Ricardo Consulting Engineers
Bridge Works
Shoreham by Sea
West Sussex BN43 5FG
United Kingdom

Telephone: +44 (0) 1273 455611 • Fax: +44 (0) 1273 464124

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

Q51052 | **RD 03/209501.6**
7 November 2003 | **Company Confidential**

Authors N.J.Owen
R.L.Gordon

Contributors J.A.Patterson
P.M.Fussey
J.D.McLaggan
D.G.Greenwood

Approved

N.S.Jackson
Technology Director

"This report has been produced by Ricardo UK Ltd. under a contract placed by the Department for Transport. Any views expressed in it are not necessarily those of the Department."

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

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.

In November 2002, Ricardo completed a study for the Department for Transport (DfT) and the Department of Trade and Industry (DTI), of the prospective evolution of low-carbon technology. This study [1] looked 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 discussed the possible evolution from current vehicle technology toward a possible zero CO_2 future, based on sustainably-produced Hydrogen fuel.

The DfT and the DTI commissioned Ricardo to carry out an update and re-evaluation of the technology options suggested in the 2002 study. This update uses feedback received from industry stakeholders on the original work, and new information on low carbon technologies, to re-evaluate the technology options studied in the original work. As before, 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 down-sized, 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 for volume production – this excludes "image vehicles" which may appear earlier.

The feedback confirms the findings of the 2002 study, and the technologies suggested in the 'Low Carbon' route in particular. Almost all manufacturers and component suppliers are highly active in the technologies described in the 2002 study.

Methodology

For each vehicle type along the routes, updated 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.

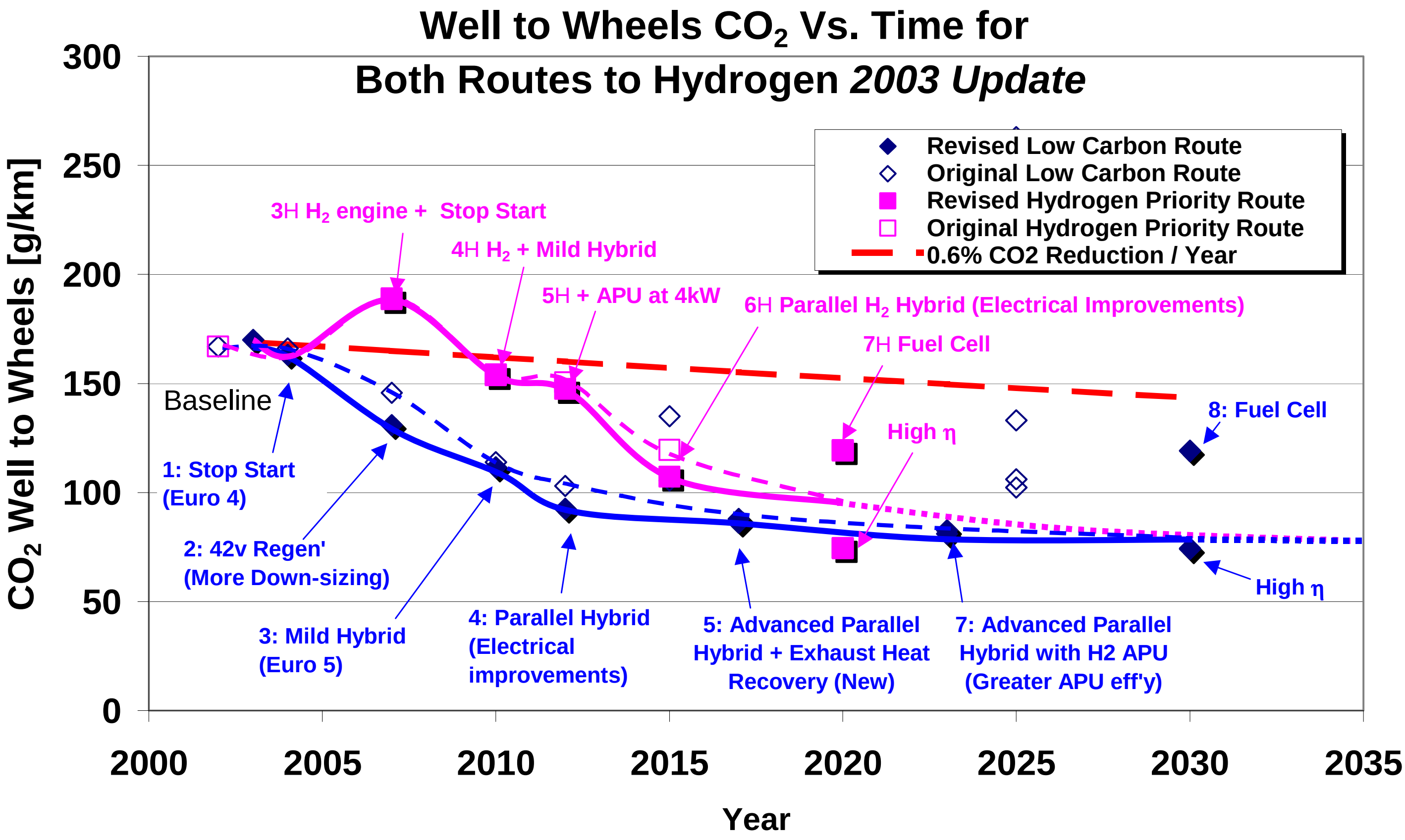
Compared to the original 2002 study, key differences in the analysis assumptions are:

- All cost figures have been re-based to 2003 prices
- In addition to the original assumption of exhaust emission legislation (which impacts both CO_2 and cost) evolving towards the UK "Foresight Vehicle" research targets for 2020, a second scenario has been added whereby

legislation progresses to a "Euro 5" standard (principally an NOx level equivalent to a Euro 4 Petrol engine) at 2010, then no further legislation, reflecting the view of many that emissions will then be as low as required

- Where new information is available suggesting that the technology previously assumed can be improved in terms of its performance versus cost, the vehicle specification has been altered and estimates revised

Illustrative vehicle types provide for all prospective future safety, air quality emissions, and driver demands. The report focuses on vehicle technology, and 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. Key data is summarised in a table at the end of this Executive Summary, while the evolution of well-to-wheels CO_2 performance is shown graphically below.



Low Carbon evolution

The 2002 study suggested that **Low Carbon Step 4** (Parallel hybrid plus Advanced Diesel) was the lowest-CO_2 vehicle which was feasible for volume production until fuel cell vehicles which realised the full efficiency potential of the technology became available. Some further intermediate technologies were found to be non-feasible in a passenger car application, while others could be promoted as bridging technologies towards fuel cell vehicles but did not provide worthwhile CO_2, driver or cost benefits and so would not be put on the volume market.

However, in this update, significant improvements to the Low Carbon evolution are suggested in the light of the latest available technology, such that there is now a continuous feasible evolution through to the Fuel Cell. These improvements include:

- Improvements to the CO_2 performance of the first four steps, via increased engine down-sizing, improved electrical technology and selection of the most effective approach to emission control. The projected price of early vehicles is now lower, although the dominant effect here is the drop in list price of the baseline vehicle. As an example, in the 2002 study, the "Step 4" full hybrid vehicle had an estimated Well to Wheel CO_2 of **104g/km** (Tank to Wheel 92g/km). **The updated estimate is 93g/km** (83g/km Tank to Wheel), as a result of expected improvements in hybridisation technology. The list price estimate for this vehicle is now £18,728 (rising from £18,500 due to specification improvements, but this increase is justified by the CO_2 improvement). The CO_2 savings in the **Step 1, 2 and 3 vehicles** have also been revised upwards by the updating, as a result of further use of down-sizing and revised emissions control
- Adoption of a **New Step 5**, which adds exhaust heat recovery to the Step 4 concept to deliver further CO_2 savings, down to **86g/km** (77g/km Tank to Wheel), and which *could* represent a marketable vehicle, depending on progress on heat recovery technology, and component production costs
- Deletion of the former **Step 6** (Series Hybrid plus Hydrogen APU) as it now looks unlikely to be technically feasible, and is not discussed further in the update
- Adoption of a **New Step 7** (Step 4/5 plus Hydrogen, Fuel Cell APU), based on the Step 7c option in the 2002 study but with better system efficiencies which appear feasible. This now delivers a further CO_2 saving beyond new Step 5 - down to **81g/km** (72 g/km Tank to Wheel). Again, this could represent a marketable vehicle if the packaging and cost issues of the APU can be addressed in the next 20 years
- Step 8 is unchanged from the 2002 study

Hydrogen Priority evolution

The **Hydrogen Priority Evolution** has been updated to reflect improvements in the hybrid systems as discussed in the updated Low carbon evolution, fuel cell APU efficiency and changes in the hydrogen storage systems now expected to be available in 2015 and 2020. Otherwise, there are no other significant changes, and there is no significant evidence to suggest a different approach from the 2002 study.

Conclusions

Despite many significant detail changes, major conclusions remain very similar to those presented in 2002. Those conclusions are repeated here, with changes in bold text:

- 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. **An unprecedented level of new low carbon product introductions and concept demonstrations, combined with a**

re-appraisal of projected emission control impacts, has improved the projected performance and lowered the expected price of some of these technologies, compared to 2002 study estimates. 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 **of down-sized IC engines** 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 **trucks and** 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
- **Validation information suggests that the timescales presented are realistic for the first introductions of these technologies as mainstream products. A nominal threshold of 5% market penetration of each technology would follow 2-5 years later if the technology is successful**

As before, suggestions for research into technologies on the two routes have been made.

Step (Date)	**Technology** *& Changes since 2002*	**CO_2 performance - Well to wheel (Tank to wheel)**		**Cost, relative to Step 0 vehicle**	
		CO_2 g/km	% change from Step 0 (Baseline)	***Nominal Price*** *(Range)*	***% chg from Step 0 (Baseline)***
0 (2003)	C/D segment car; c100ps Diesel engine	**170** (152)	-	£15,157	
1 (2004)	12v stop-start	**163** (145)	**-4.2%** at Euro 4	£15,389 (£15,350-£15,400)	**+1.5%**
2 (2007)	42v Belt Hybrid *Euro 4, more down-sizing*	**131** (117)	**-23%** at Euro 4	£16,041 (£15940-£16140)	**+5.8%**
3 (2010)	42v Mild hybrid + D/sizing *Lower Euro 5 CO_2 penalty*	**112** (100)	**-34%** at Euro 5	£17,183 (£17,000-£17,350)	**+13.3%**
4 (2012)	Full Parallel Hybrid *Improved batts motor, Eu 5*	**93** (83)	**-45%** at Euro 5	£18,728 (£18,330-£19,130)	**+23.5%**
5 (2017)	*Parallel Hybrid + Exhaust Heat Recovery*	**86** (77)	**-49%** at Euro 5	£18,840 (£18,340-£19,340)	**+24.3%**
7 (2023)	*Parallel Hybrid + APU*	**81**	**-52%** at Euro 5	£19,318 (£19,000-£20,500)	**+27.5%**
8 (2030)	Fuel Cell Series Hybrid	**74-119** (0)	**-56% -- 30% ZEV**	£19,672 (£18,400-£21,400)	**+29.7%**
3H (2007)	H_2 Mild Hybrid	**189** (0)	**+11 %** *at Euro 5*	£16297 (£16100-£16500)	**+7.5%**
4H (2010)	H_2 Mild Hybrid	**154** (0)	**-9.4%** at Euro 5	£17,039 (£16,750-£17,350)	**+12.4%**
5H (2012)	Mild Hybrid + Small APU *Greater APU efficiency*	**147** (0)	**-14%** at Euro 5	£17,439 (£17,100-£17,900)	**+15.1%**
6H (2015)	H_2 Parallel Hybrid + APU *APU & Hyb efficiency*	**107** (0)	**-37%** at Euro 5	£19,434 (£18,900-£20,800)	**+28.2%**
7H (2020)	Fuel Cell Series Hybrid	**74-119** (0)	**-56% -- 30% ZEV**	£20,073 (£18,800-£22,000)	**+32.4%**

TABLE OF CONTENTS

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

1 INTRODUCTION

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.

In November 2002, Ricardo completed a study of the evolution of low-carbon technology. This study [1] looked 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 discussed the possible evolution from current vehicle technology toward a possible zero CO_2 future, based on sustainably-produced Hydrogen fuel.

The study looked at two routes:

- A "Low Carbon" route, in which the objective was progressive and significant CO_2 reductions at lowest cost and risk. It was assessed that this objective would be met by progressive hybridisation and engine down-sizing to a Diesel vehicle before switching to Hydrogen and Fuel Cell propulsion
- A "Hydrogen Priority" route which used Hydrogen in the IC engine at an earlier stage and accelerated fuel-cell introduction via auxiliary power units

Key conclusions of this original work were that:

- 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
- Progressive electrification and Hybridisation, together with other incremental improvements, 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
- 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

The objectives of this update, completed a year after the original study, are:

- To gather information on relevant technological, industrial and regulatory developments since the publication of the original Roadmap study
- To collate feedback received from the auto industry and elsewhere following publication of the original Roadmap study

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

- To detail any changes to the findings of the original Roadmap study which Ricardo believe are indicated by recent technology developments, and update the steps of the evolutionary paths accordingly

Information presented in this study is based upon projected performance and cost of technologies that are mostly un-proven in today's mainstream vehicles, although many are in most major manufacturers' research & development portfolios. Key risks that may impact this feasibility are stated, along with an assessment of confidence in predictions made for each step.

2 BACKGROUND TO THE UPDATE

2.1 Approach & Methodology

The analytical approaches used to estimate well-to-wheels performance, likely vehicle cost, and other attributes, are identical to those used in the original study [1].

Key elements of the original approach were:
- Identification of how the CO_2 performance and cost of the baseline vehicle would change over time as a result of small incremental technology improvements
- Identification of a possible scenario for increasingly stringent emission control, and its impact on both CO_2 and cost
- Identification of logical technology steps, and estimation of the impacts of those steps on CO_2, cost and other vehicle attributes based on public domain information and Ricardo engineering experience

In this update, key steps have been to:

- Identify any developments in the building-block technologies of the two evolutionary paths
- Identify any relevant changes in policy or commercial climate which may influence the direction of the evolutionary paths
- Collate all feedback received on the original work, and identify any changes arising from it
- Revise the calculated impact of each step on CO_2, cost and other vehicle attributes, where necessary making small adjustments to the technology content of each step

2.2 Industry Feedback

2.2.1 Feedback on the original study

During the past year, Ricardo has presented information from the original study [1] to a wide variety of stakeholders in the automotive industry, covering a significant proportion of the most globally important manufacturers. Feedback has been analysed from a total of 32 meetings at which "Carbon to Hydrogen" information was shown, between August 2002 and August 2003. The stakeholders involved in those meetings were:

Vehicle manufacturers:	18*
Component Suppliers:	12
Energy companies:	7
Government bodies & agencies:	5

* Includes different groups from the same manufacturer

From these discussions, over 80 items of feedback were analysed. Key findings were:

- Of these 80 items, the most common feedback was general agreement with the principle of step-wise evolution, and with the technologies suggested in the "Low Carbon" route in particular. Almost all manufacturers and suppliers are highly active in the technologies described in the earlier steps
- There was continuing interest from Government stakeholders also in the possibility of more "revolutionary" policies. However for this type of stakeholder the majority European view appears to favour the evolutionary approach
- All but one of the industrial stakeholders had some kind of product strategy corresponding in principle with the Carbon to Hydrogen evolution. However, as would be expected, most organisations were only making firm product plan commitments to very early steps – typically linked to the 2008 ACEA target [2]. Some manufacturers may add "image" vehicles at circa Step 4 (Full Hybrid) earlier than the 2012 date suggested in the Evolution. Cost remains the over-riding concern amongst manufacturers and suppliers
- There was specific feedback on the well-to-tank efficiency of Methanol manufacture. This is discussed in section 2.5.5

Based upon this feedback, there has been no evidence to suggest that major revisions to the findings of the original study are required.

2.2.2 Other feedback on Hybrids

Despite a tough economic climate in the auto industry (section 2.3.4), many manufacturers are stating a positive position on Hybrid technology, which forms the backbone of both original "evolutions". Key information to emerge in the past year has been as follows:

Toyota: Continue to pursue a variety of models based on three types of system (including a new Prius later this year, and a Lexus SUV), and have re-stated their previously stated position that they will have made 300,000 units by 2005. They also state that "The industry will support 3 million Hybrids per year in 5 years" [3]
Honda: Launched Civic IMA globally, and have shown a hybrid sportscar concept
General Motors: Will put two Hybrid models on sale late 2003 [4] GM also suggest that they could be selling "One million Hybrids per year by 2007" [5]
Ford: Launching Escape Hybrid SUV next year in the USA, Futura hybrid sedan (Mondeo-sized) in 2005 [6]; In Europe, Ford are publishing research work on 42v belt & flywheel starter-generators (Like Low Carbon Step 2) [7]. Ford are also collaborating with Ricardo and suppliers Valeo and Gates on the "Hytrans" hybrid delivery vehicle program [8]
PSA (Peugeot-Citroen): Have stated "The Group will progressively introduce three hybrid levels between 2003 and 2007—mini, mild and full hybrid—further reducing CO_2 emissions by between 5% and 30%, depending on the technology" [9]. PSA Chairman Jean-Martin Folz said at the annual shareholders' meeting on May 28 2003, that the company would launch hybrid vehicles and vehicles with stop-start engine ignition devices by 2004; Diesel hybrids are also mentioned, as opposed to Petrol powered vehicles favoured by Japanese manufacturers [10]
Fiat: State "mass production of Hybrid vehicles in the near future (5 to 10 years)", and have shown Ppojections for Hybrids to have 10-15% market by 2010; 50-70% by 2020 [11]

The industry has not universally embraced hybrid technology however. Some less favourable comments have been made by some [12]:

BMW: "Hybrids, in our summation, are in the end the worst compromise, because you put everything in the car that has to be prepared for all situations. You add weight and you deteriorate performance"
Mercedes-Benz: "...hybrids merely are filling a gap that will lead to fuel cell cars in the next 15 years. Until then…. the inefficiencies of hybrids make diesels a more feasible step toward the hydrogen economy" However, the criticism in this one article [12], focuses on Petrol (Gasoline) engined Hybrids, as available now. These are being criticised compared to today's advanced Diesels. However, these criticisms are harder to apply to a Diesel Hybrid.

In summary, this public domain information largely confirms the findings of the original study, with a mix of evolutionary mainstream vehicles and more advanced "image" hybrids being suggested by many manufacturers. Ricardo experience also suggests that information not yet in the public domain also indicates the same conclusion.

2.3 Policy and Commercial Climate

CO_2 reduction and the improvement of vehicle efficiency remains high on many policy agendas, if for different reasons. While information published in some nations (most typically Europe and Asia) cites reduction of greenhouse gas emissions as the key driving factor, in others (principally the USA), security of energy supply is seen as the major driving factor. Key information to have emerged in the past year is as follows:

2.3.1 UK & Europe

- The European manufacturers' association, ACEA, has not yet published figures for new passenger car fleet average CO_2 reduction for 2002, the most recent available being those for 2001 [2]. The European Commission is conducting a review of the agreement, publication of findings is expected at the end of 2003
- The European Commission is also studying measures to introduce mandatory fuel consumption / CO_2 measurement for N1 (light commercial) vehicles from 2009; and a corresponding voluntary agreement with manufacturers [13]
- A second study has been initiated by the Commission on the impact of air conditioning and heating usage on fuel consumption. Findings may become part of legislated test procedure, however there is no suggested timescale for this
- The European Parliament has signed a "Hydrogen Economy Pact" with the USA, with the objective of "collaborating on accelerating the Hydrogen economy". Romano Prodi has stated "It is our declared goal of achieving a step-by-step shift towards a fully integrated hydrogen economy, based on renewable energy sources, by the middle of the century" [14]
- In the UK, data from the Society of Motor Manufacturers and Traders (SMMT) [26] illustrates an upward trend in the sale of Diesel vehicles, which could be a consequence of company car "benefit in kind" being assessed based on CO_2 [27]. For example, data released in February 2003 indicates that:
    - Diesel registrations and their market share have increased for the 29th consecutive month and now account for 25.7 per cent of the market, 6.2 per cent up on the same period last year
    - While the market has cooled in 2003, diesel registrations have risen by 9.5 per cent to 73,374 units year on year

2.3.2 Asia

- Australia has introduced a Voluntary Code of Practise on passenger car fuel economy, which calls for an 18% improvement to 6.8 l/100km by 2010. This is equivalent to 163 g/km tank-to-wheels CO_2 for a Petrol vehicle, and is measured on a similar test to the European "NEDC" cycle used in this study. The target is expressed as fuel economy, not CO_2 (the two are directly related but the ratio differs for Petrol and Diesel vehicles, as explained in Appendix A of the original report [1]). This equates to a reduction of over 2.5% per year, compared to circa 2% for the European ACEA agreement. A second agreement for SUVs and Light Commercial vehicles is expected in 2004, and a fuel consumption labelling scheme for passenger cars has been introduced from July 2003 [15]
- Japan is also believed to be considering a fuel consumption / CO_2 labelling system for passenger cars

2.3.3 North America

- The USA's "FreedomCar" program focuses on Hydrogen and Fuel Cells, but also promotes evolutionary technologies and acknowledges their role in the transition to the Hydrogen economy [16]. Primary goals are stated as freedom from dependence on imported oil, and freedom from pollution - CO_2 and greenhouse gases are not mentioned in publicity material available on the website. Named "evolutionary technologies include:
  - Lightweight vehicles – an ambitious 50% weight reduction target is stated, technologies include advanced materials and coatings for up-rated, down-sized engines
  - Batteries – Nickel Metal Hydride, Lithium-Ion and Ultracapacitors
  - Internal Combustion engine technologies - advanced Diesel, Gasoline Direct Injection, Variable Compression Ratio, "HCCI" combustion for low NOx emissions
  - Low cost electronic modules - up to 100kW power
  - Robust Hybrid Drivetrains - Series and Parallel hybrids, advanced climate control and thermal management for hybrids

Most of these items are critical technologies on the Carbon to Hydrogen evolutions

2.3.4 Industry R&D Investment

Despite tough trading conditions for some (Figure 1), most car manufacturers have sustained their investment in R&D (Figure 2), although it is not possible to infer how much of this investment is directed towards low carbon technology.

It is interesting to note that Toyota, Honda and BMW are the most profitable manufacturers and also those growing their relative R&D spend the most. All are highly active in low-carbon technology including Hybrids, Hydrogen IC engines, and fuel cells as prime movers or auxiliary power units.

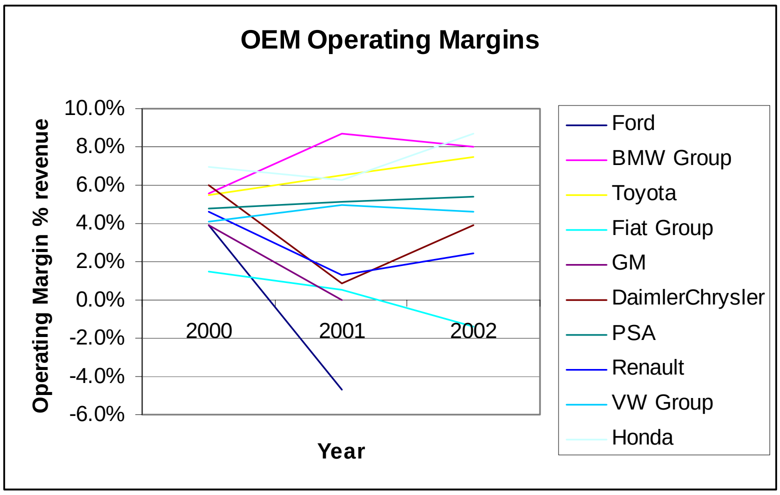


Figure 1. Operating margins (Profit as a percentage of revenue) of passenger car manufacturers. Data sourced from published accounts.

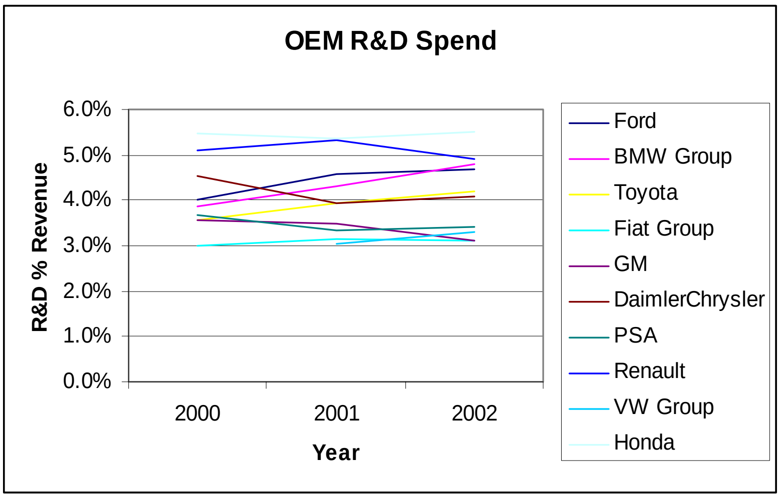


Figure 2. Research & Development spend of vehicle manufacturers, including product development and advanced research. Data sourced from published accounts.

2.4 Emission Legislation assumptions

The original study [1] assumed a series of arbitrary emission control stages introduced every 3-5 years up to 2020. The 2020 limits were assumed equal to those already published as research targets for the UK "Foresight Vehicle" program [17]. Beyond this it was assumed that there would be no further legislation as a point of diminishing return would be reached relative to other sources of pollution.

Indications are that the next stage of emission legislation, "Euro 5", will come into force from 2010, not 2008 as assumed in the original study. Emission limits have not yet been agreed. A possible scenario is:

- Particulate matter (Pm) – half of Euro 4, i.e. 0.0125 g/km
- Oxides of Nitrogen (NOx) – either half of Euro 4 (0.125 g/km) or the same as Euro 4 for Petrol engines (0.08 g/km). For this update, the more demanding "Euro 4 Gasoline" level has been assumed

There remains considerable debate as to the value of further, even more stringent emission control, with some advocating no further legislation beyond Euro 5. For this update, two scenarios are illustrated:

- As in the original study, progression towards the "Foresight" 2020 levels [17] – Emission levels equal to half a Euro 4 Gasoline vehicle, plus further controls on small particles
- Progression to a Euro 5 Diesel standard (assumed to be Euro 4 Gasoline NOx) by 2010, then no further legislation

The two scenarios have different implications for both vehicle price (due to the cost of emission control equipment), and CO_2 (due to impact, usually negative, of the emission control technology). These factors are explained in more depth in Appendix A of the original report [1].

2.5 Building-block technologies

2.5.1 Low-Emission Diesel Engines

The past year has seen significant activity in the release of "Euro 4" Diesel engines. In the UK market these offer the advantage of lower "benefit in kind" taxation to company car users, while a variety of other incentives exist elsewhere in Europe.

The original study [1] assumed that Euro 4 vehicles would adopt Diesel Particulate Filters (DPF), both as an aid to meeting legislation (although it was known that a vehicle of C/D segment inertia, as assumed for the study, could meet Euro 4 without a DPF) and as a measure to counter-act concerns voiced in the public domain about the health effects of Diesel engines. The Peugeot 607 vehicle was already in the marketplace with this technology. By addressing these needs in more vehicles, greater sales of Diesel vehicles would be achieved, with a corresponding benefit in fleet average CO_2

In practise this has not happened in the C/D segments. Diesel sales have continued to rise in most markets without the fitment of DPFs to persuade buyers to switch, and omitting the DPF saves cost at a time of extreme pressure on profitability. Vehicles such as larger cars and SUVs, which are heavier, are much more likely to adopt this technology at Euro 4 as the greater loads imposed on the engine by the vehicle's weight lead to higher particulate emissions.

Typical Euro 4 technology for a C/D segment vehicle is similar to the best Euro 3 units - common-rail fuel systems with the capability to control combustion via with multiple injections, combined with improved combustion chamber shape and injector specification. The only significant addition of technology may be an "EGR cooler" – a device for cooling exhaust gases which are re-circulated into the engine to lower the temperature of combustion gases and reduce the formation of the pollutant NOx. Many engines already had these fitted. The estimated price impact is circa £30.

In theory, the re-tuning of the combustion process to meet Euro 4 – the major challenge being NOx – should have led to a small worsening of combustion efficiency and hence CO_2. In practise this appears to have been counterbalanced by the underlying trend of year-on-year improvement in the base technology observed in the original study [1], such that Euro 4 engines have similar CO_2 to a Euro 3 forbear of equivalent performance and size.

Published research results are providing some indication of a specification for a Euro 5 Diesel engine [18]. The key ingredient of the likely approach is a "Cool combustion" system combining yet more advanced "Common Rail" technology, sophisticated boosting (turbocharging) systems and intense EGR cooling to achieve low NOx. This is illustrated in Figure 3, which shows the two emissions of greatest concern to achieving compliance, NOx and Particulates. In practise an engine can be tuned by simple adjustments to its engine-management system to achieve higher NOx and lower particulates, or vice-versa, as shown by the curves. For Euro 5, it is necessary to tune for higher particulates than today's Euro 4 engines to achieve Euro 5 NOx. However, these particulates can then be removed by fitting a DPF. In principle, it may be possible to develop a "Euro 5" C/D segment vehicle with this technology.

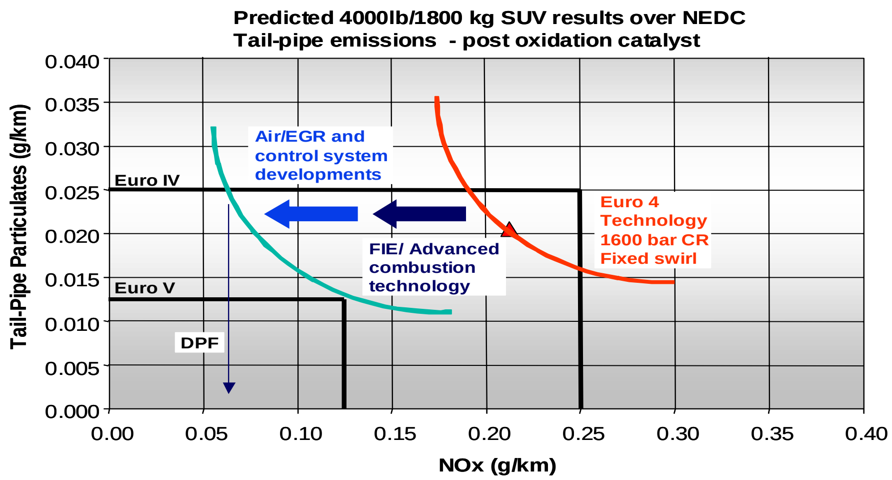


Figure 3: "Euro 5" Diesel engine research results [18]

However, such technology is very sensitive to production variations in its components, particularly the fuel injectors. Production variations of up to +/- 0.05 g/km NOx have been observed. At Euro 4, this represents just 20% of the legislated limit, hence an "engineering safety margin" of around 20% is typically used to ensure that all engines comply. However, at "Euro 5" the same variation accounts for more than half the limit, and it is not yet possible to ensure that the worst-case engine would comply.

As a result it is assumed that a small "Lean NOx Trap" (LNT) will be fitted for Euro 5 to overcome this issue. This device converts NOx to non-harmful gases, and incurs a small CO_2 penalty (as does a DPF) as a result of the need to "re-generate" it by operating the engine momentarily in an inefficient way. These issues are discussed further in the original report [1].

In the original study it was assumed that the cost of Euro 5 (Half Euro 4 Gasoline NOx) would be £500-600 (at showroom prices), with a +3-6% CO_2 penalty. Early indicators from the latest research suggest a price increment of £400-500 (factored to on-sale price), with a CO_2 penalty of 2%, compared to a Euro 4 engine. These revisions have been adopted in the update.

In conclusion, the Diesel engine remains an attractive power unit for a European low carbon vehicle, with the addition of evolutionary down-sizing and hybridisation as originally proposed. Developments since the original study indicate marginally improved CO_2 and reduced (though still challenging) cost, which have been fed through to the updated analysis.

2.5.2 Other Conventional Powertrain Technologies

Non-hybrid IC engine technology is improving in terms of its CO_2 performance. A certain degree of this, equating typically to 0.6% improvement per year, was envisaged in the original study. Improvements beyond this expectation do not undermine the original evolutions but may slow the pace at which they need to happen in order to meet CO_2 commitments. Two key technologies which could have such an impact are:

Efficient Petrol Engines: There is a growing recognition that there is a place for more efficient Petrol (Gasoline) engines. These would be unlikely to greatly surpass the equivalent Diesel engine, hence would not impact the "volume best in class" vehicle referred to in the original study. However, Diesel engines cost a great deal more to make than a Petrol unit of the same performance – more than double the cost is likely at Euro 5. Therefore, if technologies to improve the Petrol engine can obtain a better "cost / benefit ratio" in terms of CO_2 reduction, it will be commercially attractive to introduce them to the new car fleet mix.

Current Petrol units are often conceived for global markets where different countries attach varying importance to CO_2. Greater focus on CO_2 in Europe and Asia demands more tailored technologies, but these can often be applied to a global base engine which saves cost. One example is the lean-burn "Direct Injection" technology, which has been offered by Mitsubishi and others for some time but is now becoming available in mainstream vehicles from Europe. Peugeot's "HPi", Mercedes "CGI", Ford "SCi" and VW / Audi "FSi" technologies are all of this type. Competing technologies include variable valve lift (Honda "I-VTEC", BMW "Valvetronic").

The next generation product will combine more new technologies, at greater cost but with greater effect. One example is Ricardo's "Lean Boost" system [19], which combines lean-burn, direct injection, down-sizing and a variable-geometry turbocharger to achieve 20% lower CO_2 than a standard Petrol engine. This technology is more costly than a standard Petrol unit, but cheaper than a Diesel with which it competes on CO_2.

Engine Down-sizing without Hybridisation: Engine down-sizing (applicable to both Petrol and Diesel) enables lower CO_2 through better engine efficiency, lower weight and friction. Performance is maintained by turbocharging, which introduces poor driveability via "turbo-lag", the time taken for the turbocharger to spin up to speed if acceleration is requested. Low Carbon Steps 2 to 4 [1] employ increasing degrees of electrical assistance from the hybrid technology to "fill the gap" left by turbo-lag, a solution recently demonstrated on the Ricardo I-MoGen hybrid car [20].

Technological progress in turbocharging may enable some degree of down-sizing without the need to resort to hybrid systems. Technologies to achieve this include better boosting systems (electric-assisted, twin-turbo etc [18]) and better engine control systems which deliver greater responsiveness. These systems can be cost-effective, offering over half the benefits of a down-sized hybrid at a fraction of the cost, but do not offer stop-start or regenerative braking and therefore are limited in their ultimate potential. A driveable non-hybrid down-size limit is typically 25-30% on today's engines, offering 10-15% fuel economy gain.

There has been significant interest in both efficient petrol engine technology and down-sizing over the past year. However, both technologies are highly complementary to the evolutionary paths originally proposed. If these technologies enjoy greater success, and offer CO_2 reduction at lower cost, the introduction of hybrid technology will be postponed - but would, as proposed in the original study, continue to be the favoured option for achieving further CO_2 reductions.

2.5.3 Hybrid technology and Energy storage

The greatest progress in hybrid technologies has become evident through an unprecedented level of new production models and concept cars. These are discussed in the context of the carbon-to-hydrogen evolution in section 6.

42 volt electrical systems have become the subject of divided opinion in the industry. Estimated dates for introduction have been moved back to the end of the decade, as conventional 12-volt technology has adapted better than expected to the increasing electrical power demands of today's vehicles. New technologies announced in the last year show that 12-volt alternator efficiencies have improved, reaching levels of up to 75% which were previously the domain only of 42-volt systems [21]. And the first "drive by wire" systems have been launched by Mercedes (braking, [22]) and BMW (steering, [23]) using 12 volts. Previously it had been assumed that 42 volts would be necessary for these systems. There remains little doubt that higher voltages will eventually be required, and all electrical component suppliers are offering technologies from 42v to 288v and higher.

Lithium-Ion Batteries and Super-Capacitors are alternatives to the Nickel-Metal-Hydride (NiMH) battery originally assumed for Low Carbon steps 3 onward, and corresponding Hydrogen Priority steps [1]. Ricardo has observed a significant shift towards interest in these technologies in the research arena, with some suggestion that they will be cost-competitive by 2008-10. Lithium-Ion batteries, originally suggested as an "evolution" of Step 4 [1], potentially offer greater life, efficiency and ability to accept rapid input of energy. Super-capacitors cannot replace batteries altogether, but can store and release energy very rapidly and could be used in combination with a cheap lead-acid battery. It appears likely that these technologies will be significant players earlier than expected, and could see high volume introduction by 2010.

2.5.4 Transmission technology

Transmission technology has a significant role to play in CO_2 reduction. Although conventional automatics are mechanically inefficient and therefore give rise to greater CO_2 than manual units, in principle the ability to automate gear-shifting enables the engine to be operated closer to ideal conditions, hence lowering CO_2. A fast-responding automatic unit can also help to alleviate the driveability issues of a down-sized engine, thus enabling this CO_2-saving technology to be more widely used.

Until this year the state-of-the-art technology in production was the Continuously Variable Transmission (CVT). Units from Audi and Honda offered fuel consumption / CO_2 comparable to manual units, although others did not.

This year has seen the launch of the first **dual-clutch transmission**, the "DSG" from the VW/Audi group [24]. This type of transmission offers mechanical efficiency approaching a manual unit, with fully automated seamless shifting approaching the smoothness of the traditional automatic. Audi claim a 10% fuel economy / CO_2 benefit (compared to manual) on the Audi TT V6 sportscar, although there is no manual version in production to compare with. In this instance (small car, large engine) the technology is probably showing more benefit than is typical. Ricardo experience suggests that up to 5% benefit is more typical of a C/D segment family car, and such a unit was incorporated in the Step 2 concept onward.

2.5.5 Fuels

There continues to be vigorous international debate on the topic of energy supply. Summation of this is beyond the scope of this study, which retains its original assumption of conventional fuels as a starting point and Hydrogen as an end-point. Specific feedback has been received on the “well to tank” data cited in the original study for Methanol [1]. Information from the Methanol technology company Zero-M, citing figures from the International Energy Agency [25], suggests that the well-to-tank efficiency for Methanol manufacture should be 87.4%, not 65% as originally suggested. Other data from this reference is consistent with that used in the original study. A revised “well to tank” efficiency table is shown in Figure 4 below.

Liquid fuels offer the attraction of easier storage (both on the vehicle and at depots), easier refuelling and greater compatibility with existing infrastructure. There are those that favour the suggestion that sustainable liquid fuels, perhaps manufactured from renewable energy sources, offer a better solution than the much-promoted “Hydrogen economy”. That issue is, however, not within the scope of this study to resolve.

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)	**87.4%**
Hydrogen (made from Natural Gas, compressed 300 bar)	66.0%

Figure 4: Revised well-to-tank efficiencies

2.5.6 Advanced Control

Control strategy is critical to the performance of many of the advanced technologies used in the Low Carbon and Hydrogen Priority evolutions. Optimised control allows engines, batteries and motors to be operated together in the most efficient manner.

The field of vehicle electronics is advancing rapidly, with a wide variety of information becoming available on the vehicle. Currently this information tends to be restricted to its own sub-system. The next generation of electronic architecture could however enable this information to be more widely used, including for powertrain control.

Probably the most useful type of information in this respect is knowledge of forthcoming road conditions – type of road (and likely driving style that it encourages), topography (hills), traffic and junctions (likelihood of stopping). This information can enable improvements in aspects of powertrain control such as energy storage strategy (for example, it is not necessary to charge the vehicle’s battery if there is a long down-hill stretch ahead), as well as diagnostic systems.

Early systems are likely to use information from on-board devices like GPS/map devices (satellite navigation) and radar sensors (smart cruise control). Vehicle-to-vehicle communication and telematics could add to the functionality of this technology in later years. There is some suggestion that this technology could bring about real-world CO_2 improvements of greater than 10%. However, there has been very little study of this to date, so this technology has not yet been incorporated into the carbon-to-hydrogen Evolutions.

3 CARBON-TO-HYDROGEN ROUTES

3.1 Changes to the Baseline

The original baseline vehicle was a composite average of seven popular C and D segment cars that were available in Europe. The baseline has been updated by using the 2003 equivalents of these seven vehicles. Key changes have been:

- The new Renault Megane was launched earlier this year in UK. It uses a 120ps engine in place of the old 100ps unit (both 1.9l). A 100ps, 1.5l unit is due next year, and should illustrate the principle of non-hybridised engine downsizing by offering better fuel economy – however, data on this unit is not yet available
- A "Euro 4" compliant Ford Mondeo Diesel is being launched in October 2003, but only as a 130ps unit. The 115ps engine used in the original baseline remains unchanged and has been retained
- The new Vauxhall Astra was launched at the Frankfurt show in September 2003, and features a new Euro 4 1.9 Diesel from Fiat-GM Powertrain venture. However, homologation data was not available for this study so the old model's values have been retained
- The new VW Golf was also launched at Frankfurt, and features an upgraded Diesel range, again Euro 4. Likewise, homologation data was not available at the time of the study so the old vehicle's values were retained
- The Ford Focus, Renault Laguna and Vauxhall Vectra remain unchanged

Details of the new Baseline vehicles are given in Appendix A. Figure 5 summarises the changes, and indicates that differences to the original 2002 baseline are actually quite small.

Key Headings Summary for the Baseline:
- 2001 to **2003** model year
- Modern HSDI Diesel engine with Euro 3 and Euro 4 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 **152 g/km** (**170 g/km** CO_2 Well to Wheels)
- Average weight of **1351 kg**
- Average retail (list) price of **£15,157** (October 2003 monetary value)

C & D Segment - DI European Vehicle Baseline				
		2002 Baseline	2003 Baseline	% Change
Engine		**1.9L**	**1.9L**	**1.9L**
Power (kW)		81	82	2%
Weight (kg)		1333	1351	1%
0->100kph (s)		12	11	-4%
Top Speed (km/h)		191	193	1%
Fuel Cons' (L/100km)	**Combined**	**5.5**	**5.6**	**1%**
	ECE	7.4	7.4	0%
	EUDC	4.5	4.5	1%
Emission level		E3	E3/4	E3/4
UK retail price (£) - 5dr h/back		£15,323	£15,157	-1%

Figure 5: Summary of the Baseline Vehicle Changes

From this baseline point **(taken as 2003)** the scenarios are developed as stated in the original report [1]. The average parameters are modified by the applied technologies with reference to the New European Drive Cycle including the change in CO_2 emissions, weight, cost and general characteristics of the vehicle. This information has been used to adjust the Low Carbon road map as described in subsequent sections. The full baseline vehicle calculation information is given in Appendix B.

3.2 Suggested changes to the original routes

The original Low Carbon and Hydrogen Priority routes [1] have been improved in a number of ways. Detail of these changes is given in sections 4 and 5, and Appendix B. Key changes are:

- Achievement of "Euro 4" emissions in a C/D segment vehicle without a Diesel Particulate Filter (DPF), which reduces cost and removes a small CO_2 penalty
- Adoption of two new emission scenarios as described in section 2.4, one stopping at Euro 5, and a second more aggressive scenario achieving the Foresight targets for 2020
- Increased use of engine downsizing at some steps (section 2.5.2)
- Improved batteries using Li-ION technology (section 2.5.3); and improved motor technology with no weight penalty in later steps of both evolutions, reflecting recent developments
- Revised Low Carbon technologies beyond Step 4, replacing technologies which the original study showed to be ineffective. These include Exhaust Heat Recovery devices, and more efficient Auxiliary Power Units (APU). The final Low Carbon Step, the Fuel Cell vehicle of 2030, remains unchanged but is now the seventh step (albeit named Step 8 as before)
- Correction of a small error in the cost calculation of Low Carbon Step 4
- Improvements in Hydrogen storage technologies to reflect US DoE storage system mass targets for 2015 and beyond
- Fuel Cell APU efficiency increased from 40% to 50%, reflecting strategy of avoiding full load operation of the APU

The revised Low Carbon and Hydrogen Priority routes are described in Sections 4 and 5 below. It should be noted that the impacts of each step are now compared to the Baseline vehicle (whereas the original study compared each step to the one before). In making comparisons to original study prices, these original prices have been increased by the UK Government standard inflation multiplier of 1.028.

4 LOW CARBON EVOLUTION

In each step, changes from the 2002 study [1] are summarised. The "Key Headings Summaries" from the 2002 study are then repeated, with changes shown in bold font. The benefits of each step are now shown relative to the new Baseline vehicle, whereas the original study referenced each step to the one before.

4.1 Step 1 – Stop Start Vehicle 2004

From the baseline, Step 1 adds a stop-start system for introduction in 2004. This technical step is being readied for production by OEMs now. This vehicle is at Euro 4 emissions level.

Summary of Technical Change from 2002 study:

- Diesel Particulate Filter not now required, as Euro 4 can be achieved without a Diesel Particulate Filter for a vehicle of this weight
- The time period for implementation of a 0.6% improvement per year in powertrain CO_2 emissions is reduced to just 1 year

Result:

- Vehicle weight, cost and CO_2 emissions are reduced compared to the 2002 study
- Including the effect of the baseline change, the overall Step 1 vehicle CO_2 reduction from Step 1 in the 2002 Low Carbon vehicle is 1.4%

Key Headings Summary for Step 1:

Impacts (relative to step 0):

- Fuel consumption **–4.2%** to **163** Well to Wheels g/km CO_2 (**145g/km** Tank to Wheels) at Euro 4
- Weight (kg) **+1.0%** to **1365** at Euro 4
- Retail Price (£2003) **+1.5%** to **£15,389** at Euro 4 (estimated range **£15,350** to **£15,400**)

Technologies:

- Belt alternator starter on 12V standard electrical system
- 6 speed manual transmission

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

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)

4.2 Step 2 - Stop Start + Regenerative Braking Vehicle 2007

From Step 1, Step 2 adds improved battery and motor systems to allow a basic level of regenerative braking for production in 2007. This vehicle is at Euro 4 emissions level.

Summary of Technical Change from 2002 study:

- Diesel Particulate Filter not now required, as Step 1, and removal of need to comply with speculated “Euro 5” emissions at this step
- Increase engine downsize ratio from a 1.8 litre engine to 1.6 litre engine. There have been significant gains in downsized Diesel engine technology and the date it is bought to market. Several manufacturers are likely to replace 1.8 to 2.0 litre high output diesel engines with units of 1.5 to 1.6 litre capacity and similar performance between 2004 and 2007 model year. This offers economy and weight improvements and so is implemented in this Step

Result:

- CO_2 emissions of the Step 2 engine are reduced by 5% due to engine downsizing from the Step 1 unit
- Overall, the vehicle CO_2 emissions improves by 10% over the 2002 Low Carbon Step 2 vehicle, due to downsizing and less restrictive emission control

Key Headings Summary for Step 2:

Impacts: (ALL RELATIVE TO THE STEP 0 VEHICLE)

- Fuel consumption (Well to Wheels g/km CO_2) **–23%** to **131g/km** (**117g/km** Tank to Wheels) at **Euro 4**
- Weight **1345** kg
- Retail Price (£2003) **+5.8%** to **£16,041** at **Euro 4** (estimated range **£15,940** to **£16,140**)

Technologies beyond Step 1:

- 42V starter/motor/generator – belt driven with dual 42V / 12V electrical architecture system
- VRLA battery
- 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

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 **(but improved over original step 2)**, leading to perhaps 2-5% 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

4.3 Step 3 - Mild Hybrid + Significant Downsize 2010

From Step 2, Step 3 adds further improved battery and motor systems to allow significant levels of regenerative braking. In addition, the engine has been downsized to 1.2 litres for production in 2010. This vehicle is now at Euro 5 emissions level through the use of a DPF and a small lean NOx Trap (LNT).

Summary of Technical Change from 2002 study:
- No technical changes required from original plan
- Changes to calculations to take account of revised previous steps

Result:
- Overall, the vehicle CO_2 emissions improves by 3% over the 2002 Low Carbon Step 3 vehicle due to changes in previous steps, principally a revised and lower estimate of the impact of "Euro 5" emission control on fuel economy

Key Headings Summary for Step 3:

Impacts: (ALL RELATIVE TO STEP 0 VEHICLE)

- Fuel consumption (Well to Wheels g/km CO_2) **–34%** to **112** (**100 g/km** Tank to Wheels) at assumed Euro 5
- Weight **1327** kg
- Retail Price (£2003) **+13.3%** to **£17,183** at assumed Euro 5 (estimated range **£17,000** to **£17,350**)

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 (**1.6 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 excluding high margins often charged on spares). 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 3-6% 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 of the original report [1]
- 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
- **High voltage technology (144-288v), combined with slightly larger motors and batteries, may be an alternative if 42v technology is not adopted. This enables a small improvement in efficiency, with a small cost penalty, relative to a 42v system**
- 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.

4.4 Step 4 - Parallel Hybrid + Advanced Diesel 2012

From Step 3, Step 4 develops a parallel diesel hybrid with excellent fuel economy. Advanced motor and battery technology has been combined with a small diesel engine for production in 2012. This vehicle is at Euro 5 emissions level through the use of a DPF and a small lean NOx Trap (LNT).

Summary of Technical Change from 2002 study:

- The motor power has been upgraded to 40kW for the same weight, dimensions and cost, reflecting improvements such as those seen in the latest generation Toyota Prius (Appendix B)
- The battery has been changed to Li-Ion technology (section 2.5.3) allowing lower weight and increased energy recovery during regenerative braking, also, increased vehicle performance

Result:

- Regenerative braking improvements reduce CO_2 emissions by about 1% compared to the original Step 4 (This is possibly pessimistic, but takes account of battery life considerations which are critical for this type of vehicle – very high re-generating currents can shorten battery life) This technical step does also allow significant vehicle performance improvements
- Overall, the vehicle CO_2 emissions improves by 9.8% over the 2002 Low Carbon Step 4 vehicle due to the technical improvements here (motor efficiency and battery performance) and changes in previous steps (principally a less aggressive emissions control scenario and improvements in the CO_2 penalty of emissions control)

Key Headings Summary for Step 4:

Impacts: (ALL RELATIVE TO STEP 0)

- Fuel consumption (Well to Wheels g/km CO_2) **–45%** to **93** (**83g/km** Tank to Wheels) at assumed **Euro 5**
- Weight **1381** kg
- Retail Price (£2003) **+23.5%** to **£18,728** at assumed **Euro 5** (estimated range **£18,330** to **£19,130**)

Technologies beyond Step 3:

- High voltage, high power motor and generator (permanent magnet)
- **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 **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. **The alternative system most likely to gain favour could be the single motor / twin clutch system as used on various Ford concepts (Appendix B), as this may prove cheaper to manufacture, offers almost as much benefit and is perhaps easier to evolve from Step 3. It can also, potentially, use a standard gearbox**
- This technology is equally applicable to Petrol (Gasoline) and Diesel engines and offers the building blocks to head towards alternative prime movers such as Fuel Cells

4.5 Step 5 - Parallel Hybrid + Advanced Diesel + Heat Recovery 2017

In the previous Low Carbon Roadmap [1], Step 5 was a series hybrid with the intention of developing hardware suitable for a future fuel cell vehicle. The study showed that these technologies worsened well to wheels CO_2 by nearly 30% from Step 4 due to the poor efficiency chain present in the passenger car series hybrid. Even the most optimistic improvements in series hybrid technologies allowed it to match Step 4 but not improve on it. It was therefore concluded in the previous Low Carbon Roadmap that although car makers might develop such a vehicle as part of their technology development towards fuel cell vehicles, they would not put these models onto the volume market because there were not worthwhile CO_2, driver or cost benefits.

On the basis of advances over the last year, a revised Step 5 configuration is suggested, which develops Step 4 in a logical approach adding a means of recovering wasted energy in the engine exhaust and applying natural improvements to the overall powertrain system. Also, the introductory date has been moved to 2017 to allow technology maturity time.

From the updated Step 4, Step 5 develops the parallel diesel hybrid with general system efficiency improvements (4%) and adds an exhaust heat recovery system.

Unlike Step 5 in the original report, this revised Step 5 vehicle would deliver a CO2 saving beyond Step 4, and might be considered for volume production, depending on progress on this technology, and the production costs.

Exhaust heat recovery systems are typically being researched in three technology areas:

- Thermo-electric, where temperature differential drives the flow of electrons through a material junction (as with a thermocouple), creating electrical energy
- Thermo-fluid, where heat differential changes the state of a fluid and allows energy extraction with a turbine or expander of some nature
- Fuel reforming, where exhaust heat is used to chemically alter the fuel, adding more energy to it

The latter two of these three options appears, so far, to be the more effective. All these technologies rely on heat differential and so the hotter the source and the colder the ambient, the more energy that can be recovered. Toyota have been active in thermo-fluid technology and, in 1993, stated that a 3% fuel economy improvement was seen with a small vehicle over an urban drive cycle [28]. Step 5 is a highly efficient drivetrain, but the engine will be operated at high load (high efficiency) and so 3% was assumed practicable due to high exhaust temperatures.

In practice, this type of system has not been proven, however, it is one remaining area of waste that has yet to be the focus of significant study, hence its inclusion here perhaps to promote interest. Cost assumptions used here are highly speculative, as there is no published information available.

This vehicle is at Euro 5 emissions, through the use of a DPF and a small lean NOx Trap (LNT). There is an option for the “Euro 7” level of the original study [1], which would require the same technology but larger devices with greater back-pressure, higher precious metal content and requiring more frequent re-generation. This is likely to result in higher CO_2 and cost.

Summary of Technical Change from 2002 study:

- **Completely new Step 5 concept as described above**
- The powertrain system has been improved in efficiency by 4% through motor, battery engine and control system natural improvements over Step 4
- An exhaust heat recovery system has been added giving a 2% CO_2 reduction (weight and cost additions are Ricardo estimates)

Result:
- Overall, the vehicle CO_2 emissions improves by 36% over the 2002 Low Carbon Step 5 vehicle (5% relative to the 2003 Step 4 vehicle) although please note, this is a new technology step and is introduced at a different date

Key Headings Summary for Step 5 (ALL DIFFERENT TO ORIGINAL STEP 5):

Impacts: (ALL RELATIVE TO STEP 0)

- Fuel consumption (Well to Wheels g/km CO_2) **–49%** to **86** (**77g/km** Tank to Wheels) at assumed **Euro 5**
- Fuel consumption (Well to Wheels g/km CO_2) **–48%** to **88** (**78g/km** Tank to Wheels) at assumed **Euro 6**
- Weight **1391** kg
- Retail Price (£2003) **+24.3%** to **£18,840** at assumed **Euro 5** (estimated range **£18,340** to **£19,340**)
- Retail Price (£2003) **+25.1%** to £**18,965** at assumed **Euro 6** (estimated range **£18,470** to **£19,470**)

Technologies beyond Step 4 (ALL DIFFERENT TO ORIGINAL STEP 5):
- Exhaust heat recovery system, either thermo-electric, thermo-fluid or reformer
- Improvements to a higher voltage, high power motor and generator (permanent magnet) system
- Improvements to the Li-Ion battery at higher voltage
- Friction and control improvement to the highly downsized engine (1.0 litre) with high ratings (over 63kW/litre), a slightly smaller speed range and lightweight materials.
- Further refinement to a torque sharing transmission or similar
- Improvements to the Supervisor control system to take account of an additional source of power and to improve on the previous Step.

Risks:
- No more than Step 4 assuming the heat recovery system can be robust – for thermo-fluid this may be a challenge due to the extremes of operating temperature range
- High ambient temperatures will affect the efficiency improvements

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

Impact on Manufacture:
- **Over Step 4, the heat recovery system may be difficult to install unless carefully modularised with the exhaust system**

Impact on Infrastructure:

- **The heat recovery system will require care in its treatment during servicing**

Read Across to Other Vehicle Types:

- Technically applicable to most vehicle applications, however, the larger the vehicle the greater the price increase. **Heat recovery technology may be introduced first on heavy trucks, as their high capital cost and sensitivity to operating cost could make early (bulky, costly) versions of the technology attractive**

Read Across to Other Usage Patterns:

- Hybrid technology has greatest benefits in heavily congested conditions. In suburban and motorway use, a small further increase in powertrain efficiency will be seen due to technology improvements, leading to perhaps 1-2% reduction in CO_2 relative to step 4. **Heat recovery devices will be most effective at high engine load and low ambient temperatures – highway and cross-country driving, especially in northern Europe**

Degree of Confidence in Analysis:

- High for the basic Hybrid technology, based on real world experience of production vehicles, engineering programmes and technical publications
- **Low for Heat Recovery devices due to the relative lack of published information on this technology**

Alternative Technologies:

- **As for Step 4 and the discussion above on Heat Recovery Devices**

4.6 Step 6 - Deleted

The original 2002 Low Carbon roadmap Step 6 [1] suggested a reversible fuel cell as an alternative to a battery for high power storage. However it is now considered that, unless there is a breakthrough in this technology, it is not as efficient as batteries and the power capacity improvement (allowing more regenerative energy storage) does not offset the loss in system efficiency. Therefore, this Step has been omitted in this update. For clarity the numbering jumps straight to steps 7 and 8, as these are similar to the technologies used in the original study with those step numbers.

4.7 Step 7 - Parallel Diesel Hybrid + with a Hydrogen APU 2023

As in the original study, technology is desired to bridge the gap between the advanced and highly efficient hybrid vehicles which may be available in rising numbers by 2020, and the Hydrogen fuelled, fuel cell vehicle which is suggested for volume feasibility for 2030. In the Hydrogen Priority evolution explored in section 5, this gap is bridged using Hydrogen internal combustion engines, assisted by hybridisation and small fuel cell auxiliary power units (APUs).

In the absence of a Hydrogen Priority policy it is likely that Hydrogen availability may be more restricted for a longer period. The philosophy originally suggested was therefore that the Diesel Hybrid technology evolved in steps 1 through to 5 could be enhanced by a Hydrogen-fuelled APU. This would allow the vehicle to operate with limited performance as a Hydrogen-fueled Zero Emission Vehicle (perhaps in cities where ZEV capability is desired and Hydrogen available), but return to using Diesel fuel for higher speeds or distances (which will typically happen outside emission-sensitive areas).

This step was originally introduced as Step 7c [1], but has been simply adopted as Step 7. The introduction date of this Step has been delayed until 2023 which may give time for a hydrogen infrastructure to have been implemented sufficiently widely to allow the use of hydrogen in vehicles – albeit probably reformed from natural gas.

The improved Step 5 vehicle hybrid diesel powertrain is used as the basis for the new Step 7, in which the heat recovery system is replaced with an 8kW Proton Exchange Membrane fuel cell hydrogen burning auxiliary power unit (APU). This is used to provide 50% of the vehicle's power requirement over the drive cycle. An APU efficiency of 50% has been chosen which is an improvement from 40% chosen for the original Low Carbon Step 7c Parallel Diesel with APU system. 50% efficiency represents good performance of a part load, ambient temperature PEM fuel cell stack and supporting systems. Hydrogen is stored as compressed gas and is assumed generated from steam reformation of natural gas.

The emissions levels of this vehicle are shown for Euro 5 and assumed Euro 7 (meeting the assumed 2020 Foresight vehicle emissions targets).

Summary of Technical Change from 2002 study:

- The powertrain system has been improved in efficiency by 6% through the addition of a H_2 APU generating 50% of the vehicle's power requirements over the NEDC
- The addition of further emissions controls to 2020 emissions targets hinders the fuel consumption by an estimated 2%

Result:

- Overall, the vehicle CO_2 emissions improves by 61% over the 2002 Low Carbon Step 6 vehicle although again, please note, this is a new technology step and is introduced at a different date

Key Headings Summary for Step 7:

Impacts: (ALL RELATIVE TO STEP 0)

- Fuel consumption (Well to Wheels g/km CO_2) **–52%** to **81** (**72**g/km Tank to Wheels) at assumed **Euro 5**

- Fuel consumption (Well to Wheels g/km CO_2) **–51%** to **83** at assumed **Euro 7**
- Weight **1496** kg
- Retail Price (£2003) **+27.5%** to **£19,318** at assumed **Euro 5** (estimated range **£19,000** to **£20,500**)
- Retail Price (£2003) **+28.4%** to **£19,468** at assumed **Euro 7** (estimated range **£19,150** to **£20,650**)

Technologies beyond Step 5:
- The PEM fuel cell is a significant technology advancement from Step 5 with associated risks
- Hydrogen storage is now required which is currently a difficult and fast changing area of technology

Risks:
- The PEM fuel cell is now quite a well known technology but the application of a system to real automotive use is a difficult task. Start-up time, actual total system efficiencies, cost and life remain the greatest risks to the technology
- Hydrogen storage is developing fast however technologies still do not meet the US DoE targets for H_2 storage mass efficiency. Also there are a number of technologies competing all with advantages and disadvantages. This is reflected in the wide cost range shown above

Vehicle Attributes:
- Driveability and noise will be good but variable depending on operating mode and battery state of charge
- The APU is expected to be near silent – this will depend on the support system development applied

Impact on Manufacture:
- Over Step 5, the hydrogen storage will require specialist treatment in manufacturing, assembly and servicing

Impact on Infrastructure:
- A hydrogen infrastructure is required for full operation, although this vehicle can also operate on diesel fuel alone
- Hydrogen fuel is not currently allowed in some car parks, Eurotunnel etc

Read Across to Other Vehicle Types:
- Technically applicable to most vehicle applications, however, the larger the vehicle the greater the price increase
- **APU technology is likely to be deployed first in trucks, to power load refrigerators and cabin comfort equipment. Anti-idling laws (to ban idling engines at truck rest stops) proposed in the USA are providing a strong driver for this technology**
- A system this complex is likely to be used first in larger cars then filter down to the C/D segments

Read Across to Other Usage Patterns:
- Greatest benefits in heavily congested conditions, performance similar to previous step on highway

Degree of Confidence in Analysis:
- Medium, based on experience with modelling fuel cells and published data

Alternative Technologies:

- The engine could be hydrogen fuelled if the infrastructure permits
- Solid Oxide and Alkaline fuel cell technologies may be equally suitable. Current efforts for APU technology are favouring the Solid Oxide type, which can be compatible with liquid fuels. With this technology a different Step 6, using only Diesel fuel, offers a possibly slightly cheaper vehicle but without the dual fuel capability

4.8 Step 8 - Hydrogen Fuel Cell Vehicle 2030

Few changes have been made to the original Step 8 Fuel Cell vehicle. Battery storage (Fuel Cell Hybrid) is likely to be part of the system, and knock-on impacts of previous changes to technologies and prices in previous steps have been carried forward where similar technology is used.

Key Headings Summary for Step 8:

Impacts (ALL RELATIVE TO STEP 0):

- Fuel consumption (Well to Wheels g/km CO_2**) – 30-56%** (efficiency range of technology) to **119 to 74** (ZEV)
- Fuel Consumed: **1.43 to 0.89 kg/100km Hydrogen**
- Weight **1468** kg
- Retail Price (£2003) **+30%** to **£19,672** (estimated range **£18,400** to **£21,400**)

Please note, this price includes the correction of an error in cost calculation of the original low Carbon Step 4 hybrid which affected the original cost of this Step.

Technologies beyond Step 7:

- PEM Fuel Cell as a complete vehicle system rather than a supporting APU

Risks:

- The fuel cell system at high power ratings has many risks: precious metal content is very high meaning price is volatile, power density is increasing but improvements in 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

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 – 7 vehicles, depending on the provision of package space for Hydrogen storage

Impact on Infrastructure:
- Same as Step 7 except that Step 8 is a hydrogen only vehicle and so requires an infrastructure as wide as the current gasoline and diesel system for mass introduction

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 (regenerative 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. **There have been reports that DaimlerChrysler and General Motors are giving lower priority to, or perhaps abandoning, their reformer technologies. All new concepts and prototypes shown this year have been of Direct Hydrogen type.** 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
- A more radical approach may be the consideration of the electric vehicle which is by far a more efficient route to transfer renewable energy (most likely generated as electricity) into the vehicle. By 2030, battery technology will have improved, however, it is unlikely that the current autonomy enjoyed by the carbon based fuelled vehicles would be reproduced for similar cost in the electric vehicle unless a step change in battery technology is achieved

4.9 Low Carbon Update Analysis

Except in detail, the technical principle of the Low Carbon roadmap does not differ from the original roadmap until updated Step 5 is reached. Here, the series hybrid in the original Step 5 is replaced with an evolution of the diesel parallel hybrid. This forms a more logical progression of technologies and in Well to Wheels CO_2 as can be seen in Figure 6.

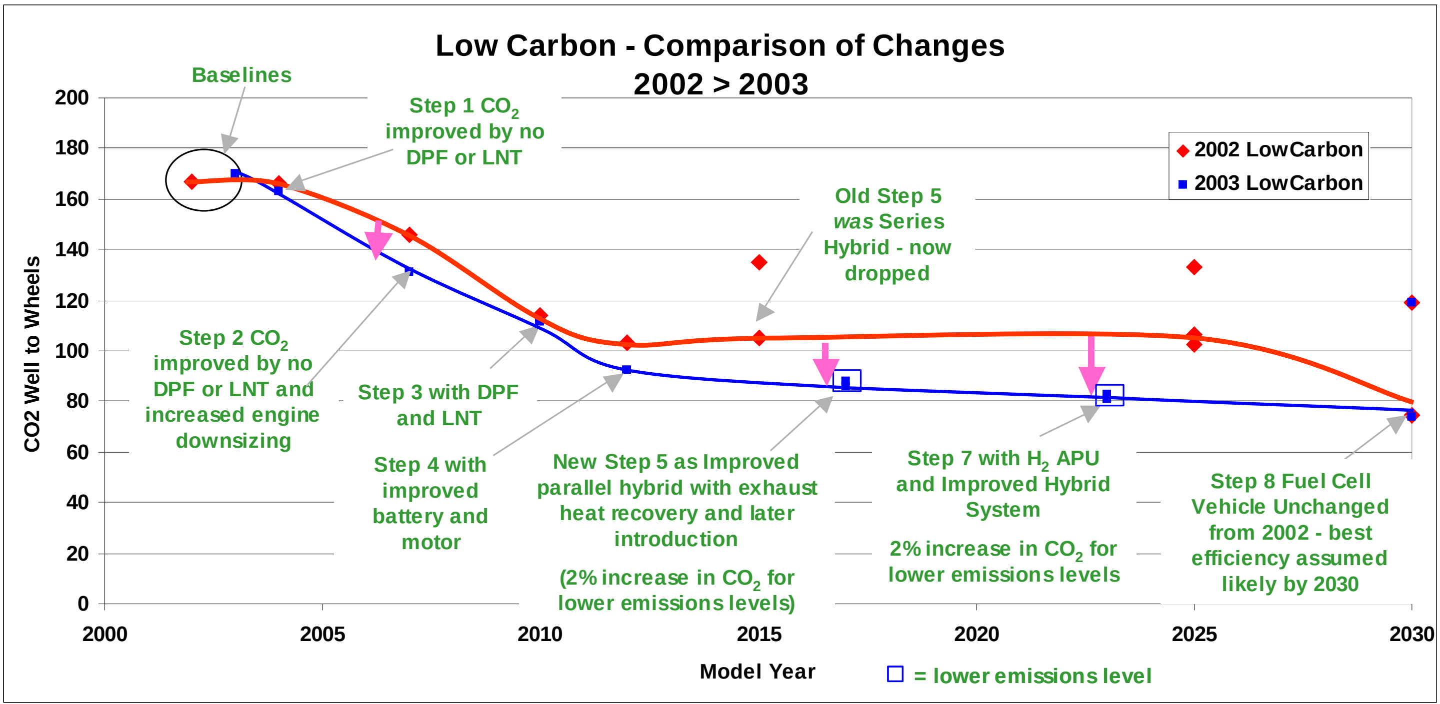


Figure 6: The Updated Low Carbon CO_2 Roadmap compared with the 2002 Roadmap

A comparison of projected vehicle costs (list price) is shown in Figure 7, with the 2002 prices having been corrected by the Government's recommended inflation factor of 1.028 for the elapsed year.

The early steps are improved by advances seen in emission control technology and engine downsizing, together with a revised assumption of less demanding future emission legislation (in recognition of diminishing air quality returns and potential negative impacts on CO_2). The result is small percentage reductions in both CO_2 and cost compared to the original prediction.

The revised Steps 5 and 7 can be seen to improve strongly on the previously suggested technologies for Step 5, 6 and 7c (which was also a parallel diesel hybrid with a hydrogen APU). This is because of better new approaches, and the updated roadmap taking account of the improvements that have been made up to that point in hybrid technology and also includes improved efficiency of the fuel cell APU compared to that used in the 2002 road map.

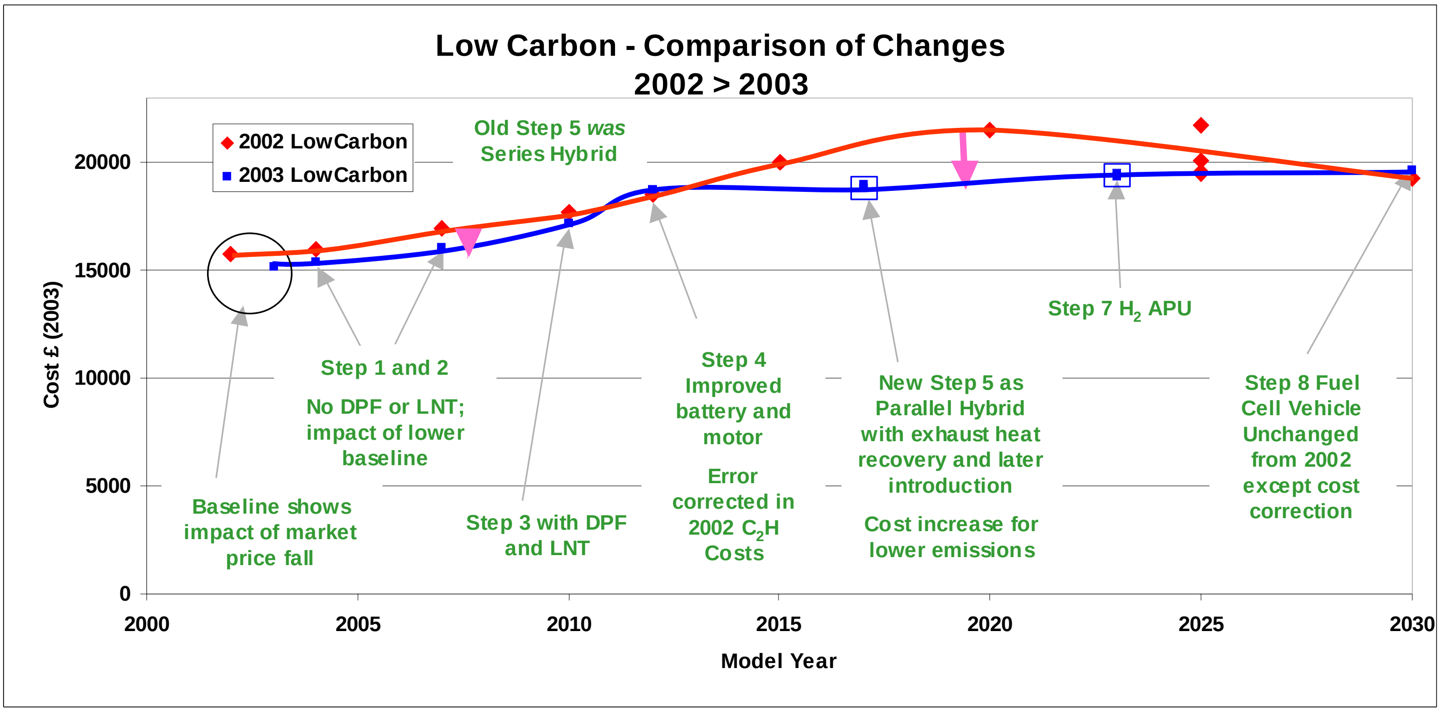


Figure 7: The Updated Low Carbon Costs Roadmap compared with the 2002 Roadmap

The weight changes are mostly due to changes in the baseline, an increase in engine downsizing for Step 2 and the changes in technology for Step 5 and 7 as depicted in Figure 8:

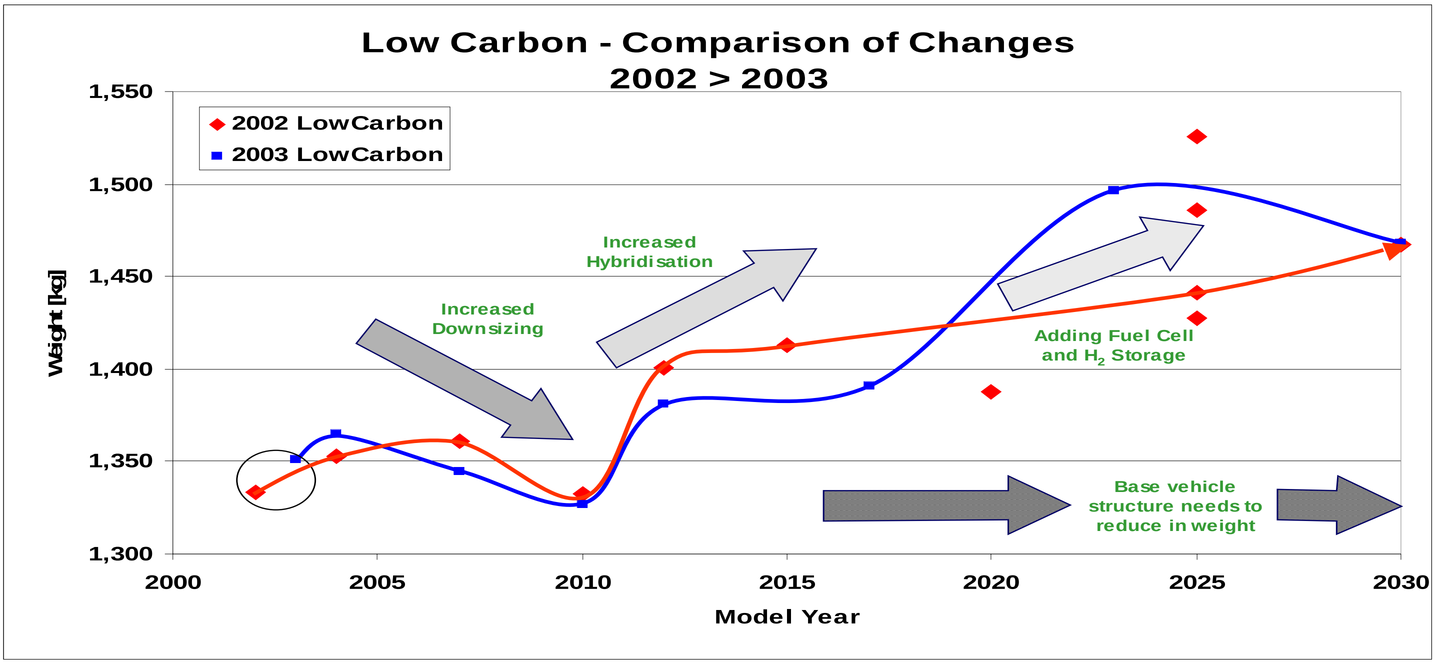


Figure 8: Low Carbon Update to Vehicle Weight

Generally, the revised roadmap does not significantly alter the conclusions made in 2002:

- Steps 1 to 3 represent valuable and cost effective technology introductions that will strongly decrease the CO_2 emissions of the vehicle fleet
- Step 4 offers the lowest CO_2 emissions using traditional and hybrid technologies however, the cost increases at its steepest rate with this introduction
- Beyond Step 4 should be a natural evolution of effective technologies
- Step 5 now adds new technology for exhaust heat recovery with a small increase in cost for a small reduction in CO_2
- Step 7 (as in the 2002 Step 7c) introduces the hydrogen fuel cell APU to start gaining customer acceptance of fuel cells and for the accrual of useful field information (also allowing renewable energy to be used if appropriate)
- The viability of Step 7 depends on the accessibility of a hydrogen infrastructure and the will of the manufactures to introduce this technology. They would incur significant development costs for a small improvement in cycle based CO_2 emissions. However, this makes valid progress towards Step 7 and is likely to be pursued for technical robustness reasons as the Japanese have done with hybrids in the late nineties, disregarding short term financial losses at the time
- Step 8 shows a likely worsening of CO_2 emissions unless best efficiencies are obtained. However with time, the technology will improve and the hydrogen is likely to slowly decrease in carbon basis so leading to an effective, low carbon vehicle

5 HYDROGEN PRIORITY EVOLUTION

The Hydrogen Priority evolution has been updated to reflect improvements in the hybrid systems as shown in the Low Carbon evolution, the Fuel Cell APU efficiency and also changes in the hydrogen storage systems that are expected in 2015 and 2020. Otherwise, nothing has been changed, as there is no significant evidence to suggest a different approach. Any changes are noted in bold text.

It is worth noting that the original start time for the Hydrogen Priority route was based on an assumed timetable of political agreement and product development [1]. It is not clear whether the intervening year has achieved what it needs to have done for a Hydrogen Priority start in 2007. However, since the early steps of Hydrogen Priority simply adapt Low Carbon hybrid technologies it is possible initiate a Hydrogen Priority evolution at a later stage if needed.

5.1 Step 3H - H_2 Powered Stop Start + Regen Vehicle 2007

No technical changes to this Step made during this update however, the percentage changes have been updated to reflect the change in the baseline (Step 2 from the Low Carbon Roadmap) and the weight and price have been updated slightly from the baseline.

Key Headings Summary for Step 3H:

Impacts (relative to Step 2 from UPDATED Low Carbon Roadmap):

- Fuel consumption (Well to Wheels g/kmCO_2) **+44%** to **189** at assumed Euro 5
- Fuel Consumed: **2.27kg/100km** Hydrogen
- Weight (kg) **+6.25%** to **1429kg**
- Retail Price (£2003) **+0.7%** to **£16,297** at Euro 5 (estimated range **£16,100** to **£16,500**)

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). **Claims made by Ford surrounding their “Model U” and “H2RV” programs (Appendix B) suggest that this risk may not be as severe as assumed, however these programs used a less aggressively boosted engine**
- 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 Low Carbon in respect of vehicle architecture to accommodate hydrogen tanks, 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
- Otherwise as per Step 2 (LC)

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 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.

5.2 Step 4H - H_2 Mild Hybrid Vehicle 2010

Again, no technical change has been made to this Step.

Key Headings Summary for Step 4H:

Impacts (relative to Step 3H):

- Fuel consumption (Well to Wheels g/km CO_2) **–18.5%** to **154** at assumed Euro 5
- Fuel Consumed: **1.85kg/100km** Hydrogen
- Weight ([kg]) **–1.3% to 1411** at assumed Euro 5
- Retail Price ([£2003]) **+4.6% to £17,039** at assumed Euro 5 (estimated range **£16,750** to **£17,350**)

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
- **As with Step 3 (LC), higher voltage systems are an alternative to 42v**

5.3 Step 5H - H_2 Mild Hybrid Vehicle Step with Small Fuel Cell APU 2012

This step introduces the solid oxide fuel cell as a small APU to minimise the risk and cost of new technology introduction. As for Step 6 LC, APU efficiency is increased to 50% as the APU is operating part load which is where fuel cells are most efficient. The solid oxide fuel cell was originally chosen as this currently has had the most development as an APU for passenger cars to date. The PEM fuel cell as used above in the LC road map would be an alternative choice with similar characteristics but operating at a lower temperature. No other changes have been made.

Key Headings Summary for Step 5H:

Impacts (relative to Step 4H):

- Fuel consumption (Well to Wheels g/km CO_2) **–4.1%** to **147** at assumed Euro 5
- Fuel Consumed: **1.76kg/100km** Hydrogen
- Weight (kg) **+2.8%** to **1451**
- Retail Price (£2003) +2.31% to £**17,439** (estimated range **£17,100 to £17,900**)

Technologies beyond Step 4H:
- 4kW solid oxide Fuel Cell 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
- The PEM fuel cell is a viable alternative in this application.

5.4 Step 6H - Parallel Hybrid with 8kW Fuel Cell APU 2015

This step adopts full hybrid technology from step 4 (LC), with a bigger APU. It is therefore similar to step 6 (LC) but introduced 8 years earlier with less developed technology and a Hydrogen IC engine in place of Diesel. Again, the fuel cell efficiency has been increased to 50% and the hybrid system improvements made to Step 4 of the Low Carbon roadmap have been carried over to this Step. The hydrogen storage system mass has been reduced by 15kg to represent the US DoE mass targets for 2015 as shown in Reference 3. No other changes have been made.

Key Headings Summary for Step 6H:

Impacts (relative to Step 5H):

- Fuel consumption (Well to Wheels g/km CO_2) **–27.3%** to **107** at assumed Euro 5
- Fuel Consumed: **1.28kg/100km** Hydrogen
- Weight (kg) **+7.2%** to **1555**
- Retail Price (£2003) +10.9% to **£19,434** (estimated range **£18,900** to **£20,800**)

Technologies beyond Step 5H:

- 8kW Solid Oxide APU operating on average at 2.85W over the drive cycle
- **Updated** 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. As with step 6LC, APUs are likely to cross over from truck technology

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
- The PEM fuel cell is a viable alternative in this application

5.5 Step 7H - Series Hybrid with 40kW Fuel Cell 2020

The only change made to this step is the reduction in mass of the hydrogen storage system by 14kg to extrapolated US DoE weight targets [29].

Impacts (relative to Step 6H):

- Fuel consumption (Well to Wheels g/kmCO_2) **+11.4% to –30.5%** (range of efficiencies) to **119 to 74** (ZEV)
- Fuel Consumed: **1.43 to 0.89kg/100km** Hydrogen
- Weight (kg) –7% to **1446**
- Retail Price (£2003) **+0.7%** to **£20,073** (estimated range £18,800 to £22,000)

Technologies beyond Step 6H

- PEM Fuel Cell for automotive use

Risks:

- Fuel cell system has many risks, as per new step 7LC. These risks will be higher with earlier introduction.
- Hydrogen storage as for previous steps

Vehicle Attributes:

- As per new Step 7LC

Impact on Manufacture:

- As per new Step 7LC, but achieving a manufacturing infrastructure ten tears earlier is an enormous challenge
- Vehicle architecture would need to be compatible with Fuel Cell package, again this is a bigger challenge ten years earlier than step 7LC

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 7

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 7

5.6 Hydrogen Priority Analysis

The original 2002 road map is technically unaltered with this update except for small detailed changes. These are limited to changes to the baseline, a development of the hybrid technologies used as with the Low Carbon road map and an improvement in hydrogen storage technology. Consequently, the conclusions do not change.

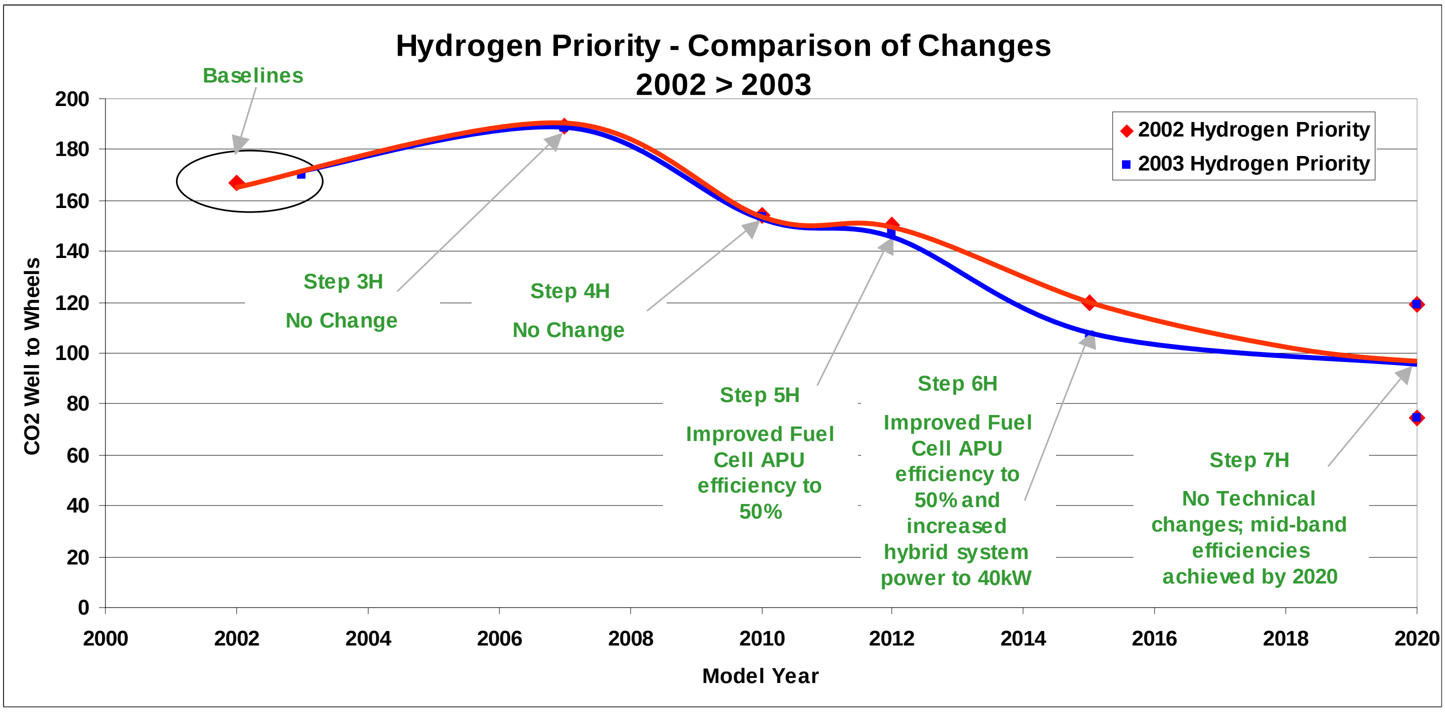


Figure 9: Hydrogen Priority Update Comparison of CO_2 Emissions

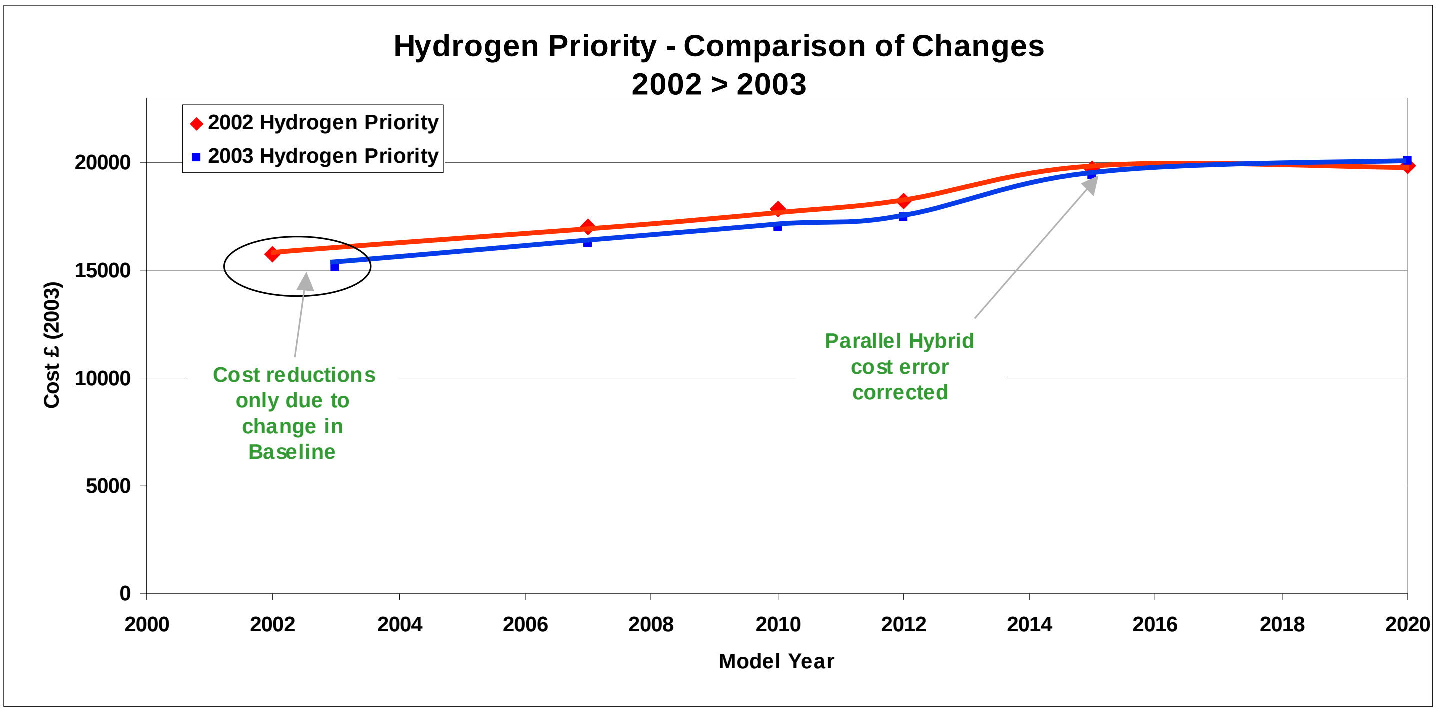


Figure 10: Hydrogen Priority Cost Comparisons

The CO_2 performance of Step 5H is improved slightly by increasing the APU efficiency to 50% and Step 6H has improvements made to the hybrid system as applied to Step 4 of the Low Carbon roadmap. There is no information to indicate that the cost of the Hydrogen Priority roadmap should change, except via shifts to the baseline, and this is reflected in Figure 10 (2002 costs again corrected by the Government's recommended factor of 1.028). Weight increases with the 2003 Baseline, but is slightly improved at steps 5 to 7 due to improvements in hydrogen storage systems as shown in Figure 11:

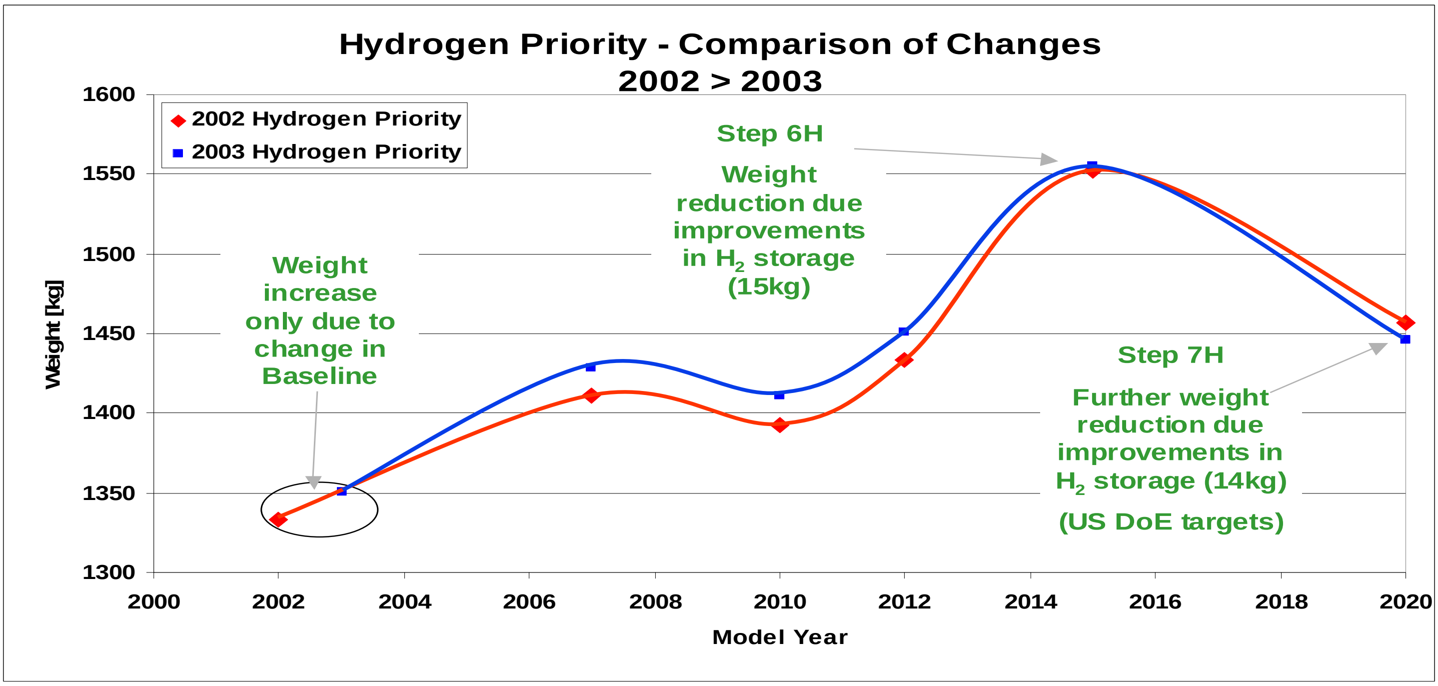


Figure 11: Hydrogen Priority Weight Comparisons

The conclusions are therefore:

- If the Hydrogen Priority route is pursued, there are clear benefits in pursuing interim steps toward the fuel cell vehicle rather than focussing all efforts on Step 7 with nothing in between
- The route is totally dependant on the growth of the hydrogen infrastructure allowing the effective use of the vehicles - this will require significant incentive as the number of vehicles sold will initially be low
- The technical risks in this route are mostly the effective and safe storage of hydrogen, PEM or SOFC fuel cells and the support systems for air, water and cooling. Developments here currently indicate that the technology is feasible in the future at the current rate of development although cost effectiveness is and will have to be a major focus of effort. Accelerating this development to follow the Hydrogen Priority roadmap will require considerable application of incentives for manufactures and purchasers

6 VALIDATION OF THE ORIGINAL STUDY AND REVISED EVOLUTIONS

The past year has seen an unprecedented level of activity from vehicle manufacturers in terms of release or announcement of new low-carbon vehicles, or display of show cars and new technologies. Appendix A contains more information on these vehicles, and their comparison to the steps of the original Evolutions. The information is summarised in Figures 12 and 13 below, compared to the original study results (with 2002 prices corrected to 2003 values using the UK government's recommended multiplier of 1.028) and the proposed modifications arising from the 2003 update.

Figure 12 shows validation data for the Low Carbon evolution. There is no numerical validation data for heat recovery devices or auxiliary power units (new steps 5-6) The following is apparent:

- Developments since the original report confirm that technologies validating the earlier steps are being readied for volume production in Europe. Developments relating to the later steps tend to be concept cars, or niche "image" vehicles from Japan and the USA, sold alongside conventional alternatives
- The developments also confirm the estimates of CO_2 benefits, taking into account currently available fuel type, vehicle type, weight, technology specification and duty cycle (as explained further in Appendix A for the Renault Ellypse)

Figure 13 compares similar data for the Hydrogen Priority evolution:

- The Ford Hydrogen Hybrid concepts fit well with the technology assumed in the original study. Hydrogen consumption is lower, perhaps because the US cycle typically gives circa 10% better fuel consumption results. The greater degree of engine down-sizing assumed in original Step 7b, or 6H, should itself give more benefit, indicating perhaps that a Hydrogen hybrid has greater potential than originally estimated. However it is not possible to improve the prediction without a great deal of detailed simulation and / or hardware experience
- There is as yet no hard data on the impact of using Fuel Cell Auxiliary Power Units (FC-APUs) to supplement hybrid vehicles as suggested in the Hydrogen Priority route
- Claimed fuel consumption for Fuel Cell vehicles varies widely and is worse than the best level assumed for Step 8. Worse performance is likely to be due to higher weight and lower efficiency (step 8 assumed the benefit of further development up to 2030), the variation between vehicles may be due to varying degrees of hybridisation (energy storage) alongside the fuel cell, and differences in test cycle

In summary this data, which mostly become available only in the last year and was not used in the original study, provides excellent validation of the overall direction and CO_2 performance of the two evolutionary routes and of the updates proposed. It is much harder to validate price predictions as data rarely enters the public domain, and on-sale prices of image vehicles may not reflect true cost.

Data on the early steps suggest that some vehicles with more mainstream production intent will be on sale around the dates suggested in the Evolutions, with niche "image" vehicles already in the market in some cases. However, it is unlikely that the "5% market share for technology type" criterion originally proposed [1] will be met by these dates. The dates on the Evolutions have not been altered, but should be considered as the dates when the first "mainstream intent" products go on sale. If the technology is successful it may typically reach 5% of the market some 2-5 years later.

Step (Date)	**Technology** ***& Changes since 2002***	**Validation** **(With CO_2 impact relative to conventional car if known)**	**CO_2 performance - Well to wheel (Tank to wheel)**						**Cost, relative to Step 0 vehicle**		
			Oct 2002 Review *Assuming continuing emission legislation to Foresight targets*		**Oct 2003 Review** Assuming continuing emission legislation to Foresight targets		**Oct 2003 Review** Assuming Euro IV/V only		***Oct 2002 Review*** *(Prices corrected to 2003 value)*	**Oct 2003 Review** Assuming continuing emission legislation to Foresight 2020 targets	**Oct 2003 Review** Assuming Euro IV/V only
			CO_2 *g/km*	***% chg***	**CO_2** g/km	**% chg**	**CO_2** g/km	**% chg**	***Nominal Price % change***	***Nominal Price*** *(Range)* ***% change***	***Nominal Price*** *(Range)* ***% change***
0 (2003)	C/D segment car; c100ps Diesel engine	Seven vehicles currently on sale	***167*** *(149)*	-	**170** (152)	-	**170** (152)	-	*£15,752*	£15,157	£15,157
1 (2004)	12v stop-start	Two OEMs to launch petrol products 2004; Visteon SpeedStart **5%** claimed (Petrol)	***166*** *(148)*	**-1%** at Euro 4 **(3.6%** @ E3)	**163** (145)	**-4.2%** at Euro 4	**163** (145)	**-4.2%** at Euro 4	*£16,014* ***+1.7%***	£15,389 (£15,350-£15,400) **+1.5%**	£15,389 (£15,350-£15,400) **+1.5%**
2 (2007)	42v Belt Hybrid *Euro 4, more down-sizing*	'Hytrans' project announced Toyota Crown THS-M (non d/sized Gasoline) **15%+** benefit	***146*** *(130)*	**-13%** at Euro 5	**131** (117)	**-23%** at Euro 4	**131** (117)	**-23%** at Euro 4	*£16,941* ***+7.6%***	£16,041 (£15940-£16140) **+5.8%**	£16,041 (£15940-£16140) **+5.8%**
3 (2010)	42v Mild hybrid + Downsizing *Lower Euro 5 CO_2 penalty*	Renault Ellypse Concept (**85** g/km ttw, lighter, no LNT); Honda Civic IMA (144v) **26%;** Suzuki Twin (192v) **23%**	***114*** *(102)*	**-32%** at Euro 5	**112** (100)	**-34%** at Euro 5	**112** (100)	**-34%** at Euro 5	*£17,704* ***+12.4%***	£17,183 (£17,000-£17,350) **+13.3%**	£17,183 (£17,000-£17,350) **+13.3%**
4 (2012)	Full Parallel Hybrid *Improved batteries and motor, Euro 5*	Toyota Prius (Petrol) **104** g/km ttw; Ford Escape; Lexus RX300 upto **50%**	***103*** *(92)*	**-38%** at Euro 6	**93** (83)	**-45%** at Euro 5	**93** (83)	**-45%** at Euro 5	*£18,504* ***+17.5%***	£18,728 (£18,330-£19,130) **+23.5%**	£18,728 (£18,330-£19,130) **+23.5%**

Figure 12a: Validation and Data Comparison of Low Carbon steps 1-4

Step (Date)	Technology *& Changes since 2002*	Validation (With CO_2 impact relative to conventional car if known)	CO_2 performance - Well to wheel (Tank to wheel)						Cost, relative to Step 0 vehicle		
			Oct 2002 Review *Assuming continuing emission legislation to Foresight targets*		**Oct 2003 Review** Assuming continuing emission legislation to Foresight targets		**Oct 2003 Review** Assuming Euro IV/V only		***Oct 2002 Review*** *(Prices corrected to 2003 value)*	**Oct 2003 Review** Assuming continuing emission legislation to Foresight 2020 targets	**Oct 2003 Review** Assuming Euro IV/V only
			CO_2 *g/km*	***% chg***	**CO_2** g/km	**% chg**	**CO_2** g/km	**% chg**	***Nominal Price % change***	***Nominal Price*** *(Range)* ***% change***	***Nominal Price*** *(Range)* ***% change***
5 (2017)	*Parallel Hybrid + Exhaust Heat Recovery*	Toyota experimental device reduced CO_2 by 3%	*Not Applicable – old Step 5 replaced*		**88**	**-48%** at Euro 6	**86** (77)	**-49%** at Euro 5	*Not Applicable – old Step 5 replaced*	£18,965 (£18,470-£19,470) **+25.1%**	£18,840 (£18,340-£19,340) **+24.3%**
6	Step Deleted										
7 (2023)	*Parallel Hybrid + APU*	Work by Delphi / BMW & US DoE on APUs; no data available on this configuration	***106***	***-37%*** at Eu 7	**83**	**-51%** at Eu 7 (=Fore-sight)	**81**	**-52%** at Euro 5	£19,539 **+24.0%**	£19,468 (£19,150-£20,650) **+28.4%**	£19,318 (£19,000-£20,500) **+27.5%**
8 (2030)	Fuel Cell Series Hybrid	Honda FCX **1.05** Kg H_2 per 100km (US cycle); Toyota FCHV **0.97** Kg H_2 per 100km (Japan cycle); GM HyWire **1.45** Kg H_2 per 100km (US cycle)	***74-119*** *(0)*	***-56% - -29%*** *ZEV*	***74-119*** (0)	**-56% - -30%** ZEV	***74-119*** (0)	**-56% - -30%** ZEV	*£19,254* ***+22.2%***	£19,672 (£18,400-£21,400) **+29.7%**	£19,672 (£18,400-£21,400) **+29.7%**
			Hydrogen consumption **0.89 Kg H_2 per 100km (NEDC, Best Effy) 1.43 Kg H_2 per 100km** (worst)								

Figure 12b: Validation and Data Comparison of Low Carbon steps 5-8

Step (Date)	Technology *& Changes since 2002*	Validation **(With CO_2 impact relative to conventional car if known)**	**CO_2 performance - Well to wheel (Tank to wheel)**						**Cost, relative to Step 0 vehicle**		
			Oct 2002 Review *Assuming continuing emission legislation to Foresight targets*		**Oct 2003 Review** Assuming continuing emission legislation to Foresight targets		**Oct 2003 Review** Assuming Euro IV/V only		***Oct 2002 Review*** *(Prices corrected to 2003 value)*	**Oct 2003 Review** Assuming continuing emission legislation to Foresight 2020 targets	**Oct 2003 Review** Assuming Euro IV/V only
			CO_2* *g/km	***% chg***	**CO_2** g/km	**% chg**	**CO_2** g/km	**% chg**	***Nominal Price % change***	***Nominal Price*** *(Range)* ***% change***	***Nominal Price*** *(Range)* ***% change***
3H (2007)	H_2 Mild Hybrid	As LC Step 2	***189*** *(0)*	***+13 %*** *at Euro 5*	This has not been estimated separately for Hydrogen Priority as spark-ignited emission limits are considered less demanding relative to baseline		**189** (0)	**+11 %** *at Euro 5*	*£17,050* ***+8.2%***	This has not been estimated separately for Hydrogen Priority as spark-ignited emission limits are considered less demanding relative to baseline	£16297 (£16100-£16500) **+7.5%**
4H (2010)	H_2 Mild Hybrid	As LC Step 3	***154*** *(0)*	***-7.8%*** *at Euro 5*			**154** (0)	**-9.4%** at Euro 5	*£17,813* ***+13.1%***		£17,039 (£16,750-£17,350) **+12.4%**
5H (2012)	Mild Hybrid + Small APU *Greater APU efficiency*	As LC Step 3	***151*** *(0)*	***-10%*** at Euro 6			**147** (0)	**-14%** at Euro 5	*£18,224* ***+15.7%***		£17,439 (£17,100-£17,900) **+15.1%**
6H (2015)	H_2 IC engine Parallel Hybrid + APU *(Step 4LC improvemts, greater APU efficiency*	As LC step 4-6; plus Ford Model U Concept; Ford H[2]RV **1.38** Kg H_2 per 100km (US cycle, no APU)	***120*** *(0)*	***-28%*** *at Euro 7*			**107** (0)	**-37%** at Euro 5	*£19,709* ***+25.1%***		£19,434 (£18,900-£20,800) **+28.2%**
7H (2020)	Fuel Cell Series Hybrid	Honda FCX **1.05** Kg H_2 per 100km (US cycle); Toyota FCHV **0.97** Kg H_2 per 100km (Japan cycle); GM HyWire **1.45** Kg H_2 per 100km (US cycle)	***74-119*** *(0)*	***-56% - -29%*** *ZEV*			**74-119** (0)	**-56% - -30%** ZEV	*£19,852* ***+26.0%***		£20,073 (£18,800-£22,000) **+32.4%**
			Hydrogen consumption **0.89 Kg H_2 per 100km (NEDC, Best Effy) 1.43 Kg H_2 per 100km** (worst)								

Figure 13: Validation and Data Comparison of Hydrogen Priority steps 3H – 7H (Steps 1 & 2 as Low Carbon)

7 DISCUSSION AND CONCLUSIONS

The discussion and conclusions presented below are carried forward from the original study, with significant changes being highlighted in bold font.

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 updated and compared with the 2002 analysis. This section reviews the changes to both the updated routes 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.

7.1 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 14.

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 the update to the roadmap, the Low Carbon route is now not equalled by the Hydrogen Priority route until 2025-2030 for CO_2 (in the original study this equality occurred at circa 2020-2025) due to improvements made in Low Carbon steps 5 and 7.** The hydrogen priority route does, however, allow the use of hydrogen some sixteen years earlier so bringing with it a considerable advancement in the infrastructure, safety and customer education associated with hydrogen.

The well-to-wheel emission performance of Hydrogen Priority vehicles would improve with natural engineering developments 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 & Step 7H), in common with all the Hydrogen Priority IC engined vehicles, has the additional potential to become completely zero-carbon if renewably produced Hydrogen becomes available. Fuel Cell vehicles also have near-zero tailpipe emissions, unlike Low Carbon vehicles, though the air quality emissions of vehicles at Step 4 and beyond are at or lower than current Euro 4 Petrol standards, **and believed by many to be as low as required.**

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 due to the addition of Diesel Particulate Filters (DPF) and Lean NOx Traps (LNT).

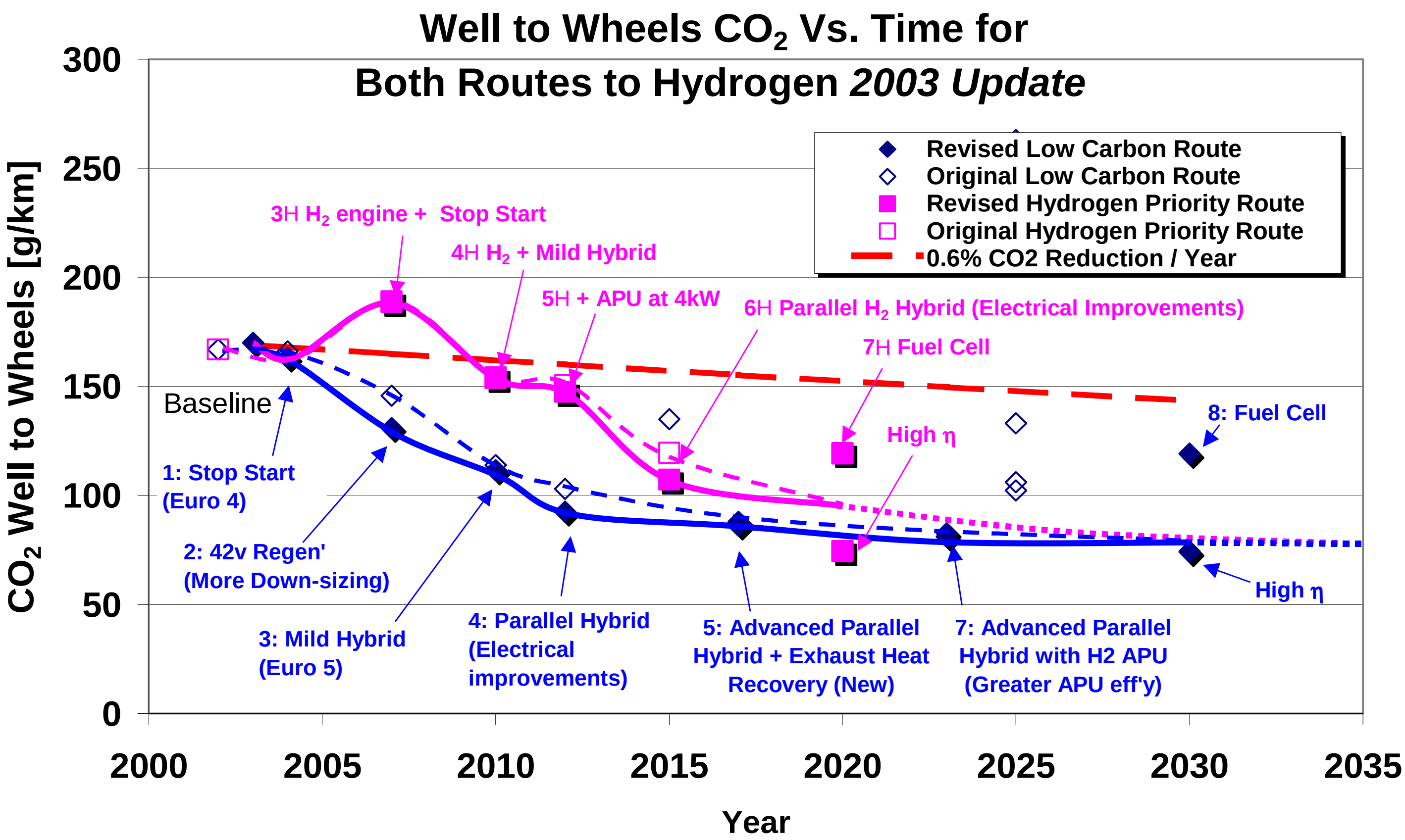


Figure 14: Well to Wheels CO_2 Vs. Time for the Low Carbon and Hydrogen Priority Roadmaps

7.2 Discussion - Low Carbon Route

The Low Carbon route (Section 4) develops currently emerging technologies such as stop start, engine downsizing, Mild Hybridisation and advanced Parallel Hybrids so that, by Step 4, Well to Wheels CO_2 of the best-in-class vehicle has been reduced by **45%, to 93g/km (or 83g/km Tank to Wheel), compared to Step 0. This is a significant advance on the 2002 assessment, which predicted a 38% reduction to 103 g/km (92 g/km Tank to Wheel), due to:**

- **Assumed improvements to motor and battery technology by that time, as already exemplified by the new Toyota Prius**
- **Revised and less pessimistic assumptions about the negative impact of emission control on** CO_2 **emission**

The 2003 projected cost of a Step 4 vehicle is also higher than in the 2002 report - £18,728 compared to £18,500 (in 2003 prices), due to small specification improvements and the correction of an error in the original estimate. But the consumer fuel saving also increases on the 2002 assessment, with fuel economy going up from 81mpg to 90mpg.

The estimate of the CO_2 emission reductions from the Step 1, 2 and 3 vehicles has also been revised upwards, as a result of revised emission control assumptions and increased use of down-sizing at step 2. The projected costs of these vehicles have been revised *downwards*, although the dominant effect here is the drop in list price of the baseline vehicle.

Up to Step 4, this Low Carbon evolution is likely to happen naturally, though at a slower pace, given a correct level of incentive, through 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.

As regards the possible progression beyond Step 4 (Parallel Diesel Hybrid), developments since the previous assessment suggest that the technological improvements set out in the updated Steps 5 and 7 (based on the previous Step 7c) develop this concept further. An exhaust heat recovery system is applied to the parallel hybrid vehicle in updated Step 5, which gives an estimated 3% improvement in fuel economy. This is a technology area that has not received much effort over the last ten years. However, the exhaust stream represents upwards of 30% of the fuel energy and so any recovery is beneficial. It is expected that these systems will improve in efficiency and effectiveness and may well be seen on some main stream vehicles by 2017 hence the inclusion in this road map.

Revised Step 7 (based on previous Step 7c) adds an advanced hydrogen burning fuel cell auxiliary power unit (APU) at 50% efficiency to the further improved diesel parallel hybrid. This increments the technology towards the fuel cell vehicle in another logical step whilst still improving the well to wheel CO_2 emissions, assuming the hydrogen used is from steam reformed natural gas. This step could be useful for manufacturers to explore and trial as part of their development of full Fuel Cell vehicles. This would also start to develop the Hydrogen infrastructure in a non-critical way, and also promote the Fuel Cell technologies, 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 from the technologies proposed in Steps 1-7 (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 **(possibly also revised Step 5 and 7, depending on progress on the key technologies involved, and level of component costs)**
- Promotion of these low-carbon technologies on a mass-market basis, with a view to 100% coverage of the car fleet by 2020-25

- **Consideration of exhaust heat recovery systems if the technology can be made robust, effective and cost efficient**
- Development and trailing 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, **Bio-fuels and other energy carriers** 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

7.3 Discussion - 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 14 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 and at greater system efficiency.

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 of the original report [1] 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.

7.4 Infrastructure and Alternative Fuels

Appendix C8 of the original report [1] presents issues associated with the Hydrogen infrastructure. **These issues do not appear to have changed over the past year, although there is growing recognition of their significance.** 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 of the original report [1]. 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. **Alternatively, liquid fuel blends with an increasingly sustainable biofuel content could prove worthy of exploration as they are highly compatible with today's vehicle and fuel distribution technology.**

7.5 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 an over-simplification - **a view which is increasingly taken by both the industry and policy-making bodies.** 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

7.6 Conclusions

The two routes toward mass-produced Hydrogen fuelled, Fuel Cell vehicles have been studied. **Despite many significant detail changes, major conclusions remain very similar to those presented in 2002:**

- 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. **An unprecedented level of new low carbon product introductions and concept demonstrations, combined with a re-appraisal of projected emission control impacts, has slightly improved the projected performance and lowered the expected price of some of these technologies.** 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 **of down-sized IC engines** 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 **trucks and** 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
- **Validation information suggests that the timescales presented are realistic for the first introductions of these technologies as mainstream products. A nominal threshold of 5% market penetration of each technology is however unlikely to be met by these dates, but will follow 2-5 years later if the technology is successful**

As demonstrated in Appendix D of the original report [1], 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
- **Study of the potential of information-enabled control technologies (based on GPS/map, radar, telematics and other information) to improve the benefits of low carbon technologies; and of how to assess real world benefits on a test cycle**

Medium Term:

- Further Hybrid system improvements especially energy-dense batteries or alternative devices, and better motor/generator and other system efficiencies
- **Exhaust heat recovery systems, using heat to create electricity, create mechanical power, or reform the fuel**
- 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
- **First generation information-enabled control systems using on-board data such as GPS/map and radar to improve the control of the powertrain**

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 highly effective energy recovery from waste heat
- **Second generation information-enabled control systems using vehicle-to-vehicle communications and telematics to improve the control of the powertrain**
- Potential for technology crossover from biotechnology, nanotechnology and other areas

APPENDIX A

Validation Data for Baseline and Evolutions

Several new vehicle launches impact on the composite baseline

RICARDO

- New Renault Megane launched earlier this year in UK
  - 120ps engine in place of old 100ps - both 1.9l
  - 100ps 1.5l due next year - down-sizing in action!
- Euro 4 Ford Mondeo Diesel launching now
  - Same power, 6-speed gearbox
- New Vauxhall Astra launched at Frankfurt show this month
  - New Euro 4 1.9 Diesel from Fiat-GM Powertrain venture
  - Smaller 1.7 Diesel available as Euro 3 or Euro 4 on outgoing model - Euro 4 at £400 premium
- New VW Golf also launched at Frankfurt
  - Upgraded Diesel range, again Euro 4
- Ford Focus, Renault Laguna, Vauxhall Vectra remain unchanged, but Euro 4 engines will arrive soon
- So far, none of these Euro 4 vehicles has a Diesel Particulate Filter (DPF) fitted
  - Original study assumed that they would, by Step 1
  - Opel (Vauxhall) and others showing systems at Frankfurt

 RD03/209501.1 Carbon to Hydrogen 23

Overall impact is not that great - 2003 baseline is slightly faster, thirstier, heavier and cheaper; some Euro 4 engines available

RICARDO

- Small differences in performance, weight and fuel consumption could be due to exact seven models chosen - probably not significant
  - Though recent trend is to faster, heavier, thirstier, cheaper cars…
- Price reduction may not be echoed in manufacturing cost

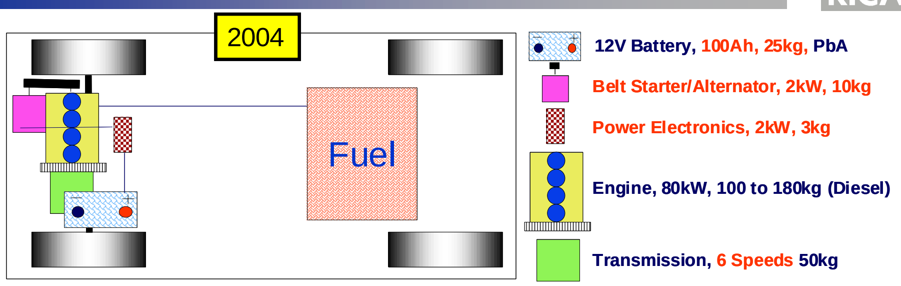
C & D Segment - DI European Vehicle Baseline				
		2002 Baseline	2003 Baseline	% Change
Engine		**1.9L**	**1.9L**	**1.9L**
Power (kW)		81	82	2%
Weight (kg)		1333	1351	1%
0->100kph (s)		12	11	-4%
Top Speed (km/h)		191	193	1%
Fuel Cons' (L/100km)	**Combined**	**5.5**	**5.6**	**1%**
	ECE	7.4	7.4	0%
	EUDC	4.5	4.5	1%
Emission level		E3	E3/4	E3/4
UK retail price (£) - 5dr h/back		£15,323	£15,157	-1%

 RD03/209501.1 Carbon to Hydrogen 24

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 Duratorq TDCi (115 PS)**	**2.0 DTI**	**2.0 DTI 16V**	**1.9 dCi**	**1.9 dCi 120**	**1.9 TDI**	**C+D Class**
Power (kW)		85	85	74	74	88	88	81	82
Weight (kg)		1293	1496	1320	1470	1270	1350	1260	1351
0->100kph (s)		10.7	10.8	12.0	12.0	10.5	10.7	11.3	11.1
Top Speed (km/h)		193	196	188	192	196	200	188	193
Fuel Cons' (L/100km)	Combined	**5.5**	**5.6**	**5.7**	**5.9**	**5.4**	**5.5**	**5.3**	**5.6**
	ECE	7.2	7.8	7.6	7.9	7.1	7.7	6.8	7.4
	EUDC	4.5	4.4	4.6	4.8	4.4	4.6	4.4	4.5
Emission level		E3	E3	E3	E3	E3	E3	E3	
Release date		Jul-01	??	??	??	2003	??	?	
Engine FIE technology		2nd Gen CR	2nd Gen CR	HP Rotary Pump	Direct Injection	CR	CR	PD unit inj	
UK retail price (£) - 5dr h/back		£14,600	£15,900	£14,300	£15,780	£14,100	£15,835	£15,585	£15,157

Step 1 technology is committed to European production in 2004, but not at 5% of the market

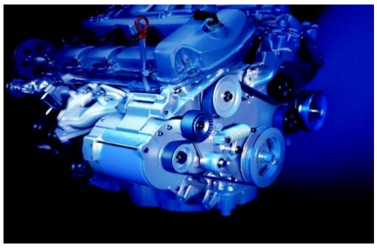
RICARDO

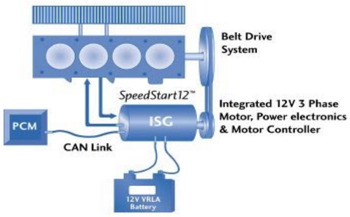


- **Two European OEMs expected to launch Step 1 Gasoline products in 2004**
  - No Diesel products yet - concern over cold start torque capability, and stop/start benefit is greater on a Gasoline car
- **Suppliers claiming much interest in 12v ISG** - including Diesel
- **New Bosch LI-X alternator range, to be made at Llantrisant, offer up to 76% efficiency, 3.8kW at 12v**
  - These are not starter-alternators, but the more efficient technology could boost the case for 12v stop/start devices
  - 5-6mpg benefit claimed (probably under optimum conditions, not NEDC)
- **5% volume criterion will not be achieved in 2004 - perhaps circa 2006-7?**

Visteon SpeedStart™ is an example of the state of the art - At least two other suppliers are working on similar technology

- **Visteon SpeedStart™**
  - Belt-driven ISG, 3kW, 12V
  - 5% fuel economy improvement claimed
  - 20% more efficient generation
  - Start-to-idle in 400 ms
  - Operates at -30°C





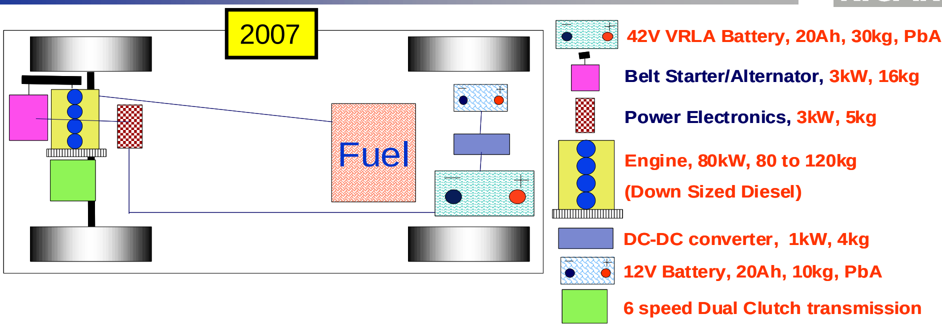
- Incorporates motor & power electronics in one unit
- Requires an upgraded belt system and battery
- Additional cost ~€150 (£103)
- Demonstrated in Ford Mondeo
- Available for production vehicle by 2005

- **Competing technologies include**
  - **Improved conventional starters** - similar 400ms start claimed, 20% the cost
  - **Direct-start Gasoline DI** - motorless start by firing fuel into cylinder & sparking

References: www.visteon.com, www.e4engineering.com, www.autoexpress.co.uk. Pictures from www.visteon.com

 RD03/209501.1 Carbon to Hydrogen 26

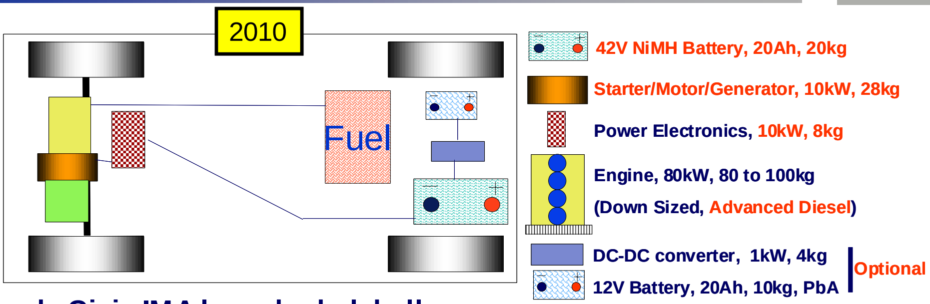
There is not yet commitment to Step 2 or 42v as a volume production reality, but supply base is preparing itself for 2007 introduction



- **HYTRANS (Hybrid Transit - Ford/Ricardo/Valeo/Gates) EST program to be announced using non-downsized engine and Step 2 technology**
- **Some European OEMs and suppliers considering first technology introduction 2007-9, focus shifting to Diesel vehicles**
  - Japanese Toyota Crown remains the only Step 2 vehicle, with gasoline engine
  - General industry consensus that 42v is "delayed", 12v OK for now
  - Power requirements of X-by-wire could help justify 42v: First 12v products now
- **Dual Clutch Transmission launching now on VW/Audi products**
- **First product may appear in 2007, 5% volume unlikely until circa 2010?**

 RD03/209501.1 Carbon to Hydrogen 27

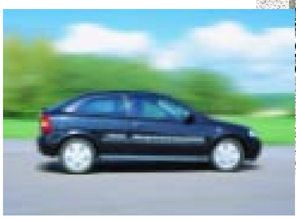
Step 3 type technologies are appearing on vehicles from Japan, but introduction is too far off to be visible on European volume product plans



- **Honda Civic IMA launched globally**
  - "Step 3 plus" with down-sized Gasoline engine, 10 kw motor and higher voltage
- **Suzuki Twin launched in Japan**
  - 2-seat microcar with 5kW 192v motor as supplement to gasoline engine
- **European supplier view on belt vs crank mounted ISG mixed**
  - 10kW, as used here, may become feasible with a belt device
- **Significant progress with Li-Ion batteries and Supercapacitors**
  - European research being directed away from NiMH
- **Step 3 Diesel products are probable by 2010, but not at 5% of the market**

Renault's Ellypse concept - like Ricardo's *i-MoGen* - demonstrates synergy of hybridisation and major down-sizing

- **Ellypse achieves outstanding fuel economy by**
  - **Much lower weight (25% less - 10% CO_2 gain?)**
  - **AMT transmission (5-10% CO_2 gain?)**
- **In practise, 2010 vehicle will probably have a driveable, efficient automated transmission, but won't be this light**
- **DPF and LNT not mentioned in Ellypse specification - could penalise CO_2 up to 3%?**



	Step 3 (2010)	***i-MoGen***	**Renault Ellypse**
Vehicle	C/D car	C car (Astra)	C segment concept
Weight	1332kg	1300kg	980kg
Engine	1.2l Diesel, E5, 80kW	1.2l Diesel, E4/5, 74kW	1.2l Diesel, 72kW
Transmission	6 speed DCT	5 speed manual	5 speed AMT
Hybrid System	42v FMED, 10kW	42v FMED, 6 kW	42v FMED, 12kW
Battery	20 Ah NiMH	14Ah NiMH	NiMH or Li-Ion?
CO_2 Tank-Wheel	102 g/km	105 g/km	85 g/km

References www.autointell.com/european companies/renault/renault-ellypse and www.lequotidienauto.com/mag/020819/renault-ellypse

Honda's Civic IMA uses hybridisation for torque assist with a downsized engine, which is a key Step 3 principle

	SE Executive	Diesel SE	IME SE Executive
Weight	1194kg	1315kg	1202kg
Engine	1.6 VTEC (gasoline) 81kW	1.7 Turbo (diesel) 74kW	1.3l VTEC (gasoline) 66kW
CO_2 Tank-Wheel	157g/km	134g/km	116 g/km
Price	£14,000	£14,000	£15,000

- **Civic IMA is a global product - hence Gasoline engine**
- **Unlike other UK Civics, available only as 4-door saloon**
  - Batteries positioned at front of the boot
- **Performance, economy and list price comparable to Diesel Civic**

	Step 3 (2010)	Honda Civic IMA
Vehicle	C/D car	C segment
Weight	1332kg	1202kg
Engine	1.2l Diesel, E5, 80kW	1.3l i-DSI VTEC Gasoline, 90PS
Transmission	6 speed DCT	5 speed manual (in US available with CVT)
Hybrid System	42v FMED, 10kW	IMA (FMED), 10kW
Battery	20 Ah NiMH	6.0 Ah 144V Ni-MH
CO_2 Tank-Wheel	102 g/km	116 g/km

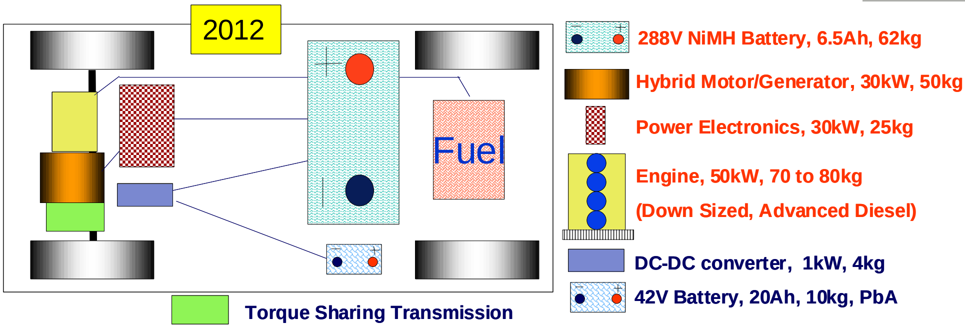
References www.honda.co.uk & Civic brochure

The Suzuki Twin city car uses hybridisation to enhance the performance and economy of the standard gasoline engine

- **Suzuki Twin**
  - 2-seater minicar (Japanese K model)
  - Launched in Japan, Jan 2003
  - Gasoline-hybrid option available
  - Suzuki plan to sell 200 units/month in UK – expect 10 units to be hybrids

		Suzuki Twin	Suzuki Twin Hybrid
Vehicle		A-segment (minicar)	A-segment (minicar)
Weight		560kg	730kg
Engine		0.66L 3-cyl Gasoline, 32kW	0.66L 3-cyl Gasoline, 32kW
Transmission		Manual / Automatic	Automatic
Hybrid System		---	FMED, 5kW
Battery		---	192V (16 x 12V batteries)
CO_2 Tank-Wheel		92 g/km (Japan 10-15)	70.4 g/km (Japan 10-15)
Cost	**Japan**	490k – 840k yen	1.29m – 1.39m yen
	UK (est)	£4,000	£7,500 (at higher spec?)

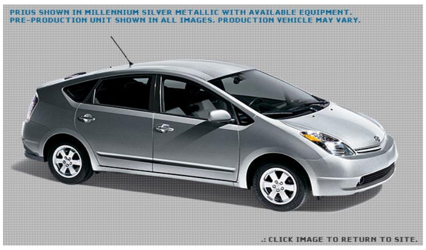
Full hybrids, equivalent to Step 4, remain the popular choice for image vehicles - including SUVs with electric 4x4



- **New generation Toyota Prius announced, just launched in Japan**
  - Significant improvements in performance, efficiency & load space
- **Ford Escape and Lexus RX300 SUV Hybrids announced, on sale 2004**
  - First production hybrid SUVs, Lexus uses electric 4x4
- **GM "Advanced Hybrid System" to debut in Saturn Vue, 2005**
  - Gasoline powered, two 20kW motors plus AMT (Ref Automotive Industries, February 2003)
- **Growing interest in performance-focussed full hybrids**
  - Often with electric 4x4, in segments where margins can absorb cost better

The new Toyota Prius is a significant step: The 5-door hatchback layout is key for Europe

- **All-new model launched 1st September in Japan**
  - 5-door hatchback body with split-fold rear seats
  - High voltage (500v) power electronics, 50% greater electric motor power
  - Increased engine power and vehicle performance



	Step 4 (2012)	**Prius** (2004 model)
Vehicle	C/D car	D car
Weight	1401kg	1308kg
Engine	1.0l Diesel, Euro 6, 50kW	1.5l Gasoline, PZEV, 58kW
Hybrid System	288v powersplit, 30kW	500v powersplit, 50kW
Battery	6.5 Ah NiMH	NiMH, 21kW max output
0-100km/h	11.7 sec	TBC
CO_2 Tank to Wheels	92 g/km (NEDC)	67.5 g/km (Japan 10-15) (Old Prius 114 g/km NEDC)
Boot volume	350-500 litres	263 litres (TBC)

References www.toyota.com/prius; www.toyota.co.jp/Irweb/corp_info/pr/2003/0901.html; www.priusview.com

The Ford Escape and Lexus RX300 Hybrids address SUV fuel consumption concerns, CO_2 benefits up to 50% claimed over baseline

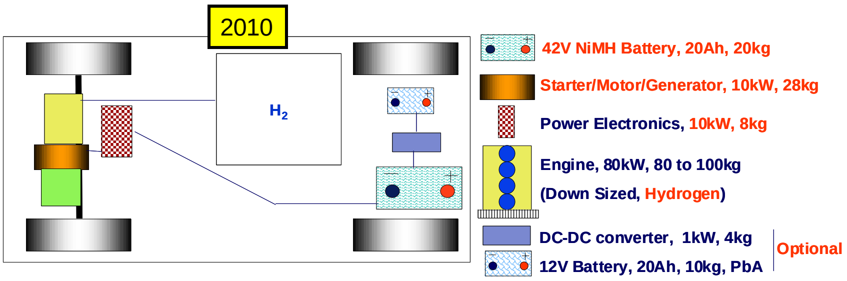
- **Benefits of hybrid SUVs:**
  - Additional cost of hybrid system is smaller proportion of total
  - Potential for more dramatic fuel consumption improvement
  - In U.S. gasoline-electric hybrid considered alternative to diesel
- **New hybrid SUVs:**
  - Ford to launch Escape SUV hybrid in USA, summer 2004
  - Lexus to launch Lexus RX300/RX330 SUV hybrid, 2004 / 2005
  - Hybrid pickups expected from GM & Chrysler

	Ford Escape Hybrid (2004)	Lexus RX300 Hybrid (2004)
Vehicle	SUV	SUV
Weight	1436kg	TBC
Engine	2.0L I4 Gasoline, 95kW	3.3L V6 Gasoline, 172kW
Hybrid System	Parallel Hybrid, Mech 4x4 (65kW motor, 28Kw generator)	Hybrid Synergy Drive Series-Parallel, electric 4x4
Battery	300V NiMH	TBC
0-100km/h	est 8.9 sec	est 7.5 sec
CO_2 Tank to Wheels	est 140-160g/km (city)	est <200g/km

Sources: http://www.startribune.com/stories/432/4018016.html; http://www.lexusownersclub.co.uk/articles/publish/article_97.shtml
http://www.auto123.com/en/info/news/news.view.spy?artid=13635; http://www.gizmo.com.au/public/News/news.asp?articleid=1669
http://www.infomotori.com/a_165_IT_2178_2.html; http://www.conceptcarz.com/folder/vehicle.asp?car_id=6706
http://www.geocities.com/escape_hybrid; http://www.autosdesign.com/ford-escape.htm
http://www.ford.com/en/vehicles/autoShows/detroit2002/vehicles/ford/fordEscapeHEV/default.htm

 RD03/209501.1 Carbon to Hydrogen 37

The idea of combining a hydrogen IC engine with hybrid technology (Steps 7b & 3H to 6H) is gain-ing momentum as a stepping stone to fuel cells



Step 4H illustrated

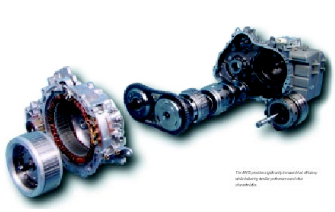
- **Ford "Model U" and "H²RV" concept cars combine supercharged Hydrogen engine with "Step 4" Hybrid technology**
- **Ford and Ballard have announced a Hydrogen IC engine for Gensets**
- **BMW continue to vigorously promote the Hydrogen IC engine**
- **Mazda have announced Hydrogen rotary-engine concept based on their new RX8 sportscar**
- **GM and DC abandoning onboard reformer technology for fuel cell cars**
  - Implication is that Hydrogen will be available before the Fuel Cell - as an IC engine fuel

 References www.media.ford.com
RD03/209501.1 Carbon to Hydrogen 41

Ford's "Model U" and "H^2RV" concepts illustrate a pragmatic approach to using Hydrogen before the Fuel Cell achieves commercial viability



Modular Hybrid Transmission System



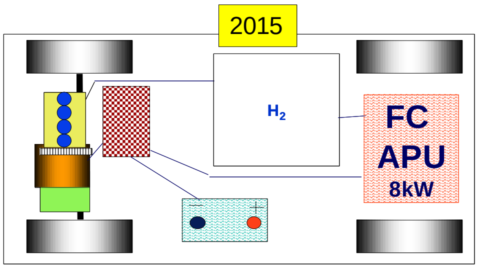
- **Both cars use same combination of Hydrogen engine and "Modular Hybrid Transmission System"**
  - H^2RV is a driveable vehicle in a Ford Focus Estate body; Model U is a show car
  - Modular Hybrid Transmission System is as used in 2004 Escape Hybrid SUV
  - Ford claim better NOx performance from engine than suggested by Ricardo

	Step 7b (2020-25)	**H^2RV** (2003 prototype)
Vehicle	C/D car	Ford Focus Estate
Weight	1441kg	1548 kg
Engine	1.2l Hydrogen, Euro 7, 80kW	2.3l Hydrogen, PZEV, 82kW
Hybrid System	288v powersplit, 30kW	288v clutched ISG, 25kW
Battery	6.5 Ah NiMH	3.6 Ah Li-Ion
0-100km/h	11.7 sec	11.0 sec (0-60)
Kg H_2 per 100km	1.60 (NEDC)	1.38 (US "MH")

References www.media.ford.com (/print.doc.cfm?article_id=14047 & /print.doc.cfm?article_id=16082)

 RD03/209501.1 Carbon to Hydrogen 42

Others are embracing the concept of the fuel cell as an APU (as in steps 7C, 4H to 6H) using either Hydrogen or liquid fuels



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

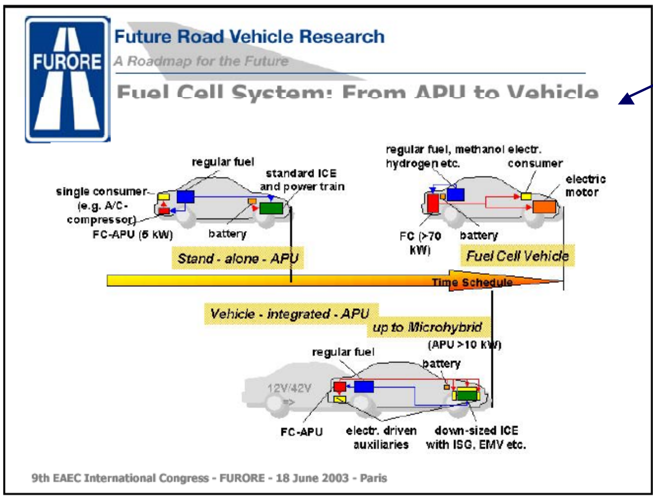
Reduces IC engine loads & enables ancillaries to run with it stopped

Torque Sharing Transmission

- **APU powers the vehicle while the engine is shut down, and extends its range as an urban-speed ZEV**
  - But the vehicle operates without it, allaying reliability fears and allowing it to be sold as an option at high margin
- **US Government research promoting use of fuel cells as APUs**
  - Initially in trucks to avoid engine idling for cab comfort, load refrigeration etc
- **Delphi / BMW collaboration promoting APU as anything from an engine-off alternator substitute to a hybrid range extender as in steps 4H to 6H**
  - Solid Oxide (SOFC) type - reforms Gasoline or Diesel, 50%+ efficient, sulphur tolerant
- **Boeing claim they will flight test a 440kW aircraft fuel cell APU next year**

 RD03/209501.1 Carbon to Hydrogen 43

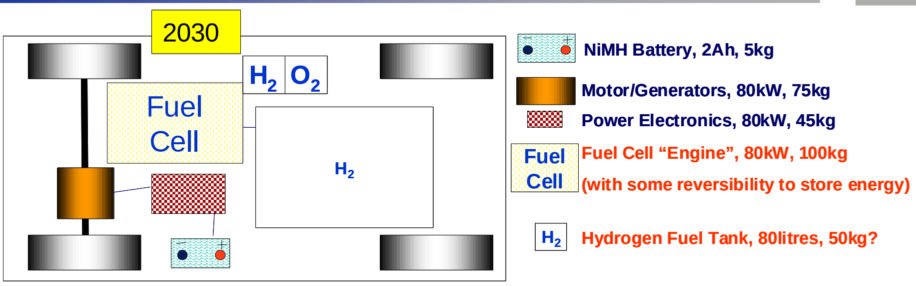
The FURORE roadmap shows liquid-fuel APUs being used with hybridised engines; The Delphi / BMW unit supplies on-board electricity needs



- **FURORE:** These concepts were not the result of Ricardo input to the FURORE project

- **BMW / Delphi: Packaged demonstrator (42v, circa 3-5kW target) shown in 2001**
  - No information available on further developments

The Fuel Cell car (Step 8 & 7H) is no nearer to volume production - but two are in the market, and interesting concepts continue to appear



- **50 Toyota and Honda vehicles on lease in Los Angeles and Tokyo**
- **Mercedes Citaro Fuel Cell busses entering service in Europe**
- **GM "HyWire" concept car shows how the vehicle structure and electronic architecture needs to evolve along with the powertrain**
- **Ford Fuel Cell Hybrid prototype packages the technology in a standard Focus**
  - Five will be trialled in Vancouver over the next 3 years
- **GM and DC now focussing efforts on direct hydrogen fuel cells, not on-board reformers**
  - Reformers add cost, weight & complexity, have poorer W2W performance
  - Implication is that fuel cell arrives in volume market after Hydrogen

These first vehicles offer acceptable range and utility, but not commercial viability

- Both vehicles are now homologated in Japan and the USA
- Both are being leased, in Tokyo and Los Angeles
- Both use 350 bar compressed Hydrogen, available in these two cities

- 30 Hondas and 20 Toyotas available
- The Toyota costs £6000/month to lease!

	Step 8 (2030)	**Honda FCX**	**Toyota FCHV**
Vehicle	C/D car	B car	SUV
Weight	1468kg	1684 kg	1860 kg
Fuel Cell	80kW PEM	78kW PEM	90kW PEM
Hybrid Storage	Via reversibility	Ultracapacitors	NiMH Batteries
0-100km/h	11.7 sec	---	12.8 sec
Kg H_2 per 100km	0.89 (NEDC best η)	1.05 (US FTP)	0.97 (Japan 10-15?)
Range	500km+	355km	300km

References www.hondacorporate.com/fcx; www.toyota.com/about/environment/technology/fuelcell_hybrid.html; www.toyota.com/shop/look_ahead/fchv.html

Ultimately, fuel cell technology can be synergistic with future vehicle design

- **GM's Hy-Wire concept** integrates:
  - **Hydrogen fuel cell**
  - **Flexible common platform**
  - **Steer & brake-by-wire**
    - All of which could move to high volume production in the 2020-2030 period

	Step 8 (2030)	**GM HyWire**
Vehicle	C/D car	D car
Weight	1468kg	1900 kg
Fuel Cell	80kW PEM	94kW PEM
Hybrid Storage	Via reversibility	Batteries
0-100km/h	11.7 sec	16 sec
Kg H_2 per 100km	0.89 (NEDC best η)	1.45 (EPA)*
Range	500km+	500km

* = Estimate based on claimed 41 miles / US Gallon Gasoline equivalent, ratioed by Calorific Value

References: www.gm.com/company/gm_exp_live/events/paris_2002/gm/hywire; http://www.fuelcells.org/fct/carchart.pdf; http://www.gm.com/company/gmability/environment/road_to_future/adv_tech_vehicles/future_fuel_cells/ http://www.motortrend.com/future/concepts/112_0304_first_hyw/; http://www.azcentral.com/class/marketplace/cars/0206hy-wire06.html

Appendix B
Updated calculations for both routes

DfT Study Results	Low Carbon Route	Step 1 Stop Start Vehicle 2004	Version 2
Topic	**Data**	**Comment**	**Source**
Step:	**1**		
Principal Technologies:	Stop start (belt starter/alternator) + 6 spd transmission		
Emissions Achievements:	**Euro 4 (2004)**		
Emissions Technologies used	Particulate filters **NOT Required** for Euro 4		
CO_2 improvement breakdown:		**Changes - Removed DPF and LNT bars RLG 19/09/03**	
Starting point (g/km CO2):	152	g/km	
Engine Evolution Improvements	-0.6%	General improvements - See report (-0.6%/year)	2
Stop Start over EUDC from 60°C eng temp	-3.6%	Average of Ricardo measured data (C and D class)	0
6 speed manual transmission	0.0%	No effects from 6 speed transmission as change points are forced	3
Total *Scenario* CO_2 reduction	**-4.2%**	**%**	
Final Vehicle Cycle CO_2	**146**	**g/km**	
Well to Wheels CO_2	**163**	**g/km - DIESEL**	
Vehicle Weight Change:	(-ve = reduction)	**Changes - Removed DPF and LNT bars RLG 19/09/03**	
Starting Point	1351	kg	
Engine weight Improvements	0.00%	Not significant at this time	0
Stop Start over EUDC from 60°C eng temp	0.60%	Removal of starter and alternator, addition of machine and electronics	4, 5
6 speed manual transmission	0.41%	5.5kg heavier on average	6
Expected vehicle body weight change	0.00%	Weight neutral	0
Total Step 1 Vehicle Weight Impact:	**1.01%**	**%**	
Total Vehicle Weight:	**1,365**	**kg**	
Effect on Handling	None	Weight distribution unchanged	
Effect on Packaging	Small increase in complexity and thermal management	Power electronics need careful cooling	
Effect on Maintenance and Reliability	None	None	
Effect on Passenger and Pedestrian Safety	None	None	
Cost Change:	(-ve = reduction)	**Changes - Reduced Powertrain cost reduction period to 1 year RLG 19/09/03**	
Starting Point	£15,157		
Powertrain Cost Reduction Evolution Improvements	-0.75%	Powertrain only cost reduction: 0.75% per year	2
Stop Start over EUDC from 60°C eng temp	1.76%	+£134 for change from traditional comp'ts to belt mach. (*1.5 sales ratio)	7
6 speed manual transmission	0.52%	+£80	0
Total Retail Price Impact (2002 £ value):	**1.53%**		
Total Vehicle Retail Price (2002 £ value):	**£15,389**	**£**	

DfT Study Results	Low Carbon Route	Step 2 Stop Start + Regen Vehicle 2007	Version 2
Topic	Data	Comment	Source
Step:	2		
Principal Technologies:	Step 1 + regen braking, new battery, 42V AMT2		
Emissions Achievements:	Euro 4 (2008)		
Emissions Technologies used	Particulate filters NOT Required for Euro 4		
CO_2 improvement breakdown:		Changes - No Aftertreatment for E4 RLG 19/09/03 and high down size ratio	
Starting point (g/km CO2):	146	g/km	
Engine Evolution Improvements	-1.8%	General improvements - See report (-0.6%/year)	2
Down size engine (Ratio of 0.8)	-10.0%	2.0 to 1.6 litres (Fuel Cconsumption ratio from i-MoGen)	0
3kW Regeneration over drive cycle	-3.0%	Ratio of i-MoGen data	0
6 speed DUAL CLUTCH transmission	-5.0%	Power shifting and auto but without the losses (data from Renault)	
Total *Scenario* CO_2 reduction	-19.8%	%	
Final Vehicle Cycle CO_2	117	g/km	
Well to Wheels CO_2	131	g/km - DIESEL	
Vehicle Weight Change:	(-ve = reduction)	Changes - No Aftertreatment for E4 RLG 19/09/03	
Starting Point	1365	kg	
Down size engine (Ratio of 0.8)	-2.93%	-40kg (22% engine weight)	0
42V 3kW Regeneration over drive cycle plus DC-DC converter, new bat tech	-0.07%	Upgraded belt machine +2kg, pow. elec. +4kg, smaller new batt. -7kg	0, 11
6 speed DUAL CLUTCH transmission	1.54%	Some increase in hardware complexity (+21kg)	0, 6
Further LNT developments	0.00%	No hardware changes	0
General Vehicle Development	0.00%	Vehicle changes are weight neutral at this time	0
Total Step 1 Vehicle Weight Impact:	-1.47%	%	
Total Vehicle Weight:	1,345	kg	
Effect on Handling	None	Weight distribution unchanged	
Effect on Packaging		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)	Changes - No Aftertreatment for E4 RLG 19/09/03	
Starting Point	£15,389		
Powertrain Cost Reduction Evolution Improvements	0.00%	Cost reduction deleted due to significant new technology introduction	0
Down size engine (Ratio of 0.9)	0.00%	Savings in material weight usualy balance higher tech. components	0
3kW Regeneration over drive cycle	1.65%	+£30 for motor, +£64 for pow. elec., +£75 for batt. (*1.5 sales ratio)	0, 7, 11
6 speed DUAL CLUTCH transmission	2.59%	£266 extra (*1.5 sales ratio)	8, 9
Total Retail Price Impact (2002 £ value):	4.24%		
Total Vehicle Retail Price (2002 £ value):	£16,041	£	

DfT Study Results	Low Carbon Route	Step 3 Mild Hybrid + DOWNSIZE 2010	Version 2
Topic	Data	Comment	Source
Step:	3		
Principal Technologies:	Step 2 + significant downsized engine + NiMH bat + 10kW motor		
Emissions Achievements:	Euro 5 (=E4 Gasoline) (2010 onwards)		
Emissions Technologies used	Particulate filter and Lean NOx trap		
CO_2 improvement breakdown:			
Starting point (g/km CO2):	117	g/km	
		Changes - Down size ratio RLG 19/09/03	
Engine Evolution Improvements	-1.8%	General improvements - See report (-0.6%/year)	2
Down size engine to 1.2 litres + Intelligent cooling (0.75 ratio)	-10.0%	1.6 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%	Increased recovery from 3 to 10kW (ratio'ed from i-MoGen data)	0
add hardware and engine calibration for LNT and DPF	2.0%	To achieve gasoline Euro 4 emissions (Ricardo Estimate)	0
Total *Scenario* CO_2 reduction	-14.8%	%	
Final Vehicle Cycle CO_2	99	g/km	
Well to Wheels CO_2	112	g/km - DIESEL	
Vehicle Weight Change:	(-ve = reduction)		
Starting Point	1345	kg	
		Changes - Down size ratio RLG 19/09/03	
Down size engine to 1.2 litres + Intelligent cooling (0.75 ratio)	-2.97%	-40kg (28% of 1.6 litre engine weight)	0
42V 10kW motor and regeneration over drive cycle plus DC-DC converter	0.89%	Upgraded belt machine +19kg, pow. elec. +3kg, smaller new batt. -10kg	0, 4, 11
add hardware for LNT and DPF	0.74%	+10 kg for small LNT and DPF	0
Total Step 1 Vehicle Weight Impact:	-1.34%	%	
Total Vehicle Weight:	1,327	kg	
Effect on Handling	None	Weight distribution unchanged	
Effect on Packaging	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		
Effect on Passenger and Pedestrian Safety	Packaging may change crash and pedestrian crash performance	None	
Cost Change:	(-ve = reduction)		
Starting Point	£16,041		
Powertrain Cost Reduction Evolution Improvements	0.00%	Cost reduction deleted due to significant new technology introduction	0
Down size engine to 1.2 litres + Intelligent cooling	0.62%	+£100 for intelligent cooling and high downsizing	0
42V 10kW motor and regeneration over drive cycle plus DC-DC converter	4.00%	+£30 for motor, +£48 for pow. elec., +£350 for battery (*1.5 sales ratio)	0, 7, 11
add hardware for LNT and DPF	2.49%	£400 for LNT and DPF system in MASS PRODUCTION ONLY	0
Total Retail Price Impact (2002 £ value):	7.12%		
Total Vehicle Retail Price (2002 £ value):	£17,183	£	

DfT Study Results	Low Carbon Route	Step 4 Parallel Hybrid + Advanced Diesel 2012	Version 2
Topic	**Data**	**Comment**	**Source**
Step:	**4**		
Principal Technologies:	Parallel hybrid - small diesel engine + LiION battery + 40kW motor		
Emissions Achievements:	**Euro 5 (=E4 Gasoline) (2010 onwards)**		
Emissions Technologies used	**Particulate filter and Lean NOx trap from Step 3**		
CO_2 improvement breakdown:		Changed % recovered from regen to 8% as increase motor power to 40kW also, Li-ION battery	
Starting point (g/km CO2):	99	g/km	
1.0 litre diesel downsizing	-4.0%	From ratio of i-MoGen downsizing	0
operating engine at optimum range using hybrid functions	-5.0%	Estimation from engine maps and published improvements	0
Regen braking, 300V, 40kW motor and generator plus DC-DC converter	-8.0%	Increased recovery from 10 to 40kW (ratio'ed from published discussion)	0
Total *Scenario* CO_2 reduction	**-17.0%**	%	
Final Vehicle Cycle CO_2	**83**	g/km	
Well to Wheels CO_2	**93**	g/km - DIESEL	
Vehicle Weight Change:	(-ve = reduction)		
Starting Point	1327	kg	
1.0 litre diesel downsizing	-0.79%	-10.5kg from 1.2 litre engine (8.7% of 1.2 litre engine weight)	0
Regen braking, 300V, 40kW motor and generator plus DC-DC converter	3.92%	-28+40kg for motor, +40kg for gen, similar pow. elec., similar trans.	12
Battery	0.98%	replace 20kg battery with 33kg of NiMH battery	11
Total Step 1 Vehicle Weight Impact:	**4.11%**	%	
Total Vehicle Weight:	**1,381**	kg	
Effect on Handling	Weight distribution may change - could improve handling	Weight distribution unchanged	
Effect on Packaging	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		
Effect on Passenger and Pedestrian Safety	Packaging may change crash and pedestrian crash performance	None	
Cost Change:	(-ve = reduction)		
Starting Point	£17,183		
1.0 litre diesel downsizing	0.58%	+£100 for high tech engine materials and small turbocharger	0
Regen braking, 300V, 40kW motor and generator plus DC-DC converter	7.05%	+£323 for motor, +£485 for electronics (*1.5 sales ratio)	10, 12
Battery	1.35%	+£155 for battery by 2012, Li-ION is at $360/kWh (same as NiMH)	11
Total Retail Price Impact (2002 £ value):	**8.99%**		
Total Vehicle Retail Price (2002 £ value):	**£18,728**	£	

DfT Study Results	Low Carbon Route		Step 5b Par'll Hybrid + Adv' Diesel + Heat Recovery 2017	Version 2
Topic	**Data**	**Data**	**Comment**	**Source**
Step:	**5b**	**5b**		
Principal Technologies:	Parallel hybrid - small diesel engine + LilON battery + 40kW motor	Parallel hybrid - small diesel engine + LilON battery + 40kW motor		
Emissions Achievements:	**Euro 5 (=E4 Gasoline) (2010 onwards)**	**Euro 6 (2015 onwards)**		
Emissions Technologies used	Particulate filter and Lean NOx trap from Step 3	Enhanced Particulate filter and Lean NOx trap		
CO_2 improvement breakdown:			Changed to add waste heat recovery at 3% efficiency improvement also, improved Li-ION battery and reduced cost	
Starting point (g/km CO2):	83	83	g/km	
Improve engine efficiency and control strategy	-2.0%	-2.0%	From natural improvements	0
Addition of a waste heat recovery system (thermocycle)	-3.0%	-3.0%	Adjusted from Toyota work SAE 930880	0
Improve battery for greater energy recovery	-2.0%	-2.0%	Suggesting battery and motor improvements	0
Lower Emissions		2.0%	emissions improvement from retard and improved LNT	
Total *Scenario* CO_2 reduction	**-7.0%**	**-5.0%**	%	
Final Vehicle Cycle CO_2	**77**	**78**	g/km	
Well to Wheels CO_2	**86**	**88**	g/km - DIESEL	
Vehicle Weight Change:	(-ve = reduction)	(-ve = reduction)		
Starting Point	1381	1381	kg	
Improve engine efficiency and control strategy	0.00%	0.00%	No change	0
Addition of a waste heat recovery system (thermocycle)	0.72%	0.72%	add 10 kg (Ricardo Estimate)	12
Improve battery for greater energy recovery	0.00%	0.00%	No change	11
Lower Emissions			No Change	
Total Step 1 Vehicle Weight Impact:	**0.72%**	**0.72%**	%	
Total Vehicle Weight:	**1,391**	**1,391**	kg	
Effect on Handling			Weight distribution unchanged	
Effect on Packaging			Power electronics need careful cooling	
Effect on Maintenance and Reliability				
Effect on Passenger and Pedestrian Safety			None	
Cost Change:	(-ve = reduction)	(-ve = reduction)		
Starting Point	£18,728	£18,728		
Improve engine efficiency and control strategy	0.00%	0.00%	No change	0
Addition of a waste heat recovery system (thermocycle)	0.80%	0.80%	Ricardo estimation of £150	
Improve battery for greater energy recovery	-0.20%	-0.20%	reduction of 5% of battery cost (£38) due to technology improvements and volume	0
Lower Emissions		0.67%	Increased catalyst loading (£50) + NOx sensor(£75)	0
Total Retail Price Impact (2002 £ value):	**0.60%**	**1.27%**		
Total Vehicle Retail Price (2002 £ value):	**£18,840**	**£18,965**	£	

Low Carbon Route	Step 7 Fuel Cell Vehicle 2030	RLG 11 Sept 02 & Oct 03	Version 2	Version 2	
		Comment	Source	Comment	Source
7 - Fuel Cell Vehicle	7 - Fuel Cell Vehicle				
Series hybrid with Fuel Cell Vehicle	Series hybrid Fuel Cell Vehicle WITH FUTURE ELECTRICAL Sys EFFICIENCIES				
45% efficient fuel cell system	53% Fuel Cell System + Higher Efficiency Motors etc.				
		Changes - Starting point retained from Previous C2H Results		e waste heat recovery and add APU	
See Report for Series Hybrid Method	See Report for Series Hybrid Method				
(81)	(81)	g/km (From Series Hydrogen Hybrid (Old Step 7))		ed in APU calculations	0
47%	-9%	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	J is 50% efficient on H2 total system s improvements limiting economy	0 0
47%	-9%	%			
119	74	g/km (47% to 53% better than the 2001 MY baseline vehicle if H_2 from Nat Gas)			
(-ve = reduction)	(-ve = reduction)				
1496	1496	kg			
-1.87%	-1.87%	-60kg for Diesel eng., +140kg for Fuel Cell system (40kW), -40kg for gen.	0, 12, 15	-10 kg tank + 90kg for 7kg of Hydrogen storage APU (96 Wh/kg specific energy density)	0 14 11, 0
-1.87%	-1.87%	%			
1,468	1,468	kg			
Weight distribution may change - could improve handling	Weight distribution may change - could improve handling				
Reversible Fuel Cell system is small but complicated to package	Reversible Fuel Cell system is small but complicated to package				
Fuel Cell System Introduction would require considerable training	Fuel Cell System Introduction would require considerable training				
Packaging may change crash and pedestrian crash performance	Packaging may change crash and pedestrian crash performance				
(-ve = reduction)	(-ve = reduction)				
£19,318	£19,318			-150 commended price for fuel cell system by 2010	0
1.83%	1.83%	-£500 for removal of gen., +£2000 for Fuel Cell at £50/kW (40kW), -£933 for H2 engine, - £2000 for RFC	0, 12, 15 0	£366 for H_2 storage	15
1.83%	1.83%				
£19,672	£19,672	£			

Price Sensitivity Calc

£/kW	40kW	Car Price
50	2000	19672
25	1000	18672
100	4000	21672

DfT Study Results	Hydrogen Priority Route	Step 3H H_2 Powered Stop Start + Regen Vehicle 2007	Version 2 - RLG 29 Sept 03
Topic	**Data**	**Comment**	**Source**
Step:	**3H**		
Principal Technologies:	Step 2 (from Low Carbon Route) + H2 engine and tank		
Emissions Achievements:	**Euro 4**		
Emissions Technologies used			
CO_2 improvement breakdown:		Updated to represent no change in actual starting point for powertrain No Other Changes	
Starting point (g/km CO2) (WELL TO WHEELS)	131	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***	44.0%	1.8 litre Hydrogen engine from 1.6 Diesel engine without DPF add 5% due to diesel engine improvements that do not carry over	0
Total *Scenario* CO_2 Impact (-ve is reduction)	**44.0%**	%	
Well to Wheels CO_2	**189**	**g/km - (Hydrogen from Natural Gas)**	
Vehicle Weight Change:	(-ve = reduction)		
Starting Point	1345	kg	
H_2 engine - down sized compaired to NA gasoline engine (Ratio of 0.9) H2 from ***Natural Gas***	0.30%	-14kg (134kg Diesel to 120kg 1.8 turbo hydrogen) + Baseline vehicle weight increase (18)	0
H2 Tank	5.95%	-10kg for diesel tank + 90kg for H2 tank (inc 7kg H2)	5
Total Step 1 Vehicle Weight Impact:	**6.25%**	%	
Total Vehicle Weight:	**1,429**	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: LC Step 2 but with old aftertreatment	£16,191		
H_2 engine - down sized compaired to NA gasoline engine (Ratio of 0.9) H2 from ***Natural Gas***	-1.61%	From diesel to Hydrogen	0
H2 Tank	2.26%	+£366 for H2 storage	6
Total Retail Price Impact (2003 £ value):	**0.65%**		
Total Vehicle Retail Price (2003 £ value):	**£16,297**	£	

DfT Study Results	Hydrogen Priority Route	Step 4H H_2 Mild Hybrid Vehicle 2010	Version 2 - RLG 29 Sept 03
Topic	**Data**	**Comment**	**Source**
Step:	**4H**		
Principal Technologies:	Step 3 H2 Priority + 10kW electrical machine		
Emissions Achievements:	**Euro 5**		
Emissions Technologies used			
CO_2 improvement breakdown:		No Change	
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	1429	kg	
Downsize H_2 engine to 1.1 litres + intelligen cooling	-2.10%	1.8 turbo hydrogen replaced by to 1.1 litre Hydrogen	0
42V 10kW motor and regeneration over drive cycle plus DC-DC converter	0.84%	-10kg for Diesel tank + 90kg for H2 tank (inc 7kg H2)	5
Total Step 1 Vehicle Weight Impact:	**-1.26%**	%	
Total Vehicle Weight:	**1,411**	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	£16,297		
Downsize H_2 engine to 1.1 litres	0.61%	Cost increase of £100 for intelligent cooling and high downsizing	0
42V 10kW motor and regeneration over drive cycle plus DC-DC converter	3.94%	+£30 for motor, +£48 for power electronics, +£350 for battery (*1.5 sales ratio)	1, 2, 3
Total Retail Price Impact (2003 £ value):	**4.55%**		
Total Vehicle Retail Price (2003 £ value):	**£17,039**	£	

DfT Study Results	Hydrogen Priority Route	Step 5H Mild Hybrid with Small Fuel Cell APU 2012	Version 2 - RLG 29 Sept 03
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:		Updated APU Efficiency to 50%	
Starting point (g/km CO2) (WELL TO WHEELS)	154	g/km CO_2 (Well to Wheels)	
4kW Fuel Cell Auxillary Power Unit	-4.1%	Fuel Cell APU provides 750W to the powertrain over the drive cycle	0, 9, 10
Total *Scenario* CO_2 Impact (-ve is reduction)	**-4.1%**	%	
Well to Wheels CO_2	**147**	g/km - (Hydrogen from Natural Gas)	
Vehicle Weight Change:	(-ve = reduction)		
Starting Point	1411	kg	
4kW Fuel Cell Auxillary Power Unit	2.83%	40kg increase at 0.1kW/kg for APU system	8
Total Step 1 Vehicle Weight Impact:	**2.83%**	%	
Total Vehicle Weight:	**1,451**	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	£17,039		
4kW Fuel Cell Auxillary Power Unit	2.35%	Cost increase of £400 for 4kW APU	0, 8
Total Retail Price Impact (2003 £ value):	**2.35%**		
Total Vehicle Retail Price (2003 £ value):	**£17,439**	£	

DfT Study Results	Hydrogen Priority Route	Step 6H Parallel Hybrid with 8kW Fuel Cell APU 2015	Version 2 - RLG 29 Sept 03
Topic	**Data**	**Comment**	**Source**
Step:	**6H**		
Principal Technologies:	Step 5 H2 Priority + 40kW Parallel Hybrid + 8kW APU	**Updated the Motor to 40kW Li-ION bats and so improved regen**	
Emissions Achievements:	**Euro 7**	**Improved the APU efficiency to 50%**	
Emissions Technologies used	Lean NOx trap		
CO_2 improvement breakdown:			
Starting point (g/km CO2) (WELL TO WHEELS)	147	**g/km CO_2 (Well to Wheels)**	
	-1.0%	1% improvement from 30kW to 40kW regen brakes	
ell Auxillary Power Unit providing **HALF** the required powertrain power	-26.3%	Fuel Cell APU provides 2.5 kW to the powertrain over the drive cycle (Half engine average power)	0, 9, 10
'otal *Scenario* CO_2 Impact (-ve is reduction)	**-27.3%**	**%**	
Well to Wheels CO_2	**107**	**g/km - (Hydrogen from Natural Gas)**	
Vehicle Weight Change:	(-ve = reduction)		
Starting Point	1451	**kg**	
egen braking, 300V, 40kW motor and generator plus DC-DC converter	3.58%	+52kg	2, 4
Li-ION Battery	1.86%	+27kg Li-ION	3
8kW Fuel Cell Auxillary Power Unit	1.72%	g increase at 0.1kW/kg for 8kW APU system from 4kW system - 15 kg for improved H2 st	8
Total Step 1 Vehicle Weight Impact:	**7.17%**	**%**	
Total Vehicle Weight:	**1,555**	**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	£17,589	Parallel Hybrid cost error corrected	
egen braking, 300V, 40kW motor and generator plus DC-DC converter	6.89%	-£160+£483 for motor, -£240+£725 for electronics (*1.5 sales ratio)	2, 4
Battery	1.32%	-£332+£487 for battery by 2012, NiMH is at $360/kWh	3
4kW Fuel Cell Auxillary Power Unit	2.27%	Cost increase of £400 for 8kW APU from 4kW system	0, 8
Total Retail Price Impact (2003 £ value):	**10.49%**		
Total Vehicle Retail Price (2003 £ value):	**£19,434**	**£**	

Hydrogen Priority Route	Step 7H Series Hybrid with 40kW Fuel Cell 2020	RLG 29 Sept 03	Version 2
Data	**Data**	**Comment**	**Source**
7H	**7H**		
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***		
		UNCHANGED	
107	107	**g/km CO_2 (Well to Wheels)**	
11.4%	-30.5%	Fuel Cell provides up to 40kW (63% total system H2 to electricity efficiency assumed at part load)	0
11.4%	**-30.5%**	**%**	
119	**74**	**g/km - (Hydrogen from Natural Gas)**	
(-ve = reduction)	(-ve = reduction)		
1555	1555	**kg**	
-7.01%	-7.01%	-60kg for the H2 engine, +140kg for Fuel Cell System (40kW), -30kg for generator, -80 kg for APU, -65kg AMT -14 kg improved	0, 4, 8, 11
-7.01%	**-7.01%**	**%**	
1,446	**1,446**	**kg**	
None	None		
H2 tank and Fuel Cell APU will have some packaging priorities	H2 tank and Fuel Cell APU will have some packaging priorities		
H2 system and Fuel Cell APU servicing will be new	H2 system and Fuel Cell APU servicing will be new		
None	None		
(-ve = reduction)	(-ve = reduction)		
£19,934	£19,934	Errors in hybrid cost roll-up compensated	
0.2%	0.2%		
1.6%	1.6%		
-1.17%	-1.17%	'- £500 removal of generator + £2000 for Fuel Cell at £50/kw for 40kW device - £933 for H2 engine - £800 APU	
0.70%	**0.70%**		
£20,073	**£20,073**	**£**	

REFERENCES

Further references for validation information are noted in Appendix A.

1 "Carbon To Hydrogen" Roadmaps for Passenger Cars: A Study for the Department for Transport and the Department of Trade and Industry
Richard Gordon and Nick Owen, Ricardo RD02/3280
www.roads.dft.gov.uk/cv/power/carbon/index.htm

2 Monitoring of ACEA's Commitment on CO_2 Emission Reduction from Passenger Cars (2001) - Final Report, 25 June 2002
Ivan Hodac (ACEA), Catherine Day (EC DG Environment) and Jean-Paul Mingasson (EC DG Enterprise), June 2002

3 Toyota statement in "EV Progress" Magazine, 15th April 2003

4 Clean Fuels & Electric Vehicles Report, March 2003

5 GM statement in Autobeat Daily, August 19th 2003

6 Ford Hybrids: Hybrid & Electric Vehicle Progress, 1st May 2003

7 Layout & Optimisation of the Powertrain and the Operation Strategy for a Motor Vehicle with a Starter Generator Unit - Ploumen, Kok et al, Haus der Technik - 2nd conference on Design of Experiments in engine development, Berlin, 2003

8 Powering Future Vehicles – The Government's Strategy – First annual report
www.dft.gov.uk/stellent/groups/dft_roads/documents/page/dft_roads_024731.pdf

9 www.psa-peugeot-citroen.com ; section on "Technology"

10 Auto Week magazine, June 28th, 2003

11 Scenario and trends on hybrid propulsion technologies, Rovera & Ravello, ATA Vol 56 n 3/4 Marzo-Aprile 2003 (in English)

12 Hybrid Heartburn, Ward's AutoWorld, March 2003

13 Proposal for a Directive, 2002/C51 E/12, European Commission

14 Romano Prodi's statement on Hydrogen pact,
www.hfcletter.com/letter/July03/features.html

15 www.ea.gov.au/minister/env/2003/mr15apr03.html ;
www.ea.gov.au/minister/env/2003/mr01jul03.html

16 www.ott.doe.gov/freedom_car.shtml

17 Foresight Vehicle Strategic Plan - Department of Trade and Industry, 1999

18 A New Integrated Approach for Diesels to deliver High Performance and Low Emissions for 2010 - S Whelan and B G Cooper; EAEC conference, Paris, June 2003

19 Turbocharging Concepts for Downsized DI Gasoline Engines - T. Lake, J. Stokes, R. Murphy, R. Osborne, and A. Schamel, 12th Aachener Kolloquium Fahrzeug- und Motorentechnik 2003

20 Mild Hybrid Operation with a Downsized Diesel Engine – A Practical Approach to Outstanding Fuel Economy - Gordon, R., Fussey, P., and Streater, S., Global Powertrain Congress, September 2002 (www.gpc-icpem.org); see also I-MoGen information at http://www.ricardo.com/i-MoGeN/default.htm

21 Bosch press release on Li-X alternator, www.bosch.co.uk ; see also www.kraftfahrzeugtechnik-heute.de/k/en/start/product.jsp?mfakKey=ES_6_LIX ; and Professional Engineering magazine, 13th August 2003, I Mech E

22 Mercedes Brake by Wire system: Information from: http://www.autoweb.com.au/id_MER/doc_mer0011231/cms/news/newsarticle.html; http://www.whnet.com/4x4/sbc.html; http://www.autospeed.com/cms/article.html?&A=0759

23 BMW Steer by wire – www.bmwworld.com/technology/afs

24 VW Audi DSG – A Different Automatic: Automotive Engineeering International magazine, July 2003

25 Automotive Fuels for the Future - The Search for the Alternative: International Energy Agency (IEA), Paris, France, 1999; other information supplied by Zero-M; www.zero-m.com

26 UK Society of Motor Manufacturers and Traders, www.smmt.co.uk

27 Information on UK Company Car taxation at www.inlandrevenue.gov.uk/cars

28 Toyota Heat Recovery system: Page 65 of: http://www.wws.princeton.edu/cgi-bin/byteserv.prl/~ota/disk1/1995/9514/951405.PDF; also SAE paper 930880, 1993

29 US DoE H_2 storage targets: http://www.eere.energy.gov/hydrogenandfuelcells/hydrogen/storage.html