears, contrary to conventional manual and automatic transmissions as well as AMT1's [4b].

Other transmissions

The Antonov system is a cost-effective solution for a four or six speed small/medium car automatic gearbox and is under evaluation by a number of car and transmission companies. Its key benefits are that there is no interruption of the drive during gear changing and that it is compact and inexpensive to manufacture. [14b]

The principle of this system is based on the use of the axial thrust that naturally occurs meshing gears that have helically-cut teeth (that is all gears in cars) and the centrifugal force created by rotating bodies – which includes transmission components. By using these forces, there is virtually no more need of high pressure hydraulics which are one main cause of poor fuel economy in conventional automatic transmissions.

The estimated cost of this transmission is $600 to $700 and it is claimed that it could achieve a similar fuel economy to manual transmissions, subject to being developed to its full potential [17b].

C7 Fuel Cell Technology

A Fuel Cell is an electrochemical device that combines fuel and an oxidant to produce electricity. The fuel is typically Hydrogen and oxygen the oxidant. Water and heat are the only by-products. The conversion of Hydrogen and oxygen to water and electricity takes place without combustion, and is therefore highly efficient. The Fuel Cell functions similarly to a battery (converting electrochemical energy to electrical energy) however it does not need to be recharged as long as fuel and oxygen are available.

Fuel cells are widely tipped as being the power units of future due to their high efficiency and low emissions. However, there are still significant technical and economic challenges to be overcome.

There are several Fuel Cell technologies, generally distinguished by the type of electrolyte. Showing the most promise for automotive applications is the proton exchange membrane (PEM) Fuel Cell. PEMFC are favoured for automotive applications because they have relatively high power density, operate at low temperatures, permit adjustable power output, and can be started relatively rapidly. These positive attributes outweigh its disadvantages of lower efficiency (compared to other Fuel Cell technologies) and low tolerance for carbon monoxide contamination [1c].

The choice of fuel is one of the most intractable problems for implementing FCVs [2c]. The choice is between on-board storage of Hydrogen and on-board processing of a liquid fuel (i.e. methanol and Gasoline). The table below summarises possible routes:

System	Technology of Fuel Processors				Construction of Infrastructure for Fuel
	Reforming Temperature degC	Production of Hydrogen H_2kg/liter of fuel	CO_2 emissions CO_2/kg/liter of fuel	Technology	
Hydrogen (onboard)	-	-	-	No problems (unnecessary)	Fairly difficult
methanol	about 260C	0.15	1.08	Relatively easy	Slightly difficult
Gasoline	700-800C	0.301	2.16	Relatively difficult	No problems (already available)

Table C7.1 - Fuel cell technology options [3c]

A vast majority of experts and OEM believed that pure Hydrogen Fuel Cells are the ultimate goal [4c]. Direct Hydrogen provides the highest efficiency and zero tailpipe emissions. However, Hydrogen has a low energy density and boiling point [1c] and requires an extensive new fueling infrastructure. At the present time there is no cheap convenient solution to on-board storage of Hydrogen with sufficiently high energy density to give good vehicle range [2c].

On-board reformation of a hydrocarbon fuel into Hydrogen-rich gas mixtures allows the use of more established infrastructure, but adds weight and cost, reduces vehicle efficiency, and creates some emissions [1c]. Additionally, reformer technology is relatively immature [3c]. A reformer converts hydrocarbon fuel to a synthesis gas of carbon monoxide and Hydrogen by heating to 700-1000°C (over a catalyst). This gas is reacted with steam, which splits to form additional Hydrogen and CO_2. Remaining CO needs to be removed to avoid contamination of the Fuel Cell. Reformer technologies include steam reforming, partial oxidation and autothermal reforming. Steam reforming is the most developed and least expensive method for producing Hydrogen on a vehicle, resulting in a 45-70% conversion efficiency that is limited by the endothermic nature of the reactions [1c]. Reformers have a relatively slow dynamic response and addition of ultra-capacitors may be needed [5c] for transient boost. Gasoline reformers add around 30% in cost and complexity over a methanol reformer [6c]. Companies developing on-board fuel processors include Nuvera Fuel Cells, Johnson Matthey and Hydrogen Burner Technologies [4c].

Reported Fuel Cell efficiency varies considerably, and the definition of efficiency is not always clear so care the numbers quoted must be taken in context of the original document. The efficiency of energy conversion available in the fuel into electricity is calculated for a single cell by divided the cell voltage by the ideal voltage (1.16V at 80C 1atm) [7c]. Efficiency of conversion of fuel to electricity is high at around 50% [8c]. Fuel cells are typically 30-40% efficient in automotive sizes, and up to 50% with pure Hydrogen [9c]. Fuel cell stack conversion efficiency is from 45 to 70% (compared to 30-40% typical of ICE). The Ballard Mark 900 FC (In the Ford Focus FCV) has a reported thermodynamic efficiency of between 60 and 70% [10c]. Fuel cells tend to have high efficiency at low loads [1c], this can be seen in the the GM Stack2000 has characteristic in Figure C7.1 [11c].

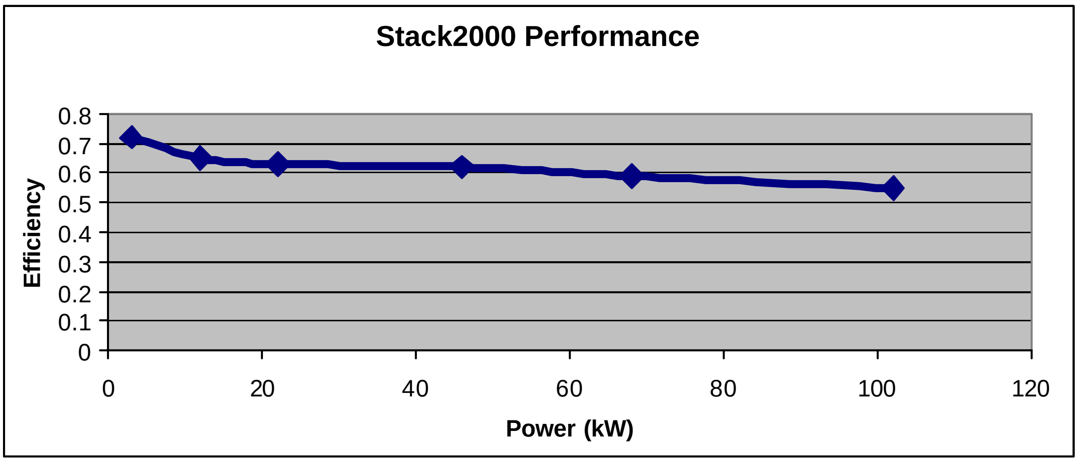


Figure C7.1 - GM Stack2000 efficiency characteristics

The specifications of the latest stack from Ballard is the Mark 902 85kW, 805x375x250 (76L), 96kg giving a power density of 0.89kW/kg and a specific power of 1.12kW/L. In comparison the latest GM stack (2001) specifications are: 102kW (129kW peak), 140x830x500mm (57.4L), 82kg, 640 cells. Figure C7.2 shows recent advances in GM automotive stack development that it claims has the best gravimetric and volumetric efficiency in the world [11c]

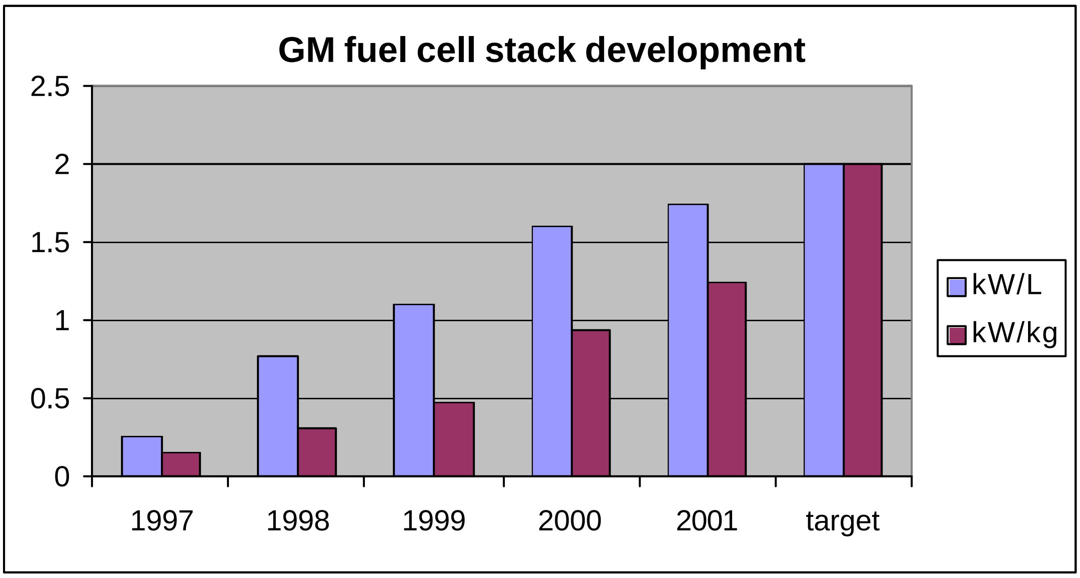


Figure C7.2 - GM Fuel Cell stack specific power evolution

Taking GMs target figures of 2kW/L and 2kW/kg with a desired power output of 80kW gives a future power unit weight of 40kg and 40L. For the current best reported technology an 80kW stack would be 45L and 64kg. (+ ancilliary devices inc storage facilities etc). The Fuel Cell technology in terms of power density is already suitable for automotive applications. Work needs to focus on reducing the cost of production.

The current costs are an order of magnitude too high [5c]. A projected cost breakdown of the stack manufactured in high volume shows that the majority of the cost resides in the catalyst and bipolar plates (Figure C7.3). [5c] reports that the bipolar plates are made from machined graphite and are not suitable for high volume manufacturing; however, Ballard’s strategic supplier (Graftech) has claimed to make flowfield plates from a flexible graphite material which is suitable for volume production [12c]. It should be noted that reductions in catalyst loading for stacks operating on reformate have not been achieved as they have for stacks operating on Hydrogen. Therefore reformate tolerant stacks are expected to cost more [5c].

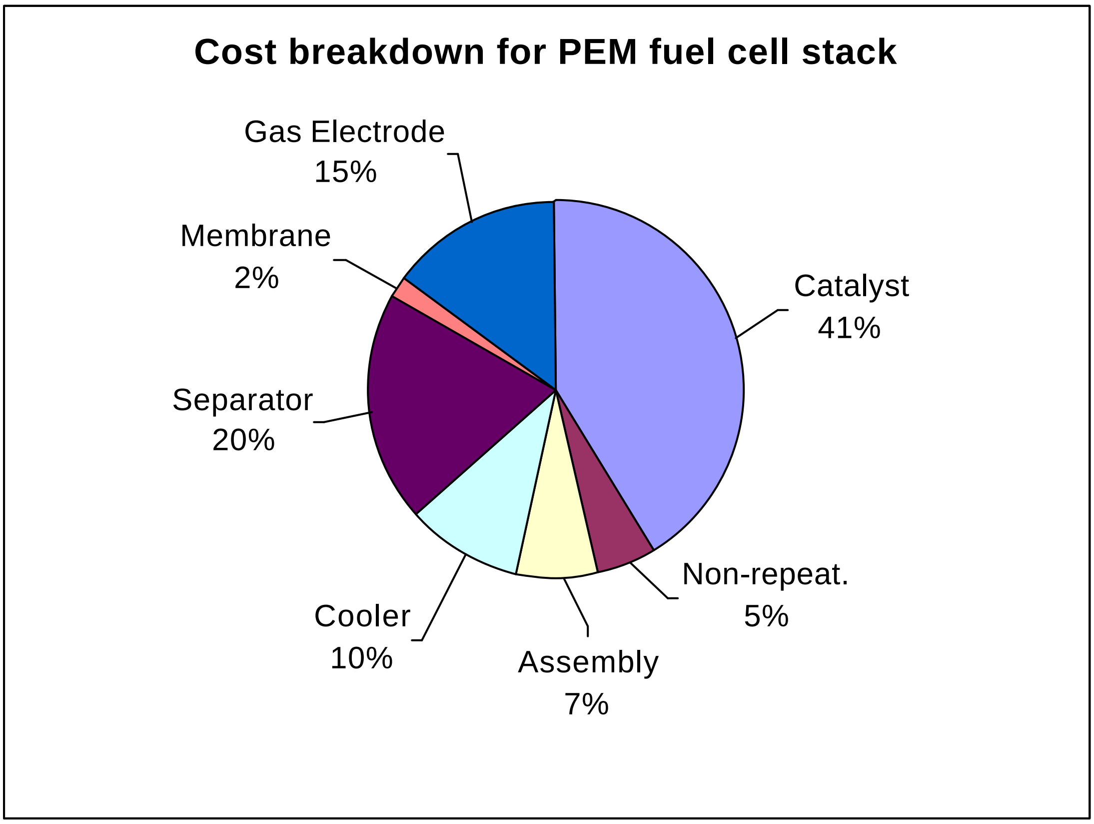


Figure C7.3 – Projected cost breakdown of Fuel Cell stack [5c]

A typical target is $4000 for the complete driveline (including reformer or Hydrogen storage tank) [2c]. There are predictions that the total stack cost could be as low as $20/kW on production of 250,000 FCVs, with a cost of $35/kW in early years. A target cost of the whole system (including turbo-compressors, power conditioners) is targeted at $40/kW (+$20/kW for an onboard reformer) [13c]. Other estimates are $50/kW or $100/kW for the entire system [14c]. Thus the predicted cost for an 80kW Fuel Cell unit is of the order $1,600-$4,000 for the stack and $3,200-$8,000 for the whole system.

As seen in Figure C7.3, a large part of the cost of the Fuel Cell system is the platinum catalyst. For direct Hydrogen FC the amount of catalyst material has dropped by an order of magnitude in the last few years, however for FC using reformate this has not been the case. Research estimates that a further reduction of platinum by a factor of 5 to 10 appears possible [1c, 5c] (the best way of reducing the amount of catalyst is to construct the catalyst layer with the largest possible surface area). Strategic studies are needed on the availability and costs of precious metal [2c], however using the average cost of platinum over the last decade ($429.50/troy ounce), and assuming 0.84gPt/kW then we would require $928 worth of Pt in a 80kW FCV [3c]. The current overall Pt content of a Fuel Cell powertrain is around 4g/kW [1c]. Thus, for an 80kW Fuel Cell, and assuming assume an order of magnitude reduction in platinum loading then we would require 32g of Pt - this is comparable to the GM estimate of a total of 35g in the reformer and stack (currently 70g for GM Stack2000) [6c]. If we assume that the catalyst is 41% of the mass produced stack (Figure C7.3), and that the 32g Pt is all in the stack then a cost estimate for an 80kW Fuel Cell stack is $1236 ($15.45/kW). Opportunities exist in finding alternative, cheaper catalysts which promote a high rate of oxygen reduction (the rate limiting step in the process) [7c]. It is expected that the platinum will be able to be recycled [13c, 14c].

There is strong competition between the OEMs, most of which have large research effort in progressing Fuel Cell technology. Several have built prototype vehicles and most claim that FCV will be available for purchase before the end of the decade.

Features	**Daimler Chrysler**	**Daimler Chrysler**	**General Motors**
Vehicle	NECAR 4A	NECAR5	HydroGen 1
Platform	A-Class	A-CLASS	Opel Zafira
Body Style	4 Door	4 Door	Van
Overall Length	3.57 m	3.57 m	4.32 m
Overall Width	1.72 m	1.72 m	2.00 m
Wheelbase	2.42 m	2.42 m	2.69 m
Curb Weight	1750 kg	1430 kg	1570 kg
Fuel	Compressed H_2	Methanol	Liquid H_2
Fuel Pressure	35 MPa	--	--
Range	190 km	480 km	400 km
Top Speed	145 km/h	150 km/h	135 km/h
Fuel Cell	Ballard Mark 900	Ballard Mark 900	GM 60 kW PEMFC
Electric Motor	55 kW	55 kW	56 kW

Features	**Ford**	**Volkswagen**	**Honda**
Vehicle	Focus FCV	Bora hymotion	FCX-V3
Platform	Ford Focus	Volkswagen Jetta	EV Plus
Body Style	4 Door Sedan	4 Door Sedan	2 Door
Overall Length	4.34 m	4.38 m	4.05 m
Overall Width	1.76 m	1.73 m	1.78 m
Wheelbase	2.62 m	2.51 m	2.53 m
Curb Weight	1727 kg	N/A	1750 kg
Fuel	Compressed H_2	Liquid H_2	Compressed H_2
Fuel Pressure	24 Mpa	--	25 Mpa
Range	160 km	355 km	180 km
Top Speed	128 km/h	145 km/h	130 km/h
Fuel Cell	Ballard Mark 900	Ballard Mark 900	62 kW Ballard PEMFC
Electric Motor	67 kW	75 kW	60 kW

Features	**Toyota**	**Hyundai**	**Nissan**
Vehicle	FCHV-4	Sanda Fe FCV	Xterra FCV
Platform	Highlander	Hyundai Santa Fe	Nissan Xterra
Body Style	SUV	SUV	SUV

Overall Length	4.68 m	4.50 m	4.52 m
Overall Width	1.83 m	1.84 m	1.79 m
Wheelbase	2.72 m	2.62 m	2.65 m
Curb Weight	N/A	1615 kg	N/A
Fuel	Compressed H2	Compressed H2	Compressed H2
Fuel Pressure	25 MPa	35 Mpa	25 Mpa
Range	250 km	200 km	
Top Speed	150 km/h	128 km/h	120 km/h
Fuel Cell	90 kW PEMFC	IFC S300	Ballard Mark 900
Electric Motor	80 kW	65 kW	N/A

Table C7.2 - Current Concept Light-Duty Fuel Cell Vehicles [1c]

An alternative technology is the direct methanol Fuel Cell (DMFC). In this special type of PEM liquid methanol is oxidised directly at the anode so no reformer is required. DMFC technology has advantages including consumer acceptance of the fuel, less new infrastructure and it does not require bulky and heavy Hydrogen storage or reforming subsystem [5c]. However, the cell efficiency is significantly lower than Hydrogen Fuel Cells, more platinum is needed and there is a problem with methanol crossover [5c, 7c]. Daimler-Chrysler and Energy Ventures [4c] are conducting research in this area.

If the Fuel Cell is also designed to operate in reverse as an electrolyser, then electricity can be used to decompose water into the gaseous components oxygen and Hydrogen. Such a dual-function system is known as a reversible or unitized regenerative Fuel Cell (URFC) [15c]. The advantage of reversible Fuel Cells is that they could enable direct Hydrogen FCV without the need for expensive infrastructure. URFC might be useful as long as the electrolysis takes place in a reasonable time scale. The disadvantage of using Hydrogen produced using electricity derived from fossil fuels is that it produces significantly more greenhouse gases than burning Gasoline in an ICE [7c]. There is a cost involved in making the Fuel Cell reversible [7c, 15c].

Some consider solid oxide Fuel Cells (SOFC) as suitable for auxiliary power units (APUs) in vehicles [8c], or for heavy-duty vehicle propulsion [1c]. SOFCs have a ceramic electrolyte and operate at high temperatures (600-800°C). SOFC is compatible with conventional Petroleum fuels, with a simple partial oxidation reforming process (requiring no noble metal catalysts). It has less stringent requirements for reformer quality (using carbon monoxide directly as a fuel) and less sensitivity to contaminants such as sulphur. There are no issues with humidification and water management is not required. High fuel-to-electricity efficiency >50% can be obtained [16c] (up to 60% [17c]). Delphi Automotive Systems and BMW and Global Thermoelectric are developing this [1c, 4c, 16c, 18c]. The SOFC APU can produce the equivalent amount of power as a mechanically driven generator with 46% less Gasoline (generator uses 1.5L) [18c]. Stack power per volume including the manifolds is currently 0.2kW/L, the projection is 2kW/L [16c].

FCV design challenges.
Vehicle cost, higher temperature operation, better powertrain density, water management, precious metal content, compatibility with environmental conditions, start-up time, system life.

Heat rejection at low driving temperature difference requires large radiator and fan system. To reject 80kW at 80C to an ambient temperature of 45C requires a radiator of the order of 0.8m2 [Ricardo experience]. This is of the order of 1.5 times larger than a compatible ICE vehicle [5c].
An opportunity in improving the thermal management requires development of higher temperature electrolytes, which are not limited to the boiling point of water [3c, 7c].

Development of non-conducting coolants capable of operating at sub-zero temperatures [5c]

C8 On-board Hydrogen Storage Technology

At present, the automotive industry is still pondering what fuel will be best suited for feeding Fuel Cell vehicles in the short term. On a longer term, regulation pressures for ZEV (Zero Emission Vehicles) and mounting interest in renewable energies suggest that Hydrogen may become the one and only energy source for Fuel Cell vehicles.

Byron McCormick, Co-director of General Motors' Global Alternative Propulsion Centre in Germany explained in the March 2000 edition of Automotive Engineering International: "The road to an affordable and consumer fuel-cell vehicle has three stages. First, we need Fuel Cell systems that will work in vehicles in the near-term, and that means processor-based Fuel Cell systems running on a readily available fuel that is familiar to the customer, such as Gasoline. Second, as the technology and innovations continue, we'll need safe and reliable onboard vehicle Hydrogen storage systems. Finally, we'll need a distribution system that delivers Hydrogen to locations convenient for the customer."

Although BMcC's first point is still being debated, the emergence of Hydrogen as the fuel of the future is widely recognised; on-board Hydrogen storage therefore constitutes one of the biggest challenges that the automotive industry needs to address.

The current methods of Hydrogen storage being developed are:

- Compressed Hydrogen in high pressure tanks. This offers the least expensive method (circa $750 for a 5000psi tank, as opposed to $125 for a Gasoline tank) for on-board storage. Daimler-Chrysler and Hyundai are now using pressure vessels capable of 5,000psi. Research work is currently conducted to look at pressure vessels of up to 10,000psi, which would permit a 645km driving range. However the main problem is size, as light duty vehicles offer relatively small platforms to accommodate pressure vessels [1d]

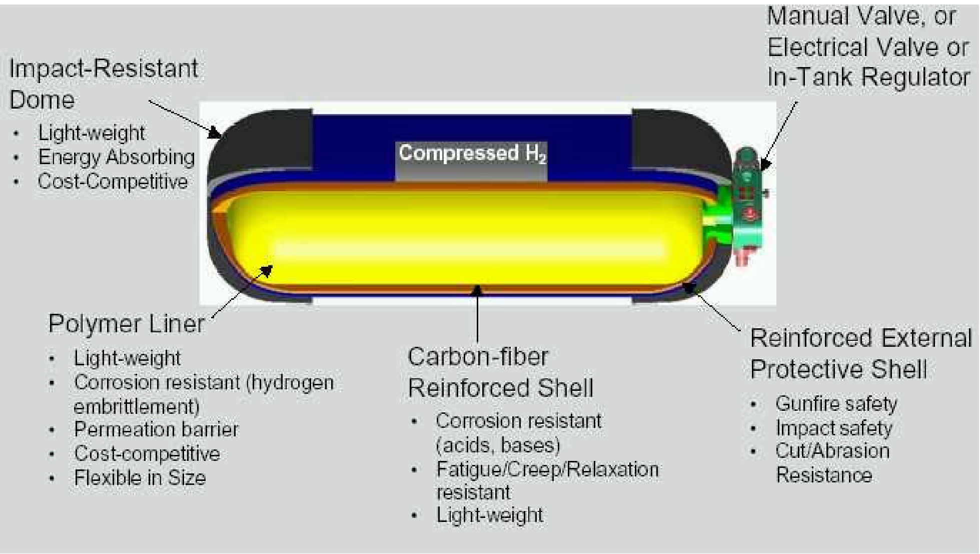


Figure C8.1 - Overview of compressed Hydrogen storage system

- Liquid Hydrogen in super insulated tanks (Hydrogen boiling point at atmospheric pressure is –253°C). This system does not have the same storage size and weight penalty as compressed Hydrogen, but it is still bulkier than Gasoline storage. Hydrogen's low boiling point requires excellent insulation of storage containers, similar to the way in which liquefied natural gas is currently stored on heavy duty vehicles. Maintaining the extreme cold temperature during refuelling and on-board storage currently poses a great technical challenge [1d]

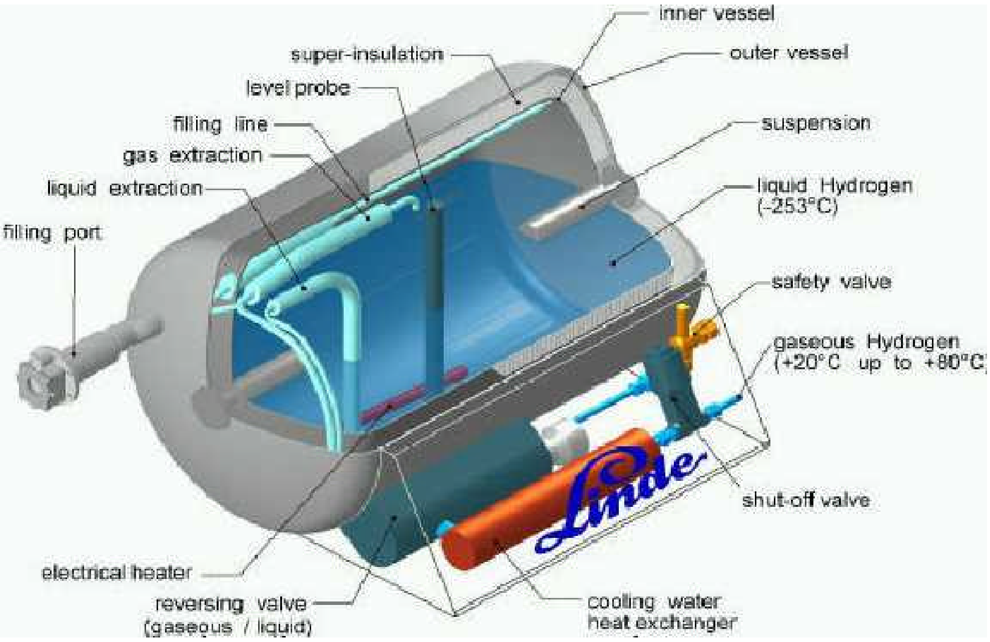


Figure C8.2 - Overview of liquid Hydrogen storage system

- Absorbed Hydrogen in a hydride system, consisting of a powder of metals, including nickel, chromium and vanadium. This system is most efficient at moderate pressures and temperatures neighbouring 300°C. Since heat is required to release the Hydrogen, it avoids safety concerns surrounding compressed and liquid Hydrogen, and is one of the safest methods for storing Hydrogen. However the metal compounds used to attract the Hydrogen tends to be very heavy, hence putting a large weight penalty on the vehicle [1d]
- Absorbed Hydrogen in an activated carbon storage system (carbon nanotubes). This technology is still at a very early stage, however it is seen by some scientists as a potential technological breakthrough to make Hydrogen powered vehicles practical [1d]

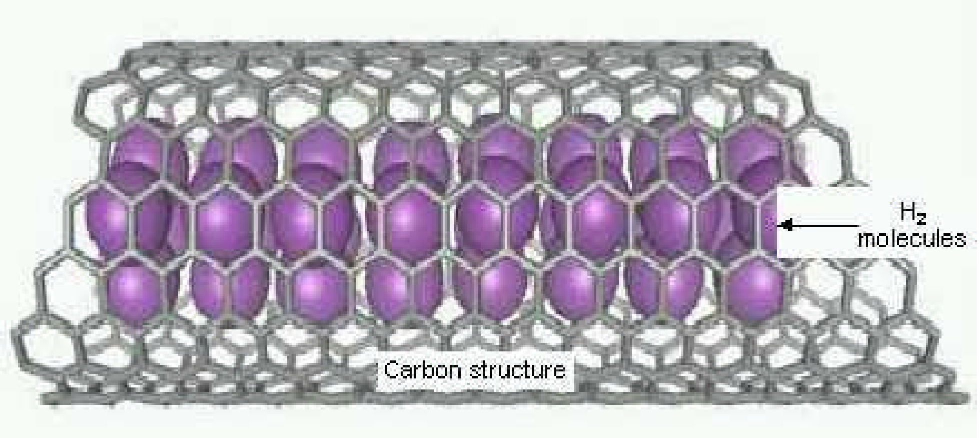


Figure C8.3 - Overview of nanotube storage system

The key factors for Hydrogen storage systems are:

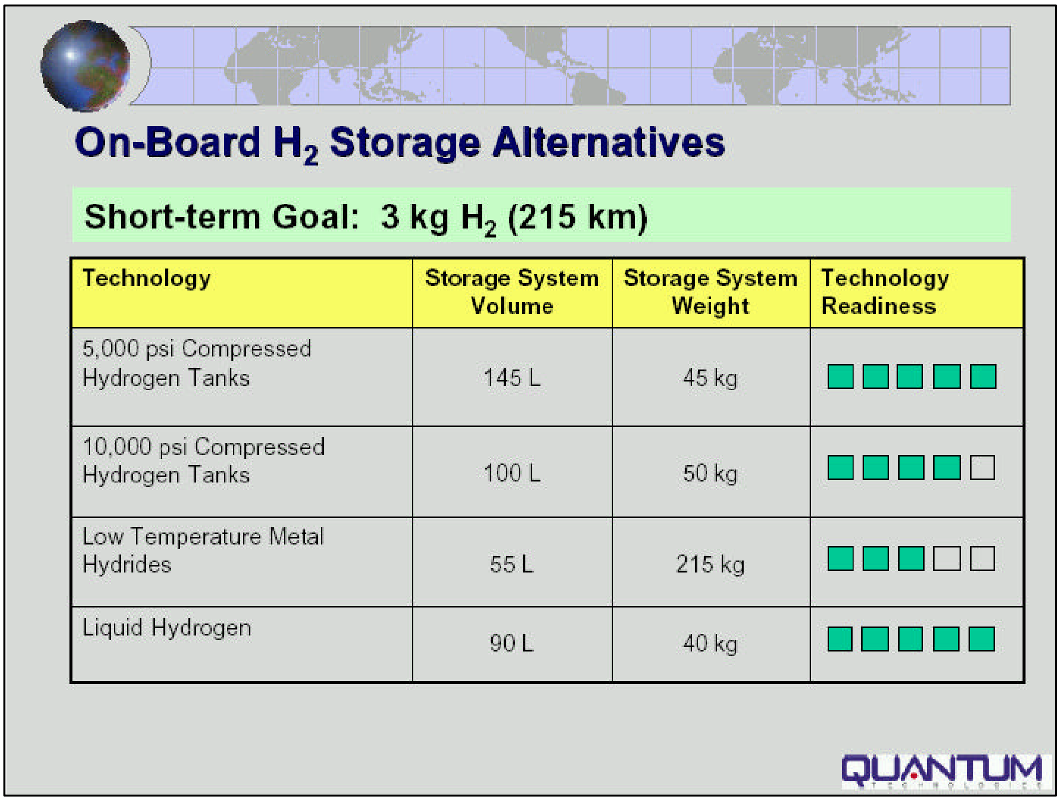
- Energy density (mass and volume)
- Interface with the propulsion system
- Refuelling infrastructure
- Safety during operation, standby and refuelling

Table C8.1 summarises the main figures on the above storage systems, together with a comparison to Gasoline tanks. In view of these figures, it becomes clear that the main issue is currently the systems' weight fraction (weight of tank compared to weight of fuel), which at best only provide 28% of the weight fraction available from a standard Gasoline tank. Universities and research centres are today actively involved in optimising these storage systems to propose higher weight fraction systems operating at ambient conditions of pressure and temperature.

The US Department of Energy (DoE) has computed recent progress in storage technologies and provided estimations of system sizes and weights, on both short term and long term bases. These are shown in Figures C8.4 and C8.5.

On-board storage system	H_2/gasoline weight fraction	Refuelling Infrastructure	Propulsion system interface	1) Pros 2) Cons
Compressed H_2 system	WF = 6 to 12%	High pressure storage tanks and compressor	Supply, venting	1) Simple rugged system 2) High pressure, safety, low capacity
Liquid H_2 system	WF = 8% VF = 40 to 60%	Low pressure cryogenic storage tanks and refrigeration equipment	Supply, thermal, control feedback, evaporative control	1) High mass and volumetric capacity 2) Evaporative loss, very low temperature, safety
Hydride system	WF = 1 to 5%	Low pressure storage tanks and compressor	Supply, thermal, control feedback	1) Crash safety, high volumetric capacity 2) Hydride poisoning, low mass capacity
Carbon nanotube system	WF = 4 to 8%	Medium pressure storage tanks and compressor, refrigeration equipment ?	Supply, thermal, control feedback, venting ?	1) Light weight, crash safety, possible low cost 2) Possible venting loss
Gasoline tank	WF = 70% VF = 85%	Low pressure storage tank and pumps	Supply, evaporative control	1) Simple known system, low cost

Table C8.1 - On-board Hydrogen storage systems comparison [2d, 3d]

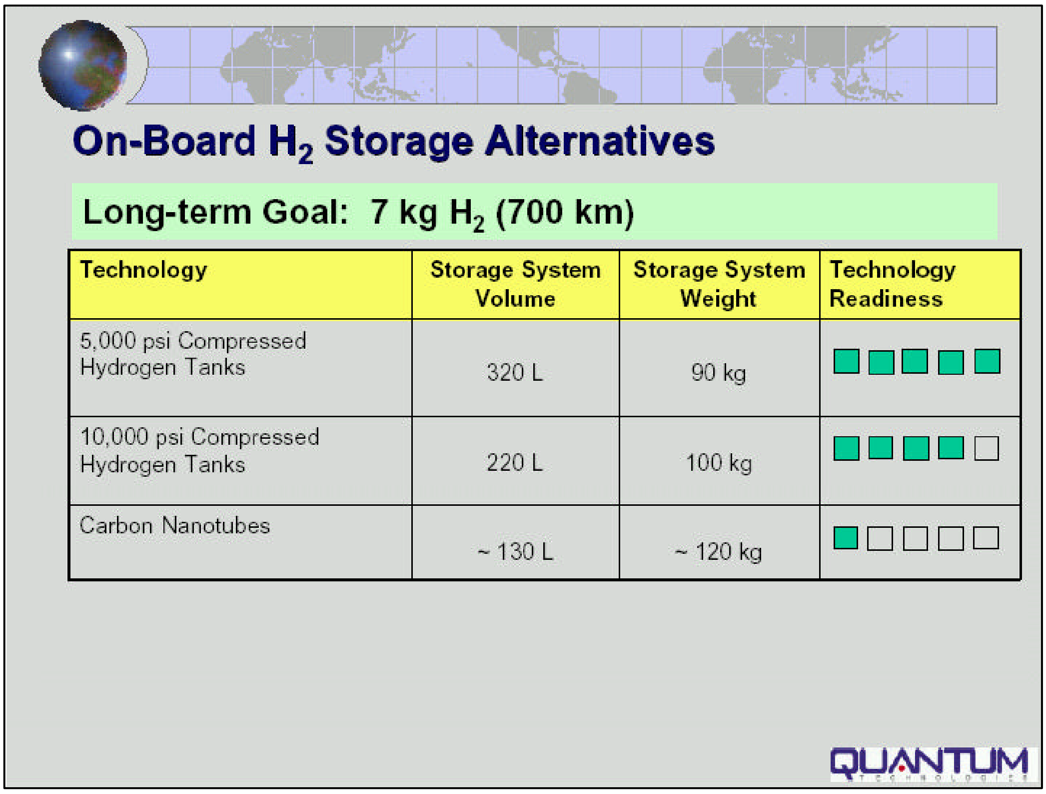


On-Board H_2 Storage Alternatives

Short-term Goal: 3 kg H_2 (215 km)

Technology	Storage System Volume	Storage System Weight	Technology Readiness
5,000 psi Compressed Hydrogen Tanks	145 L	45 kg	🟩🟩🟩🟩🟩
10,000 psi Compressed Hydrogen Tanks	100 L	50 kg	🟩🟩🟩🟩☐
Low Temperature Metal Hydrides	55 L	215 kg	🟩🟩🟩☐☐
Liquid Hydrogen	90 L	40 kg	🟩🟩🟩🟩🟩

Figure C8.4 - Status of on-board Hydrogen systems in the short term [3d]



On-Board H_2 Storage Alternatives

Long-term Goal: 7 kg H_2 (700 km)

Technology	Storage System Volume	Storage System Weight	Technology Readiness
5,000 psi Compressed Hydrogen Tanks	320 L	90 kg	🟩🟩🟩🟩🟩
10,000 psi Compressed Hydrogen Tanks	220 L	100 kg	🟩🟩🟩🟩☐
Carbon Nanotubes	~ 130 L	~ 120 kg	🟩☐☐☐☐

Figure C8.5 - Status of on-board Hydrogen systems in the longer term [3d]

C9 Hydrogen Infrastructure

The acceptance of Hydrogen as a new fuel by the market for C/D segments vehicles will be driven by several factors: the widespread availability of the fuel in sufficient quantities, its cost, and confidence that these fuels are safe to use [1e].

Many different routes are possible to produce Hydrogen, which should ease the Hydrogen refuelling infrastructure build up, depending on available feedstock and existing networks (natural gas pipelines for instance).

Filling stations availability

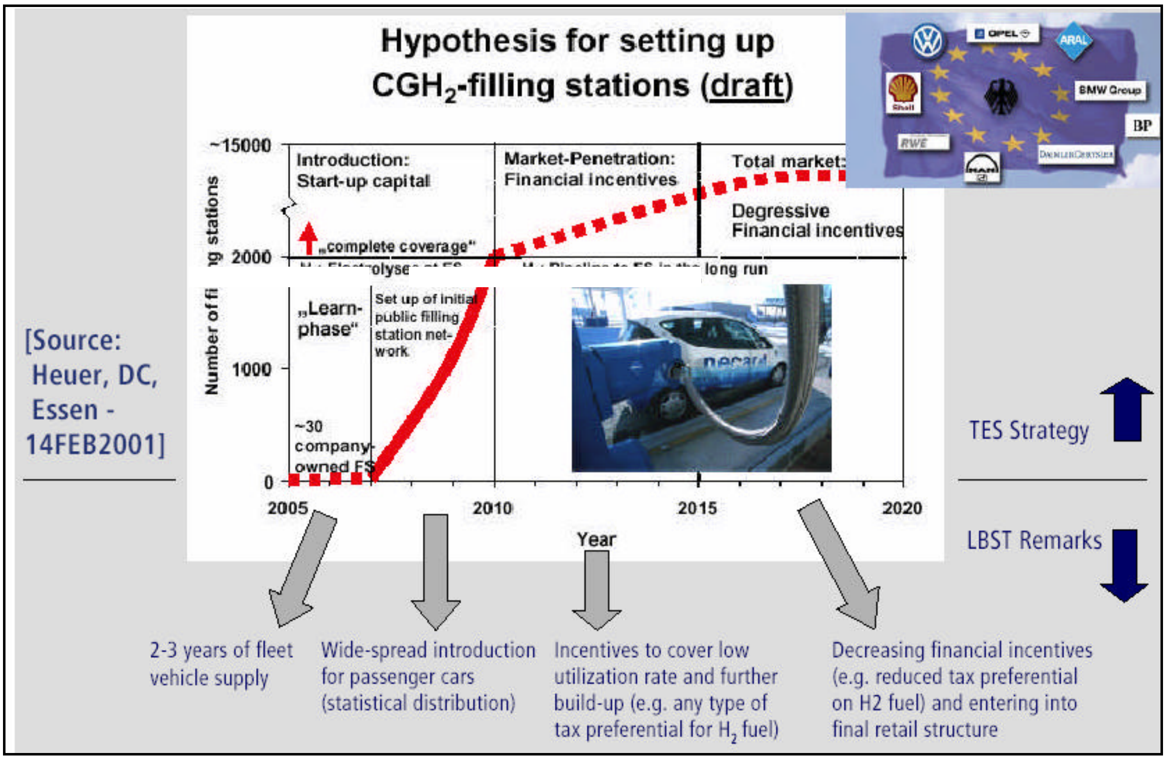
To be able to reach the stage where C/D segment vehicles can successfully be sold to the public, several issues have to be overcome. Standardisation is one of them, as for instance amongst the existing re-filling coupling components none of them are identical. Legislation about Hydrogen needs to be put in place, to standardise and regulate its production, transport, distribution, etc. This is the objective of the European Integrated Hydrogen Project, Phase II, which should end in January 2004 [7e].

The next step then is to make Hydrogen widely available. The lack of sufficiently extended network can be fatal to the development of new technologies as customers are more and more used to a high level of mobility and easy access to an ever-growing range of services. Travelling restrictions due to limited re-fuelling facilities would be perceived as a constraint, a freedom limitation, a step backwards in what new technologies can offer.

The results of a study show that in Germany the number of Hydrogen filling stations should be around 2000 by 2010 and slightly less than 15,000 by 2020. – i.e. respectively 12.5% and 94% of Germany’s current total number of filling stations (See Figure C9.1) [4e].

For Great Britain – 13,000 conventional filling stations today – this means that the number of Hydrogen filling stations should be about 1600 by 2010 and 12,200 by 2020. These figures could be the target numbers to reach if the “Low Carbon Route” is followed.

Previous experience with alternative fuels in general shows that at least 15-20% of all refuelling stations must offer the new fuel statistically well distributed in order to generate widespread acceptance [3e]. That would represent 2000 to 2600 stations in the UK. This can be considered as a minimum number of Hydrogen refuelling facilities available in Great Britain by 2008 if the “Hydrogen Priority Route” is chosen.



Hypothesis for setting up CGH_2-filling stations (draft)

[Source: Heuer, DC, Essen - 14FEB2001]

TES Strategy

LBST Remarks

2-3 years of fleet vehicle supply

Wide-spread introduction for passenger cars (statistical distribution)

Incentives to cover low utilization rate and further build-up (e.g. any type of tax preferential for H_2 fuel)

Decreasing financial incentives (e.g. reduced tax preferential on H2 fuel) and entering into final retail structure

Figure C9.1 – Germany's Hydrogen filling station information [4e]

Fuel price

Fuel price is the second key factor of the successful introduction of new fuels and technologies such as Fuel Cells. The general public is more and more aware of the greenhouse effects and feels concerned but the market acceptance of new technologies to reduce CO_2 emissions will be conditioned by a reasonable fuel price.

Figures C9.2 and C9.3 respectively show the cost of delivered compressed gaseous Hydrogen and the cost of delivered Hydrogen per km driven in Germany, compared to Gasoline and Diesel retail price.

These figures are based on German parameters for energy costs, company taxation and financial parameters. Hydrogen costs (excluding mineral oil tax) have been compared to German Gasoline and Diesel retail prices (including mineral oil tax).

The results show that in Germany Hydrogen can be produced and distributed at costs that are lower or equal to the current conventional fuel prices. As Fuel Cell vehicles consume less fuel per kilometre than conventional motor vehicles, the higher Hydrogen costs are compensated for. But as these costs do not include tax, this means that this conclusion is only valid provided little or no tax is applied to Hydrogen fuel.

These Hydrogen cost figures might be specific to Germany and would need to be re-worked for the United Kingdom. However, the fact that mineral oil taxation in the UK is one of the highest in Europe would make Hydrogen even more competitive versus Diesel in this country if all the other parameters were similar to the German values (company taxation, etc.).

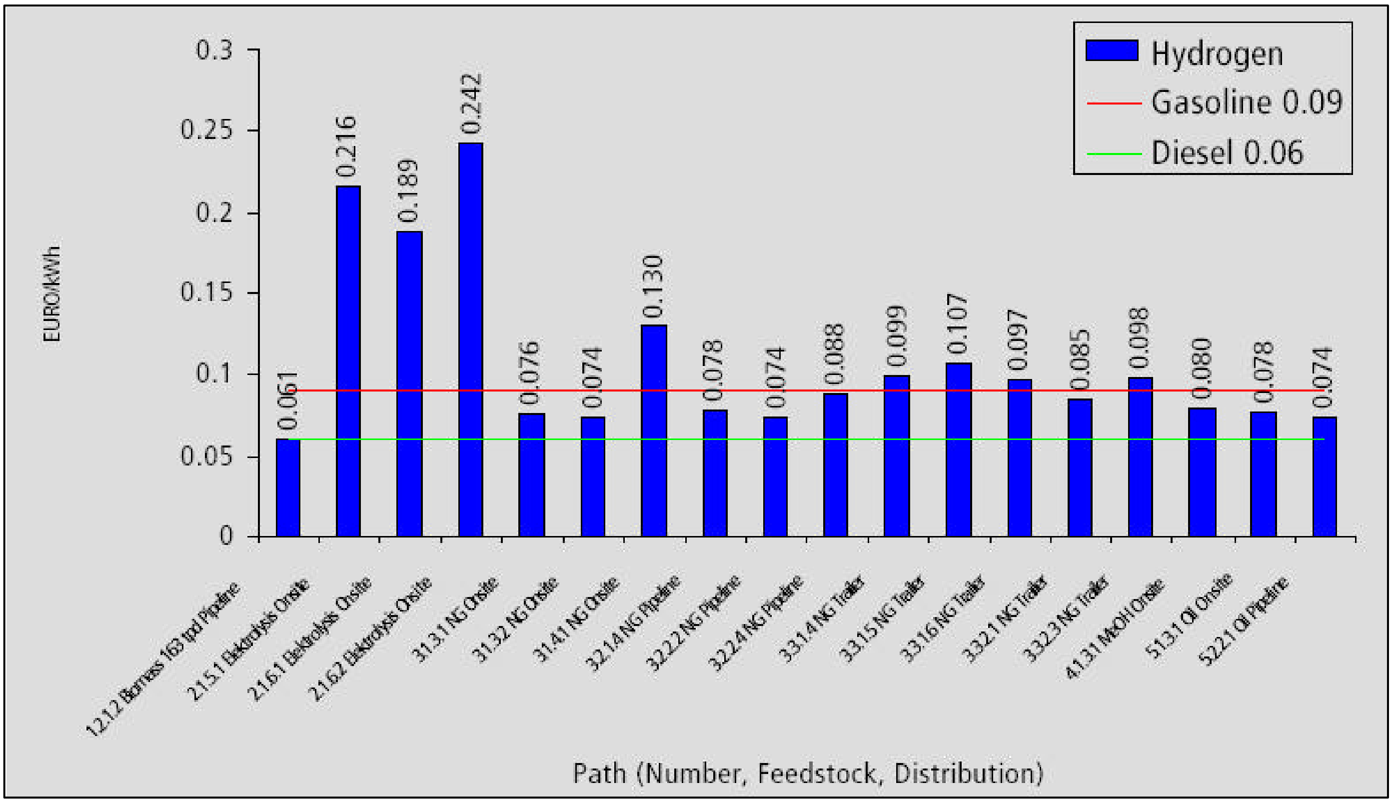


Figure C9.2 - Cost of delivered Hydrogen in Germany [5e]

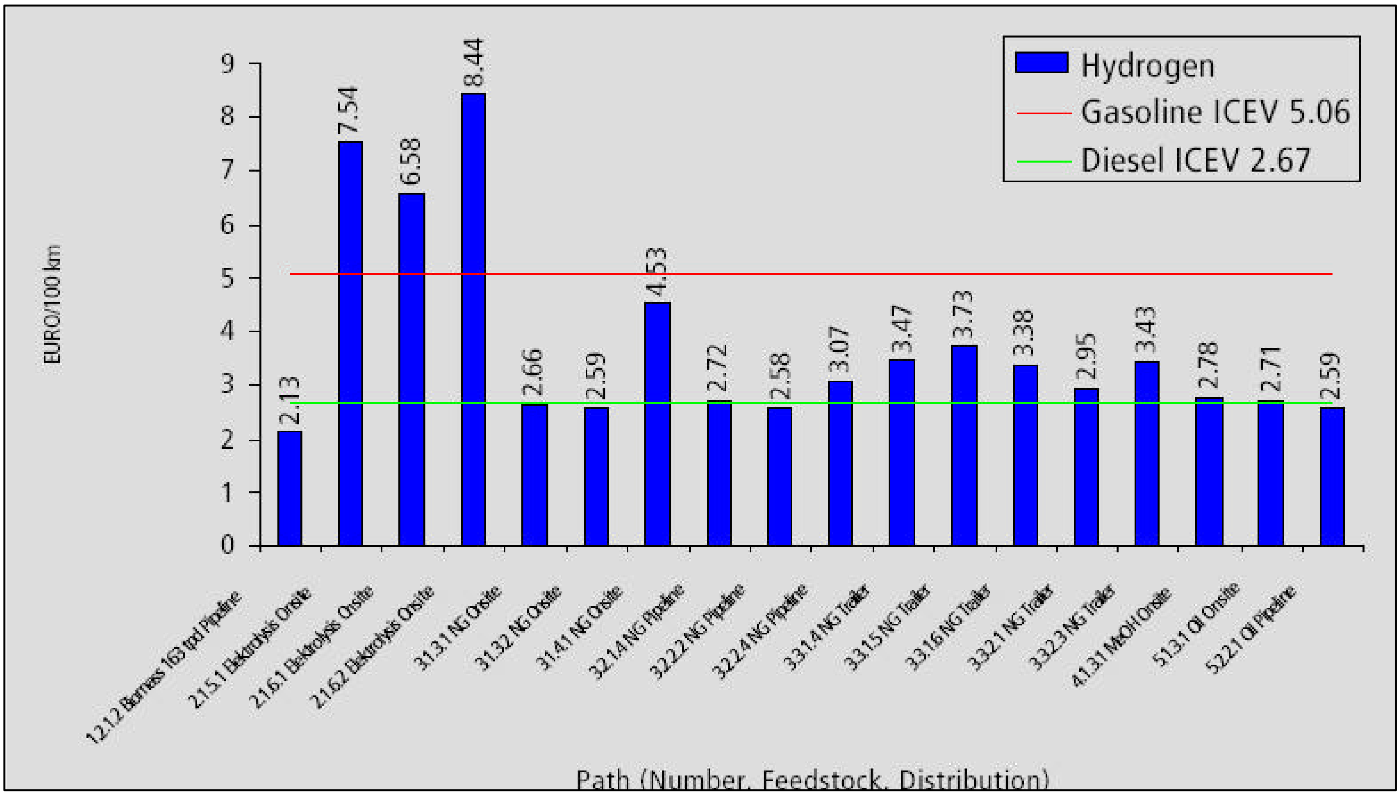


Figure C9.3 - Cost of delivered Hydrogen per Fuel Cell vehicle km driven in Germany [5e]

Fuelling stations technologies

There are many possible technologies for Fuel Cell vehicles fuelling stations depending on the fuel they dispense and under which form they dispense it.

Some Fuel Cell vehicles use liquid Hydrogen, others compressed gaseous Hydrogen. Figure C9.4 shows a Hydrogen refuelling station concept which can supply Hydrogen in both forms. Figure C9.5 shows two examples of actual Hydrogen filling stations.

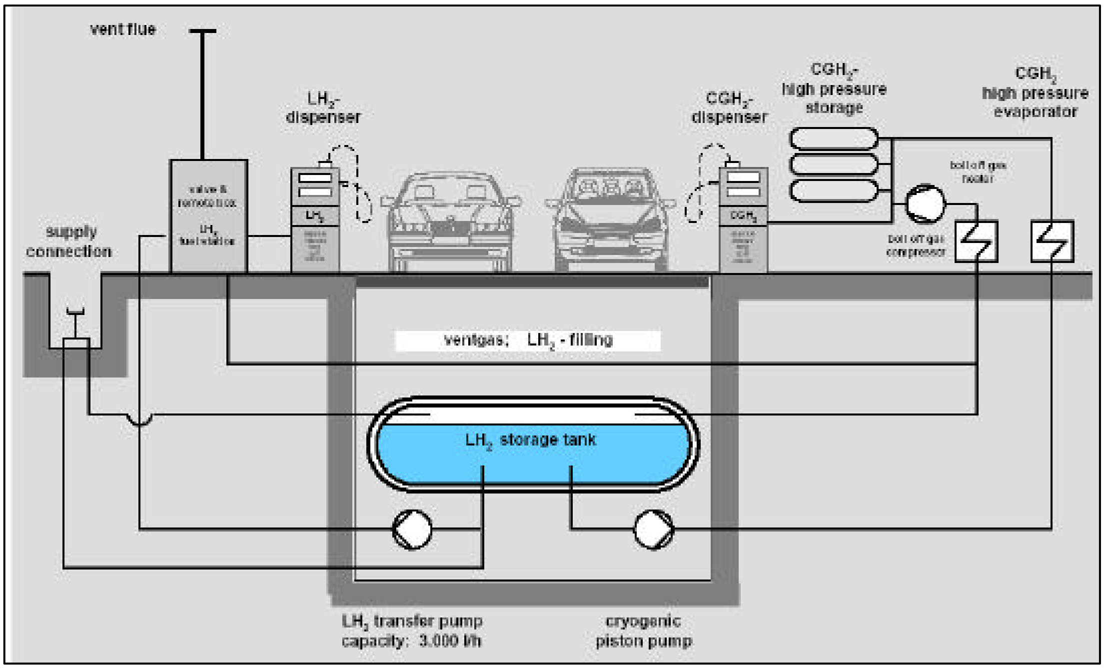


Figure C9.4 - Filling station concept [4e]

Figure C9.5 - Existing Hydrogen filling stations [6e]

Depending on the choice of path for Hydrogen production, the filling stations could either be supplied with Hydrogen or with other fuels (natural gas, methanol, etc.) and have an on-site reformer.

From the driver's point of view, refilling a Fuel Cell vehicle with Hydrogen should be a fairly similar procedure to refilling a conventional Gasoline or Diesel vehicle. In the case of the Sacramento station for instance, the driver has to connect the electrical and computer cable to the vehicle to confirm that the safety systems are established and functioning properly. The information transferred by this process to the computer includes details of the vehicle fuel tank, the vehicle manufacturer and specific conditions set by the manufacturer that must be met to begin fuelling, such as confirming the car ignition is off. Following that, the driver connects the fill nozzle and fills the vehicle [9e]. Filling times are now less than three minutes and no more Hydrogen is lost during refuelling [4e]. See Figure C9.6. The European Integrated Hydrogen Project – Phase II – is currently reviewing the refuelling procedure and the Hydrogen refuelling infrastructure components, in order to issue a European regulation document [7e].

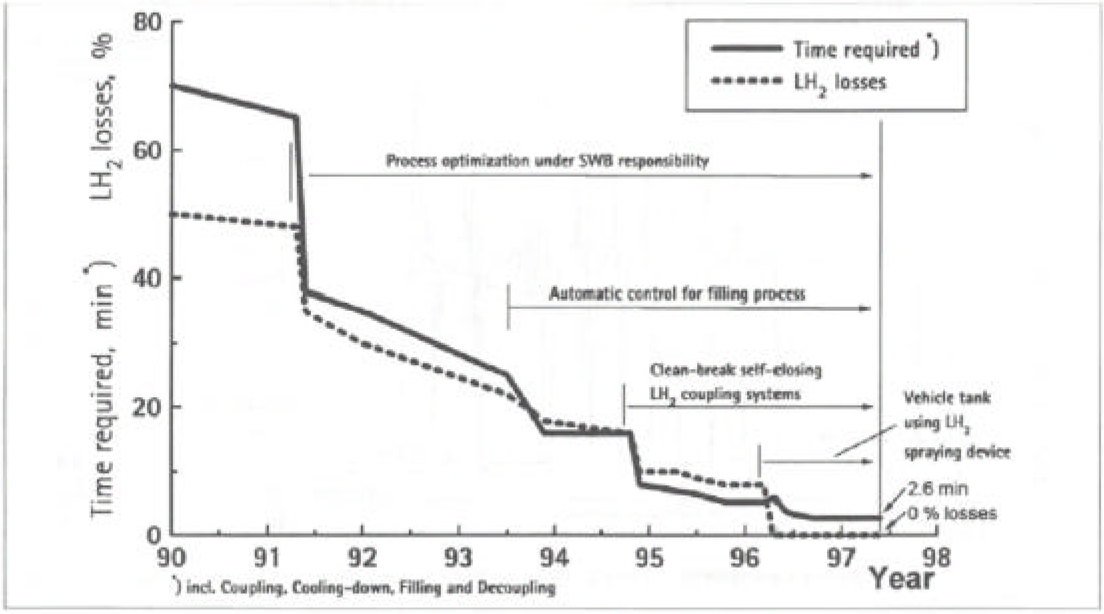


Fig. 1. LH$_2$ vehicle tank filling process (under contracts of BMW and SWB).

Source: F.-J. Wetzel in Int. Jour. Hydr. Energy N°5, 1998, Vol. 23, p. 341

Figure C9.6 - Reduction of liquid Hydrogen refuelling times and product losses [4e]

The cost of these fuelling stations will, again, depend on their technology. An American study shows that the capital cost for a filling station producing Hydrogen with an on-site reformer from natural gas can be between $280,000 and $650,000 depending on the technology used and the capacity of the station [2e]. L-B-Systemtechnik estimate that the total cost of installing 2000 filling stations in Germany by 2010 will be at least 5 billion Euros [4e].

Safety

This aspect is currently analysed by the European Integrated Hydrogen Project – Phase II. The project is addressing the issues that have been identified related to the use of Hydrogen in road vehicles.

But even if Hydrogen is a highly flammable gas, technical solutions exist to handle and transport it safely, and they keep being improved in particular for the new vehicle applications. In the chemical industry it is being used safely since more than a century. Other example, liquid and compressed gaseous Hydrogen storage containers, due to their more rigid design, behaves much better in accidents situations than conventional vehicle fuel tanks [4e].

However no doubt that the market acceptance of this new fuel will have to be preceded by public awareness and education through adapted communication, which will represent additional costs to Hydrogen powered vehicles introduction.

Regarding the filling procedure, the precautions currently taken with conventional fuels should be maintained: no smoking, ignition (and mobile phones?) off. Additional measures could be adopted such as electrically grounding the vehicle prior to refuelling, forbidding any passenger to stay in the vehicle during the operation, presence of physical barriers between the refuelled vehicle and any other traffic, forbidding refuelling during the threat of lightening storms, etc.

The design and the location choice of the Hydrogen filling stations could be more stringent than conventional one. It may even be possible that the drivers should not be allowed to refuel themselves if the regulation imposes that only trained people can perform refuelling operations [10e].

But these are only hypotheses as the European legislation is still to come.

C10 Alternative Fuels: Natural Gas

Natural gas has long been considered an alternative fuel for the transportation sector. In fact, gas powered vehicles have been around since the 1930's in places where, at that time, liquid fuels were scarce. In the UK, they were fuelled with Town Gas (produced from coal); in Italy and France natural gas was used [1f, 4f].

Figure C10.1 - A natural gas vehicle of the 1930's

The reasons for this are that natural gas is an extremely abundant resource with new discoveries emerging frequently throughout the world. It could also potentially reduce the greenhouse effect gas emissions, as it has high well to tank CO_2 efficiency.

The natural gas vehicles around the world

In Europe, Italy has been using natural gas as a vehicle fuel since the 1920's and has about 370,000 NGV's. The Italians have a network of 280 filling stations to support their use of compressed natural gas. Russia has about 75,000 NGV's and a fuelling network of some 250 stations. Outside of these countries, there are now several thousands NGV's in Europe and a slowly growing fuelling station infrastructure.

Argentina has 700,000 NGV's – the largest fleet in the world and is converting more than 3,000 vehicles a month and has over 500 fuelling stations in operation or under development.

Canada has about 36,000 vehicles converted to natural gas, and the government-supported NGV programme has created a number of incentives.

In the U.S.A. there are about 68,000 vehicles fuelled on natural gas. Natural gas vehicles have been used there since the late 1960's, but comparative prices with Gasoline and state-of-the-art technologies are only now making natural gas economically and technologically competitive with Gasoline vehicles. There are about 1,200 private and public refuelling stations [6f].

In 1998 in the U.K. there were 500 NGV's and 16 fuelling stations [4f].

Natural gas characteristics

Enough natural gas is available worldwide to meet short-term and long-term targets for feedstock supply. Most production sites presently operate at maximum capacity for only part of the year. World supplies exceed proven oil reserves by more than 20% [2f]. Natural gas is also more evenly spread around the world than oil, making it a less politically-sensitive fuel.

Natural gas consists mainly of methane (CH4) and unlike methanol it is not toxic. Because of its “simple” chemical structure, it is inherently a “clean” fuel in that it forms virtually no soot, particulates or Polynuclear Aromatic Hydrocarbons (PAH), the latter being known to cause cancer. NOx and CO are produced in engines in a similar manner and quantity as would occur with liquid fuels. Un-burnt hydrocarbons appear almost entirely as methane, which has not generally been regarded as a pollutant because it is naturally formed in vast quantities throughout the world by the decay of vegetable matter. However, it is now recognised that methane does make a contribution to the greenhouse effect.

Catalysts improve the emissions of natural gas vehicles and sulphur dioxide which contributes to acid rain and respiratory illness is negligible in NGV exhausts. Even vehicles running on low-sulphur Diesel or ultra-low sulphur Diesel cannot match the very low emissions of sulphur and particulates from NGV’s. or natural gas engines the regulated emissions (NOx, CO and HC) can be controlled by the same strategies which are employed for Gasoline engines [3f, 4f].

Natural gas has a very high Octane Number (about 130 RON) which means that it has a very high knock resistance. However this can vary depending on the composition of the gas: knock resistance will decrease if the natural gas contains a higher proportion of butane. But in general this means that engines running with natural gas can have a higher compression ratio than Gasoline engines, thus being more efficient. Diesel engine compression ratios though cannot be reached with natural gas [3f, 6f].

Typical values are:

Fuel	Maximum compression ratio	Maximum efficiency
Gasoline	9:1	30%
Natural gas	12:1	35 to 37%
Diesel	14:1	40%

Table C10.1 - Compared engine efficiencies depending on fuel and compression ratio [5f, 6f]

Natural gas has a calorific value similar to that of Diesel but due to its lower energy density it needs to be stored in pressure tanks. In order to give vehicles a running autonomy similar to that of conventional vehicles the storage capacity must be enlarged (a 50 litre capacity gas tank is equivalent to a 13 litre Gasoline tank). The gas tanks are also heavier [5f].

There are two basic concepts involved in tuning up gas engines. Stoichiometric engines run at the theoretical ratio required for combustion. Pollutants levels are high in that case and it is therefore necessary to use a three-way catalyst. The performance features of this type of engine are excellent, although the consumption is relatively high. Lean mixture engine need an oxidation catalyst to reduce the emissions of hydrocarbons. Consumption is lower, although the performance features are not so good [5f].

However, the fuel consumption of natural gas vehicles is on average in between the values for Gasoline and Diesel vehicles, for similar segments [3f]. The well-to-wheels CO2 emissions level for vehicles running with compressed natural gas is close to the average figure obtained with Diesel vehicles (see Appendix B).

The vehicle applications

There are three different types of vehicles running with natural gas. The dedicated vehicles run on natural gas only. They can be Gasoline-fuelled vehicle that have been converted to run on natural gas. Bi-fuel vehicles can run either on natural gas or Gasoline. Many are designed to switch automatically to Gasoline when the natural gas tank reaches empty. These vehicles get the same or slightly fewer miles per equivalent gallon of natural gas as do vehicles using Gasoline only. Dual-fuel vehicles run either on Diesel fuel only or Diesel fuel and natural gas simultaneously. In such a vehicle the combustion of the Diesel fuel serves to ignite the natural gas [6f].

Converting a Gasoline vehicle to operate on CNG is relatively simple for a trained mechanic but safety measures must be considered. The spark timing must be advanced as the flame speed of natural gas/air mixtures is slow compared with Gasoline. The fuel tank is the most expensive part of the conversion kit and can cost anywhere from $300 to $1000 depending on the size and the material. Conversion costs range from $2,000 to $3.000 for light-duty vehicles and from $5,000 to $9,000 for heavy-duty vehicles [7f].

The conversion of an existing Diesel engine to CNG operation is not a straightforward task and could require significant testing to obtain optimum performance. Some engine configurations may not be suitable. There are two main options. For a dual-fuel conversion the compression ratio of the engine is not altered and generally the engine can revert to full Diesel operation. In dual-fuel mode somewhere between 60% and 95% of the Diesel could be replaced by natural gas. But there will probably be a need for significant engine testing to obtain reasonable performance and emissions level for a new engine type. The other option is to redesign and convert the engine to dedicated gas operation with spark ignition. This involves reducing the engine compression ratio and installing spark plugs [6f].

In very general terms, the smaller the vehicle the longer the payback period for the cost of conversion. This is because the fuel consumption – and therefore the savings – for the smaller vehicles is lower and at the same time the cost of conversion does not go down much with the vehicle size. The cost of the fuel control system stays much the same and the price of a smaller storage cylinder will not be much lower. It may be difficult to justify a conversion on an economic basis but this does depend on annual mileage [6f].

Because of the growing demand for alternative fuels, auto manufacturers are beginning to produce and market vehicles that operate on CNG; 10 to 15 models are now available. However, for the more advanced gas engines with low emissions levels, it has been estimated that the pump price of natural gas fuel must remain 2/3 of the price of Gasoline, or an equivalent energy basis, to allow payback for the more expensive NGV over a 5 year period [3f].

Figure C10.2 - The Honda Civic GX – Super Clean NGV
Source: AFDC - DOE

One important feature of NGV vehicles is the on-board storage of the compressed natural gas which is generally done using cylinders at a maximum pressure of 200/240 bar. A 90-litre cylinder will hold about 16kg of gas and weigh about 90 kg when full. Cars are typically fitted with a single cylinder of approximately 90 litre capacity. Vans can be fitted with single or double 90 litre cylinders, or with a single 120 litre cylinder, depending on the space available and the vehicle range required [4f].

Directly linked to the CNG on-board storage technology, the vehicle autonomy is a key element of NGV's. Examples of current production vehicles show a range included between 100 and 300 miles (the highest values can be achieved thanks to an optional extra tank) [8f, 9f]

Therefore, commuter and fleet vehicles are particularly suitable for ease of refuelling. In Europe vehicle fleets operated by industry, national and local governments are the strongest candidates to use natural gas. About 10 million vehicles across Europe could, right now, be economically retrofitted with natural gas equipment. Another 40 million vehicle fleet could be converted successfully. Because the network of public natural gas fuelling stations is not yet well developed, widespread use of natural gas in privately owned, individual vehicles is something that will be more possible in the not-so-distant future [6f].

The range limitation problems could be overcome thanks to new technologies. One NGV concept unveiled by the U.S. Department of Energy can apparently achieve a range nearly double that of prior models and within 15% of comparable Gasoline models. This was possible with recent developments on natural gas on-board storage and gas [10f]. However, at least in Europe, the technology that is currently available is based mainly on either conversion of Diesel/Gasoline engines to gas after initial deployment, or so called dedicated engines that are still to a large extent based on the basic conventional option. The development of a gas powered engine from a new fundamental concept is seen as a very risky option, as there is no guarantee that the support or demand will be present at the end of the development phase for the end product [5f].

The refuelling stations – infrastructure and fuel price

The widespread use of natural gas as a transport fuel requires easy access to the fuel from a large number of suitable filling stations of a similar nature to the current network. The facilities to implement such a system consist of the following elements: national gas pipeline supply network, local filling stations comprising storage, gas compression units and refuelling pipes, high pressure gas storage tanks suitable for attachment to vehicles and capable of withstanding crash impact forces [5f].

There are several types of refuelling stations depending on whether refuelling is carried out slowly (6 to 8 hours) or quickly (3 to 10 minutes). A slow fill gets more gas into the tank than does a fast fill. The reason is that as the gas builds up the pressure in the tank it is in effect compressing the gas that is already there and this causes a rise in temperature, which turns lower the density of the gas. As the tank cools the pressure will fall. With a slow fill approach there is time for the tank to come to equilibrium with the ambient air temperature and the result is higher density and a more complete fill [6f].

Depending upon the design of the service station of vehicles to be refuelled and the fuel storage requirements, compressors and related equipment can cost from $5,000 – 10,000 (for small compressors) to $400,000 or more for stations capable of serving hundreds of vehicles. Bus fuelling stations, where 3 minute quick fill is required for large numbers of vehicles can cost $1 million or more [6f].

In the U.K. in 1998 the natural gas price at the pump was roughly equivalent to 30p per litre less than Gasoline and Diesel. Compressed natural gas though is sold by weight (per kilogram) and not by volume (per litre) [4f].

Safety

A pressurised gas cylinder is probably the strongest component on the vehicle. Vehicles that totally destroyed in collisions show the only discernible component being the intact gas cylinder. It is unlikely that cylinders will rupture due to a collision impact.

Regarding the danger of fire from leaking cylinders, the risk must be low since there are over a million CNG vehicle installation worldwide that have not experienced such problems.

It is worth pointing out that natural gas is hard to ignite and is lighter than air. In the unlikely event of a leak from piping or container the gas will dissipate upwards quite quickly. In the case of Petrol and LPG the vapour given off is heavier than air and will tend to pool near the ground. This is where there is a strong risk of some ignition source. In general terms Diesel ranks high for safety, but most people rank natural gas next [6f]. Places like underground car parks or tunnels which ban LPG make no such restrictions for NGV's [4f].

Liquid Natural Gas - LNG

LNG is natural gas that has been liquefied by reducing its temperature to –162 ºC at atmospheric pressure. In volume at standard conditions, it occupies 1/600 that of natural gas as a vapour [6f].

LNG's numerous benefits are leading to a growing appreciation of its potential as a transportation fuel for heavy-duty vehicles. These benefits include:

- Higher energy density. Since it is a liquid, a greater volume of natural gas can be stored in a smaller space. Especially on-board a vehicle, getting the greatest possible range and lowest weight are important considerations.

- Ongoing research promises to lower the cost of LNG fuelling facilities, produce lighter fuel tanks and increase engine efficiencies.

- Speed of fuelling. Large vehicles can often be filled in four to six minutes and fuel composition can be determined with a high degree of accuracy since most LNG produced for vehicles is now in the 99+ percent range for methane.

- Deliver and availability. LNG is frequently transported in trailer trucks that hold up to 44,000 litre, in small tank trucks and trailers, railcars, barges and 30 million-gallon LNG ships. LNG trailer are often used to deliver LNG to refuelling stations, much like Diesel or Gasoline delivery [6f].

There are over a dozen LNG stations in the U.K. [11f].

APPENDIX D: UK TECHNOLOGY BASE

Information on UK companies, organisations and institutions, or multinational companies, organisations or institutions with a significant UK technology base, has been collated based upon:

- Existing Ricardo contact, research partnerships etc
- Internet and Literature searches

Due to the time-scale of this study it is unlikely that this list is completely exhaustive. Information has been grouped into technology blocks, with comments on areas of particular strength or weakness.

1 Passenger Car Manufacturers

Ford have a significant manufacturing base in the UK, for Diesel engines, components, passenger cars and vans. They also have Engineering bases at Dunton, Essex (mostly of Diesel engines) and Gaydon, Warwickshire (for the Premier Automotive group including **Jaguar, Land Rover and Aston-Martin**). Ford have shown a number of Hybrid and Fuel Cell concept vehicles, although the engineering of these appears to have been on a global basis. Ford have been reported in the press to be readying a Hybrid SUV (4x4) for production in the US.

Rover manufacture and engineer passenger vehicles in the UK, based at Longbridge, Birmingham. Rover are one of the smallest independent volume manufacturers of cars, and therefore have not been able to invest in costly, speculative advanced prototype vehicles. Ricardo are not aware of any Hybrid or Fuel Cell vehicles demonstrated recently in the public domain.

Other Passenger Car manufacturers with a significant UK base include **General Motors** (using the **Vauxhall** brand), **BMW** (using the **Mini** brand), **Peugeot, Nissan, Honda** and **Toyota.** For these brands the majority of the manufacturers' own engineering capability is located outside the UK. Most have demonstrated significant advanced technology, for example Fuel Cells (GM), Hydrogen IC engines (BMW), production Hybrids (Honda, Toyota), but these technologies were mostly developed outside the UK.

From this it appears that the UK has a reasonable manufacturing base for the implementation of new technologies into a diverse range of passenger cars (and also vans, which may benefit from similar technology). One particular strength is the manufacture of engines, with both Ford (Dagenham - Diesels) and BMW (Hams Hall – 4cyl Valvetronic) manufacturing advanced products here. However, tendency for the main engineering function to be located overseas is a weakness in UK capability and may disadvantage suppliers with their engineering base in the UK.

2 Advanced Conventional Powertrain & Vehicle Components

There are numerous suppliers to the automotive industry with a UK presence. Significant ones include:

Visteon, supplier of vehicle systems including motors, alternators and power electronics, has a technology base at Dunton, Essex
Delphi, supplier of vehicle systems including motors, alternators and power electronics, have a technology base at Gillingham, Kent focussed on Diesel fuel injection equipment (formerly **Lucas**)
Federal Mogul, supplier of various vehicle systems and engine components, recently re-located their technology base (formerly **T&N**) out of the UK
Calsonic, supplier of Thermal System and Exhaust System components, have a technology base in Llanelli, Wales
Holset, supplier of turbochargers, have a technology base in the NE of England

In terms of major components and systems suppliers, the UK appears to have a reasonable portfolio although the loss of engineering centres from the UK is of concern.

3 Advanced Powertrain and Vehicle Engineering

The UK offers a surprising number of world-class suppliers of engineering expertise. Some principal organisations are:

Ricardo – Expertise in Petrol and Diesel engines, Transmission & Driveline, Vehicle Engineering, Control & Electronics, specialist Software for automotive engineering. Ricardo have recently demonstrated the **i-MoGen Diesel Mild Hybrid vehicle** together with supplier **Valeo**, and are involved in four customer Hybrid programs. Other advanced technology projects include the **"lean boost" Petrol engine**, a high efficiency concept to be demonstrated in 2003, and advanced **"dual clutch" transmission** concepts.

Lotus – Well known for their sports cars, also a major provider of engineering services. Lotus have recently demonstrated **electric and CNG versions of their Elise car** (itself noted for low weight technology), and have promoted **hydraulic valve actuation** as an enabler for advanced, efficient combustion

Cosworth – Best known for high performance engineering, major provider of engineering services and low volume cast component manufacture

Zytec – Supplier of low volume engine-management systems and engineering services for electronic systems. Zytek are reported to be working on **Hybrid and Electric vehicle programs** for DaimlerChrysler and General Motors

MIRA – Supplier of engineering services and vehicle test facilities, MIRA have demonstrated a **Hybrid vehicle**

TWR – Supplier of engineering services including motorsport and high performance vehicles

Qinetiq – Formerly **DERA**, expertise in Hybrid systems including control, battery management. Reported to be developing **Hybrid technology** for military applications

Prodrive – best known for Motorsport, especially World Rally Championship, also engineering of vehicles, transmissions, engines (at subsidiary **Tickford**)

PI Technology – control systems for Hybrids, Fuel Cell vehicles and Alternative Fuels, reported to be working on **Hybrid and Fuel Cell control system** programs for Ford

Universities – Many, including Imperial College, Loughborough, Brighton, Leeds, Cambridge, Bath, Cardiff (Engines / Combustion), Sheffield, Sussex (Electrical machines), Imperial College, Loughborough (Fuel Cells)

The UK's engineering base is a recognised strength. A number of organisations are actively involved in Hybrid vehicles, at a level which is globally competitive.

4 Batteries:

Atraverda (developing new Ceramic plates for lead acid batteries)
Hawker (Lead acid)
Chloride (Lead acid)
Zebra (www.betard.co.uk) (Sodium Sulphur for vehicle application)
Advanced Lead Acid Battery Consortium (Based in UK, developing demonstrator vehicle with various UK / European partners)

Focus here appears to be mainly on Lead Acid technology. Low cost, durable, high performance Lead Acid batteries are an important technology for the early introduction of hybrid technology (Low Carbon steps 1-3), but may not develop sufficiently to be used in further steps.

Nickel Metal Hydride (NiMH) and Lithium-Ion (Li-Ion) technologies do not appear to have a strong UK base, key global players include Panasonic (Japan) and Saft (France). This could prove a key weakness for UK industry if, as expected, the technology moves in this direction.

5 Electric Motors:

Visteon, Tier One supplier to the Automotive industry, manufacture a wide range of vehicle electrical equipment and may supply integrated starter-generators in the near future. Technology base at Dunton, Essex
Dana Corporation (Echlin Automotive), US based Tier One supplier, own a number of formerly small, independent UK suppliers including Automotive Motion Technology who have developed permanent-magnet motor technologies
Sheffield University have world class expertise in motor/generator development, via a 40-strong research team
Magnetics System Technologies, Sheffield, custom high performance motors
Aisin Seiki, technology centre at **Sussex University** (design motors for mild hybrid vehicles)
Elektomagnetix Ltd. Sussex (Electric motor engineering consultancy)

This appears to be an area of reasonable strength, encompassing both mass-production supply and academic research. Technology appears generally comparable to other global players, including Tier One suppliers Bosch, Siemens, Valeo and Delphi.

6 Fuel Cell Technologies

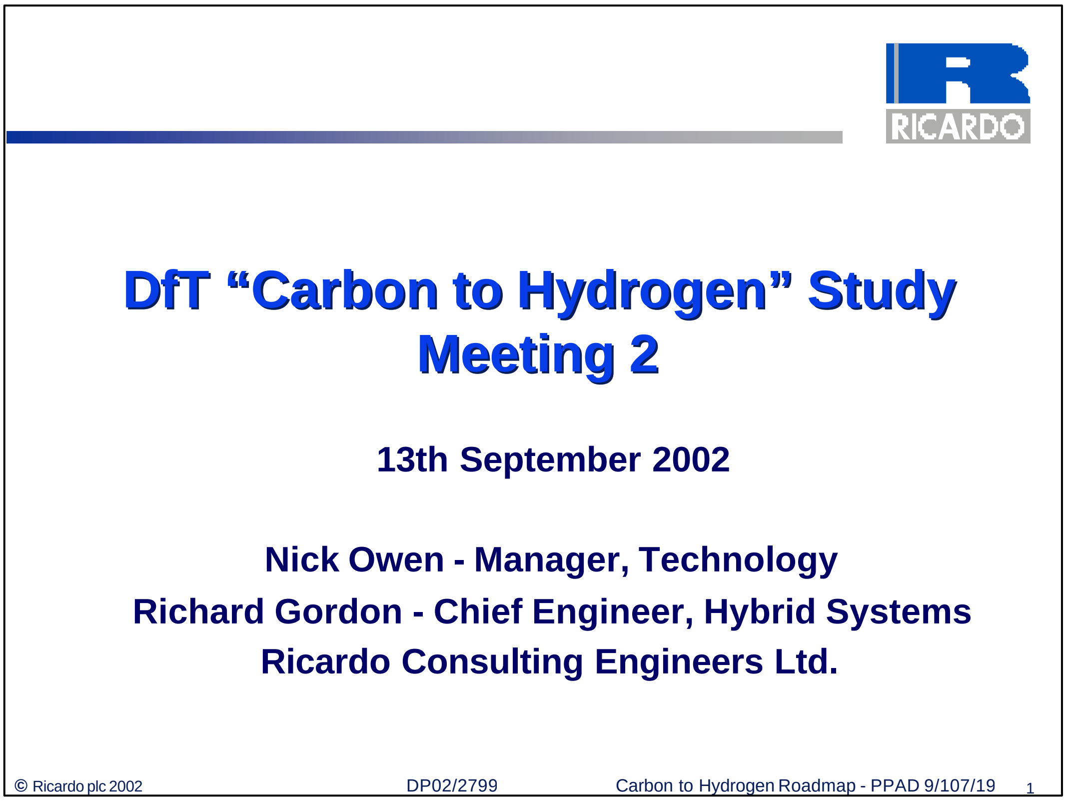
Johnson Matthey – suppliers of **precious metals** and catalysis products, are a major global stakeholder in this emerging future technology (and also in IC engine **emission control**)

ZeTek Power – Specialise in **Alkali Fuel Cell** technology, supplied a prototype **Fuel Cell van** to Westminster city council

Loughborough University / Advanced Power Systems – have very significant intellectual property in Fuel Cells, including their own **prototype PEM units**

APPENDIX E: LOW CARBON AND HYDROGEN PRIORITY ROADMAPS

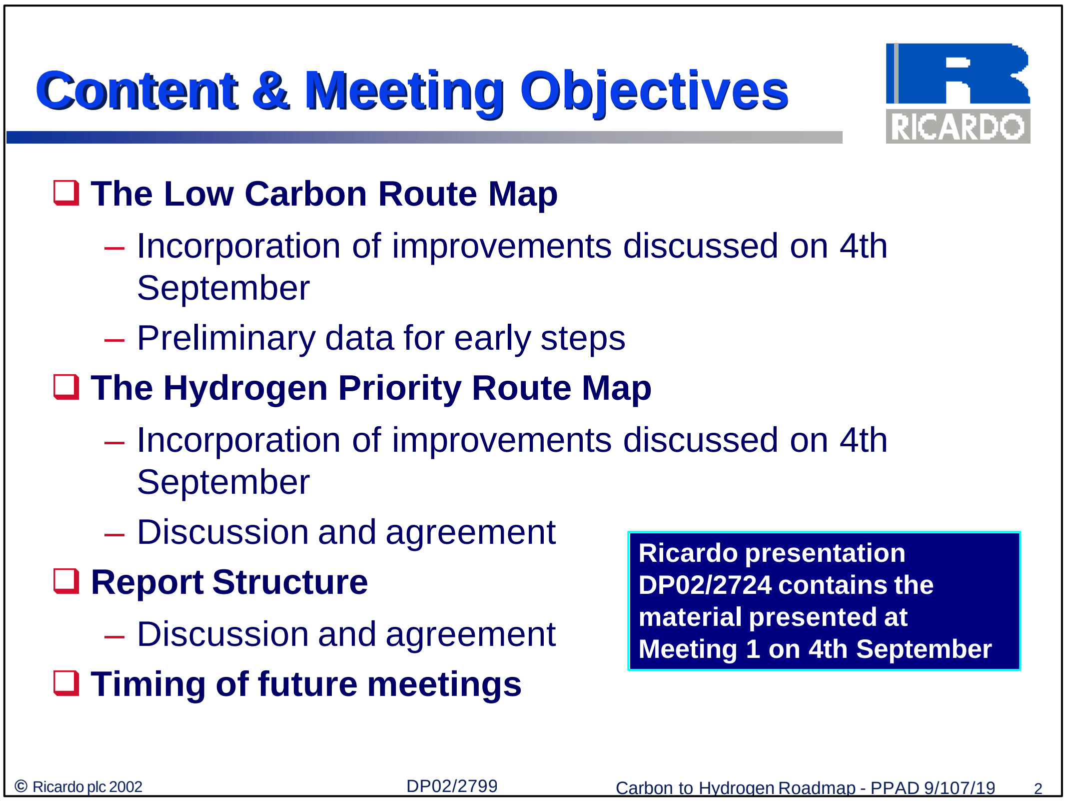
(extracts from Presentation to DfT, 13th September 2002)



DfT “Carbon to Hydrogen” Study
Meeting 2

13th September 2002

Nick Owen - Manager, Technology
Richard Gordon - Chief Engineer, Hybrid Systems
Ricardo Consulting Engineers Ltd.



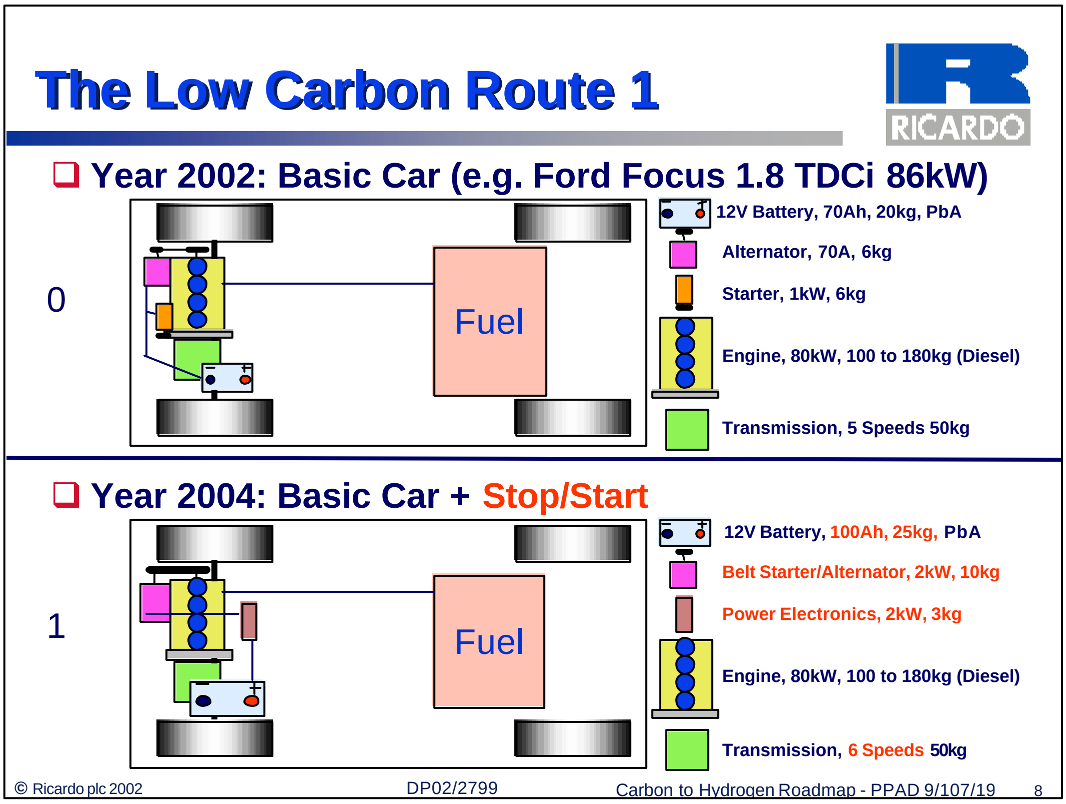
Content & Meeting Objectives

- **The Low Carbon Route Map**
  - Incorporation of improvements discussed on 4th September
  - Preliminary data for early steps
- **The Hydrogen Priority Route Map**
  - Incorporation of improvements discussed on 4th September
  - Discussion and agreement
- **Report Structure**
  - Discussion and agreement
- **Timing of future meetings**

Ricardo presentation DP02/2724 contains the material presented at Meeting 1 on 4th September

The Low Carbon Route: Rules

- ☐ Driven by stepwise introduction of increasingly stringent CO_2 targets / incentives at similar pace to current change
- ☐ Incremental development from today's products - realistic, feasible in timescales, at moderate risk
- ☐ Largely "market force" driven infrastructure change - not reliant on forced infrastructure progression
- ☐ Must be based on manufactures making money - i.e., cost effective and demanded by the mass market, but may be incentivised by taxation or legislation
- ☐ Must make environmental sense at every step, for example a technology or fuel is not adopted unless well-to-wheels CO_2 is lower



The Low Carbon Route 1

☐ Year 2002: Basic Car (e.g. Ford Focus 1.8 TDCi 86kW)

0

Fuel

12V Battery, 70Ah, 20kg, PbA

Alternator, 70A, 6kg

Starter, 1kW, 6kg

Engine, 80kW, 100 to 180kg (Diesel)

Transmission, 5 Speeds 50kg

☐ Year 2004: Basic Car + Stop/Start

1

Fuel

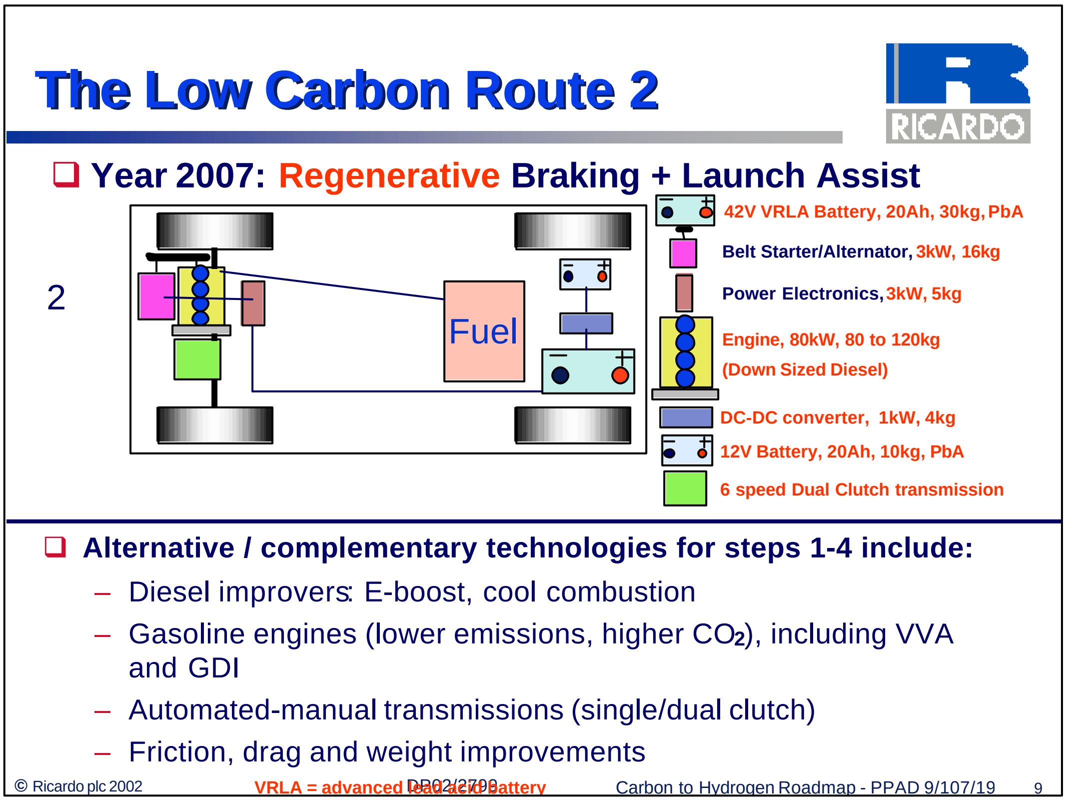
12V Battery, 100Ah, 25kg, PbA

Belt Starter/Alternator, 2kW, 10kg

Power Electronics, 2kW, 3kg

Engine, 80kW, 100 to 180kg (Diesel)

Transmission, 6 Speeds 50kg



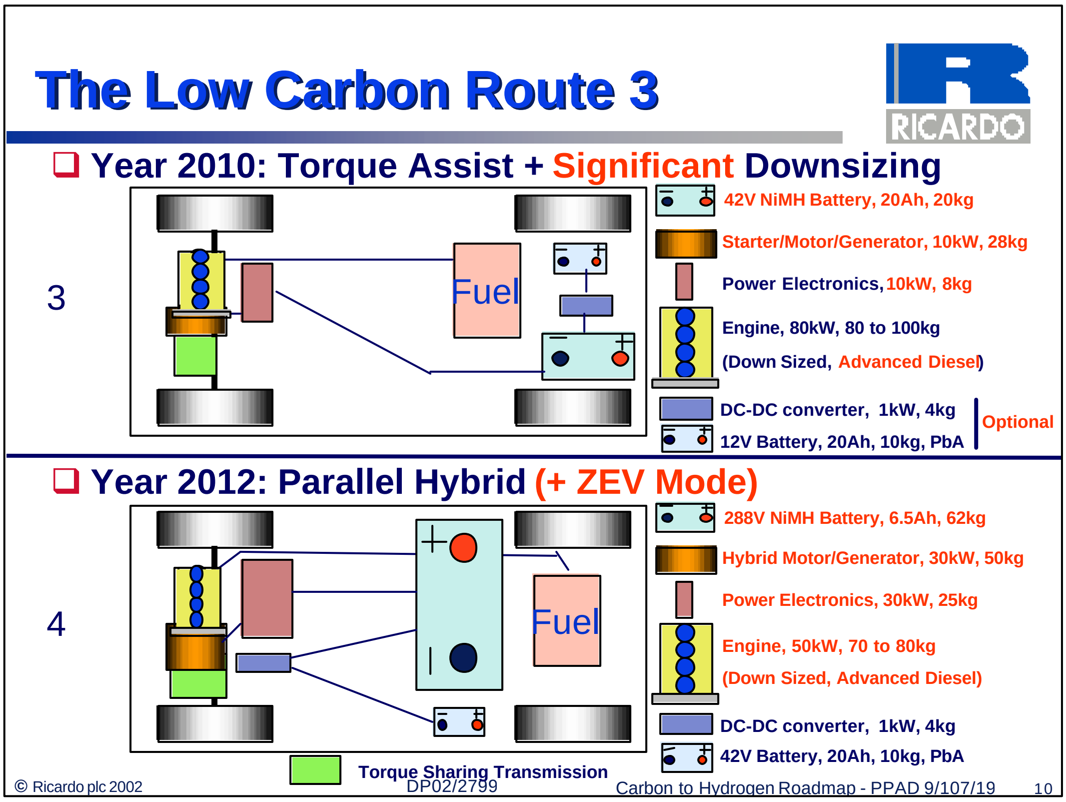
The Low Carbon Route 2

- ❑ **Year 2007: Regenerative Braking + Launch Assist**

42V VRLA Battery, 20Ah, 30kg, PbA
Belt Starter/Alternator, 3kW, 16kg
Power Electronics, 3kW, 5kg
Engine, 80kW, 80 to 120kg
(Down Sized Diesel)
DC-DC converter, 1kW, 4kg
12V Battery, 20Ah, 10kg, PbA
6 speed Dual Clutch transmission

- ❑ **Alternative / complementary technologies for steps 1-4 include:**
  - Diesel improvers: E-boost, cool combustion
  - Gasoline engines (lower emissions, higher CO_2), including VVA and GDI
  - Automated-manual transmissions (single/dual clutch)
  - Friction, drag and weight improvements

VRLA = advanced lead acid battery



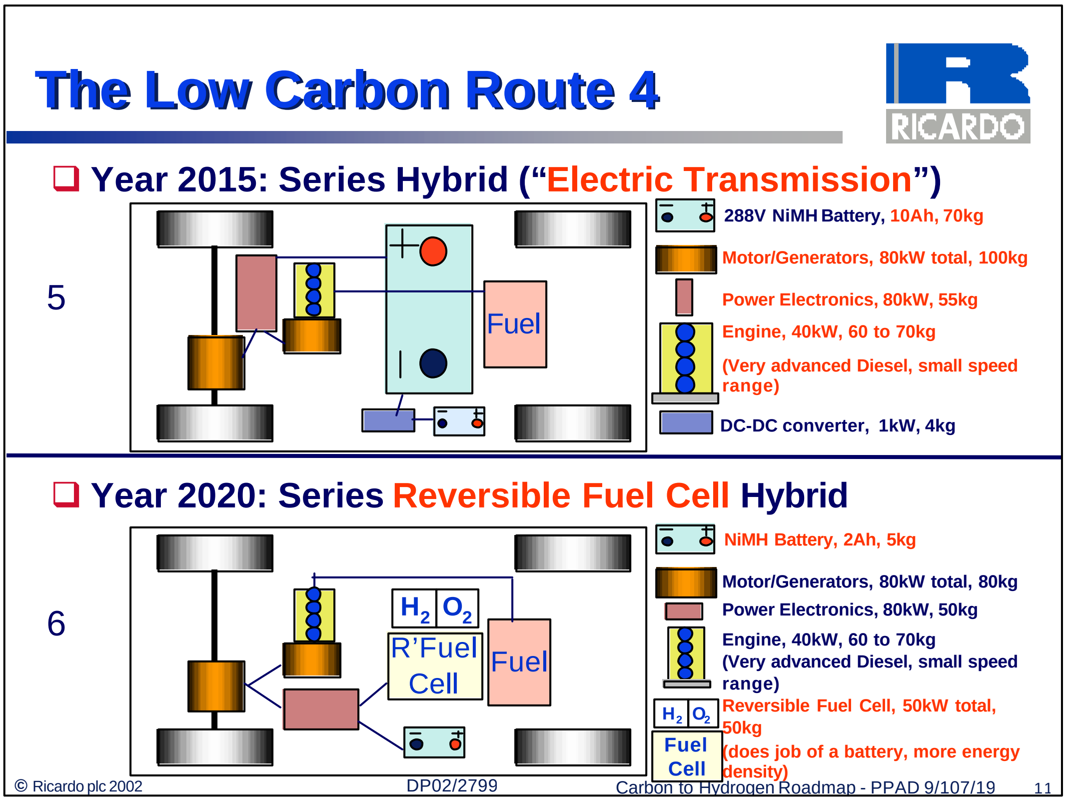
The Low Carbon Route 3

- ❑ **Year 2010: Torque Assist + Significant Downsizing**

42V NiMH Battery, 20Ah, 20kg
Starter/Motor/Generator, 10kW, 28kg
Power Electronics, 10kW, 8kg
Engine, 80kW, 80 to 100kg
(Down Sized, Advanced Diesel)
DC-DC converter, 1kW, 4kg
12V Battery, 20Ah, 10kg, PbA
Optional

- ❑ **Year 2012: Parallel Hybrid (+ ZEV Mode)**

288V NiMH Battery, 6.5Ah, 62kg
Hybrid Motor/Generator, 30kW, 50kg
Power Electronics, 30kW, 25kg
Engine, 50kW, 70 to 80kg
(Down Sized, Advanced Diesel)
DC-DC converter, 1kW, 4kg
42V Battery, 20Ah, 10kg, PbA
Torque Sharing Transmission



The Low Carbon Route 4

❑ **Year 2015: Series Hybrid (“Electric Transmission”)**

5

- 288V NiMH Battery, 10Ah, 70kg
- Motor/Generators, 80kW total, 100kg
- Power Electronics, 80kW, 55kg
- Engine, 40kW, 60 to 70kg
- (Very advanced Diesel, small speed range)
- DC-DC converter, 1kW, 4kg

❑ **Year 2020: Series Reversible Fuel Cell Hybrid**

6

- NiMH Battery, 2Ah, 5kg
- Motor/Generators, 80kW total, 80kg
- Power Electronics, 80kW, 50kg
- Engine, 40kW, 60 to 70kg (Very advanced Diesel, small speed range)
- H_2 O_2 Fuel Cell — Reversible Fuel Cell, 50kW total, 50kg (does job of a battery, more energy density)

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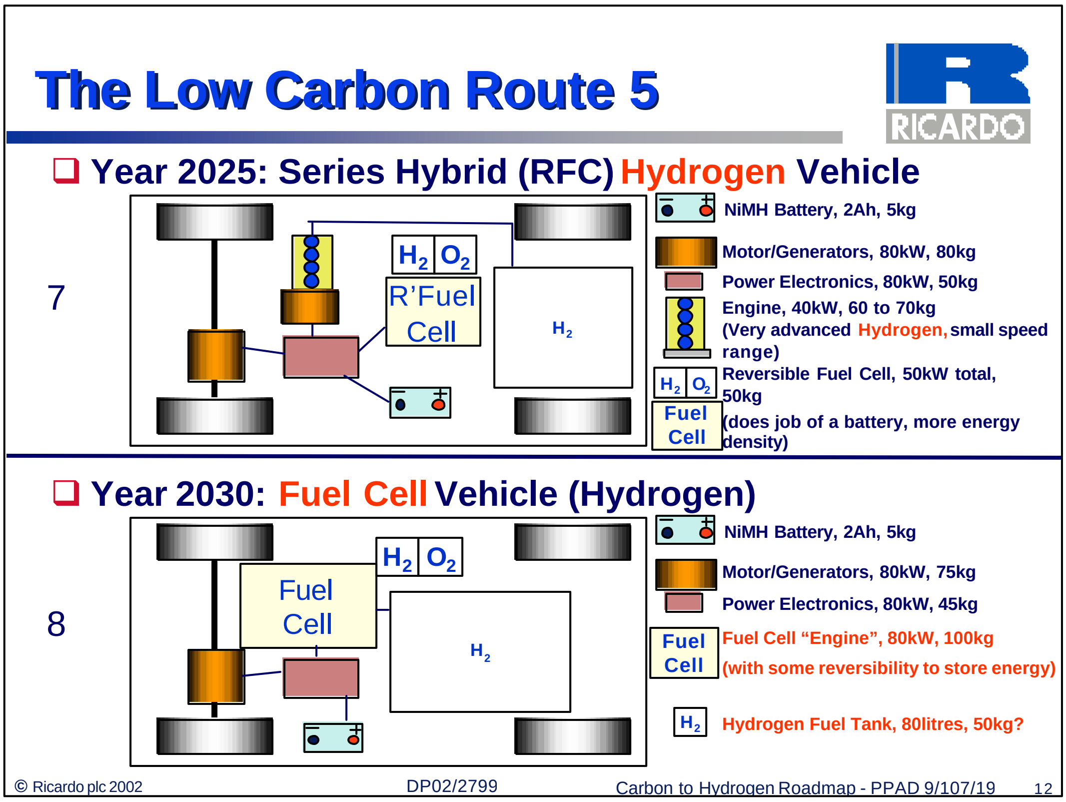

The Low Carbon Route 5

❑ **Year 2025: Series Hybrid (RFC) Hydrogen Vehicle**

7

- NiMH Battery, 2Ah, 5kg
- Motor/Generators, 80kW, 80kg
- Power Electronics, 80kW, 50kg
- Engine, 40kW, 60 to 70kg (Very advanced Hydrogen, small speed range)
- H_2 O_2 Fuel Cell — Reversible Fuel Cell, 50kW total, 50kg (does job of a battery, more energy density)

❑ **Year 2030: Fuel Cell Vehicle (Hydrogen)**

8

- NiMH Battery, 2Ah, 5kg
- Motor/Generators, 80kW, 75kg
- Power Electronics, 80kW, 45kg
- Fuel Cell — Fuel Cell “Engine”, 80kW, 100kg (with some reversibility to store energy)
- H_2 — Hydrogen Fuel Tank, 80litres, 50kg?

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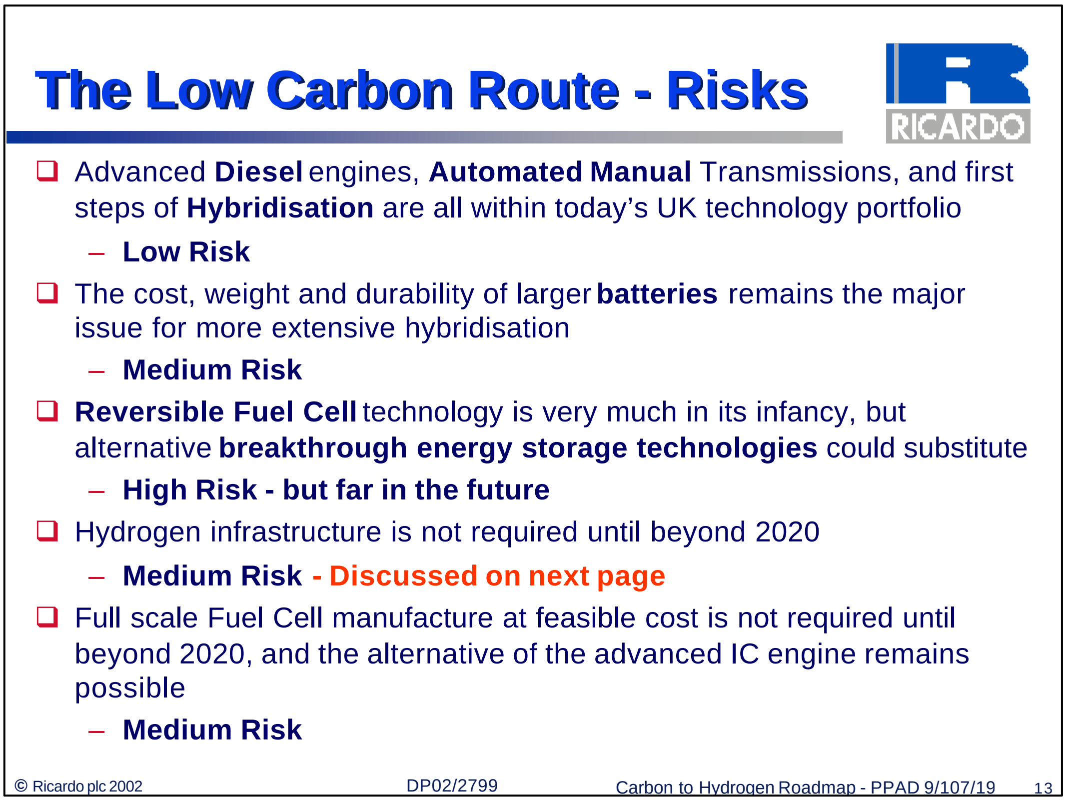
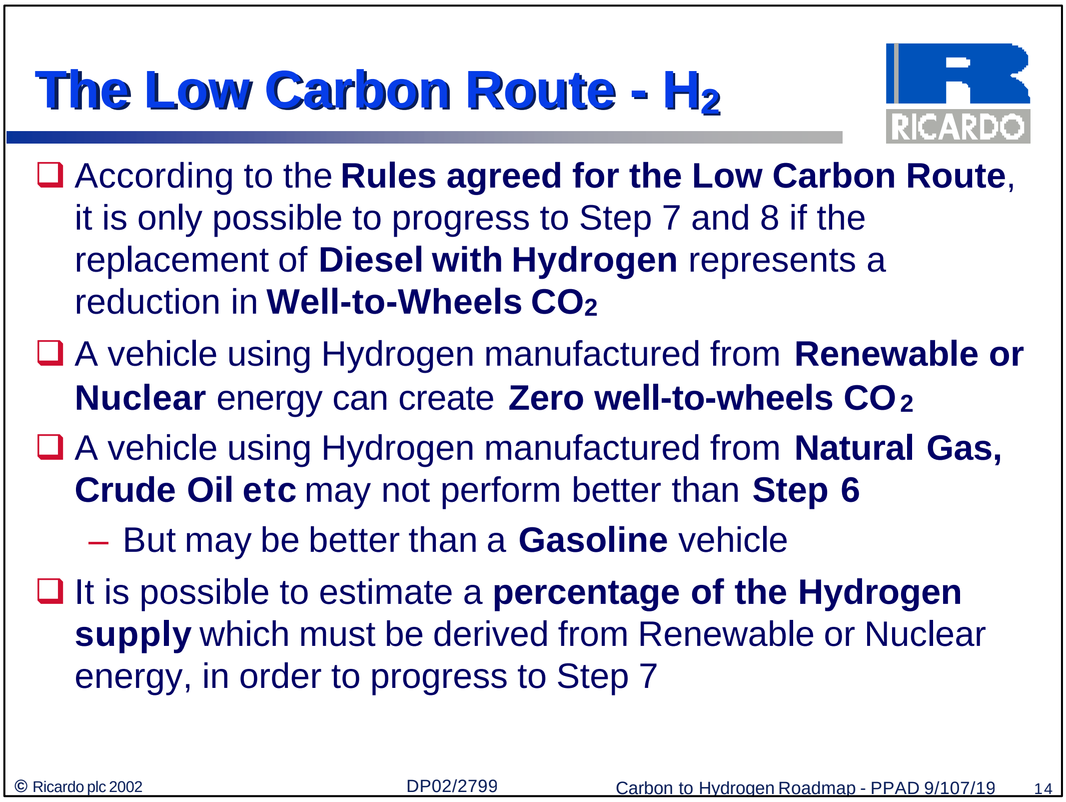


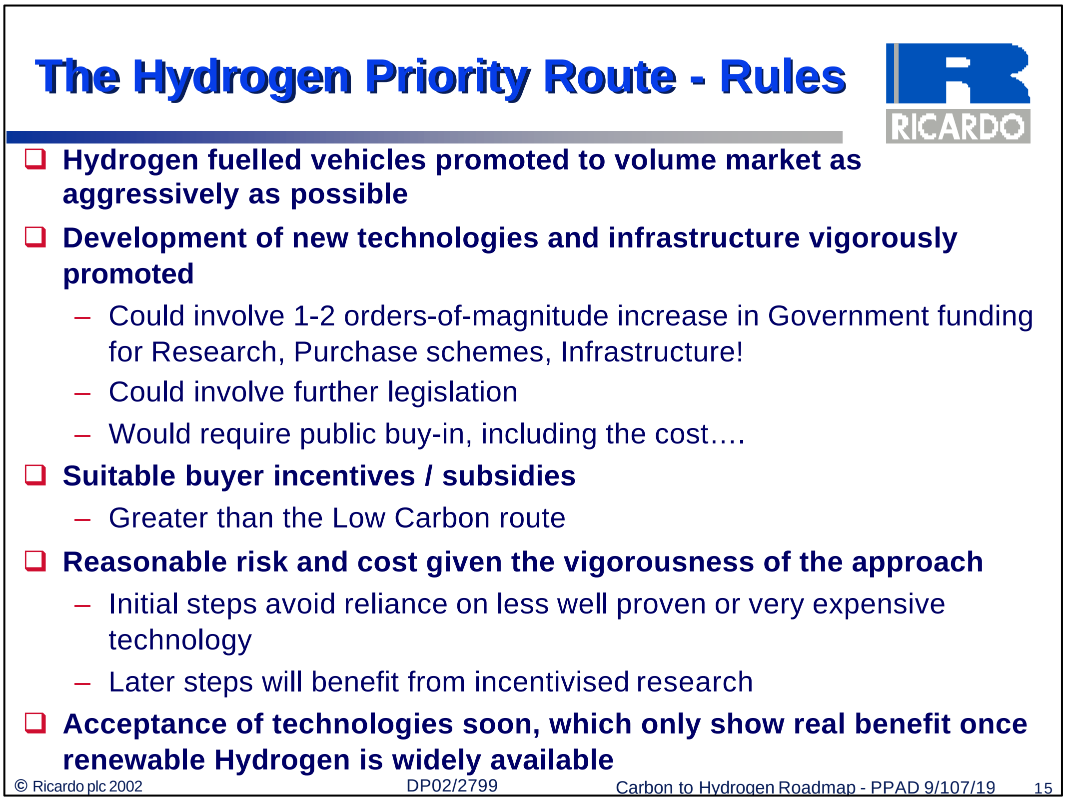
The Low Carbon Route - Risks

- Advanced **Diesel** engines, **Automated Manual** Transmissions, and first steps of **Hybridisation** are all within today's UK technology portfolio
  - **Low Risk**
- The cost, weight and durability of larger **batteries** remains the major issue for more extensive hybridisation
  - **Medium Risk**
- **Reversible Fuel Cell** technology is very much in its infancy, but alternative **breakthrough energy storage technologies** could substitute
  - **High Risk - but far in the future**
- Hydrogen infrastructure is not required until beyond 2020
  - **Medium Risk - Discussed on next page**
- Full scale Fuel Cell manufacture at feasible cost is not required until beyond 2020, and the alternative of the advanced IC engine remains possible
  - **Medium Risk**



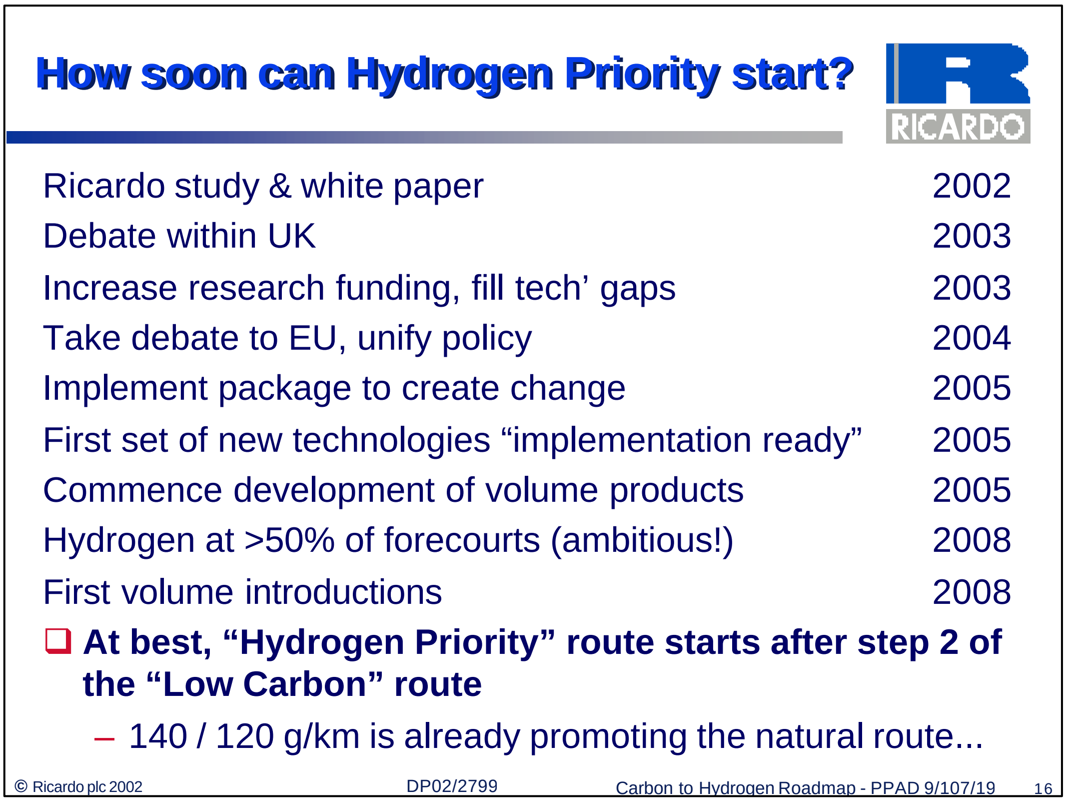
The Low Carbon Route - H_2

- According to the **Rules agreed for the Low Carbon Route**, it is only possible to progress to Step 7 and 8 if the replacement of **Diesel with Hydrogen** represents a reduction in **Well-to-Wheels CO_2**
- A vehicle using Hydrogen manufactured from **Renewable or Nuclear** energy can create **Zero well-to-wheels CO_2**
- A vehicle using Hydrogen manufactured from **Natural Gas, Crude Oil etc** may not perform better than **Step 6**
  - But may be better than a **Gasoline** vehicle
- It is possible to estimate a **percentage of the Hydrogen supply** which must be derived from Renewable or Nuclear energy, in order to progress to Step 7



The Hydrogen Priority Route - Rules

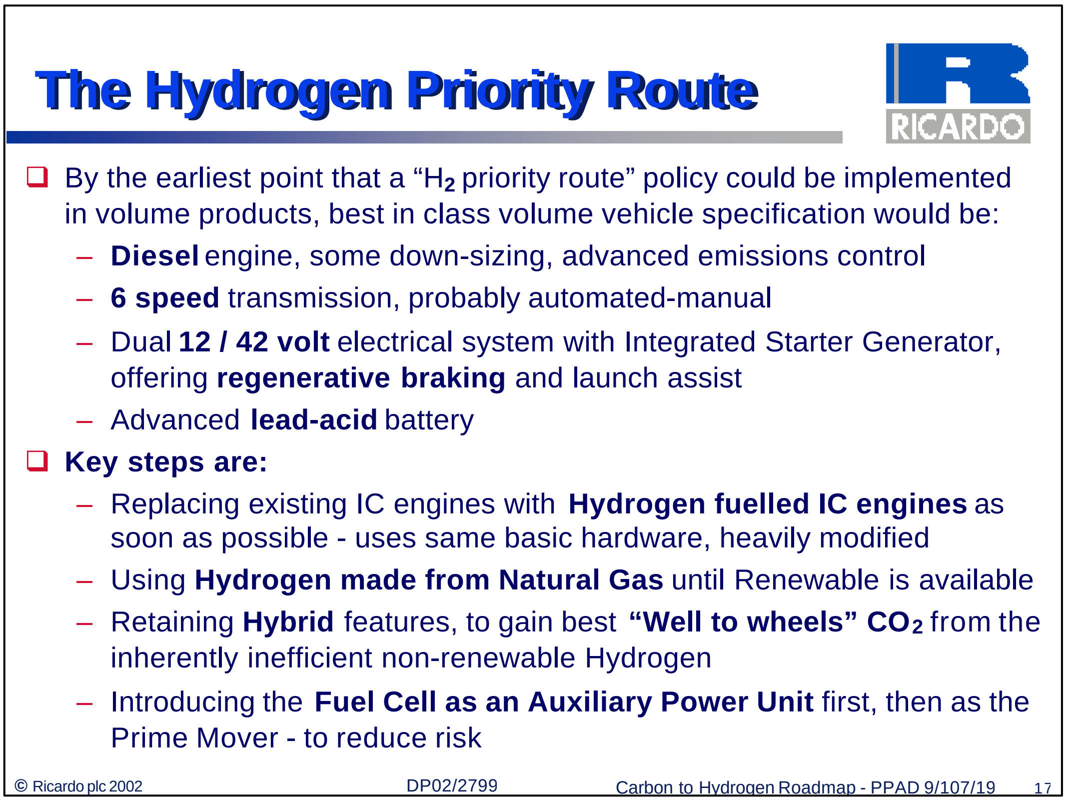
- ❑ **Hydrogen fuelled vehicles promoted to volume market as aggressively as possible**
- ❑ **Development of new technologies and infrastructure vigorously promoted**
  - Could involve 1-2 orders-of-magnitude increase in Government funding for Research, Purchase schemes, Infrastructure!
  - Could involve further legislation
  - Would require public buy-in, including the cost….
- ❑ **Suitable buyer incentives / subsidies**
  - Greater than the Low Carbon route
- ❑ **Reasonable risk and cost given the vigorousness of the approach**
  - Initial steps avoid reliance on less well proven or very expensive technology
  - Later steps will benefit from incentivised research
- ❑ **Acceptance of technologies soon, which only show real benefit once renewable Hydrogen is widely available**



How soon can Hydrogen Priority start?

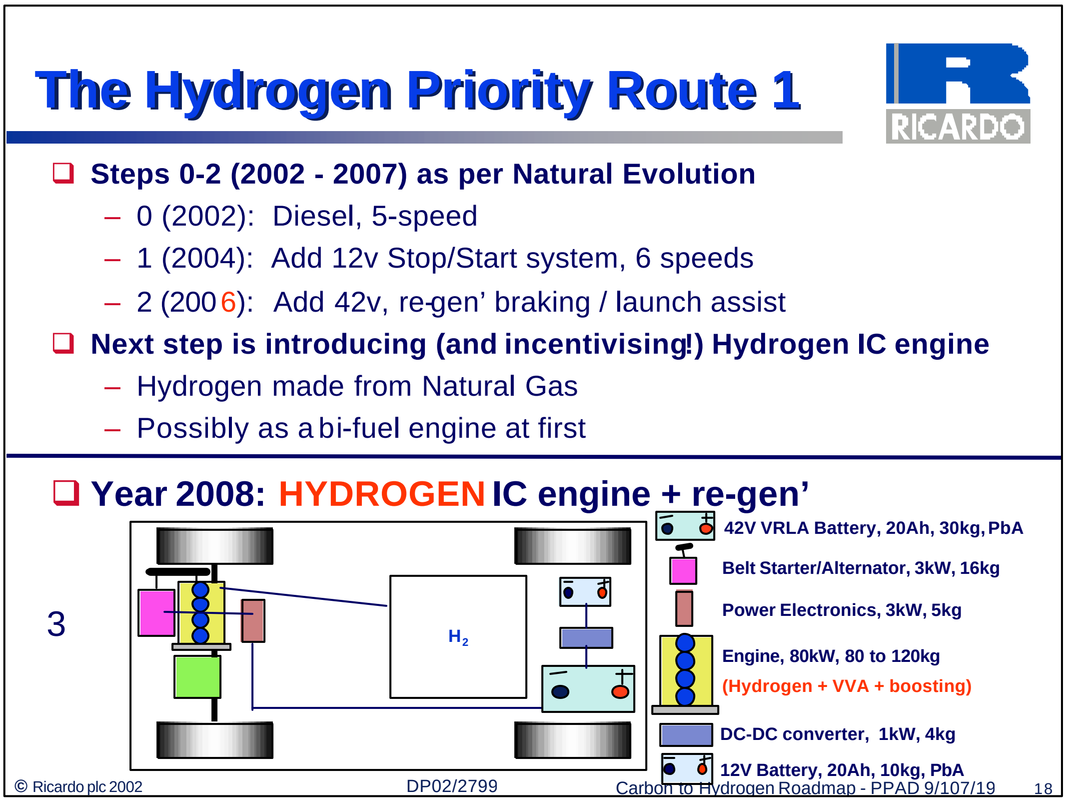
Ricardo study & white paper	2002
Debate within UK	2003
Increase research funding, fill tech' gaps	2003
Take debate to EU, unify policy	2004
Implement package to create change	2005
First set of new technologies "implementation ready"	2005
Commence development of volume products	2005
Hydrogen at >50% of forecourts (ambitious!)	2008
First volume introductions	2008

- ❑ **At best, "Hydrogen Priority" route starts after step 2 of the "Low Carbon" route**
  - 140 / 120 g/km is already promoting the natural route...



The Hydrogen Priority Route

- ☐ By the earliest point that a “H_2 priority route” policy could be implemented in volume products, best in class volume vehicle specification would be:
  - **Diesel** engine, some down-sizing, advanced emissions control
  - **6 speed** transmission, probably automated-manual
  - Dual **12 / 42 volt** electrical system with Integrated Starter Generator, offering **regenerative braking** and launch assist
  - Advanced **lead-acid** battery
- ☐ **Key steps are:**
  - Replacing existing IC engines with **Hydrogen fuelled IC engines** as soon as possible - uses same basic hardware, heavily modified
  - Using **Hydrogen made from Natural Gas** until Renewable is available
  - Retaining **Hybrid** features, to gain best **“Well to wheels” CO_2** from the inherently inefficient non-renewable Hydrogen
  - Introducing the **Fuel Cell as an Auxiliary Power Unit** first, then as the Prime Mover - to reduce risk



The Hydrogen Priority Route 1

- ☐ **Steps 0-2 (2002 - 2007) as per Natural Evolution**
  - 0 (2002): Diesel, 5-speed
  - 1 (2004): Add 12v Stop/Start system, 6 speeds
  - 2 (2006): Add 42v, re-gen’ braking / launch assist
- ☐ **Next step is introducing (and incentivising!) Hydrogen IC engine**
  - Hydrogen made from Natural Gas
  - Possibly as a bi-fuel engine at first

- ☐ **Year 2008: HYDROGEN IC engine + re-gen’**

3

42V VRLA Battery, 20Ah, 30kg, PbA

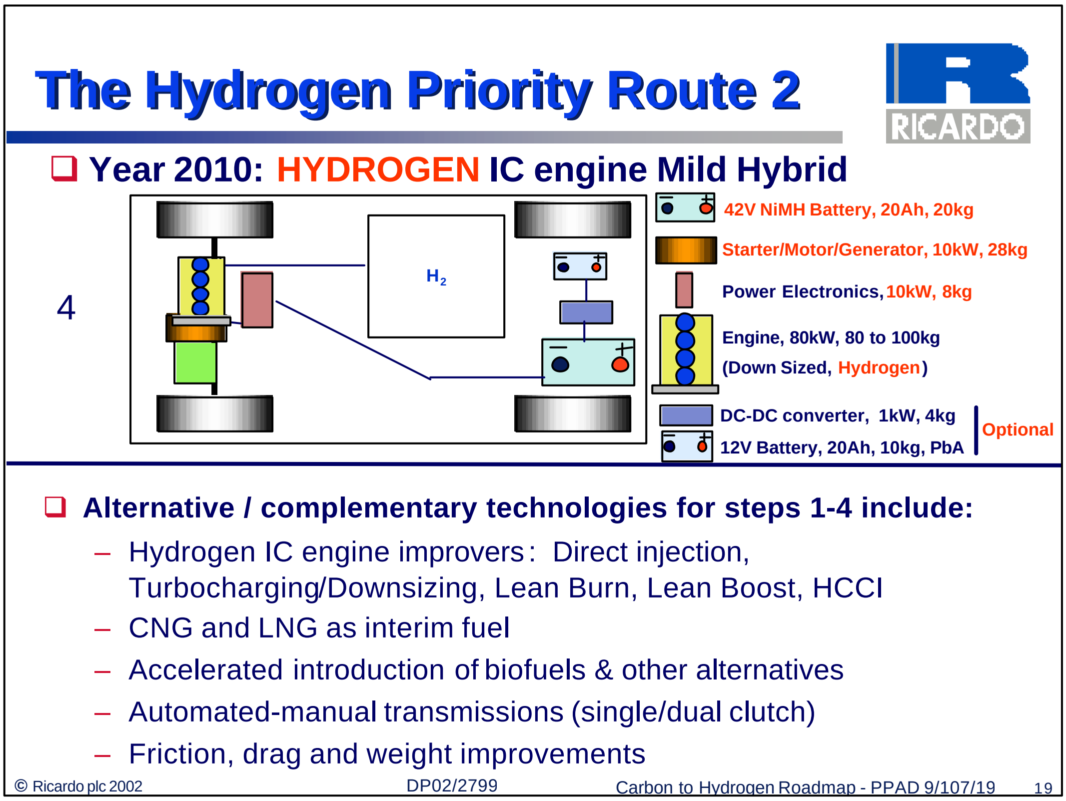
Belt Starter/Alternator, 3kW, 16kg

Power Electronics, 3kW, 5kg

Engine, 80kW, 80 to 120kg
(Hydrogen + VVA + boosting)

DC-DC converter, 1kW, 4kg

12V Battery, 20Ah, 10kg, PbA



The Hydrogen Priority Route 2

❑ **Year 2010: HYDROGEN IC engine Mild Hybrid**

4

42V NiMH Battery, 20Ah, 20kg
Starter/Motor/Generator, 10kW, 28kg
Power Electronics, 10kW, 8kg
Engine, 80kW, 80 to 100kg
(Down Sized, Hydrogen)
DC-DC converter, 1kW, 4kg
12V Battery, 20Ah, 10kg, PbA
Optional

❑ **Alternative / complementary technologies for steps 1-4 include:**

- Hydrogen IC engine improvers: Direct injection, Turbocharging/Downsizing, Lean Burn, Lean Boost, HCCI
- CNG and LNG as interim fuel
- Accelerated introduction of biofuels & other alternatives
- Automated-manual transmissions (single/dual clutch)
- Friction, drag and weight improvements

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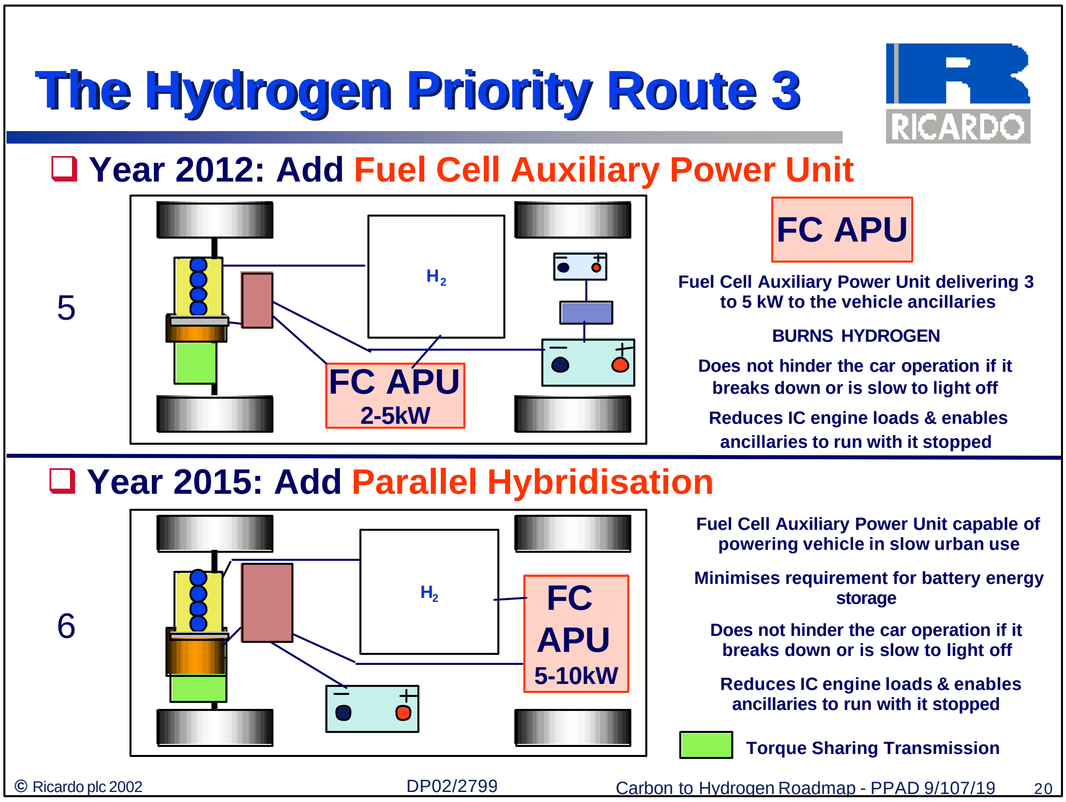

The Hydrogen Priority Route 3

❑ **Year 2012: Add Fuel Cell Auxiliary Power Unit**

5

FC APU

Fuel Cell Auxiliary Power Unit delivering 3 to 5 kW to the vehicle ancillaries

BURNS HYDROGEN

Does not hinder the car operation if it breaks down or is slow to light off

Reduces IC engine loads & enables ancillaries to run with it stopped

❑ **Year 2015: Add Parallel Hybridisation**

6

Fuel Cell Auxiliary Power Unit capable of powering vehicle in slow urban use

Minimises requirement for battery energy storage

Does not hinder the car operation if it breaks down or is slow to light off

Reduces IC engine loads & enables ancillaries to run with it stopped

🟩 **Torque Sharing Transmission**

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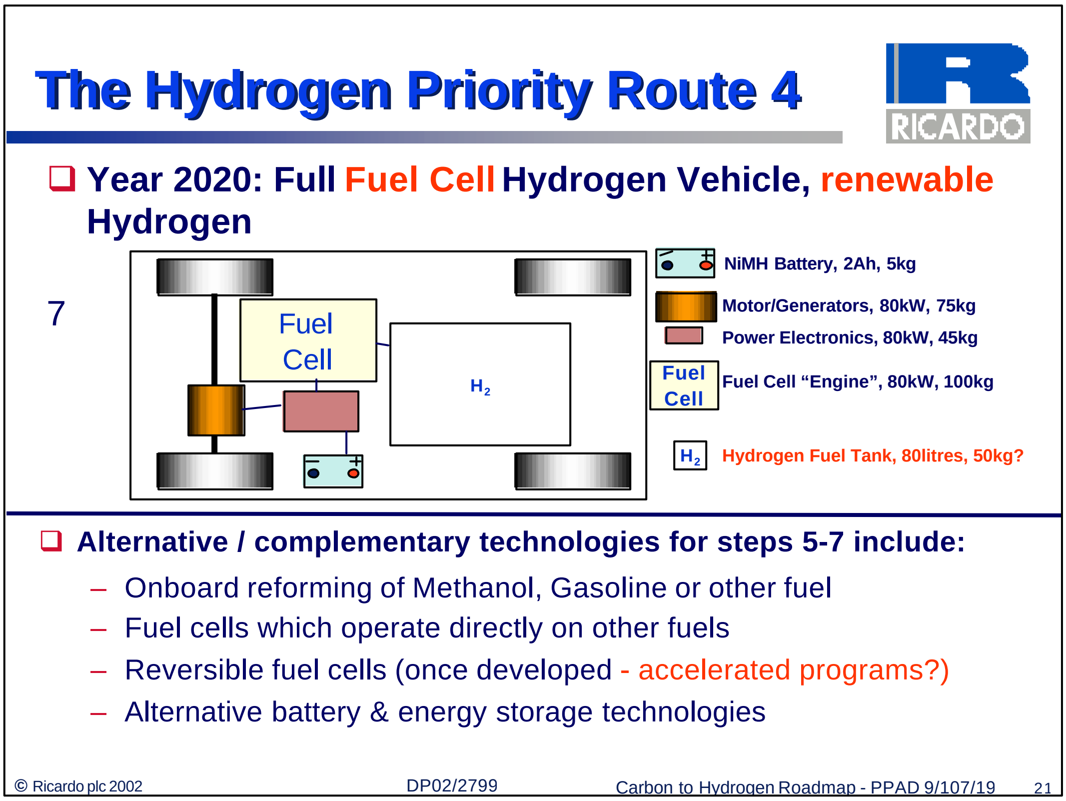

The Hydrogen Priority Route 4

- ❑ **Year 2020: Full Fuel Cell Hydrogen Vehicle, renewable Hydrogen**

7

- ❑ **Alternative / complementary technologies for steps 5-7 include:**
  - Onboard reforming of Methanol, Gasoline or other fuel
  - Fuel cells which operate directly on other fuels
  - Reversible fuel cells (once developed - accelerated programs?)
  - Alternative battery & energy storage technologies

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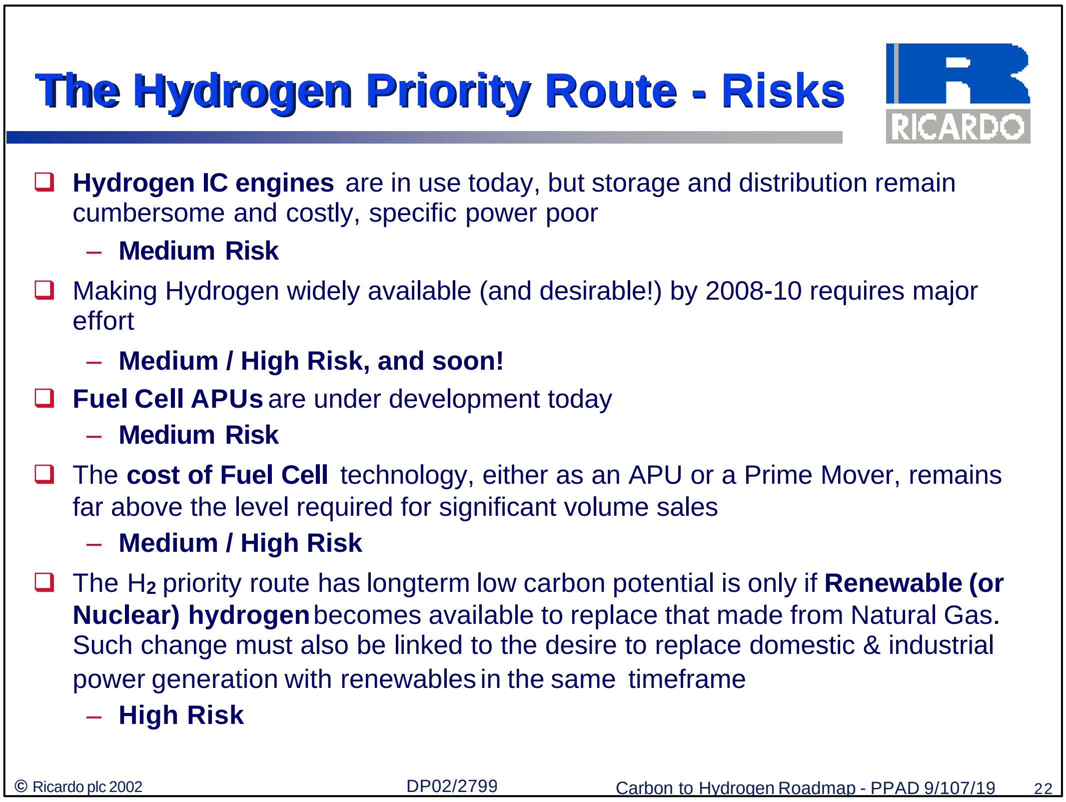

The Hydrogen Priority Route - Risks

- ❑ **Hydrogen IC engines** are in use today, but storage and distribution remain cumbersome and costly, specific power poor
  - **Medium Risk**
- ❑ Making Hydrogen widely available (and desirable!) by 2008-10 requires major effort
  - **Medium / High Risk, and soon!**
- ❑ **Fuel Cell APUs** are under development today
  - **Medium Risk**
- ❑ The **cost of Fuel Cell** technology, either as an APU or a Prime Mover, remains far above the level required for significant volume sales
  - **Medium / High Risk**
- ❑ The H_2 priority route has longterm low carbon potential is only if **Renewable (or Nuclear) hydrogen** becomes available to replace that made from Natural Gas. Such change must also be linked to the desire to replace domestic & industrial power generation with renewables in the same timeframe
  - **High Risk**

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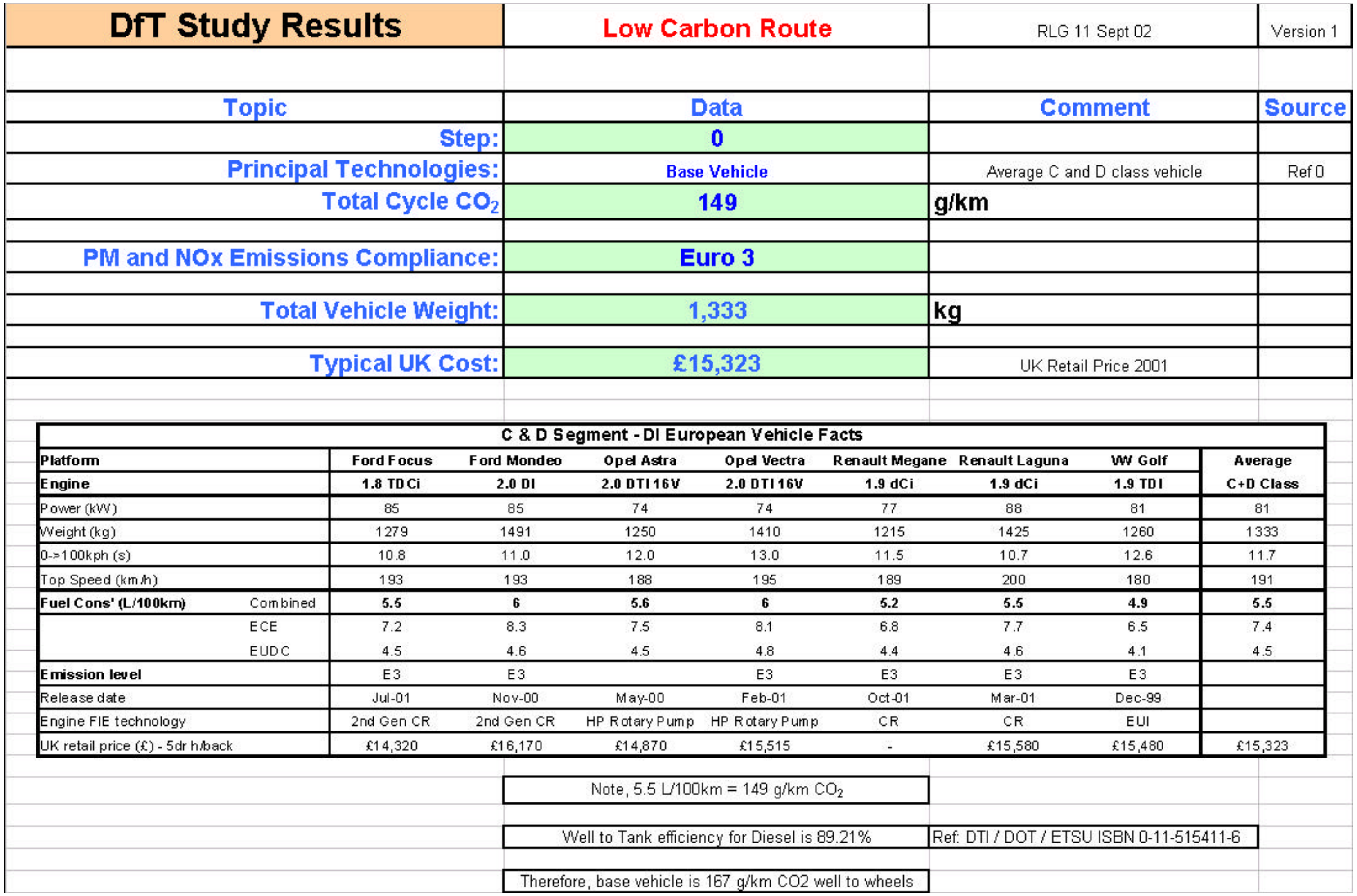
APPENDIX F: LOW CARBON AND HYDROGEN PRIORITY ROAD MAP SPREADSHEETS

Low Carbon Baseline



DfT Study Results	**Low Carbon Route**	RLG 11 Sept 02	Version 1
Topic	**Data**	**Comment**	**Source**
Step:	**0**		
Principal Technologies:	**Base Vehicle**	Average C and D class vehicle	Ref 0
Total Cycle CO_2	**149**	**g/km**	
PM and NOx Emissions Compliance:	**Euro 3**		
Total Vehicle Weight:	**1,333**	**kg**	
Typical UK Cost:	**£15,323**	UK Retail Price 2001	

C & D Segment - DI European Vehicle Facts

Platform		**Ford Focus**	**Ford Mondeo**	**Opel Astra**	**Opel Vectra**	**Renault Megane**	**Renault Laguna**	**VW Golf**	**Average**
Engine		**1.8 TDCi**	**2.0 DI**	**2.0 DTI 16V**	**2.0 DTI 16V**	**1.9 dCi**	**1.9 dCi**	**1.9 TDI**	**C+D Class**
Power (kW)		85	85	74	74	77	88	81	81
Weight (kg)		1279	1491	1250	1410	1215	1425	1260	1333
0->100kph (s)		10.8	11.0	12.0	13.0	11.5	10.7	12.6	11.7
Top Speed (km/h)		193	193	188	195	189	200	180	191
Fuel Cons' (L/100km)	Combined	**5.5**	**6**	**5.6**	**6**	**5.2**	**5.5**	**4.9**	**5.5**
	ECE	7.2	8.3	7.5	8.1	6.8	7.7	6.5	7.4
	EUDC	4.5	4.6	4.5	4.8	4.4	4.6	4.1	4.5
Emission level		E3	E3		E3	E3	E3	E3	
Release date		Jul-01	Nov-00	May-00	Feb-01	Oct-01	Mar-01	Dec-99	
Engine FIE technology		2nd Gen CR	2nd Gen CR	HP Rotary Pump	HP Rotary Pump	CR	CR	EUI	
UK retail price (£) - 5dr h/back		£14,320	£16,170	£14,870	£15,515	-	£15,580	£15,480	£15,323

Note, 5.5 L/100km = 149 g/km CO_2

Well to Tank efficiency for Diesel is 89.21% | Ref: DTI / DOT / ETSU ISBN 0-11-515411-6

Therefore, base vehicle is 167 g/km CO2 well to wheels

Low Carbon Step 1

DfT Study Results	Low Carbon Route	Step 1 Stop Start Vehicle 2004	RLG 11 Sept 02	Version 1
Topic	**Data**	**Data**	**Comment**	**Source**
Step:	**1**	**1**		
Principal Technologies:	Stop start (belt starter/alternator) + 6 spd transmission	Stop start (belt starter/alternator) + 6 spd transmission		
Emissions Achievements:	**Euro 4 (2004)**	**Euro 5 (2008)**		
Emissions Technologies used	Particulate filters probably used for Euro 4	Particulate Filter and LNT Probably used for Euro 5		
CO_2 improvement breakdown:				
Starting point (g/km CO2):	149	149	g/km	
Engine Evolution Improvements	-1.8%	-1.8%	General improvements - See report (-0.6%/year)	2
Stop Start over EUDC from 60°C eng temp	-3.6%	-3.6%	Average of Ricardo measured data (C and D class)	0
6 speed manual transmission	0.0%	0.0%	No effects from 6 speed transmission as change points are forced	3
DPF to achieve Euro 4 emissions	5.0%	5.0%	Ricardo measured data (increase due to back pressure and regen)	0
LNT Euro 5 emissions (DPF also required)	N/A	3.0%	Ricardo measured data (increase due to back pressure and regen)	0
Total *Scenario* CO_2 reduction	**-0.4%**	**2.6%**	%	
Final Vehicle Cycle CO_2	**148**	**153**	**g/km**	
Well to Wheels CO_2	**166**	**171**	**g/km - DIESEL**	
Vehicle Weight Change:	(-ve = reduction)			
Starting Point	1333	1333	kg	
Engine weight Improvements	0.00%	0.00%	Not significant at this time	0
Stop Start over EUDC from 60°C eng temp	0.60%	0.60%	Removal of starter and alternator, addition of machine and electronics	4, 5
6 speed manual transmission	0.41%	0.41%	5.5kg heavier on average	6
Expected vehicle body weight change	0.00%	0.00%	Weight neutral	0
Diesel Particulate Filter	0.45%	0.45%	6kg	0
Lean NOx Trap	N/A	0.15%	2kg	0
Total Step 1 Vehicle Weight Impact:	**1.46%**	**1.61%**	%	
Total Vehicle Weight:	**1,352**	**1,354**	**kg**	
Effect on Handling	None	None	Weight distribution unchanged	
Effect on Packaging	Small increase in complexity and thermal management	LNT and DPF difficult to package	Power electronics need careful cooling	
Effect on Maintenance and Reliability	DPF requires de-ashing at long intervals >50,000 miles	DPF + LNT requires de-ashing at long intervals >50,000 miles	LNT control system and OBD tests may be required	
Effect on Passenger and Pedestrian Safety	None	None		
Cost Change:	(-ve = reduction)			
Starting Point	£15,323	£15,323		
Powertrain Cost Reduction Evolution Improvements	-2.25%	-2.25%	Powertrain only cost reduction: 0.75% per year	2
Stop Start over EUDC from 60°C eng temp	1.76%	1.76%	+£134 for change from traditional comp'ts to belt mach. (*1.5 sales ratio)	7
6 speed manual transmission	0.52%	0.52%	+£60	0
DPF	1.63%	1.63%	£250 extra	0
LNT	N/A	1.63%	£250 extra (oxidation catalyst removal reduces cost increase)	0
Total Retail Price Impact (2002 £ value):	**1.66%**	**3.29%**		
Total Vehicle Retail Price (2002 £ value):	**£15,577**	**£15,827**	**£**	

Low Carbon Step 2

DfT Study Results	Low Carbon Route	Step 2 Stop Start + Regen Vehicle 2007	RLG 11 Sept 02	Version 1
Topic	**Data**	**Data**	**Comment**	**Source**
Step:	**2**	**2**		
Principal Technologies:	Step 1 + regen braking, new battery, 42V AMT2	Step 1 + regen braking, new battery, 42V, AMT2, LNT dev		
Emissions Achievements:	**Euro 5 (2008)**	**Euro 4 GASOLINE Emissions (+2008)**		
Emissions Technologies used	Particulate filter and Lean NOx trap or SCR (see report)	Particulate filter and Lean NOx trap or SCR (see report)		
CO_2 improvement breakdown:				
Starting point (g/km CO2):	153	153	g/km	
Engine Evolution Improvements	-1.8%	-1.8%	General improvements - See report (-0.6%/year)	2
Down size engine (Ratio of 0.9)	-5.0%	-5.0%	2.0 to 1.8 litres (Fuel Cconsumption ratio from i-MoGen)	0
3kW Regeneration over drive cycle	-3.0%	-3.0%	Ratio of i-MoGen data	0
6 speed DUAL CLUTCH transmission	-5.0%	-5.0%	Power shifting and auto but without the losses (data from Renault)	
Further engine calibration and LNT developments	N/A	3.0%	To achieve gasoline Euro 4 emissions (Ricardo Estimate)	0
Total *Scenario* CO_2 reduction	**-14.8%**	**-11.8%**	%	
Final Vehicle Cycle CO_2	**130**	**135**	**g/km**	
Well to Wheels CO_2	**146**	**151**	**g/km - DIESEL**	
Vehicle Weight Change:	(-ve = reduction)			
Starting Point	1354	1354	kg	
Down size engine (Ratio of 0.9)	-1.00%	-1.00%	-13.5kg (7.5% engine weight)	0
42V 3kW Regeneration over drive cycle plus DC-DC converter, new bat tech	-0.07 %	-0.07%	Upgraded belt machine +2kg, pow. elec. +4kg, smaller new batt. -7kg	0, 11
6 speed DUAL CLUTCH transmission	1.55%	1.55%	Some increase in hardware complexity (+21 kg)	0, 6
Further LNT developments	0.00%	0.00%	No hardware changes	0
General Vehicle Development	0.00%	0.00%	Vehicle changes are weight neutral at this time	0
Total Step 1 Vehicle Weight Impact:	**0.48%**	**0.48%**	%	
Total Vehicle Weight:	**1,361**	**1,361**	**kg**	
Effect on Handling	None	None	Weight distribution unchanged	
Effect on Packaging	LNT and DPF difficult to package	LNT and DPF difficult to package	Power electronics need careful cooling	
Effect on Maintenance and Reliability	Battery will need to be checked as it is worked hard	Battery will need to be checked as it is worked hard	LNT control system and OBD tests may be required	
Effect on Passenger and Pedestrian Safety	None	None	None	
Cost Change:	(-ve = reduction)			
Starting Point	£15,827	£15,827		
Powertrain Cost Reduction Evolution Improvements	0.00%	0.00%	Cost reduction deleted due to significant new technology introduction	0
Down size engine (Ratio of 0.9)	0.00%	0.00%	Savings in material weight usualy balance higher tech. components	0
3kW Regeneration over drive cycle	1.60%	1.60%	+£30 for motor, +£64 for pow. elec., +£75 for batt. (*1.5 sales ratio)	0, 7, 11
6 speed DUAL CLUTCH transmission	2.52%	2.52%	£266 extra (*1.5 sales ratio)	8, 9
Further LNT developments	n/a	0.63%	+£100 for control and precious metals (no s. ratio as customer won't pay)	0
Total Retail Price Impact (2002 £ value):	**4.12%**	**4.75%**		
Total Vehicle Retail Price (2002 £ value):	**£16,480**	**£16,580**	£	

Low Carbon Step 3

DfT Study Results	Low Carbon Route	Step 3 Mild Hybrid + DOWNSIZE 2010	RLG 11 Sept 02	Version 1
Topic	**Data**	**Data**	**Comment**	**Source**
Step:	**3**	**3**		
Principal Technologies:	Step 2 + significant downsized engine + NiMH bat + 10kW motor	Step 2 + significant downsized engine + NiMH bat + 10kW motor		
Emissions Achievements:	**Euro 5 (2008 onwards)**	**Euro 4 GASOLINE Emissions (+2008)**		
Emissions Technologies used	Particulate filter and Lean NOx trap or SCR (see report)	Particulate filter and Lean NOx trap or SCR (see report)		
CO_2 improvement breakdown:				
Starting point (g/km CO2):	130	135	g/km	
Engine Evolution Improvements	-1.8%	-1.8%	General improvements - See report (-0.6%/year)	2
Down size engine to 1.2 litres + Intelligent cooling	-15.0%	-15.0%	1.8 to 1.2 litres (Fuel cons. ratio from i-MoGen, incl. intelligent cooling)	0
42V 10kW motor and regeneration over drive cycle plus DC-DC converter	-5.0%	-5.0%	Increased recovery from 3 to 10kW (ratio'ed from i-MoGen data)	0
Further engine calibration and LNT developments	N/A	3.0%	To achieve gasoline Euro 4 emissions (Ricardo Estimate)	0
Total *Scenario* CO_2 reduction	**-21.8%**	**-18.8%**	%	
Final Vehicle Cycle CO_2	**102**	**109**	g/km	
Well to Wheels CO_2	**114**	**123**	**g/km - DIESEL**	
Vehicle Weight Change:	(-ve = reduction)			
Starting Point	1361	1361	kg	
Down size engine to 1.2 litres + Intelligent cooling	-2.98%	-2.98%	-40.5kg (24% of 1.8 litre engine weight)	0
42V 10kW motor and regeneration over drive cycle plus DC-DC converter	0.88%	0.88%	Upgraded belt machine +19kg, pow. elec. +3kg, smaller new batt. -10kg	0, 4, 11
General Vehicle Development	0.00%	0.00%	Vehicle changes are still weight neutral at this time	0
Total Step 1 Vehicle Weight Impact:	**-2.09%**	**-2.09%**	%	
Total Vehicle Weight:	**1,332**	**1,332**	kg	
Effect on Handling	None	None	Weight distribution unchanged	
Effect on Packaging	Larger motor and battery pack position difficult to package	Larger motor and battery pack position difficult to package	Power electronics need careful cooling	
Effect on Maintenance and Reliability	Battery life may be an issue 6 to 10 years should be achieved	Battery life may be an issue 6 to 10 years should be achieved		
Effect on Passenger and Pedestrian Safety	Packaging may change crash and pedestrian crash performance	Packaging may change crash and pedestrian crash performance	None	
Cost Change:	(-ve = reduction)			
Starting Point	£16,480	£16,580		
Powertrain Cost Reduction Evolution Improvements	0.00%	0.00%	Cost reduction deleted due to significant new technology introduction	0
Down size engine to 1.2 litres + Intelligent cooling	0.61%	0.60%	+£100 for intelligent cooling and high downsizing	0
42V 10kW motor and regeneration over drive cycle plus DC-DC converter	3.90%	3.87%	+£30 for motor, +£48 for pow. elec., +£350 for battery (*1.5 sales ratio)	0, 7, 11
Further LNT developments	N/A	0.60%	+£100 for control and precious metals (no s. ratio as customer won't pay)	0
Total Retail Price Impact (2002 £ value):	**4.50%**	**5.08%**		
Total Vehicle Retail Price (2002 £ value):	**£17,222**	**£17,422**	£	

Low Carbon Step 4

DfT Study Results	Low Carbon Route	Step 4 Parallel Hybrid + Advanced Diesel 2012	RLG 11 Sept 02	Version 1
Topic	Data	Data	Comment	Source
Step:	4	4		
Principal Technologies:	Parallel hybrid - small diesel engine + NiMH battery + 30kW motor	Parallel hybrid - small diesel engine + NiMH battery + 30kW motor		
Emissions Achievements:	Euro 6 (2012)	Euro 7 GASOLINE Emissions (2016)		
Emissions Technologies used	Particulate filter and Lean NOx trap or SCR (see report)	Particulate filter and Lean NOx trap or SCR (see report)		
CO_2 improvement breakdown:				
Starting point (g/km CO2):	109	109	g/km	
1.0 litre diesel downsizing	-4.0%	-4.0%	From ratio of i-MoGen downsizing	0
operating engine at optimum range using hybrid functions	-5.0%	-5.0%	Estimation from engine maps and published improvements	0
Regen braking, 300V, 30kW motor and generator plus DC-DC converter	-7.0%	-7.0%	Increased recovery from 10 to 30kW (ratio'ed from published discussion)	0
Further engine calibration and LNT developments	N/A	2.0%	To achieve gasoline Euro 7 emissions (Ricardo Estimate)	0
Total *Scenario* CO_2 reduction	-16.0%	-14.0%	%	
Final Vehicle Cycle CO_2	92	94	g/km	
Well to Wheels CO_2	103	105	g/km - DIESEL	
Vehicle Weight Change:	(-ve = reduction)			
Starting Point	1332	1332	kg	
1.0 litre diesel downsizing	-0.79%	-0.76%	-10.5kg from 1.2 litre engine (8.7% of 1.2 litre engine weight)	0
Regen braking, 300V, 30kW motor and generator plus DC-DC converter	3.90%	3.90%	-28+40kg for motor, +40kg for gen, similar pow. elec., similar trans.	12
Battery	2.03%	2.03%	replace 20kg battery with 47kg of NiMH battery	11
General Vehicle Development	0.00%	0.00%	Veh. ch'ges still weight neutral (C class Prius is 1368kg steel veh.)	0
Total Step 1 Vehicle Weight Impact:	5.14%	5.17%	%	
Total Vehicle Weight:	1,401	1,401	kg	
Effect on Handling	Weight distribution may change - could improve handling	Weight distribution may change - could improve handling	Weight distribution unchanged	
Effect on Packaging	Larger motor and battery pack position difficult to package	Larger motor and battery pack position difficult to package	Power electronics need careful cooling	
Effect on Maintenance and Reliability	Battery life may be an issue 6 to 10 years should be achieved	Battery life may be an issue 6 to 10 years should be achieved		
Effect on Passenger and Pedestrian Safety	Packaging may change crash and pedestrian crash peformance	Packaging may change crash and pedestrian crash peformance	None	
Cost Change:	(-ve = reduction)			
Starting Point	£16,480	£16,480		
1.0 litre diesel downsizing	0.61%	0.61%	+€100 for high tech engine materials and small turbocharger	0
Regen braking, 300V, 30kW motor and generator plus DC-DC converter	7.35%	7.35%	+€323 for motor, +€486 for electronics (*1.5 sales ratio)	10, 12
Battery	1.41%	1.41%	+€165 for battery by 2012, NiMH is at $360/kWh	11
Further LNT developments	N/A	0.81%	+€100 for control and precious metals (no s. ratio as customer won't pay)	0
Total Retail Price Impact (2002 £ value):	9.37%	10.28%		
Total Vehicle Retail Price (2002 £ value):	£18,024	£18,174	£	

Low Carbon Step 5

DfT Study Results	Low Carbon Route	Step 5 Series Hybrid + Advanced Diesel 2015	RLG 11 Sept 02	Version 1
Topic			Comment	Source
Step:	5 - with recent electrical efficiencies	5 - with required electrical efficiencies		
Principal Technologies:	Series hybrid - small diesel engine + NiMH battery + 80kW motor	Series hybrid - small diesel engine + NiMH battery + 80kW motor		
Emissions Achievements:	Euro 7 GASOLINE Emissions (2016)	Euro 7 GASOLINE Emissions (2016)		
Emissions Technologies used	Particulate filter and Lean NOx trap or SCR (see report)	Particulate filter and Lean NOx trap or SCR (see report)		
CO₂ improvement breakdown:				
	See Report for Series Hybrid Method	See Report for Series Hybrid Method		
Starting point (g/km CO2):	(94)	(94)	g/km	
1.0 litre diesel downsizing at optimum point (similar to parallel Hybrid)	0.0%	0.0%	40kW eng. (probably same displacement but reduced oper. speed range)	0
Electric transmission (generator, converter, battery, converter, motor)	37.0%	9.0%	"Electric transm." effy (improvements req'd are to match parallel hybrid)	0
Regen braking, 80kW motor and generator plus DC-DC converter	-9.0%	-9.0%	Increased recovery from 10 to 30kW (ratio'ed from published discussion)	0
Total *Scenario* CO₂ reduction	28.0%	0.0%	%	
Final Vehicle Cycle CO₂	120	94	g/km	
Well to Wheels CO₂	135	105	g/km - DIESEL	
Vehicle Weight Change:	(-ve = reduction)	(-ve = reduction)		
Starting Point	1401	1401	kg	
1.0 litre diesel downsizing at optimum point (similar to parallel Hybrid)	0.00%	0.00%	40kW engine similar to parallel hybrid	0
Electric transmission (generator, converter, battery, converter, motor)	-0.17%	-0.17%	+100kg for motor (same gen), +2.6kg for pow. elec., -65kg as trans. out	10, 12
Battery	1.00%	1.00%	+14kg for NiMH battery	11
Total Step 1 Vehicle Weight Impact:	0.83%	0.83%	%	
Total Vehicle Weight:	1,413	1,413	kg	
Effect on Handling	Weight distribution may change - could improve handling	Weight distribution may change - could improve handling	Weight distribution unchanged	
Effect on Packaging	Larger motor and battery pack position difficult to package	Larger motor and battery pack position difficult to package	Power electronics need careful cooling	
Effect on Maintenance and Reliability	Engine operation would favour long life, battery used hard	Engine operation would favour long life, battery used hard		
Effect on Passenger and Pedestrian Safety	Packaging may change crash and pedestrian crash performance	Packaging may change crash and pedestrian crash performance	None	
Cost Change:	(-ve = reduction)	(-ve = reduction)		
Starting Point	£18,174	£18,174		
1.0 litre diesel downsizing at optimum point (similar to parallel Hybrid)	0.00%	0.00%	40kW engine similar to parallel hybrid	0
Electric transmission (generator, converter, battery, converter, motor)	0.26%	0.26%	+€700 for motor, -€86 for pow. elec., - €583 as trans. out (*1.5 sales ratio)	10, 12
Battery	1.76%	1.76%	+€216 for battery by 2015 (NiMH is at $350/kWh)	11
Total Retail Price Impact (2002 £ value):	2.05%	2.05%		
Total Vehicle Retail Price (2002 £ value):	£18,546	£18,546	£	

Low Carbon Step 6

DfT Study Results	**Low Carbon Route**	**Step 6 Series Hybrid + Reversible FC 2020**	RLG 11 Sept 02
Topic		**Comment**	**Source**
Step:	**6 - with Future electrical efficiencies**		
Principal Technologies:	Series hybrid - Small Diesel Engine + Rev Fuel Cell + 80kW motor		
Emissions Achievements:	**Euro 7 GASOLINE Emissions (2016)**		
Emissions Technologies used	Particulate filter and Lean NOx trap or SCR (see report)		
CO_2 improvement breakdown:			
	See Report for Series Hybrid Method		
Starting point (g/km CO2):	(94)	g/km (from Series Hybrid with BEST powertrain efficiencies)	
Electric transmission (generator, converter, Reversible Fuel Cell, converter, motor)	**98.0%**	Reversible Fuel Cell efficiency is poor (65% in and 70% out at best)	0
Total *Scenario* CO_2 reduction	**98.0%**	%	
Final Vehicle Cycle CO_2	**186**	g/km	
Well to Wheels CO_2	**209**	**g/km - DIESEL**	
Vehicle Weight Change:	(-ve = reduction)		
Starting Point	1413	kg	
Electric transmission (generator, converter, Reversible Fuel Cell, converter, motor)	-1.77%	-55kg for battery, +30kg for Reversible Fuel Cell (96 Wh/kg specific energy density)	11, 0
Total Step 1 Vehicle Weight Impact:	**-1.77%**	%	
Total Vehicle Weight:	**1,388**	kg	
Effect on Handling	Weight distribution may change - could improve handling	Weight distribution unchanged	
Effect on Packaging	Reversible Fuel Cell system is small but complicated to package	Power electronics need careful cooling	
Effect on Maintenance and Reliability	RFC would be unknow at this time		
Effect on Passenger and Pedestrian Safety	Packaging may change crash and pedestrian crash performance	None	
Cost Change:	(-ve = reduction)		
Starting Point	£18,546		
Electric transmission (generator, converter, Reversible Fuel Cell, converter, motor)	7.86%	+£2000 for reversible fuel cell (40kW stack size at £50/kW), -£543 for NiMH battery	0, 11
Total Retail Price Impact (2002 £ value):	**7.86%**		
Total Vehicle Retail Price (2002 £ value):	**£20,003**	£	

Low Carbon Step 7

DfT Study Results	Low Carbon Route	Step 7 Series HYDROGEN Hybrid + Reversible FC 2025	RLG 11 Sept 02
Topic		**Comment**	**Source**
Step:	**7 - with Future electrical efficiencies**		
Principal Technologies:	Series hybrid - Small Hydrogen Engine + Rev Fuel Cell + 80kW motor		
Emissions Achievements:	**Euro 7 GASOLINE Emissions (2016)**		
Emissions Technologies used	Particulate filter and Lean NOx trap or SCR (see report)		
CO_2 improvement breakdown:			
	See Report for Series Hybrid Method		
Starting point Well To Wheels (g/km CO_2):	(209)	g/km (from Series Diesel Hybrid with RFC and BEST powertrain efficiencies)	
Change from Diesel to Very Advanced Hydrogen engine (H_2 from Natural Gas)	26.0%	Reversible Fuel Cell efficiency is poor (65% in and 70% out at best)	0
Total *Scenario* CO_2 reduction	**26.0%**	%	
Well to Wheels CO_2	**263**	**g/km NOTE - 60% worse than 2001 MY baseline if H_2 from Nat Gas**	
Vehicle Weight Change:	(-ve = reduction)		
Starting Point	1308	kg	
Change from Diesel to Very Advanced Hydrogen engine (H_2 from Natural Gas)	-2.66%	-100kg for the diesel +60kg for the H2 engine	13
Hydrogen Storage	5.77%	-10 kg for diesel tank, + 90kg for 7kg of Hydrogen storage	14
Total Step 1 Vehicle Weight Impact:	**2.88%**	%	
Total Vehicle Weight:	**1,428**	kg	
Effect on Handling	Weight distribution may change - could improve handling	Weight distribution unchanged	
Effect on Packaging	Reversible Fuel Cell system is small but complicated to package	Power electronics need careful cooling	
Effect on Maintenance and Reliability	RFC would be unknow at this time		
Effect on Passenger and Pedestrian Safety	Packaging may change crash and pedestrian crash performance	None	
Cost Change:	(-ve = reduction)		
Starting Point	£20,003		
Change from Diesel to Very Advanced Hydrogen engine (H_2 from Natural Gas)	-1.03%	- £205 for H2 engine compared to Diesel engine with expensive fuel injection equipment	0
Hydrogen Storage	1.83%	+£366 for H2 storage	15
Total Retail Price Impact (2002 £ value):	**0.80%**		
Total Vehicle Retail Price (2002 £ value):	**£20,163**	£	

Low Carbon Step 7b

DfT Study Results	Low Carbon Route	Step 7b Parallel HYDROGEN Hybrid + NiMH battery 2025	RLG 11 Sept 02
Topic		Comment	Source
Step:	7b - with Parallel Hybrid efficiencies		
Principal Technologies:	Parallel hybrid - Small Hydrogen Engine + NiMH battery + 30kW motor		
Emissions Achievements:	Euro 7 GASOLINE Emissions (2016)		
Emissions Technologies used	Particulate filter and Lean NOx trap or SCR (see report)		
CO_2 improvement breakdown:			
	See Report for Series Hybrid Method		
Starting point Well To Wheels (g/km CO_2):	(105)	g/km (From Parallel Diesel Hybrid)	
Change from Diesel to Very Advanced Hydrogen engine (H_2 from Natural Gas)	26.3%	Reversible Fuel Cell efficiency is poor (65% in and 70% out at best)	0
Total *Scenario* CO_2 reduction	26.3%	%	
Well to Wheels CO_2	133	g/km NOTE - 19% better than 2001 MY baseline if H_2 from Nat Gas	
Vehicle Weight Change:	(-ve = reduction)		
Starting Point	1401	kg	
Change from Diesel to Very Advanced Hydrogen engine (H_2 from Natural Gas)	-2.86%	-100kg for the Diesel engine, +60kg for the H_2 engine	13
Hydrogen Storage	5.71%	-10 kg for diesel tank, + 90kg for 7kg of Hydrogen storage	14
Total Step 1 Vehicle Weight Impact:	2.86%	%	
Total Vehicle Weight:	1,441	kg	
Effect on Handling	Weight distribution may change - could improve handling	Weight distribution unchanged	
Effect on Packaging	Reversible Fuel Cell system is small but complicated to package	Power electronics need careful cooling	
Effect on Maintenance and Reliability	RFC would be unknow at this time		
Effect on Passenger and Pedestrian Safety	Packaging may change crash and pedestrian crash performance	None	
Cost Change:	(-ve = reduction)		
Starting Point	£18,024		
Change from Diesel to Very Advanced Hydrogen engine (H_2 from Natural Gas)	-1.14%	- £206 for H_2 engine compared to Diesel engine with expensive fuel injection equipment	0
Hydrogen Storage	2.03%	+£366 for H_2 storage	15
Total Retail Price Impact (2002 £ value):	0.89%		
Total Vehicle Retail Price (2002 £ value):	£18,184	£	

Low Carbon Step 7c

DfT Study Results	Low Carbon Route	7c - Diesel Parallel Hybrid with H_2 APU	RLG 11 Sept 02
Topic		**Comment**	**Source**
Step:	**7c - Diesel Parallel Hybrid with H2 APU**		
Principal Technologies:	Parallel hybrid + Small Diesel Engine + APU		
Emissions Achievements:	**Euro 7 GASOLINE Emissions (2016)**		
Emissions Technologies used	Particulate filter and Lean NOx trap or SCR (see report)		
CO_2 improvement breakdown:			
	See Report for Series Hybrid Method		
Starting point Well To Wheels (g/km CO_2):	(105)	g/km (From Parallel Diesel Hybrid)	
Parallel diesel +APU providing 1/2 the required average power	**0.7%**	Hydrogen APU is providing 50% of the cycle average power at 40% efficiency	0
Total *Scenario* CO_2 reduction	**0.7%**	%	
Well to Wheels CO_2	**106**	**Note, does not include increase in WEIGHT now significant (below**	
Vehicle Weight Change:	(-ve = reduction)		
Starting Point	1401	kg	
Add APU	6.71%	-100kg for the diesel +60kg for the H_2 engine	13
Hydrogen Storage	3.21%	-10 kg for diesel tank + 90kg for 7kg of Hydrogen storage	14
Total Step 1 Vehicle Weight Impact:	**8.92%**	%	
Total Vehicle Weight:	**1,526**	**kg**	
Effect on Handling	Weight distribution may change - could improve handling	Weight distribution unchanged	
Effect on Packaging	Reversible Fuel Cell system is small but complicated to package	Power electronics need careful cooling	
Effect on Maintenance and Reliability	RFC would be unknow at this time		
Effect on Passenger and Pedestrian Safety	Packaging may change crash and pedestrian crash performance	None	
Cost Change:	(-ve = reduction)		
Starting Point	£18,024		
Add APU	4.44%	£800	
Hydrogen Storage	1.02%	+£366 for H_2 storage	15
Total Retail Price Impact (2002 £ value):	**5.45%**		
Total Vehicle Retail Price (2002 £ value):	**£19,007**	**£**	

Low Carbon Step 7d

DfT Study Results	Low Carbon Route	7d - CNG Parallel Hybrid with H_2 APU	RLG 11 Sept 02
Topic		**Comment**	**Source**
Step:	**7d - CNG Parallel Hybrid with H_2 APU**		
Principal Technologies:	Parallel hybrid + Small Diesel Engine + APU		
Emissions Achievements:	**Euro 7 GASOLINE Emissions (2016)**		
Emissions Technologies used	Particulate filter and Lean NOx trap or SCR (see report)		
CO_2 improvement breakdown:			
	See Report for Series Hybrid Method		
Starting point Well To Wheels (g/km CO_2):	(105)	g/km (From Parallel Diesel Hybrid)	
Parallel diesel +APU providing 1/2 the required average power	-2.9%	Hydrogen APU is providing 50% of the cycle average power at 40% efficiency	0
Total *Scenario* CO_2 reduction	**-2.9%**	%	
Well to Wheels CO_2	**102**	**Note, does not include increase in WEIGHT now significant (below)**	
Vehicle Weight Change:	(-ve = reduction)		
Starting Point	1401	kg	
Add APU Subtract diesel replace CNG engine	2.86%	(Engine is potentially 40kg lighter)	13
Hydrogen Storage	3.21%	+90kg for 7kg of Hydrogen storage - Assuming CNG strorage similar to diesel for simplicity	14
Total Step 1 Vehicle Weight Impact:	**6.07%**	%	
Total Vehicle Weight:	**1,486**	kg	
Effect on Handling	Weight distribution may change - could improve handling	Weight distribution similar	
Effect on Packaging	Reversible Fuel Cell system is small but complicated to package	Power electronics need careful cooling	
Effect on Maintenance and Reliability	RFC would be unknown at this time		
Effect on Passenger and Pedestrian Safety	Packaging may change crash and pedestrian crash performance	None	
Cost Change:	(-ve = reduction)		
Starting Point	£18,024		
Add APU Subtract diesel replace CNG engine	3.30%		
Hydrogen Storage	1.02%	+£366 for H_2 storage	15
Total Retail Price Impact (2002 £ value):	**4.31%**		
Total Vehicle Retail Price (2002 £ value):	**£18,801**	£	

Low Carbon Step 8

DfT Study Results	Low Carbon Route	Step 8 Fuel Cell Vehicle 2030	RLG 11 Sept 02	Version 1
Topic			Comment	Source
Step:	8 - Fuel Cell Vehicle	8 - Fuel Cell Vehicle		
Principal Technologies:	Series hybrid with Fuel Cell Vehicle	Series hybrid Fuel Cell Vehicle WITH FUTURE ELECTRICAL Sys EFFICIENCIES		
Emissions Achievements:	45% efficient fuel cell system	63% Fuel Cell System + Higher Efficiency Motors etc.		
Emissions Technologies used				
CO_2 improvement breakdown:				
Starting point Well To Wheels (g/km CO_2):	See Report for Series Hybrid Method (263)	See Report for Series Hybrid Method (263)	g/km (From Series Hydrogen Hybrid (Step 7))	
From Advanced H_2 engine to Fuel Cell (H_2 from Nat Gas) + remove gen	-55%	-72%	Improvement due to Fuel Cell efficiency higher than engine and generator from H2 to electricity. Fuel Cell taken as 63% efficient at part load.	0
Total *Scenario* CO_2 reduction	-55%	-72%	%	
Well to Wheels CO_2	119	74	g/km (47% to 53% better than the 2001 MY baseline vehicle if H_2 from Nat Gas)	
Vehicle Weight Change:	(-ve = reduction)	(-ve = reduction)		
Starting Point	1428	1428	kg	
From Advanced H_2 engine to Fuel Cell (H_2 from Nat Gas) + remove gen	2.80%	2.80%	-60kg for H_2 eng., +140kg for Fuel Cell system (40kW), -40kg for gen.	0, 12, 15
Total Step 1 Vehicle Weight Impact:	2.80%	2.80%	%	
Total Vehicle Weight:	1,468	1,468	kg	
Effect on Handling	Weight distribution may change - could improve handling	Weight distribution may change - could improve handling		
Effect on Packaging	Reversible Fuel Cell system is small but complicated to package	Reversible Fuel Cell system is small but complicated to package		
Effect on Maintenance and Reliability	Fuel Cell System Introduction would require considerable training	Fuel Cell System Introduction would require considerable training		
Effect on Passenger and Pedestrian Safety	Packaging may change crash and pedestrian crash performance	Packaging may change crash and pedestrian crash performance		
Cost Change:	(-ve = reduction)	(-ve = reduction)		
Starting Point	£20,163	£20,163		
From Advanced H_2 engine to Fuel Cell (H_2 from Nat Gas) + remove gen	-7.11%	-7.11%	-£900 for removal of gen., +£2000 for Fuel Cell at £50/kW (40kW), -£933 for H2 engine, - £2000 for RFC	0, 12, 15 0
Total Retail Price Impact (2002 £ value):	-7.11%	-7.11%		
Total Vehicle Retail Price (2002 £ value):	£18,730	£18,730	£	

Low Carbon References

DfT Study Results		Low Carbon Route	RLG 11 Sept 02	Version 1

			Added info for traceability
Ref	0	Ricardo experience / databases / measured data	
Ref	1	Data from Automobilismo Mars 2002, Vehicle Certification Agency for emission class and Ricardo (LDD) database for FIE	
Ref	2	Ricardo calculations based on in-house data looking at base engine and vehicle technology efficiency evolution	
Ref	3	Vehicle Certification Agency	www.vca.gov.uk/
Ref	4	Visteon electro mechanical drive system data	www.visteon.com
Ref	5	General overview of dual architecture automotive electrical systems using DC-DC converters	Ricardo document DP 01/2685
Ref	6	Transmissions technologies / Trends (efficiencies, issues, etc. for 2002)	Backup material for transmission trends.ppt, John Bennett, Ricardo DTS
Ref	7	Electric machines and power electronics CONFIDENTIAL DATA	Ricardo document DP 01/2685
Ref	8	Presentation by Antonov Transmission	Antonov, about year 2001
Ref	9	Ward's auto world, dec 2000	Article "Teaching an old tranny new tricks"
Ref	10	Power electronics main facts	Murray Edington, Bedford Office
Ref	11	The prospects for hybrid vehicles, 2005-2020	SAE Paper 1999-01-2942
Ref	12	Electric motors main facts	Keith Ramsay, Ricardo DTS
Ref	13	Reference to Honda Insight engine weight reduction techniques (56kg for 50kW)	HdT Technical Publication 2001 Hybrid Vehicles conference
Ref	14	Energy Efficiency and Renewable Energy Network , US DoE	Hydrogen Vision Meeting, Alan Niedzwiecki
Ref	15	Northease Advanced Vehicle Consortium	Future wheels discussion document

Hydrogen Priority Road Map Step 3H

DfT Study Results	Hydrogen Priority Route	Step 3H H_2 Powered Stop Start + Regen Vehicle 2007	RLG 11 Sept 02
Topic	**Data**	**Comment**	**Source**
Step:	**3H**		
Principal Technologies:	Step 2 (from Low Carbon Route) + H2 engine and tank		
Emissions Achievements:	**Euro 5 (2008)**		
Emissions Technologies used	Lean NOx trap		
CO_2 improvement breakdown:			
Starting point (g/km CO2) (WELL TO WHEELS)	146	**g/km CO_2 (Well to Wheels) Starting point is Step 2 LowCarbon Diesel**	
H_2 engine - down sized compaired to NA gasoline engine (Ratio of 0.9) H2 from ***Natural Gas***	29.5%	1.8 litre Hydrogen engine from 1.8 Diesel engine	0
Total *Scenario* CO_2 Impact (-ve is reduction)	**29.5%**	%	
Well to Wheels CO_2	**189**	**g/km - (Hydrogen from Natural Gas)**	
Vehicle Weight Change:	(-ve = reduction)		
Starting Point	1361	kg	
H_2 engine - down sized compaired to NA gasoline engine (Ratio of 0.9) H2 from ***Natural Gas***	-2.20%	-30kg (150kg Diesel to 120kg 1.8 turbo hydrogen)	0
H2 Tank	5.88%	-10kg for diesel tank +90kg for H2 tank (inc 7kg H2)	5
Total Step 1 Vehicle Weight Impact:	**3.67%**	%	
Total Vehicle Weight:	**1,411**	**kg**	
Effect on Handling	None	Weight distribution unchanged	
Effect on Packaging	LNT and DPF difficult to package	Power electronics need careful cooling	
Effect on Maintenance and Reliability	Battery will need to be checked as it is worked hard	LNT control system and OBD tests may be required	
Effect on Passenger and Pedestrian Safety	None	None	
Cost Change:	(-ve = reduction)		
Starting Point	£16,480		
H_2 engine - down sized compaired to NA gasoline engine (Ratio of 0.9) H2 from ***Natural Gas***	-1.58%	From diesel to Hydrogen	0
H2 Tank	2.22%	+£366 for H2 storage	6
Total Retail Price Impact (2002 £ value):	**0.64%**		
Total Vehicle Retail Price (2002 £ value):	**£16,586**	£	

Hydrogen Priority Step 4H

DfT Study Results	Hydrogen Priority Route	Step 4H H_2 Mild Hybrid Vehicle 2010	RLG 11 Sept 02
Topic	**Data**	**Comment**	**Source**
Step:	**4H**		
Principal Technologies:	Step 3 H2 Priority + 10kW electrical machine		
Emissions Achievements:	**Euro 5 (2008)**		
Emissions Technologies used	Lean NOx trap		
CO_2 improvement breakdown:			
Starting point (g/km CO2) (WELL TO WHEELS)	189	g/km CO_2 (Well to Wheels)	
Downsize H_2 engine to 1.1 litres + intelligen cooling	-13.5%	Ricardo calculations	0
42V 10kW motor and regeneration over drive cycle plus DC-DC converter	-5.0%	Ricardo calculations	0
Total *Scenario* CO_2 Impact (-ve is reduction)	**-18.5%**	%	
Well to Wheels CO_2	**154**	**g/km - (Hydrogen from Natural Gas)**	
Vehicle Weight Change:	(-ve = reduction)		
Starting Point	1411	kg	
Downsize H_2 engine to 1.1 litres + intelligen cooling	-2.13%	1.8 turbo hydrogen replaced by to 1.1 litre Hydrogen	0
42V 10kW motor and regeneration over drive cycle plus DC-DC converter	0.85%	-10kg for Diesel tank + 80kg for H2 tank (inc 7kg H2)	5
Total Step 1 Vehicle Weight Impact:	**-1.28%**	%	
Total Vehicle Weight:	**1,393**	**kg**	
Effect on Handling	None	Weight distribution unchanged	
Effect on Packaging	H2 tank will have some packaging priorities	Power electronics need careful cooling	
Effect on Maintenance and Reliability	H2 system servicing will be new	LNT control system and OBD tests may be required	
Effect on Passenger and Pedestrian Safety	None	None	
Cost Change:	(-ve = reduction)		
Starting Point	£16,586		
Downsize H_2 engine to 1.1 litres	0.60%	Cost increase of £100 for intelligent cooling and high downsizing	0
42V 10kW motor and regeneration over drive cycle plus DC-DC converter	3.87%	+£30 for motor, +£48 for power electronics, +£350 for battery (*1.5 sales ratio)	1, 2, 3
Total Retail Price Impact (2002 £ value):	**4.47%**		
Total Vehicle Retail Price (2002 £ value):	**£17,328**	**£**	

Hydrogen Priority Step 5H

DfT Study Results	Hydrogen Priority Route	Step 5H Mild Hybrid with Small Fuel Cell APU 2012	RLG 11 Sept 02
Topic	Data	Comment	Source
Step:	5H		
Principal Technologies:	Step 3 H2 Priority + 10kW electrical machine		
Emissions Achievements:	Euro 6		
Emissions Technologies used	Lean NOx trap		
CO_2 improvement breakdown:			
Starting point (g/km CO2) (WELL TO WHEELS)	154	g/km CO_2 (Well to Wheels)	
4kW Fuel Cell Auxilary Power Unit	-2.3%	Fuel Cell APU provides 750W to the powertrain over the drive cycle	0, 9, 10
Total *Scenario* CO_2 Impact (-ve is reduction)	-2.3%	%	
Well to Wheels CO_2	151	g/km - (Hydrogen from Natural Gas)	
Vehicle Weight Change:	(-ve = reduction)		
Starting Point	1393	kg	
4kW Fuel Cell Auxilary Power Unit	2.87%	40kg increase at 0.1kW/kg for APU system	8
Total Step 1 Vehicle Weight Impact:	2.87%	%	
Total Vehicle Weight:	1,433	kg	
Effect on Handling	None		
Effect on Packaging	H2 tank and Fuel Cell APU will have some packaging priorities		
Effect on Maintenance and Reliability	H2 system and Fuel Cell APU servicing will be new		
Effect on Passenger and Pedestrian Safety	None		
Cost Change:	(-ve = reduction)		
Starting Point	£17,328		
4kW Fuel Cell Auxilary Power Unit	2.31%	Cost increase of £400 for 4kW APU	0, 8
Total Retail Price Impact (2002 £ value):	2.31%		
Total Vehicle Retail Price (2002 £ value):	£17,728	£	

Hydrogen Priority Step 6H

DfT Study Results	Hydrogen Priority Route	Step 6H Parallel Hybrid with 8kW Fuel Cell APU 2015	RLG 11 Sept 02
Topic	**Data**	**Comment**	**Source**
Step:	**6H**		
Principal Technologies:	Step 5 H2 Priority + 30kW Parallel Hybrid + 8kW APU		
Emissions Achievements:	**Euro 7**		
Emissions Technologies used	Lean NOx trap		
CO_2 improvement breakdown:			
Starting point (g/km CO2) WELL TO WHEELS)	151	**g/km CO_2 (Well to Wheels)**	
30kW Parallel Hybrid + IC engine and 8kW Fuel Cell Auxillary Power Unit providing HALF the required powertrain power	-20.6%	Fuel Cell APU provides 2.85 kW to the powertrain over the drive cycle (Half engine average power)	0, 9, 10
Total *Scenario* CO_2 Impact (-ve is reduction)	**-20.6%**	**%**	
Well to Wheels CO_2	**120**	**g/km - (Hydrogen from Natural Gas)**	
Vehicle Weight Change:	(-ve = reduction)		
Starting Point	1433	kg	
Regen braking, 300V, 30kW motor and generator plus DC-DC converter	3.63%	+52kg	2, 4
Battery	1.88%	+27kg	3
8kW Fuel Cell Auxillary Power Unit	2.79%	+40kg increase at 0.1kW/kg for 8kW APU system from 4kW system	8
Total Step 1 Vehicle Weight Impact:	**8.30%**	**%**	
Total Vehicle Weight:	**1,552**	**kg**	
Effect on Handling	None		
Effect on Packaging	H2 tank and Fuel Cell APU will have some packaging priorities		
Effect on Maintenance and Reliability	H2 system and Fuel Cell APU servicing will be new		
Effect on Passenger and Pedestrian Safety	None		
Cost Change:	(-ve = reduction)		
Starting Point	£17,328		
Regen braking, 300V, 30kW motor and generator plus DC-DC converter	6.99%	-€160+€483 for motor, -€240+€725 for electronics (*1.5 sales ratio)	2, 4
Battery	1.34%	-€332+€487 for battery by 2012, NiMH is at $360/kWh	3
4kW Fuel Cell Auxillary Power Unit	2.31%	Cost increase of £400 for 8kW APU from 4kW system	0, 8
Total Retail Price Impact (2002 £ value):	**10.64%**		
Total Vehicle Retail Price (2002 £ value):	**£19,173**	**£**	

Hydrogen Priority Step 7H

DfT Study Results	Hydrogen Priority Route	Step 7H Series Hybrid with 40kW Fuel Cell 2020	RLG 11 Sept 02	Version 1
Topic	**Data**	**Data**	**Comment**	**Source**
Step:	**7H**	**7H**		
Principal Technologies:	Series Fuel Cell Hybrid with *45% FC efficiency and Std Series Hybrid Efficiencies*	Series Fuel Cell Hybrid with *63% FC efficiency and Potential Series Hybrid Efficiencies*		
CO$_2$ improvement breakdown:				
Starting point (g/km CO2) (WELL TO WHEELS)	120	120	g/km CO$_2$ (Well to Wheels)	
80kW Series Hybrid and 40kW Fuel Cell providing all the required powertrain power	-0.3%	-37.8%	Fuel Cell provides up to 40kW (63% total system H2 to electricity efficiency assumed at part load)	0
Total *Scenario* CO$_2$ Impact (-ve is reduction)	**-0.3%**	**-37.8%**	%	
Well to Wheels CO$_2$	**119**	**74**	**g/km - (Hydrogen from Natural Gas)**	
Vehicle Weight Change:	(-ve = reduction)	(-ve = reduction)		
Starting Point	1552	1552	kg	
80kW Series Hybrid and 40kW Fuel Cell providing all the required powertrain power	-6.12%	-6.12%	-80kg for the H2 engine, +140kg for Fuel Cell System (40kW), -30kg for generator, -80 kg for APU, -65kg AMT	0, 4, 8, 11
Total Step 1 Vehicle Weight Impact:	**-6.12%**	**-6.12%**	%	
Total Vehicle Weight:	**1,457**	**1,457**	kg	
Effect on Handling	None	None		
Effect on Packaging	H2 tank and Fuel Cell APU will have some packaging priorities	H2 tank and Fuel Cell APU will have some packaging priorities		
Effect on Maintenance and Reliability	H2 system and Fuel Cell APU servicing will be new	H2 system and Fuel Cell APU servicing will be new		
Effect on Passenger and Pedestrian Safety	None	None		
Cost Change:	(-ve = reduction)	(-ve = reduction)		
Starting Point	£19,173	£19,173		
Series Hybrid Motors	0.3%	0.3%		
Battery	1.7%	1.7%		
40kW Fuel Cell from 8kW APU	-1.22%	-1.22%	- £500 removal of generator + £2000 for Fuel Cell at £50/kw for 40kW device - £933 for H2 engine - £800 APU	
Total Retail Price Impact (2002 £ value):	**0.72%**	**0.72%**		
Total Vehicle Retail Price (2002 £ value):	**£19,312**	**£19,312**	£	

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APPENDIX G: CURRENT GOVERNMENT INCENTIVISATION OF NEW TECHNOLOGY

The UK government currently operates a number of initiatives to assist the uptake of future vehicle technologies. These are listed to identify the current trends. The most significant of these are currently as follows:

G1 Incentives Available to Vehicle Users

A number of incentives are offered to vehicle users to purchase and operate vehicles featuring low emissions and low CO_2 technologies. The most significant of these are as follows:

PowerShift

The PowerShift grant scheme, administered by the Energy Savings Trust, provides grants towards the additional cost of alternative fuelled (LPG and CNG) and Hybrid vehicles. These grants range from a few hundred to a few thousand pounds, and cover a proportion of the conversion cost or purchase price of the vehicle. To be eligible, the vehicle must be less than one year old, and must be listed on the PowerShift register of approved vehicles / conversions. The total budget for the scheme is £30M, covering the period 2001-2004

CleanUp

The CleanUp campaign, administered by the Energy Savings Trust, provides grants to assist the retrofitting of emissions reduction equipment to the most polluting vehicles in the following nine pollution hotspot areas in the UK: London, West Midlands, Greater Manchester, West Yorkshire, Tyneside, Liverpool, Sheffield, Nottingham and Bristol.

Grants can cover up to 75% of the cost of emissions reduction achieved by exhaust aftertreatment, conversion to LPG/CNG, or upgrading to a more modern engine. The grants are applicable only to Diesel vehicles over 3.5 Tonnes, and to some models of black cab. The total budget for the campaign is £36M, covering the period 2000-2004

MotorVate

Managed by AEA Technology, the MotorVate certification scheme provides companies with information and advice to improve fleet fuel efficiency and transport management. Membership of the scheme costs companies from £500 to £1000 per year depending on fleet size.

Road Haulage Modernisation Fund

Administered by the Energy Savings Trust, under the CleanUp campaign, a further £30M budget has been made available for the fitting of emissions reducing technology to haulage applications. A further £15M is available to cover advice on fuel efficiency to haulage operators to enable savings of around 5 to 10 per cent in carbon emissions and fuel bills. Smaller amounts will be allocated to training initiatives, to help enforce regulations and to fund schemes to improve business performance. Further funding is expected to become available following consultation between government and industry.

Transport Taxation

Vehicle Excise Duty for private cars is now related to CO_2 emissions and fuel type for vehicles registered after 1 March 2001. This has the effect of introducing a £100 per year differential between the cleanest and most polluting vehicles. For vehicles registered before 01 March 2001, a £55 reduction in VED is available for vehicles of less than 1500cc engine capacity.

Company Car Taxation is now strongly related to vehicle CO_2 emissions. For 2002/2003 the percentage of a car's value which is subject to taxation rises from 15% for cars emitting less than 165g/km, to 35% for cars emitting more than 265g/km with a series of 20 intermediate taxation bands. Diesel cars are subject to a 3% supplement in all but the highest taxation bands. For 2003/2004, and 2004/2005 the qualifying CO_2 ratings for each taxation band are reduced by 10g/km each year.

Where approved CO_2 data is not available for a vehicle the percentage of a car's value which is subject to taxation is related to engine size, with three taxation bands: <1500cc (15%), 1500cc-2000cc (25%), and >2000cc (35%).
Cars registered prior to 1 January 1998 are also taxed according to engine size, with three taxation bands: <1500cc (15%), 1500cc-2000cc (22%), and >2000cc (32%).

Fuel Duty differentials for low sulphur fuels of 3p per litre have been introduced to encouraged uptake of low sulphur fuels. It is open to question whether this measure has benefited the consumer financially, but of little doubt that it has incentivised fuel producers to switch towards low sulphur fuels which are costlier to manufacture.

Rates of duty on LPG and CNG remain significantly lower than those for Gasoline or Diesel low in order to encourage use of dual fuel vehicles. Hydrogen is currently exempt from fuel duty.

G2 Incentives Available to Vehicle Manufacturers and Researchers

A number of incentives and government sponsored research programmes are available to vehicle developers to encourage development of low CO_2 and low emissions technology. The most significant of these are currently as follows:

New Vehicle Technology Fund
Administered by the Energy Savings Trust, this DfT funded initiative supports demonstration projects of new low carbon vehicle technologies. The programme has a budget of £9M over three years.

Foresight Vehicle Programme
The UK government's main automotive research and development programme, The Foresight Vehicle Programme offers opportunities for collaborative research between UK industry and academia, sponsored by the DTI, DfT and EPSRC. Funding is available to cover up to 50% of the cost of research into future automotive industry products and processes.

New and Renewable Energy Programme - Fuel Cell Programme
Part of the New and Renewable Energy Programme (see below) the Fuel Cell Programme focuses on the development of Fuel Cell technology for stationary and

transport applications. Research activity is in the form of collaborative industry / academic projects, with part funding available from the New and Renewable Energy Programme. Current focus is on Solid Polymer and Solid Oxide Fuel Cells, however this policy is subject to regular review.

Sustainable Technologies Initiative

The STI is a programme to support collaborative research and development aimed at improving the sustainability (energy, materials use and environmental impact) of UK businesses. It is jointly funded by the DTI, EPSRC, ESRC, BBSRC and DEFRA. Total budget for the programme is £21M over 5 years. Funding is available as part funding to industry/academic research programmes, or as a grant to individual businesses towards specific projects.

Green Technology Challenge

Operated by the Treasury office, the Green Technology Challenge offers companies enhanced capital allowances for investment in specific green technologies. The applications for these technologies are: reduction of water use and improvement of water quality, use of energy saving technologies to tackle climate change, and cleaner road fuels and vehicles.

European Research Programmes

The CEC funds research into automotive technologies as part of its Framework Research Programmes. At the time of writing, the automotive Work Programmes for Framework 6 have yet to be announced, however the budget allocations for the relevant thematic priorities have been announced as follows: Sustainable energy systems - €810M, Sustainable surface transport €610M. These budgets cover the period 2002-2006, and are available via a number of instruments, the two most significant of which are:

- Integrated projects – large collaborative projects typically of €30-40M in size, lasting 3-5 years, and having 15-20 partners. Funding at 50% for industry, 100% for academia, and 100% for project management.
- Networks of Excellence – grants available to networks of researchers in a similar field to facilitate information transfer within a field of research. Funding covers only the networking aspects of research, and not the actual research activities.

G3 Incentives Available to Fuel and Infrastructure Providers

Green Fuels Challenge

Administered by HM Customs and Excise, the Green Fuels Challenge offers exemption or reduction of rates of duty on alternative transport fuels for pilot projects. Specific fuels considered are Hydrogen, methanol, bioethanol and biogas.

New and Renewable Energy Programme

This programme funds development of new and renewable energy sources (for all energy supply purposes – not just transport). The Programme is managed by ETSU on behalf of the DTI, and has a budget of £260M over three years, and is sponsored by DTI, DEFRA, National Lottery, and the Prime Minister's office.

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The STI is a programme to support collaborative research and development aimed at improving the sustainability (energy, materials use and environmental impact) of

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