Institute for European Environmental Policy

ANALYSIS FOR PIU ON TRANSPORT IN THE ENERGY REVIEW

Malcolm Fergusson
Institute for European Environmental Policy

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INTRODUCTION

This report seeks to address future energy demand in the transport sector, as an input to the PIU's review of UK energy policy. It seeks to cover all subsectors of the transport sector, although the principal focus is on road vehicles and, secondarily, on aviation. Further, the main focus is on future vehicle and fuel technologies. That is, the scale and conditions of future transport demand are for this purpose taken largely as a 'given' which provides the context of the study, although they are mentioned in some places and are, of course, a critical determinant of future levels of transport energy demand and environmental impacts.

The first and largest part of the report therefore consists of a brief technology assessment of future fuels and vehicles across the various transport subsectors, which characterises the energy and environmental attributes of each option; its technical and commercial potential; indicative date and scale of introduction; and, where possible, its costs. The second part discusses the refuelling infrastructure implications of the main alternative fuelling pathways for future vehicles, while the final section summarises the main drivers and constraints on the pathway to the various alternative transport energy futures. It also presents a 'vision' of one possible development path up to the year 2050.

PART I: FUTURE DEVELOPMENTS IN VEHICLE TECHNOLOGY

Introduction

This section outlines likely developments in key vehicle technologies over the next two to three decades, and the principal technical and economic barriers to their deployment. For road vehicles, this section covers primarily hybrids, electric battery vehicles and fuel cells. However, brief observations are included on ‘intermediate’ alternative fuels; on conventional internal combustion engines (ICEs); and on other aspects of vehicle technology, as all three of these areas impact directly or indirectly on the prospects of future vehicle technology, and on the policies required to foster desirable technical developments. Possible developments in aircraft engines and airframes are also considered.

However, in assessing alternative technologies, one needs to be clear which is the priority in terms of environmental benefits (ie air quality, greenhouse gases or noise) or energy policy (ie security of supply, diversity, economy, etc). Defining the problem and the objectives of future policy would be a useful first step, but one which is all too rarely taken. Without this, the answer is likely to be confused, and quite possibly misleading. As a result there is no shortage of advocates for a wide range alternative technology solutions for transport systems: the difficulty in many cases is to determine what problem the technology was meant to solve.

For the purposes of the energy review, therefore, the key criteria and issues to be addressed are assumed to be as follows:

- *environmental objectives* – although this may cover a range of issues where relevant, it is assumed that the major emissions issue for future transport energy policy is CO_2 and other greenhouse gases.
- *economic objectives* – are always important on all timescales, so the cost effectiveness of all possible measures is indicated wherever possible.
- *social objectives* – eg social exclusion and ‘travel poverty’ – are addressed where relevant. Although highly pertinent to wider transport policy, however, they tend to impinge less on the transport technology issues which are the focus of this paper.
- *security of supply* – with reference primarily to reduced oil use, either through demand reduction or fuel switching away from petroleum-based fuels. However, availability natural gas supplies may also become problematic at some point in the future, so reference is also made to this issue in relevant sections.

In comparing alternative fuels or engines to conventional ones in a given vehicle type, a sensible and forward-looking baseline needs to be set. That is, it is pointless to compare a typical alternatively-fuelled vehicle (AFV) to an average conventional one on the road today: what counts is testing the best AFV technology available against what one can expect of cutting edge conventional technology, perhaps ten years ahead or more. This must be seen against the background that the base line for conventional engines is moving rapidly: Euro IV standards foresee dramatic improvements in regulated pollutants from conventional engines by 2005, and some production models of equivalent standards are already on or near the market. Similarly, car manufacturers have agreed to a 25 per cent reduction in average CO_2 emissions by the end of the decade. It would therefore be pointless to spend large sums of money on new fuel infrastructure or vehicle designs which, given the time lag, might result in emissions performance that is not significantly better than that of conventional engines, and probably not be any quicker on to the market either.

1.1 Road Vehicle Technology

1.1.1 Vehicle Design and Technology

Before considering the various future alternatives for vehicle engines, it is important to bear in mind that there are a range of possibilities to improve efficiency which concern the vehicle itself. These include weight reductions, improved aerodynamics, better tyres, etc. These are considered first because they might reduce the energy demands of the vehicle, and thus improve its energy efficiency *often irrespective of the engine or fuel technology used*.

Wells (2001) highlights the following current developments:

Basic System	**Development**	**State of Development**
Gearbox	Manual 6 or 7 speed	Increasingly widespread
	Automated manual	In Saab Sensonic
	Automatic	Widespread in US and Japan
	CVT or Torotrack	CVT with metal belt drive (Ford and Fiat)
Body structure	Steel space-frame	Some Fiats
	Aluminium space-frame	Audi A8 and other specialist models
	Aluminium unitary body	Audi A2, Honda NSX
	Multiple materials	Ford Think
	Structural plastics, carbon fibre, etc	Currently in Formula One and specialist sports models

Most of the elements from this list are already incorporated into existing car models, and even more so into new prototypes. Thus for example, Ford's P2000 aluminium body is 55 per cent lighter than its conventional equivalent, and even larger reductions are possible using advanced materials.

It is however difficult to distinguish the specific impact of these single developments from that of the associated engine, or indeed from one another, as the biggest benefits come from the synergies between a range of design elements. Thus for example, the Rocky Mountain Institute highlights the concept of 'mass decompounding', whereby a lighter vehicle reduces the power demands on a hybrid-electric drive, thereby making it more affordable and lighter in turn.

1.1.2 Conventional ICE Engines

Light Duty Vehicles

Although average passenger car fuel economy has improved very little in recent years, at least prior to the effects of the EU voluntary agreement with the car manufacturers, this does not reflect a failure to improve the efficiency of ICEs. On the contrary, ICE technology continues to evolve and improve as it has throughout its long history. There are four main groups of reasons why this has not translated into downsized engines and reduced fuel demands:

- There has been a degree of ‘size inflation’ in cars over the years – that is, people are on average buying larger cars - and the additional weight has required additional motive power. This trend results not only from people ‘trading up’ to a larger class of car, but also to a gradual increase in the size and weight of specific car types. A classic illustration of the latter point is the fact that the current (Mk IV) Volkswagen Polo is larger than the earliest (Mk I) VW Golf[1].
- Consumer expectations of the ‘driveability’ of cars have resulted in increases in average power to give better acceleration, a smoother ride, etc
- Ancillary demands for power in vehicles are increasing, for a range of reasons. One is the trend towards additional accessories and ‘luxury’ features fitted as standard. Perhaps the most important example of this for the near future is that air conditioning is expected to become virtually universal in new cars in the coming years, even in cool temperate markets such as the UK, and this in itself could add several percentage points to fuel consumption. Beyond this, however, a growing range of servo control systems are expected to move from hydraulic to electrical (as they have in aircraft, for example) as these are more efficient, responsive, reliable and cheap to manufacture. As a result, some large cars are already moving from 12volt to 42volt electrical systems – a development which itself yields energy efficiency benefits. However this trend also renders a shift to electricity-based engine types (ie batteries, hybrids or fuel cells) much more attractive.
- Ever-tougher safety standards (eg for side impact protection) have in the past added significantly to the weight of some car models. With good design this effect can be kept to a minimum, but it is a further constraint which can work against the requirements of light weight and efficiency.

All of the above reflect the fact that fuel prices have not risen greatly in real terms over the past two decades (although they fell to lower levels around 1990), and other motoring costs, including purchase costs, have fallen. As a result, fuel economy has not been a priority for most new car buyers. It should be cautioned that most of these trends appear likely to continue, so it cannot be assumed that all improvements in fuel efficiency or carbon content will be translated in full into absolute reductions in fuel consumption or CO_2 emissions.

A further point is that ICEs run at their most efficient in steady state operation. They are particularly inefficient at low speeds and with varying loads – most obviously in congested traffic conditions. Thus continuing growth in traffic, if accompanied by increasing congestion, will itself lead to a deterioration in the average on-road fuel economy of conventional vehicle fleets, and may in part offset improved specific fuel economy.

However, it should also be stressed that there are a number of further developments in conventional engine technology which are already in the pipeline, and which suggest that efficiency improvements in the ICE will continue. Wells[2] remarks that

> ‘A key problem with emerging environmental technologies for the automotive industry is that there are so many choices.’

He summarises the main engine-based options from these as follows:

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[1] Kågeson P (2000) *The Drive for Less Fuel*, European Federation for Transport and Environment, Brussels

[2] Wells P (2001), *[insert reference to AEA article]*

Fuel	**Engine Development**	**State of Development**
Petrol	Direct injection (GDI)	Already growing rapidly
	Variable compression	Saab application likely in future
	Refined existing	Eg variable intake geometry
Diesel	Common rail	Well established
	High pressure unit injectors	Eg in VW diesels

This is to make the point that there are a range of options available which could allow conventional ICEs to continue their improvement in fuel economy for some time to come, provided that innovation takes place in a suitable climate to ensure that it translates at least partly into improved efficiency rather than higher power. Sulphur-free fuel should enable the introduction of advanced conventional technology by the end of the decade, which could itself bring typical fuel consumption levels for new cars down towards 5litres/100km, compared to a current UK fleet average of around 9 litres.

Heavy Duty Vehicles

The potential for fuel efficiency improvements in HGVs is less well understood, and perhaps more hotly disputed, than for cars. It is argued, for example, that high diesel prices and commercial competition have already delivered an optimum level of fuel efficiency. This, however, seems unlikely to be the case, as many operators still do not take even the most elementary steps to improve aerodynamic efficiency of their trucks, or to manage fuel demand.

There are already certain truck engines which offer substantially better economy than the average, and these should be encouraged. A recent report from the OECD[3], for example, noted the significant variations in average fuel consumption per tonne-kilometre of freight between some of its Member States, with the UK towards the upper end of the range. It also quoted an earlier UK survey which had found a 22 per cent variation in fuel consumption across 11 models of 38-tonne trucks.

Further in the future, there should not be major technical obstacles to the use of hybrid engines or even fuel cells in a widening range of heavy duty applications, as the latter can accommodate the size of new technologies and fuel storage systems more easily than cars.

It is also suggested that there are important improvements to vehicle design which could reduce total weight, thus allowing an increase in payload for the same power requirements. Other efficiency improvements are also possible. The OECD study, in particular, cites three recent estimates of these possibilities, as follows:

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[3] OECD (2001), *Saving Oil and Reducing CO_2 Emissions in Transport*

Study	Tyres	Aerodynamics	Weight	Total Savings per Vehicle
Sierra (1999)	10% cut in rolling resistance possible to 2020, giving 2% cut in fuel consumption	10% improvement to 2/3 of new HDVs, giving 3% cut in fuel consumption	600kg reduction, giving 0.5% cut in fuel consumption	3% by 2010; 7% by 2020
ANL (1999)	10-20% cut in rolling resistance possible: impact on fuel consumption not indicated	20% improvement in aerodynamics 'may' be realistic	1,200-2,300kg reduction possible with extensive use of aluminium and magnesium	15% reduction (though no time frame specified)
Taylor (1999)	2-3% fuel use reduction	Not considered	1000kg reduction assumed, yielding 1-3% reduction in fuel use	3.5-5.5% reduction by 2010

Note: These studies refer to US fleet. It is unclear how far they are applicable to Europe.

There is a need for further research in this area in order to establish the true technical options and scope for improvements in conventional technology. It appears from the above that there are possibilities to make improvements through both incremental and radical changes, but these are not in most cases being actively pursued at present.

1.1.3 Hybrid Electric Vehicles (HEVs)

Hybrid vehicles have the potential to deliver some of the benefits of both battery electric and ICE technology, while mitigating some of the more serious limitations of both. Although they include important technical developments, hybrids may also be viewed as a specific and advanced phase of the ever-increasing efficiency and improved emissions performance of the conventional engine.

In a hybrid, a small ICE engine generates power on-board the vehicle much more efficiently than in a conventional ICE vehicle, not only because it is smaller, but also because it can be operated at near maximum efficiency during most of its operating time, because it does not need to provide all the power required during periods of high engine load. For the same reasons, it can also be far cleaner in term of other pollutants, and less noisy. In a parallel hybrid, auxiliary power is supplied by the electric motor during start up and acceleration, using electricity generated by the ICE engine and stored in a battery, thus providing greater efficiency overall.

The principal drawback of hybrid technology is that the vehicle must accommodate two distinct engine technologies, and sophisticated systems to ensure that they work together effectively. This is partly offset by the advantages of being able to employ a smaller and simpler ICE engine, but there are nonetheless problems to be overcome in terms of weight, technical complexity and manufacturing cost.

There are already two HEV car models commercially available (both with small, conventional petrol engines), although others are reported to be 'production ready'. The first to market was the Toyota Prius. This is retailed at approximately £3,000 above the price of a conventional equivalent - a premium of around 20 per cent, which is arguably not excessive when taking into account the lifetime post-tax fuel cost savings which result.

Even at this price premium, the manufacturer is subsidising the initial price, as the true manufacturing cost is believed to be approximately twice that of a conventional ICE at present. Cost therefore remains a significant hurdle, but the price premium can be expected to fall rapidly both as sales volumes increase and as the technology matures. Particularly if fuel prices were to rise, and/or if emissions standards forced up the costs of conventional ICEs (as they seem set to do in California), hybrids could be fully competitive in only a matter of years.

Calculating the precise fuel economy (and hence CO_2) benefit of hybrid engines is difficult, as existing models and prototypes incorporate other vehicle features (eg lightweight structures discussed above) which are not integral to the hybrid technology and could as well be applied to comparable vehicles of any other fuel or engine type to equally good effect. **Nonetheless, other things being equal, efficiency gains of at least 20 or 30 per cent, and possibly as much as 50 per cent, appear possible.** Hybrid technology will soon be applied to diesel engines as well, adding diesel's advantage in fuel efficiency and CO_2 emissions to that of the hybrid configuration itself. Advanced direct injection petrol engines may also be employed to similar effect. Especially when combined with other advanced features, a doubling of fuel economy may well be possible.

Since they can run on conventional motor fuels, it is possible to view hybrids as merely another interim technology or even a 'dead end' which will in time be superseded by a better alternative, probably hydrogen fuel cells. It can even be argued that successful deployment of hybrids might compete with fuel cells and delay their deployment. This is possible, but may be an unduly negative view, and the potential importance of hybrids should be emphasised for several reasons.

First, since they run on conventional fuels, they do not require a dedicated infrastructure, and could therefore be introduced quickly and at no infrastructure cost. Second, they do have the potential for substantial gains in terms of fuel economy and environmental impacts. Third, and perhaps most important, much of the technology which will need to be developed for advanced hybrids will also be necessary or desirable for fuel cell vehicles. That is, improvements to electronic control systems, electric drive trains, development of super-capacitors, etc, are all vital elements of the progressive 'electrification' of the motor vehicle from which fuel cell technology will benefit, and progressive enhancements will themselves contribute to the speed and ease of introduction of fuel cells.

There remains a window of several decades at least in which conventional fuels are likely to be widely available, and it will be largely up to manufacturers how and how far they choose to develop this particular technology in order to exploit that availability. As noted above, two models are already on the market, and the Toyota Prius is proving extremely popular, with sales expected to reach 36,000 worldwide in 2001. This is only the tenth of the number sold of a typical commercial car model, and demand appears to have outstripped supply, but sales will receive a further boost in 2003 when California introduces its EZEV standard, and it is estimated that hybrids might make up 6 per cent of sales in California from that date. This is a substantial number of vehicles, so if this prediction comes true, then HEVs could make up a significant share of car sales and become cost-competitive later in the decade.

In summary, hybrids should be viewed as an important stepping stone, not only in improving the fuel efficiency of conventional vehicles, but also in developing and commercialising many of the new technologies which will be needed for fuel cell vehicles and the ‘electrification’ of the car. In addition, they hold out the prospect of an efficient renewable fuel pathway (probably bioethanol) as an alternative if fuel cell technology is significantly delayed.

1.1.4 Battery Electric Vehicles (BEVs)

BEVs have been available for many decades, and predate the internal combustion engine. They also offer a number of distinct benefits. First amongst these is that they have zero emissions at the point of use, and are also very quiet. This makes them attractive for specialist uses in built-up areas, most notably in the past as milk floats, but also for some other types of small municipal vehicles (eg handcarts) and, occasionally, buses. Peugeot and Citroen also have BEV versions of standard small car models, which a number of UK local authorities are using successfully for tasks involving low daily mileage.

In spite of these benefits, they continue to suffer major drawbacks relative to ICE technology, in terms of performance, range, recharging times, availability of recharging infrastructure, etc. Most of these limitations relate to battery performance, as **decades of R&D have failed to produce a lighter and more powerful alternative to the lead-acid battery at an acceptable cost**. Owing to the characteristics of battery performance, BEVs must balance the demands for acceptable range and high power outputs for acceleration, generally resulting in compromises to one or both of these parameters.

No sufficiently major developments are currently anticipated in battery technology to overcome the performance deficiencies of BEVs, and even if they do come about, they will also benefit hybrid vehicles and possible fuel cell vehicles as well as BEVs. It now seems most likely, therefore, that BEVs will be rapidly superseded by other advanced technologies (hybrids and/or fuel cells) in all but a few niche markets, such as small, specialist vehicle fleets in inner city areas.

1.1.5 Fuel Cell Vehicles

Fuel Cell Technology

The fuel cell was invented in the UK nearly two hundred years ago, but there were no obvious uses for it at the time. Only in the 1960s was it first applied in earnest in the US’s Gemini spacecraft. Since that time the pace of technological progress has picked up dramatically, and now we seem to be on the verge of production cars with fuel cell power sources. With persistent air quality problems forcing ever tighter emission standards, the fuel cell appears to be offering the sort of ‘emissions free’ performance which battery-powered electric cars have so long failed to deliver.

Cell Type	**Electrolyte**	**Operating Temp ^{o}C**	**Development Status**	**Applications**
Solid polymer (SPFC) aka proton exchange membrane (PEM)	Sulphonic acid incorporated in a solid polymer membrane	50-90	250kW CHP systems and several cars and buses being demonstrated, but not yet commercial. Most car companies investing in this option.	CHP, distributed power, portable power and in vehicles
Solid oxide (SOFC)	Ceramic, solid oxide, zirconia	700-1000	Tubular systems available for demonstration; planar technology still under development.	CHP, power generation, ships and trains
Intermediate temperature SOFC (IT-SOFC)	Ceramic, solid oxide, ceria-gadolinia	650-750	Fundamental research still required.	CHP, power generation, ships and trains
Molten carbonate (MCFC)	Molten lithium carbonate	630-650	250kW systems being demonstrated, and previously 2MW as well, but further R&D needed.	CHP, power generation, ships and trains
Phosphoric acid (PAFC)	Phosphoric acid	190-210	200kW systems offered for sale, but not commercially competitive in UK	CHP, power generation
Alkaline (AFC)	Potassium hydroxide	50-200	Fully developed for space systems. Transport systems also available for initial demonstrations.	Space, transport
Direct methanol (DMFC)	Sulphonic acid incorporated in a solid polymer membrane or sulphuric acid solution	50-110	Fundamental research still required.	Portable power, possibly transport

Source: DTLR, DTI, DEFRA, HMT (2001) Powering Future Vehicles: Draft Government Strategy

A wide range of configurations of fuel cell are under development, although not all appear to show the characteristics necessary for use in vehicles (eg small size, light weight, low operating temperature, robustness and capability of cheap mass production). Some of the main cell types are illustrated in the table above.

From the road transport technology perspective, there have in recent years been important and substantial technical advances in fuel cell technology, at a rapid pace, most notably in relation to low temperature fuel cells. These are less efficient than high temperature cells, but in several respects more practical for mobile applications. Of these, the most promising at present appears to be the proton exchange membrane (PEM) cell type for light duty vehicles, and this is the path being most actively investigated by manufacturers seeking to produce working models for passenger cars in the next few years. Costs remain very uncertain, but there are strong possibilities for simple mass production of this particular technology, which in turn suggests that costs could fall rapidly once the technology began to be deployed on a significant scale.

In addition, there is some possibility that solid oxide (SO) will be used for trucks (especially those with high ancillary electricity demands, eg for refrigeration) or other larger vehicles. These are larger and run at higher temperatures, but this is less of a drawback in larger vehicles. They also have the significant advantage that they can run on a much wider range of fuels, including diesel. However, the precise technology which will be employed is not critical to the discussion which follows.

PEM fuel cells require pure hydrogen as a fuel, which combines with oxygen in the fuel cell to generate electricity, which then drives an electric motor. The result is an extremely quiet vehicle with a motor which is much more responsive in terms of power output than is possible in a BEV, and with little or no exhaust emissions apart from water. Regardless of their fuel source, fuel cells have the advantage that they are inherently far more energy-efficient than ICEs in road vehicles, in particular because they operate effectively at low and variable loads, which ICEs do not. Fuel cells can deliver a sustained 60 per cent energy conversion efficiency, whereas ICEs have a maximum efficiency of 40 and 45 per cent for petrol and diesel respectively, and normally operate well below this level. Energy consumption can thus be halved in urban driving in particular.

Car manufacturers have become quite bullish in recent years as to the prospects for this technology, predicting first models reaching the market in 2003 or 2004. This may prove somewhat optimistic, as there are still substantial technical hurdles to be overcome before full scale production can be envisaged. As yet the costs are also far too high for fuel cell cars to be commercially viable, and there are too many technical and commercial imponderables to allow of any certainty as to how soon they will become fully viable. The point at which FCVs become cost-competitive with advanced ICEs will depend crucially on levels of demand in the early years as well as the solutions adopted to certain critical technical obstacles which have yet to be overcome – most notably the on-board storage or reformation of hydrogen[4].

Subject to these uncertainties, however, rapid development from around 2004 and commercial production by the end of the decade now seem quite plausible. Fuel cells would then progress to take a significant market share in the next decade – optimists suggest 10 per cent of new car sales by 2015, but others are more cautious. Under this scenario they would then become the dominant vehicle technology, perhaps around 2030 or thereafter.

Few of the early constraints on fuel cell cars apply so strongly to buses, where the additional space on board, dedicated fuelling and maintenance infrastructure, supervision by trained mechanics, and predictable operating regimes all help to overcome the technical barriers. As a result, demonstration models are already in operation, and commercial production is likely to start shortly.

Fuel Sources for Fuel Cells

As noted above, fuel cells for vehicles are powered by hydrogen. Perhaps the key question for the development of fuel cell engines, however, is how the hydrogen is to be generated and stored. There are three main routes whereby the hydrogen can be delivered to the fuel cell, as follows:

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[4] DeCicco J (2001) *Fuel Cell Vehicles: Technology, Market and Policy Issues*, SAE Research Report RR-010, Society of Automotive Engineers

- Hydrogen generated in a stationary plant and pumped into a tank in the vehicle in either compressed or liquefied form;
- Methanol fuel, reformed to hydrogen on board the vehicle;
- Petrol (with very low sulphur content) reformed on board the vehicle.

There are currently differing perspectives on the most commercially advantageous path to pursue out of these three options. Provided that on-board storage of hydrogen can be adequately addressed, vehicle manufacturers prefer the off-vehicle hydrogen formulation options, as this greatly reduces the technical challenges to be overcome within the vehicle, along with the resultant complexities and higher costs of manufacture. Energy suppliers tend, in contrast, to favour on-board reformation of clean petrol or methanol, as these two pathways require much more limited changes to the fuel supply systems than hydrogen would.

If hydrogen manufactured outside of the vehicle is to be used, it is clear that a number of different sources may be utilised on the pathway to the longer term goal of hydrogen from purely renewable sources. In the short term these include use of hydrogen from oil refineries or other industrial plant (although this source is limited in extent and not a low carbon option), followed later by a wide range of alternatives including steam reforming of natural gas (large scale or local); generating hydrogen from oil or coal (ideally with CO_2 sequestration); pyrolysis of biomass; and electrolysis of water (preferably using renewable or low-carbon electricity). Costs of these various sources also vary significantly:

Hydrogen source	**Cost ($US/GJ)**
Natural gas (small scale)	11-12
Coal or oil	10-12
Pyrolysis of biomass	9-13
Hydroelectric power	10-20
Wind power	20-40
Solar power	50-100

Source: Padro and Putsche, 1999

In addition, other costs (eg for carbon sequestration if fossil sources are used) and ancillary benefits (eg of the possible uses of waste materials) must also be taken into account, and can have a marked effect on cost estimations.

This diversity is itself a strength of hydrogen as an energy carrier. That is, it may be manufactured from a range of sources, either centrally or locally. Indeed, the Institute for Public Policy Research (IPPR) argues that the potential for local production as an integral element of a system of embedded renewable capacity is an important benefit of the 'hydrogen economy' in the medium to long term[5]. In the short term, however, there may be reservations as to the wisdom of generating hydrogen from natural gas on a large scale, given the many demands on this premium fuel and the fact that supplies of it, like oil, will increasingly need to be imported.

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[5] Institute for Public Policy Research (2001), *H_2: Driving the Future*

Regarding the means of supplying hydrogen to the vehicle, there are compelling reasons of cost and technical complexity to concur with the conclusion set out in the recent IPPR report on hydrogen fuel – ie that on-board reformation of methanol is likely to prove an expensive dead end, and that reformation of gasoline is both technically demanding and offers few long-term benefits in terms of either energy supply or environment. Furthermore, either of them may distract attention from, or even delay, the introduction of a full hydrogen fuel system. These on-board reformation options cannot be ruled out, but they should be left to the vehicle manufacturers to pursue if they wish. There is a good argument for focusing public policy instead on helping to foster the long term goal of a hydrogen fuelling infrastructure, as discussed in the section on infrastructure development.

Regarding the environmental implications of these various options, a recent report from the Pembina Institute in Canada[6] found that only the reformation of natural gas reduces greenhouse gas emissions substantially, on the assumption that renewable or nuclear electricity is not yet available. The two on-board reformation options were argued offer much smaller savings - arguably no better than the improvement expected over the next ten years in conventional engines. Unfortunately the latter options are, as noted above, the ones likely to be favoured by a range of industrial interests, so it is important to ensure that the most environmentally-beneficial development path is the one to be pursued.

Another ‘well to wheel’ analysis of energy use and greenhouse gas (GHG) emissions by Shell Global Solutions broadly supports this analysis, as follows:

Fuel Type	**Engine Type**	**Energy Use (MJ/km)**	**GHG Emissions (g/km)**
Gasoline	Conventional ICE	2.84	220
Diesel	Conventional ICE	2.07	152
Hydrocarbon	Fuel Cell	1.70	133
Methanol	Fuel Cell	2.15	117
Compressed Hydrogen	Fuel Cell	1.84	109
Liquefied Hydrogen	Fuel Cell	2.32	139

Note: Hydrogen assumed generated from steam reformation of natural gas

It should be stressed that both studies assume that hydrogen from electrolysis using renewable or nuclear sources is not available. This may be a reasonable assumption for the present, but perhaps not from the perspective of several decades ahead. Thus the GHG emissions of future hydrogen systems may be considerably better than those indicated above, and could approach zero if the source of power is carbon-free.

The Shell study also highlights the importance of the form of on-board storage in determining the energy and CO_2 balance of hydrogen. That is, comparing the last two rows of the table above, it can be seen that it becomes far less advantageous if it is stored in liquefied form rather than as a gas, as a large amount of electricity is required to cool it to the requisite temperature (equivalent to around 29 per cent of the energy value of the fuel). As a result, liquefied hydrogen was found to be no better than methanol in terms of fuel economy or GHG emissions.

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[6] Pembina Institute (2000), *[title to be inserted]*

Conversely, it should be noted that the compressed hydrogen option requires instead very high gas pressures to store enough fuel on board the vehicle within a reasonable amount of space. At moderate pressures (say, 200 to 300 atmospheres) the energy requirement for compression is not large, but the tanks remain quite bulky. Much higher pressures (upwards of 700 atmospheres) are now mooted, but the energy overhead rises rapidly at these higher pressures, again greatly diminishing the energy and/or CO_2 benefits as with liquefied hydrogen. This in itself is a significant technical hurdle for hydrogen fuel cell cars to overcome, although less so for heavy duty vehicles.

1.1.6 Alternative Fuels - Biofuels

Biofuels offer amongst the few possibilities of producing liquid fuel for conventional motor vehicles from non-fossil sources. In principle they can offer diversification away from oil-dependence and a substantial reduction in CO_2 emissions, although in practice, the scope is rather limited. Other environmental benefits are frequently claimed for biofuels (most notably in terms of other exhaust pollutants) but as conventional engines improve, these are becoming, at best, marginal.

Biodiesel

For the UK, the most promising primary crop source of domestically-produced biodiesel is rape methyl ester (RME) from rapeseed oil. It can also be made from used vegetable oil. There is already a significant level of commercial production from rapeseed in a number of other countries with the encouragement of substantial fuel duty reductions and other incentives. In the UK, the duty on biodiesel is to be cut by 20p per litre from the standard diesel rate of 45.82p/litre as of April 2002, although there is some doubt as to whether this will be sufficient to stimulate a significant level of new production.

Biodiesel can be used as a direct substitute for mineral diesel fuel, but this presents some technical problems and requires minor engine modifications. Given the likely limitations on supply, blending up to 5 per cent of RME into conventional diesel is a far preferable approach which presents no significant technical problems – indeed, biodiesel can be used to enhance the lubricity of low-sulphur diesel.

In theory, biofuels can be carbon-free, as the carbon emitted when they are burned was absorbed from the atmosphere as they grew. In practice, however, the carbon saving from biodiesel made from primary food crops is limited, because growing and processing the crops requires a high level of energy use and other inputs. The energy efficiency of the process can be argued not to be a critical factor if the input fuel is itself renewable, but this is not always the case, and resource efficiency remains important because the inputs (eg available land) are likely to remain a constraint. Other greenhouse gases (GHGs) are also emitted during the cultivation process – notably nitrous oxide from fertiliser applications. Biodiesel from waste oil is far more attractive in terms of its net GHG balance, as it is an effective way of utilising the energy content of a product which would otherwise go to waste.

In terms of contributing to overall national energy supply, even the strongest advocates of biodiesel recognise its other limitations. That is, even if all set-aside land in the UK were given over to rape production for non-food purposes, only a few percent of diesel demand could be substituted. The government’s Low Carbon Options initiative estimates that the real potential is only around 2 per cent of *diesel* (ie not total road fuel) demand, and the total greenhouse gas benefits are less than half of this figure.

In either case, this modest benefit would be achieved at very high cost in fuel subsidy, and through the instigation of a major new production industry. Perhaps equally important would be the opportunity costs of such an approach. It could, for example, threaten important new developments in agri-environment schemes and other more environmentally-benign options. From the energy perspective, it would also preclude other potential biomass energy crops, notably ligno-cellulosic crops such as short rotation coppice or miscanthus grass (see below) – or their use in electricity generation, which might be more efficient.

The potential for biodiesel from waste oils is even more limited than that from crops, but it does not have such serious drawbacks either. It could therefore make a useful contribution as a diesel extender, giving modest GHG reduction benefits in that it would substitute a low-carbon for a fossil fuel source. It has the additional attraction of contributing to the policy objective of waste minimisation.

Bioethanol

In the short term, production of bioethanol from wheat or sugar beet suffers from many of the same limitations as biodiesel, only more so. Large scale production is found in several other countries (notably the US and Brazil), but less so within Europe, and always with heavy subsidies. As with RME, only a few percent of national motor fuel requirements could be met from domestic agriculture, even through the use of all available land, including set-aside. Furthermore, the production process is energy-inefficient as a large amount of heat is needed to obtain ethanol of the required concentration.

In the longer term, however, new technologies may make it possible to produce ethanol commercially from ligno-cellulosic crops, or vegetable waste materials, at more cost-effective prices. An advantage of this approach is that the residues from the process could also be efficiently utilised as an energy source. If this option becomes viable, then ethanol can be used initially as a fuel extender for conventional petrol (or even diesel) requiring no modifications to vehicle engines up to at least 5 per cent of the fuel by volume. Bioethanol might then form part of a more efficient utilisation of biomass energy in the medium term. This, however, will also depend upon the degree to which the woody biomass available in the UK is needed for other purposes.

Other research undertaken during the PIU’s energy review has calculated that domestic production of liquid biofuels from woody crops could deliver a substantial share of UK motor fuel demand (perhaps 15 to 40 per cent), but almost certainly not all of it. This is based on the assumptions that 2 million hectares of agricultural land (11 per cent of the UK total) might be available for biomass crops, with the most productive (wood and some grasses) yielding about 12t/ha/year, or possibly more in the long term. Total resource in the foreseeable future is therefore around 24Mt/year. The energy yield of these crops is about 5,500kWh/t, so this is equivalent to around 130TWh per year. Assuming a maximum conversion efficiency to ethanol of 75 per cent (which is not yet demonstrated), the UK biomass resource could supply 100TWh/year – far more than what would be available from annual crops such as rapeseed and sugar beet.

This contribution could thus be significant, but only on the assumption that transport was the main sector to be supplied from this source. On the other hand, domestic production could in principle be supplemented by imports, and/or biofuels derived from the substantial quantities of plant-based waste materials which are generated each year.

If this scenario were to come to pass, there would also then be a possibility in the longer term of using ethanol from this source in an advanced hybrid engine (with some adaptations). This is one of the few configurations which might even match the potential of hydrogen/fuel cell vehicles to provide a renewable long term energy source for transport.

1.1.7 Alternative Fuels - Mineral Gases

Although petrol and diesel are by far and away the dominant road fuels, other fossil fuels can also be used in ICEs. Of these, the most common are liquefied petroleum gas (LPG) and compressed natural gas (CNG).

Liquefied Petroleum Gas

LPG comprises primarily propane and butane, which are amongst the lightest and most volatile components of crude oil. In spite of this volatility, they can be compressed to a liquid at very low pressures. In this form they have properties very similar to petrol, and can be used in a standard spark-ignition engine with very minor adjustments. The main modification required is the provision of an alternative fuel tank and supply to the engine. Most LPG vehicles are dual fuelled (ie they retain a petrol tank and fuel supply as well) in order to be able to use petrol in areas where LPG is not available.

Extensive LPG fleets are in operation in several countries (in the EU notable examples are Italy and the Netherlands). These fleets were built up over a period of years and have now been in place for some time. It is also worth noting that this was done not only for environmental reasons, but also for purposes of fuel security. Since LPG is one of the less well utilised parts of the average oil barrel, its use as an automotive fuel has attractions from the perspectives both of the economic interests of the oil companies themselves, and of the efficient utilisation of crude oil. On the other hand, the relatively small share of the LPG components in the oil barrel limits the possible penetration of LPG to only around 5 per cent relative to the petrol and diesel-powered share of the vehicle fleet, or possibly less if much of it is used for other purposes.

The UK LPG fleet reached 39,000 vehicles by the end of 2000, of which one in three had received financial incentives from the Government’s Powershift programme. This ratio suggests that, with current reduced levels of fuel duty, the market is now well on the way to being self-supporting, with or without additional vehicle subsidies. A rapid increase in numbers is now expected, possibly to 250,000 by the end of 2004, or about 1 per cent of the light vehicle fleet.

However, **Powershift estimates the CO_2 benefits of LPG over conventional fuels to be typically around 8 per cent relative to a petrol car, and negative when compared to diesel**. Thus on average their contribution to offsetting emissions is currently small or non-existent. LPG does offer benefits in terms of NOx and particulates relative to diesel, so there is some air quality benefit, but it can be seen that the environmental advantages of LPG (which would in terms of regulated pollutants have been relatively substantial 10 years ago) are now rather marginal.

One particular problem of dual fuelling is that the engine cannot be optimised to run on both fuels equally well. Most LPG vehicles continue to be tuned to run on petrol, but now that LPG is becoming more widely available the engines could be optimised for this instead, offering better benefits in terms of CO_2 and other pollutants. A further problem identified by Powershift has been the rather poor quality of some of the conversions undertaken, which has exacerbated the basic difficulties of dual-fuelling. Steps have now been taken to improve on the latter, and so a somewhat better environmental performance may be possible in the future.

Nonetheless, even at its maximum feasible level of penetration into the vehicle fleet, it can be seen that LPG has, and is likely to have, only a very small impact in terms of air quality, greenhouse gas emissions, or fuel demand.

Natural Gas

Natural gas can also be burned in ICEs, and has several natural advantages as an automotive fuel relative to petrol and diesel. The first of these is that, as it is a gas at ambient temperatures, it can be mixed with air and burned very cleanly and efficiently. The second is that, as methane is the simplest of the hydrocarbons, it has the highest hydrogen to carbon ratio. As a result, its carbon content per unit of energy is relatively low.

The principal drawback of natural gas as an automotive fuel is that, like hydrogen, it must be liquefied (to LNG) or compressed (to CNG) for on-board storage, and still cannot compete with the energy density of petrol or diesel. As a result, both of these options require bulky tanks and yet limit the range of the vehicle relative to that of a diesel. Specialist refuelling infrastructure and expertise is also needed, and refuelling is neither as quick nor as straightforward as with liquid fuels. Hence there is little prospect of a widespread and high density refuelling infrastructure in any way comparable to that currently in place for petrol or diesel. The costs would be too high, and the benefits too small.

These drawbacks severely limit the prospects of natural gas being deployed for the passenger car fleet. However, many of the drawbacks are greatly reduced for certain fleet vehicles (eg buses, delivery vehicles and municipal fleets) which operate from depots. These are sometimes referred to a ‘captive fleets’. The main advantages of deploying gas in these fleets are as follows:

- Many of these types of vehicle are large, so the penalty of a large tank is relatively small and easily accommodated;
- The required range is often quite limited, and generally predictable;
- Most are parked overnight at depots, so overnight refuelling by specialist staff and from a fixed refuelling point is generally possible.

In addition, the environmental benefits in terms of regulated pollutants are greatest relative to conventional heavy diesels, which are still problematic in terms of their NOx and particulate emissions. A further benefit is that heavy duty CNG engines are less noisy than their diesel counterparts, and this too could be a significant factor in some urban areas..

Takeup of natural gas in the UK has thus far been small – there are only around 300 CNG and LNG vehicles currently in use. Few manufacturers produce dedicated natural gas vehicles, and so costs are high. Powershift is now seeking to increase the takeup of CNG buses in particular, by subsidising the fuelling infrastructure as well as the vehicles.

Thus there are clear (if fairly modest) environmental benefits to be gained from the use of CNG in large fleet vehicles. In Germany, a large-scale trial of gas vehicles has recently been completed, and has shown that they can provide a practical alternative to diesel for high-mileage fleet applications such as buses, taxis, and vans. Around 3,300 vehicles were bought or adapted to run on CNG in four major municipalities which won government funding of 21.5 million euros to subsidise the scheme. The benefits are argued to come mainly from NOx and particulates avoided.

However, CNG in the UK is likely to remain confined mainly to buses and perhaps some vans, with niche markets such as supermarket deliveries in areas where noise levels are important. This argues that it will never account for more than a few per cent of (heavy) vehicle fleet fuel consumption, and hence probably less than 1 per cent of total transport fuel demand. Given that there are concerns over the future availability of gas as well as oil; that the UK will be increasingly dependent on imports; and that an increase in the demand for gas for other purposes is also expected, this is perhaps just as well.

It is sometimes argued that there are additional benefits to the use of CNG in that it is a natural ‘stepping stone’ to hydrogen as a fuel for fleet vehicles. It is true that use of CNG in buses (say) does promote the idea that they can be run, and run more cleanly, on fuels other than diesel. It also gives operators some familiarity with using gaseous rather than liquid fuels, and highlights depots as the natural locus of this infrastructure development pathway. These benefits are not very substantial, however, and do not add greatly to the case for CNG.

1.1.8 Alternative Fuels - Hydrogen

The principal long-term application of hydrogen is likely to be in fuel cells, which are discussed above. In the short term, however, one motor manufacturer is pursuing the option of burning hydrogen directly in a passenger car with an ICE engine. This vehicle uses liquefied hydrogen stored in a cryogenic tank, and a motor with only minor adaptations. This technology presents relatively few problems and demonstration vehicles are already in use. They have very clean tailpipe emissions, as these are primarily water vapour with some NOx generated by the combustion process.

Burning hydrogen in ICEs currently makes little sense from the energy consumption or environmental perspectives. This is because the hydrogen must be formulated from fossil sources, and energy is lost in converting the fossil fuel; then again in cooling the hydrogen for liquefaction; and finally the fuel is burnt quite inefficiently, as is the case with all ICE engines. Ability to generate hydrogen from renewables would reduce some, though not all, of these drawbacks.

Thus burning hydrogen in ICE engines will never be the ideal solution, but in the context of the possible development of a hydrogen-fuelled fuel cell fleet in the future, the ICE hydrogen option has been argued to present some benefits:

- It would accelerate the development of hydrogen refuelling infrastructure and the development of safety and other relevant standards for handling hydrogen.
- It would foster experience in optimising hydrogen storage on board vehicles, as a hydrogen storage system sufficient for a hydrogen ICE engine should be more than adequate for a comparably-sized vehicle using fuel cells.

Although these arguments are both true, the same could largely be said of the prototype fuel cell vehicles themselves. There is also no immediate urgency to develop a large-scale hydrogen refuelling system, so this pathway appears to be rather a sideline in terms of the development of a new transport fuelling system.

1.2 Aircraft Technology

In 1999, the Intergovernmental Panel on Climate Change (IPCC) published a major report on the environmental implications of aviation[7]. This authoritative report is the only peer reviewed international consensus document on the highly technical and controversial issues of aviation's global impacts, mitigation issues and economics. As such, it informs much of the discussion which follows. Additional comments and suggestions have been received from a number of other industry experts[8]

1.2.1 Energy Use, Environmental Impacts and Trends

Under current inventory rules, the major part of aviation CO_2 emissions falls outside of national inventories – one estimate puts this figure at 60 per cent of the global total. Thus for the UK, aviation comprises only around 1 per cent of total national emissions, out of the 25 per cent arising from the transport sector as a whole. However, taken instead on the basis of UK bunker fuels, a very different picture emerges. In 1999, aviation consumed over 11 million tonnes of oil equivalent (Mtoe) out of nearly 54 million for the transport sector as a whole, and 78Mtoe of consumption by all end users, giving it 20 per cent and 14 per cent shares respectively[9]. Thus aviation is a major consumer of fuel, and a major emitter of greenhouse gases.

Although globally aviation CO_2 emissions constitute only a little over 2 per cent of the total, the UK figure is much higher owing to the status of the UK as a major European and transatlantic hub. This is not to imply, however, that the UK and its residents are necessarily responsible for all of these emissions. A range of methods have been devised to 'share out' aviation emissions between nations (eg on the basis of nationality of passengers or carriers), and most of these would result in a lower share for the UK as many of its visitors and transfer passengers are from other countries.

A further point to be made is that, for aviation, CO_2 is not the only exhaust gas of concern from the global warming perspective. Owing to the high altitude at which most aircraft exhaust is emitted, NOx, particles and water vapour are also important. As a result, the total radiative forcing effect of aviation emissions appears on current knowledge to be nearly three times that of the CO_2 alone. Furthermore, this estimate reflects a number of major

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[7] IPCC (1999) *Aviation and the Global Atmosphere*, Cambridge University Press

[8] eg QinetiQ advisory group – personal communications from members of the Combustion & Environment Group

[9] DTI (2001) *Digest of United Kingdom Energy Statistics 2001*

uncertainties (notably over the effect of contrail formation) which currently suggest that the true figure could be higher still.

Kerosene constitutes a distinctive element of the takeoff weight of a typical commercial aircraft (typically over 10 per cent on long haul flights), and also accounts for an appreciable share of the direct operating cost of a flight (around 15 per cent overall, or slightly more for long haul). This is rather more than the energy cost share in many other industries, but still limits the extent to which improving fuel economy further is economic for airlines. There have nonetheless been significant efforts to improve aircraft fuel economy over time, resulting in a nearly 2 per cent per annum improvement in fuel efficiency year on year over the past few decades on a per-passenger kilometre basis. This has been achieved partly through engine and airframe developments, and partly through the use of larger aircraft and other structural changes which improve efficiency.

Given the very long lifetimes of civil aircraft (typically over 25 years) this is a quite impressive rate of change. However, given the very high prices of large aircraft, any attempt to increase the rate of improvement significantly by accelerating fleet turnover would be very costly.

A further problem, from the environmental perspective, is that this rate of improvement is far outstripped by demand, which has been increasing by approximately 6 per cent per annum in Europe. For the UK, aircraft movements have grown on average by 4 per cent per annum over the past decade, passenger movements by 5.8 per cent, and passenger kilometres by even more than this as average aircraft size increases and long-haul destinations become more popular. Latest UK statistics indicate a steady increase through the year 2000 – a 5 per cent increase in aircraft movements, and a 7 per cent rise in passenger numbers, which is in line with that of recent years. Combining this with the improvement to fuel efficiency leads to a net increase in fuel demand of approximately 4 to 5 per cent per annum.

Although there has been a substantial fall in demand since the events of 11 September, it seems at present unlikely that this will result in any major change in the trend, and demand growth is likely to resume at some point soon. The Gulf War led to a marked dip in demand, but this rapidly returned to trend with a strong ‘bounce back’ effect in the ensuing years. Indeed, owing in part to the growing success of a range of new ‘budget’ airlines, high growth rates may yet persist in the UK for some years to come.

There is, however, an expectation that the level of growth will decline as the European market matures, to perhaps 4 to 4.5 per cent per year in the medium term. Nonetheless the rate of improvement in fuel efficiency is also likely to decline on current trends, as further improvements become technically more demanding, and more expensive, to achieve. Thus it can be expected that GHG emissions and warming impacts from aviation will continue to increase by at least 3 per cent per year for the foreseeable future.

It therefore appears quite likely that aviation could increase from around 20 per cent of UK oil demand to 30 per cent some time between 2010 and 2020, depending on the trajectory of demand in other sectors. This in turn will require reconfiguration of refinery infrastructure to deal with the changing shares of petrol, kerosene and diesel, although this appears not to present overwhelming difficulties.

There remains strong pressure, especially around the Pacific Rim, to develop a second generation of supersonic airliners. However, fleets of such aircraft would have especially damaging effects on account of their high levels of fuel consumption and the stratospheric altitudes at which they cruise. The IPCC has calculated that a substantial supersonic fleet could more than double the global warming impact of aviation by 2050 relative to the impact of conventional aircraft, and it seems likely that such developments will be strongly resisted for this reason.

1.2.2 Engine and Airframe Technology

There are a range of technical options available to improve engine and air frame efficiency.

Engine technology is constantly improving, but there are design compromises which manufacturers have to make between the demands of fuel economy, noise, NOx emissions, safety, etc. For this reason, there are doubts as to whether past rates of improvement can even be maintained, far less increased. Nonetheless, improvements to engine cycles are thought capable of improving the thermal efficiency of engines further, and delivering a further 10 to 20 per cent improvement in fuel economy in the medium term. As a guide, EU and NASA engine development programmes target demonstration of about 8 to 10 per cent reduction by 2010 relative to current production engines, but it will probably be some years later before this will be reflected in the aircraft fleet.

More radically, propfan engines may supersede turbofans in the longer term. These are significantly more fuel-efficient, but also slower, and substantial issues of in-flight noise remain unresolved. It cannot therefore be regarded as certain that this change will take place in the foreseeable future.

It is also possible to re-engine some older planes, although this is rarely economic at current prices and is not possible in all cases. Where applicable, it is estimated that a modern engine could save up to 10 per cent of fuel consumed relative to one 20 years old.

Airframe improvements are expected to play an increasingly important part in future improvements through better aerodynamic efficiency, new and lighter materials, and improvements to controls and handling. Most of these are major structural or design modifications, such as larger aircraft with a blended wing body, which are unlikely to appear before 2020. One study[10] also envisages a 10 per cent overall weight reduction for new aircraft in the medium term, and even higher figures can be found, but IPCC is less optimistic on this score.

Some other changes, however, are less fundamental. Thus for example, blended winglets on aircraft wingtips can save up to 4 per cent of fuel consumption of new aircraft. They could also be retrofitted to existing aircraft, although the benefits may be less great for retrofits, and are not applicable to many of the existing models. A plastic coating with ‘riblets’ to improve air flow could also produce savings of 1 to 2 per cent.

Taking these together, the IPCC predicted that a 20 per cent improvement in fuel economy might be achieved by 2015, and 40 to 50 per cent by 2050, relative to aircraft produced today. This however is less than 1 per cent per annum improvement, and less than the historical rate.

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[10] Grieb H and Simon B (1990) in Schumann U (ed) *Air Traffic and the Environment – background, tendencies and other potential global effects*, proceedings of a DLR international colloquium, Bonn, 15-16 November 1990

Other studies[11] suggest that a faster rate is technically possible, to at least double this rate, but this will certainly not occur without policy changes or a dramatic escalation of fuel costs.

Note that there is also a danger that, as engine efficiency increases through higher bypass ratios, exhaust gases become cooler and so the rate of formation of contrails (the visible white vapour trails behind some aircraft at high altitude) is likely to grow. These are believed to have a significant global warming effect (probably more than that of the CO_2 emitted), and given the substantial scientific uncertainties which remain in this area, it appears quite possible that this effect could undo much of the benefit of improved fuel economy.

1.2.3 Alternative Engines or Fuels

No substantial change in engine technology away from gas turbine engines can be anticipated in even the medium term.

Similarly, no alternative fuel presents even medium term options of a substitute for kerosene, in terms of performance, energy density or cost. Hydrogen may offer possibilities in the very long term, but the technical barriers to be overcome are enormous. In particular, the much lower energy density of stored hydrogen would require very substantial changes to aircraft design to accommodate the volume of fuel needed. A further problem is that a switch to hydrogen would eliminate CO_2 emissions, but increase water vapour emissions, and the latter may well emerge as the bigger problem of the two at high altitudes.

1.2.4 Operational Changes

A number of operational changes could in theory also lead to improvements in overall aviation fuel economy. For example, it is claimed that 350,000 avoidable flying hours are generated annually in Europe through congestion and suboptimal routings. Thus it is argued that improved air traffic management could reduce fuel burn by 6 to 12 per cent over twenty years, although in reality, the improvements would probably stimulate additional demand growth thus offsetting some at least of the benefits.

Efficiency can also be improved in some cases by having aircraft fly more slowly. This might well prove unacceptable on long hauls, but not for the more energy-intensive shorter flights. It has been calculated that reducing cruising speed from 870kph to 750kph on a 1,000km flight would reduce fuel consumption by 12 per cent, while adding only a few minutes to the journey time. However, this estimate may no longer be widely applicable to modern airliners, so the total reduction achievable may be significantly less than the quoted figure implies.

Load factor is also important, as each additional passenger adds very little to the fuel consumption of an aircraft and therefore improves the efficiency on a passenger-kilometre basis. There may be scope in add a few more percentage points to average load factors, but estimates are typically based on revenue-paying passengers, and may ignore non-revenue passengers such as staff and loyalty scheme flyers which may make up several per cent of the total passenger list. Anecdotal information from airlines suggests that it may not be practicable to increase load factors significantly, at least not without changes to current operating practices such as flexible tickets and overbooking,

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[11] See in CE (1999) *European aviation emissions: trends and attainable reductions*, background study, Delft

Auxiliary power units (APUs) on board each aircraft are used to provide power when the aircraft is stationary at a boarding gate. This is a significant source of fuel consumption which could be eliminated by providing electric power from stationary sources. It is estimated that this could save an average of 3.7 per cent of aircraft CO_2 emissions.

1.2.5 Conclusions

In short, the technical options either for a substantial reduction in specific energy consumption or for a shift away from kerosene are quite limited for the aviation sector, and reductions in either fuel consumption or greenhouse gas emissions can be expected to be significantly outstripped by growing demand in all plausible scenarios. A recent Dutch study[12] anticipated that European aircraft CO_2 emissions would increase to more than 250 per cent of 1995 levels by 2025 under a business as usual (BAU) scenario, with a corresponding growth in kerosene demand. The IPCC presented a lower central case in its recent analysis (270 per cent by 2050), but its other scenarios present a very wide spread of values above and below this figure.

There are nonetheless options to improve fuel economy more rapidly than a BAU case would suggest, but these would require substantial policy action at regional or global level, as they are not cost-effective at the current (tax free) price of kerosene. The Dutch study referred to above calculated that it was ‘technically feasible’ to limit the growth in CO_2 to less than 50 per cent, but that this would require a range of interventions to stimulate more rapid innovations in aircraft design and technology, improved load factors, operational changes, etc. As noted above, moreover, accelerating fleet turnover would entail substantial costs. The IPCC is markedly less optimistic as to the likely potential for further improvements.

1.3 Trams, Trains and Ships

These constitute much smaller elements of total fuel demand than road transport, and are not therefore treated in any detail here. Shipping in particular is inherently the most fuel efficient means of motorised transport. The energy efficiency benefits of rail are however much less clear cut (at least compared to road), and depend critically on the load factor of the train and the type of technology in use.

Local and regional air quality concerns are likely to drive some improvements in the near to medium term such as introduction of cleaner diesel engines in trains, which could also be more fuel efficient. For railways, however, further electrification offers the most assured medium term route towards cleaner and lower-carbon energy use, as a recent study suggests that UK high speed electric trains have only half the CO_2 emissions level of the equivalent diesels[13]. Clearly much greater benefits could be achieved if electrification were associated with increased availability of low or zero-carbon electricity. In the UK, only 30 per cent of railway lines are currently electrified, compared with an EU average of 48 per cent.

In the medium to longer term, a range of fuel cell configurations should become available for these larger vehicles, and could use either hydrogen or one of a number of liquid fuels. Some demonstration projects, eg for ships, are now emerging. Fuel cell trams are also under consideration, as these would obviate the need for complex and costly overhead power lines.

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[12] CE (1999) *European aviation emissions: trends and attainable reductions*, background study, Delft

[13] AEA Technology (2001) *A Comparative Study of the Environmental Effects of Rail and Short-haul Air Travel* Culham

PART II: INFRASTRUCTURE FOR ALTERNATIVE FUELS

The development of fuel distribution and refuelling infrastructure poses a substantial challenge to the uptake of any of the alternative transport fuels. For conventional fuels, a distribution system and a network of refuelling stations has been built up, with substantial investment, over many decades: for the alternatives, significant elements of this infrastructure would need to be replicated from scratch.

2.1 Refuelling Stations

With road transport being in its nature a dispersed activity, refuelling the transport fleet as a whole requires a broad but quite dense network of refuelling points, currently totalling around 13,000 across the UK. These sites vary enormously in size and nature, from major motorway service stations to small rural sites offering only a very limited range of fuels, and including some on islands and in very remote areas.

It would not be necessary to have an alternative fuel available at all these sites in order to give adequate coverage. Vehicles operating mainly in urban areas, for example, could manage with a much smaller network, and it would be possible to achieve significant penetrations of alternatively-fuelled vehicles (AFVs) on this basis. As an indication, it has been estimated that a network of 1,300 LPG refuelling points will constitute an adequate network for Britain. However most LPG vehicles are bi-fuelled (see below) and not therefore fully dependent on this network. Dedicated AFVs would probably need rather more than this to have full freedom of movement around the country, but still substantially less than the full 13,000.

It seems likely that alternative fuels for use in the vehicle fleet at large would mainly be delivered from the same network of sites, or a subset thereof. Much of the cost of a completely new infrastructure is avoided if existing facilities are used, and in their nature, these sites are generally conveniently located, purpose-built and well distributed to give effective coverage. For the larger sites, supplying alternative fuels is essentially a question of ‘adding an extra pump’ and fuel storage tanks. This is already happening for LPG. For liquid fuels (eg methanol or ethanol) the technical challenges are not too great as they behave rather like petrol or diesel. With methanol, however, its toxicity raises particular concerns in terms of fuel handling by the general public, and its corrosive properties require some materials which can be used in petrol or diesel pumps to be avoided.

Gaseous fuels pose more serious challenges, as they must be stored either in high pressure tanks, or if liquefied, in cryogenic tanks. Radically different and more sophisticated designs of refuelling nozzles are also needed, either to ensure adequate pressure seals for gases at high pressure, or to eliminate the possibility of spillage of extremely cold liquefied fuels. At least initially, such equipment would be far more costly than conventional pumps. As an indication, fast-fill CNG installations, including compressors and ancillary equipment, cost up to £250,000 each.

These technical and cost barriers underscore that a refuelling infrastructure will not emerge overnight, or without a clear expectation of returns on investment. For this reason, most alternative fuels are caught in a classic ‘chicken and egg’ dilemma whereby vehicle manufacturers will not deploy new technologies if there is no refuelling infrastructure to fuel them, whereas energy supply companies are reluctant to invest in substantial new infrastructure while there is no significant or assured demand.

Four clear conclusions emerge from this discussion regarding a national refuelling network:

- that the challenges are substantial for the introduction of any alternative fuel, so a comprehensive national infrastructure is unlikely to be developed for an interim fuel which will be used only for a limited number of years;
- that it is very unlikely that this exercise will be undertaken on a national scale for a number of different alternatives, so the expectation of a clear long term ‘winner’ is required before widespread introduction of new technology will be possible;
- that the above does not preclude the possibility of a different alternative fuel being used for some niche areas, most obviously heavy duty ‘captive’ fleets, where the alternative has clear technical or cost advantages;
- that the international nature of road transport requires that, for some classes of vehicle in particular, it is desirable or essential that developments in the UK should be in parallel with those on the Continent;

There are however two important routes to deployment of alternative fuels which limit the need for such a large scale installation of new refuelling technology, at least at the outset. These are to focus on fleet vehicles, and to deploy bi-fuelled vehicles.

2.2 Vehicle Fleets

As noted elsewhere, fleet vehicles offer substantial benefits when introducing alternative fuels. It is thus likely that whichever of the alternatives are developed, the initial focus will be on fleet vehicles in urban areas, operating from a single depot or using a very limited private network of refuelling points. The vehicles most likely to be the first to use alternative fuels and engine technologies are therefore buses, taxis, municipal vehicles and delivery fleets.

Note, however, that because of their distinctive nature, it is possible that some vehicle fleets or types will develop along a different fuel and/or technology path to that which is eventually determined for other vehicles.

2.3 Bi-Fuelled Vehicles

The second pathway which can be adopted for some other types of vehicles is bi-fuelling. This involves retaining the option of refuelling with conventional petrol or diesel when the vehicle is being operated in an area away from its dedicated refuelling infrastructure. This is not practicable for all possible vehicle types, but is useful in some cases. The most obvious example of this to date is the use of LPG, which is generally in vehicles which have the capability of using conventional fuel instead through a simple switch in the fuel systems. As a result, the current network of approaching 1,000 LPG refuelling points across the UK now constitutes virtually an adequate basic network. This number continues to grow, and it is estimated by industry sources that 1,300 will constitute a full network on the assumption that the vehicles will continue to be bi-fuelled. Once this level of coverage is attained, it may be possible to scale down the conventional fuel tank, as it would only be needed in emergency to allow the vehicle to reach the next LPG station.

For the longer term options, some other bi-fuelling configurations can be envisaged. Some fuel cells, for example, are quite versatile as to the fuel which they use, although this may be at the cost of other technical drawbacks or some loss of efficiency. However this does not apply to the PEM cells currently judged the most promising for light vehicles, so complex on-board reformation of liquid fuels is currently needed for these if direct hydrogen is not stored in the vehicle. Developing technology may however make this a more viable option in the future.

As noted above, a possible alternative development path would be for long term development of hybrid engines capable of running on liquid biofuels. In this case, it might be possible to retain the option of their also running on petrol in areas where biofuels were not available, or to use blends of fossil and biofuel, at least during a transitional period.

2.4 Fuel Production and Distribution

Petroleum products are brought ashore and refined at a very small number of points around the UK. Refined transport fuels are then distributed to the large number of depots and fuel stations through the use of both pipelines and tankers.

A fuel distribution system for alternative fuels would probably have a substantially different structure. One important difference is that large scale manufacture of liquid or gaseous fuels from renewable sources would be likely to be more widely dispersed and decentralised than that of petroleum fuels, making bulk distribution through pipelines less straightforward, but perhaps also less necessary.

Coupled with this, the lower energy density of alternative fuels (especially hydrogen) makes distribution by tankers much less efficient, as it would take around 13 tanker trips for hydrogen to move as much energy as from a single trip for petrol or diesel. This suggests that, if tankers were to be used to deliver fuel to filling stations, then shorter trips from a denser network of distribution depots would be needed. Even then, this would probably cause a significant additional traffic problem in major urban areas, and a pipeline delivery network would increasingly be needed.

For this reason the prospect of local generation of hydrogen, either reformed from natural gas or generated from water through electrolysis (with either gas or electricity supplied through their existing distribution networks) is particularly attractive for transport fuels. In either case this does not present serious technical obstacles, as the technology to generate the hydrogen can be scaled down to very small sizes if needed.

As the recent IPPR study emphasised, hydrogen could also, under this type of scenario, become an integral element of a radically different energy supply network based around a ‘mosaic’ of local renewable energy sources. Here, hydrogen would be generated locally from excess electricity, thereby both providing an energy storage buffer to help level out the peaks and troughs of renewable energy supply sources, and minimising the need for long distance transportation of the fuel. These aspects extend beyond the scope of the current study, but it should be emphasised that a switch to hydrogen should be seen in the context of the whole energy economy rather than just the transport sector, and could have an important role in circumventing the problems posed by the intermittent nature of many renewable generation sources, and the lack of capacity to store electricity.

Initially, hydrogen for transport demonstration projects and beyond would be likely to be delivered by tankers from oil refineries or other industrial sources. The latter might increasingly include large scale natural gas reformers and/or electrolytic plant, depending on the economics of the energy sources available. A recent US study suggests that sufficient hydrogen to fuel a quite substantial fleet could be generated from existing or readily-available plant.

There are important issues, however, as to the nature of the hydrogen infrastructure which might develop. It has already been noted that tankering the fuel would have serious drawbacks beyond a certain point, but developing a comprehensive new system of pipeline distribution would be expensive. A recent US study quotes costs of $1 million per mile for a small diameter pipeline in a built up area, and IPPR quote an industry estimate of US$1.5 billion for a distribution network for one quarter of the UK’s filling stations. The latter estimate appears rather low, but nonetheless illustrates that some level of distribution infrastructure could be developed at reasonable cost, and might be preferable to wholesale reinforcement of the electricity grid.

As demand for hydrogen as a road fuel became more widespread, however, (perhaps from around 2020) it would also be increasingly desirable to generate hydrogen on site at filling stations, depots or other local centres, initially through reforming natural gas, which is already widely available by pipeline. US studies indicate that this pathway would be cheaper overall (averaging out at around £200 per car) than the additional equipment needed to reform a liquid fuel on board each vehicle.

Subsequently, as renewable electricity sources developed, generation of hydrogen from water by electrolysis would be likely to increase. Other means of generating hydrogen, eg pyrolysis of biomass, might also feed into the supply system. A particular advantage of hydrogen is that a range of different means of production could be used according to local conditions.

As noted above, methanol presents fewer problems of supply and refuelling than hydrogen. It is even possible that existing fuel storage tanks could be used for methanol with little or no modification. A recent US study estimated the cost of adding methanol capacity to a typical existing refuelling site would be in the region of $60,000 to $70,000 per site. This lower cost must, however, be offset against the technical difficulties and much higher costs of on-board reformation of methanol if it is to be used with fuel cells.

If the path to commercial fuel cell vehicles proves too difficult, alternatively, it becomes the more likely that a network to supply liquid biofuels (preferably from woody crops or waste materials) will emerge alongside the existing petrol and diesel facilities. Either of these could then be used in hybrid vehicles or other forms of advanced engines.

2.5 The European Dimension

For the majority of fleet vehicles, it has been argued that developments in alternative fuelling can develop on a national or even a local basis. Even here, however, developments in other countries are relevant, because vehicle markets operate on a continental if not global scale. Hence the type and design of vehicles on offer will be influenced by developments in the other major European vehicle markets (notably Germany, France and Italy).

If alternative fuels are ever to fully penetrate the road haulage fleets, or even private cars, however, it will be essential that developments in the UK are in step with those on the Continent. That is, not only must the same sorts of fuels be made available through a viable network of outlets, but there must be sufficient technical harmonisation to ensure that vehicles can be refuelled with the right grade of fuel, at a standard temperature and pressure, and through a standardised refuelling nozzle.

This will require concerted efforts from national authorities if technical barriers to new developments are to be avoided. As an example of the differences which currently exist, it is reported that the US has regulations covering vehicle gas storage systems with pressures of up to 350 atmospheres, whereas the upper limit in Europe is 200 atmospheres. In France, hydrogen is not even allowed as a transport fuel at present.

PART III: DRIVERS AND CONSTRAINTS ANALYSIS

3.1 Drivers

There are a number of important drivers which might or will operate to encourage technological change to alternative transport fuels and technologies:

- The UK transport system is the principal source of demand for petroleum products, and is 99 per cent oil dependent. A desire to avoid dependence on imported oil, or rising oil prices, could stimulate either increased fuel efficiency or diversification away from oil-based fuels, or both.
- Similarly, transport is a large and growing sector of energy demand. Thus, even if alternative (and renewable) fuel sources prove technically and commercially feasible on a large scale, there may be insufficient total supply available to meet all needs, and transport will have to continue to compete in commercial terms for the available energy supplies. Thus the efficiency, as well as environmental impacts, of the transport system may need to be addressed.
- Serious constraints on CO_2 emissions, such as a decision to aim to meet the RCEP's 60 per cent reduction target, would necessitate substantial changes in the transport sector. Again these might include both fuel efficiency and fuel switching
- For road vehicles, improvements to conventional vehicle technology should be sufficient to ensure that air quality in general remains a shorter term problem, and hence less of a driver of major technological innovations in vehicle fuels and technologies for the long term. For light duty petrol vehicles, substantial reductions in regulated pollutants have already been achieved and further reductions are possible. This is not yet fully the case for diesels, where NOx and particulates remain problematic, but further improvements, especially for light duty diesel engines, can be expected as a result of closer integration of particulate traps and de-NOx catalysts..
- There may also be a growing demand for quiet, 'zero-emission' vehicles in air quality management areas, Clear Zones and other such designated areas. This demand would be most strongly felt for buses, taxis, and delivery vehicles.
- ICEs, especially heavy duty ones, are inherently noisy. As societies become more affluent – and if they become more aware of the health and quality of life impacts of ambient noise – it is likely that toleration of conventional engine noise in built up areas will diminish. Demand for much quieter vehicles might be further stimulated by an increase in pedestrianised areas, and/or a growing demand for home deliveries outside normal working hours.
- The discussion of advanced engine types tends at this stage in their development to focus on technical obstacles to be overcome, the need to bring down manufacturing costs, etc. This should not be allowed to obscure the fact that advanced engines (eg fuel cell electric) may offer many positive consumer advantages over the ICE in the long term, aside from environmental or fuel supply considerations. For example, supplying traction through a small electric motor on each wheel would greatly improve the driveability and road-holding of vehicles, while eliminating the need for a mechanical drive system, clutch and gearbox, separate braking system or a large engine 'under the bonnet'. Hybrids and fuel cells would also assist with the 'electrification' of a number of other servo-assisted systems and accessories, making them cheaper, more mechanically efficient and more reliable.

- Fuel cell electric vehicles would have far fewer moving parts than a modern ICE vehicle, and electric motors are cheap, well-developed and reliable. The alternatives might thus in the long run prove to be even cheaper, better performing and more reliable than ICEs.
- It is also possible that changing consumer expectations will in future place more emphasis on quiet, clean, economical and compact vehicles, thus facilitating a change to cleaner fuels and vehicles. The availability of quiet vehicles may itself divert consumer expectations away from the 'roar of the engine', and the early success of the Toyota Prius in spite of its high price may suggest that this is already beginning to happen. Once quieter vehicles (eg hybrids or fuel cells) begin to appear in any numbers, this too might stimulate additional demand until quiet vehicles become the norm.
- Demographic trends in driver's licence holders, and in the population in general, both dictate that women and elderly drivers will increase as a proportion of the total number. These trends are likely to support such a change in values and expectations, as older drivers are known to drive more carefully and safely, while survey evidence shows that women typically drive smaller cars than men, drive more slowly, less aggressively and more safely than men, and tend to value fuel economy, safety and the environmental aspects of their cars more highly.
- For aviation, concerns over its serious impacts on the global atmosphere are likely to grow, not only as air traffic and impacts increase, but also in line with developing scientific understanding of the effects of aircraft emissions at high altitude. Air quality concerns have in the past been a major driver of technological improvements in aircraft engines, and will remain an important consideration. Equally, if public sensitivity to noise and other local impacts also increases, this too may tarnish the image of civil aviation and increase pressures for improvements. These effects may in time force an acceptance that current rates of growth, which are not likely to be met by technological improvements, are not acceptable, and that policy intervention is needed.

3.2 Constraints

- There are some serious technical challenges yet to be overcome in fully commercialising a fuel cell hydrogen car in particular. These include the fuel cell technology itself, and the need either to reform an intermediary fuel to hydrogen within the vehicle, or to store hydrogen on board.
- As noted above, transport is by far the fastest-growing energy demand sector, and even radical alternatives go only some way to improve the efficiency of transport energy use. Thus it may still prove necessary to address transport energy demand through long term transport demand management or changing the modal balance, as well as through technology change alone.
- Radically new and unfamiliar technologies require a great deal of preparatory work to be undertaken to set out standards, guidelines, design norms, etc – for example to establish standard refuelling nozzles, to ensure safe handling of novel fuels, to set land use planning provisions, etc. There is a natural reluctance to undertake such efforts until it is clear that a new technology will be forthcoming; but their absence also generates uncertainties which can impede technological development and innovation.
- There are important barriers to be overcome in securing public acceptance of a radically new technology so close to home. For example, people will need to be reassured that the new systems are both safe and reliable; and there is a natural tendency to overlook the drawbacks of familiar technology, while exaggerating the problems of the unknown.
- In most cases with alternative fuels, there is a 'chicken and egg' problem whereby vehicle manufacturers will not deploy new technologies if there is no refuelling infrastructure to

fuel them, whereas energy supply companies are reluctant to invest in substantial new infrastructure while there is no significant or assured demand.

- With a range of vested interests competing for future markets, with genuine uncertainty as to which technology will win out, and in the absence of clear leadership, there is a danger that the 'pathway dilemma' will persist for a long time, making actors hesitate to back any one technology decisively. Furthermore, past experience shows that, where major technological choices are left purely to the market, the most technically advantageous solution does not always become the dominant one.
- On the other hand, governmental attempts to foster a particular technology often end in expensive failures, so care is needed to construct an appropriate government policy response.
- Growth in air travel continues, and, from the perspectives of energy use or a range of environmental impacts, cannot be offset by advances in aircraft technology. Most governments and nations remain protective of their 'national flag' airlines, even after these have left public ownership. At the same time, the civil aviation industry is fiercely competitive, so EU governments are often reluctant to intervene to address problems such as fuel demand, noise or greenhouse gas emissions if this is seen as likely to impose additional burdens on them, especially when these priorities do not appear to be shared by governments in the US or developing countries.

3.2 Future Pathways

It is not possible to set out a blueprint of how transport technologies will develop, nor when. The box below sets out a possible future vision based on a range of expert views, while the discussion thereafter indicates some of the main alternatives.

A Vision of Future Technological Developments in the Transport Sector

Road Transport

- In the short to medium term (ie for at least a further 20 years ahead), further significant improvements in the fuel efficiency of petrol and diesel vehicles are possible, and could reduce the fuel consumption of new cars by 50 per cent. This might well include progressive introduction of hybrid technology, which is already starting to appear on the market and could become significant during the second half of the present decade.
- Improvements in vans and more particularly in heavy duty engines will proceed more slowly than for cars, at least in the short to medium term. Use of hybrid technology is, however, at least as viable for larger vehicles as it is for cars, and other improvements to engines and vehicles could be pursued..
- Use of LPG will continue to expand slowly, provided that reduced rates of fuel duty continue to apply, but its environmental advantages over conventional fuels have been substantially eroded and may yet diminish further. An effective network of at least 1,000 refuelling points should be available shortly. LPG use cannot in practice exceed around 5 per cent of the total petroleum-based fuels market, and is unlikely to reach even this level if other alternatives develop rapidly.
- In the short term, biofuels can make only a limited contribution to transport energy demand, and will not develop without substantial fuel duty reductions and possibly other subsidies. Although in theory carbon-neutral, currently available biofuels offer substantially smaller CO_2 benefits. In the medium term, bioethanol from woody biomass

(or perhaps even vegetable refuse) may prove attractive, initially to be blended into conventional petrol supplies.

- More radical alternative technologies will initially have a strong focus in buses and other fleet vehicles (delivery vans, taxis, etc). Use of CNG buses will continue to expand initially, but will be superseded by hydrogen fuel cell buses, probably within the decade.
- Fuel cell cars are expected to first appear around 2004, but it will take at least five years from this point to the marketing of a full scale consumer product. If technical barriers are overcome, they could take a significant market share (perhaps up to 10 per cent of new vehicle sales) by 2015, and become the dominant technology by 2030 or thereafter.
- As the use of fuel cells penetrates a wider range of vehicle applications, a broader network of refuelling infrastructure (probably for hydrogen) will be needed. This will involve substantial costs and will take many years to reach the necessary density for fully effective coverage.
- Hydrogen will initially come from reformation of natural gas, but may in future come from a range of sources (eg reformation from biomass, or electrolysis of water). A mosaic of many different local sources may also emerge to reflect local circumstances. The natural gas option offers significant CO_2 reductions relative to conventional engines, and these improve further if renewable fuel sources can be deployed.

Rail and Shipping

- These constitute much smaller elements of total fuel demand than road transport, and shipping in particular is inherently quite fuel efficient.
- Local and regional air quality concerns are likely to drive some improvements in the near to medium term – eg use of low-sulphur fuel oils in ships in European waters, and introduction of cleaner diesel engines in trains.
- For railways, further electrification offers the most assured medium term route towards cleaner and lower-carbon energy use, although at significant capital cost.
- In the medium to longer term, a range of fuel cell configurations should become available for these larger vehicles, and could use either hydrogen or one of a number of liquid fuels. Fuel cell trams are already under consideration, as these would obviate the need for complex and costly overhead power lines.

Aviation

- Aviation will be the most problematic of the transport subsectors in terms of either curbing the growth in petroleum-based energy demand or reducing greenhouse gas emissions.
- Some technical improvements will continue to be made, and larger aircraft will continue to improve fuel efficiency relative to passenger numbers. However, demand growth will significantly outstrip technical innovations to improve fuel efficiency for most of the next decade at least. Concerns over the impact of emissions into the upper atmosphere are likely to grow.
- Additional measures could be stimulated by significant policy interventions, probably at EU level, and perhaps beginning by 2010. These could result in immediate operational changes and accelerated introduction of advanced engine and airframe technologies. The increase in CO_2 emissions could be significantly reduced in the medium term as a result, primarily of technological advances, but at greater cost.
- No alternative fuel to kerosene can be envisaged even in the medium term, although hydrogen may begin to be used in the long term.
- A new generation of supersonic airliners appears unlikely to be developed in the foreseeable future, as their environmental impacts on the upper atmosphere would be disproportionate, even in relation to the rest of the civil aviation industry.

There is an emerging consensus that hydrogen and fuel cells represent the ‘dream ticket’ for future road transport technology, as outlined in the box above. Several national governments around the world are now actively pursuing this goal.

There are however some substantial technical barriers to be overcome, and it is possible that one of these will prove sufficiently difficult or expensive that this new technology will be long delayed or even abandoned. In spite of the rapid advances in hybrid and fuel cell technologies, their introduction and market penetration are more likely to be delayed than accelerated relative to the timelines set out above.

Conversely, an alternative option may prove to be more attractive or cost-competitive than is currently thought, or something completely new might emerge. The latter cannot of course be anticipated; but some alternatives can be envisaged, and these might supersede the hydrogen/fuel cell pathway.

One possibility is that liquid biofuels from biomass might in the long run prove more attractive or technically viable as a fuel for light vehicles than hydrogen. The likelihood is that this would be ethanol derived from ligno-cellulosic crops (and/or possibly vegetable waste) in the medium term, rather than from conventional agricultural crops. Such a fuel could be regarded as renewable, and to have important environmental benefits (eg possibly reducing the need for landfill or incineration, as well as cutting CO_2 emissions). As a liquid it would have advantages in terms of ease of handling relative to hydrogen.

In this case, two main alternatives emerge. If there proved to be substantial problems in developing reliable mobile fuel cells, then ethanol fuel could be burned in the small conventional engines of hybrid vehicles. Alternatively, if fuel cell technology is successfully developed but hydrogen supply or storage on board vehicles proves problematic, then ethanol could be used as a fuel for fuel cells instead. The ethanol might be used directly in some types of advanced fuel cell, or could be reformed on board the vehicle to produce hydrogen.