Transport and sustainability

About this free course

This free course is an adapted extract from the Open University course T213 *Energy and Sustainability* http://www3.open.ac.uk/study/undergraduate/course/t213.htm.

This version of the content may include video, images and interactive content that may not be optimised for your device.

You can experience this free course as it was originally designed on OpenLearn, the home of free learning from The Open University:
http://www.open.edu/openlearn/science-maths-technology/transport-and-sustainability/content-section-0.

There you'll also be able to track your progress via your activity record, which you can use to demonstrate your learning.

Contents

Introduction

This free course explores transport and the issues of sustainability. Transport plays a critical part of most people's life but it also creates complex issues for sustainability. You will first investigate the concerns with respect to the use of transport energy, which here mainly concentrates upon road transport vehicles. There is then a detailed consideration of road transport technologies, starting with the established technologies of petrol and diesel, before moving on to explore how these can be made more sustainable. This includes a short overview of petrol and diesel engines and how they work. Finally, you will look at the question of how to achieve a move to radically cleaner transport technologies and transport systems for a low-carbon future.

Table 1 provides an overview of the content of this free course.

Table 1 course Overview

Section	Content	What to look out for
Introduction	Introduction to the free course	
1 The transport energy challenge	The important role that energy security and shortages play in determining transport policy	Different countries have different needs for transport energy
2 Transport's environmental impacts	A consideration of both direct and indirect impacts, focusing on CO_2 in the UK from all sources	The differences in energy and emissions due to the transport sector
3 Petrol and diesel engines	A recap of why diesel engines and fuels have slightly higher energy efficiency than petrol systems	The growing penetration of diesel into the vehicle market – and how the market continues to change
4 Petrol and diesel emissions	Typical emissions of each vehicle under real-world conditions; how different technologies lead to lower impacts	How the total life-cycle emissions for a vehicle are dependent on each stage of the life of a car
5 Cleaner conventional car technologies	How hybrid technologies can help to reduce the overall fuel consumption of a vehicle	The limitations of hybrid systems and the variety available to most consumers
6 Lower-carbon fuels	An overview of CNG, LPG and biofuel systems for personal cars	Subtle differences between the various generations of biofuels
7 Electric vehicles	Information on pure electric vehicles, 'plug-in' hybrids and fuel-cell powered vehicles	The fact that any type of new technology (fuel or battery) requires an abundant supply system to fully establish those vehicles
8 Decarbonized transport	An explanation of the decarbonized pathways towards various transport scenarios	The lowest possible tailpipe emissions; the various life-cycle emissions that each technology accrues
Review	A brief summary of this free course	

This OpenLearn course is an adapted extract from the Open University course T213 *Energy and Sustainability*.

Learning Outcomes

After studying this course, you should be able to:

- outline the energy and environmental impacts of transport activities, and their importance
- identify the key points of relevant legislation and targets relating to vehicle emissions
- describe the low-carbon fuels and vehicle technologies that are becoming available to reduce emissions
- compare the environmental improvements that these transport technologies and fuels can deliver
- understand that both technical and behavioural changes have a role in achieving transport sustainability.

1 The transport energy challenge

Activity 1 (exploratory)

Before reading the rest of this section, make a list of what you consider to be the main issues and challenges concerning energy use in transport.

Provide your answer...

Energy use in transport reflects a mix of concerns that varies over time and between countries. The list that you have just made will contain a number of issues and may well be influenced by what is happening at the time you are studying (e.g. if there has been a recent fuel price rise, change in vehicle taxation, an international incident affecting energy supplies or the launch of a low-carbon vehicle initiative).

It can be useful to think of transport energy issues and challenges as representing an interaction between three key groups of factors. Figure 1 shows these as three sides of a triangle: click on one of the three factors to reveal more about the concerns it involves.

Interactive content is not available in this format.

Figure 1 Transport's energy challenges

Source: based on Berridge, 2010, Figure 1-1

In recent years our growing awareness of the environmental impacts of the use of energy has attracted considerable attention, but energy shortage and the security of energy supplies are longstanding powerful concerns. Recent manifestations (as of 2012) include concerns around:

- the role of high oil prices in triggering the 2008–2010 recession
- the implications for energy security in the wake of Russia's growing power through its oil and gas reserves
- the rapidly growing energy demand in China and India
- the uncertain political fallout of the 2011–2012 democracy protest movements among oil-producing countries in the Middle East.

Transport energy strategies and policies are all part of this overall picture and, from the global to the local scale, approaches and measures need to address all these issues.

Addressing the transport energy challenge

Overall energy for transport is becoming expensive, involving difficult, costly and (as illustrated by the 2010 Deepwater Horizon disaster in the Gulf of Mexico) potentially riskier situations. Thus economic drivers are set to make energy an increasingly prominent factor in twenty-first century geopolitics. This is typified by the USA's 2007 Energy Independence and Security Act, which describes itself as:

> an Act to move the United States toward greater energy independence and security, to increase the production of clean renewable fuels, to protect consumers, to increase the efficiency of products, buildings, and vehicles, to promote research on and deploy greenhouse gas capture and storage options, and to improve the energy performance of the Federal Government, and for other purposes.

Although it cites environmental factors as support issues, this policy's core desire is to reduce reliance by the USA on obtaining hydrocarbon fuels from politically unstable regions. This is what is emphasized in US politics; for example, George W. Bush's preference was to label hydrogen as the USA's 'freedom fuel' to symbolize its potential for energy security.

However, energy security and shortage can be less compatible with environmental requirements. The easiest and most secure way to obtain energy may not be to develop environmentally clean energy. This is typified by the burgeoning interest in and development of oil shale reserves. In environmental terms, oil shale is an extremely 'dirty' fuel; Brandt and Unnasch (2010) note that fuel-chain carbon dioxide emissions from oil shale derived liquid fuels are likely to be 25–75% higher than those from conventional liquid fuels, and the processing also requires major water use (see also Boak, 2007). But oil shale is abundant and obtained from politically secure areas (with the USA and China having large domestic reserves).

For sustainable transport, the strategic energy challenge is to achieve a low-carbon transport future that simultaneously ensures adequate and secure supplies of energy. Although it is crucial to cut transport's CO_2 emissions, if an environmentally sustainable transport energy approach cannot also deliver economic, political and social sustainability then it is likely to be entirely sidelined.

2 Transport's environmental impacts

The analysis in the previous section shows that transport energy strategies need to take into account economic, political and social sustainability, as well as being environmentally sustainable. But transport's environmental impacts are proving to be particularly difficult to address.

Transport can produce both direct and indirect environmental impacts (Potter and Bailey, 2008). These are defined as follows.

- *Direct impacts*: the results of transport operations, such as pollutants emitted by vehicles, noise intrusion, traffic accident casualties, and the *land take* of roads, railways and airports (i.e. the amount of land they use).
- *Indirect impacts*: how changes in travel behaviour lead to urban sprawl, changes in activity patterns and unhealthy lifestyles.

For transport, the energy impacts tend to be more the direct impacts concerning the source and amount of energy used in vehicles. Existing forms of transport have a high dependency on oil, and are a major source of local air pollution and carbon emissions.

Local air pollution

Local air pollutants from burning transport fuels include:

- **Carbon monoxide (CO)** – this is a highly toxic gas that can impair brain function and, in sufficient concentrations, kill. Transport is the major source of CO, with some 90% coming from cars.
- **Nitrogen oxides (NO_x)** – these cause respiratory problems and contribute to low-level ozone formation and acid rain. Dinitrogen oxide (N_2O) contributes to global warming. Transport produces about half of all NO_x emissions. Diesel vehicles are an important source.
- **Particulate matter (PM)** – this is responsible for respiratory problems and is thought to be a carcinogen. Small particulate matter, known as PM_{10} and $PM_{2.5}$ (particles smaller than 10 μm and 2.5 μm in diameter respectively), is particularly dangerous as it can penetrate deep into the lungs.
- **Sulfur dioxide (SO_2)** – this is an acidic gas that can affect health and damage vegetation.
- **Volatile organic compounds (VOCs)** – benzene and 1,3-butadiene are both carcinogens and are easily inhaled owing to their volatile nature. Other chemicals in this category are responsible for the production of ground-level ozone, which is toxic in low concentrations.

To date, the main response to transport's air-quality issues has been the use of technical measures to cut engine emissions (driven by national and regional regulation) coupled with cleaner fuel formulations (a result of international standards). These different aspects will be considered later in this free course.

During the 1980s and 1990s, this approach worked well in developed countries. For example, the UK Air Quality Pollutant Inventory Report (National Atmospheric Emissions Inventory, 2011) stated that 'overall air quality in the UK is currently estimated to be better than at any time since the industrial revolution' (p. 1). Tighter European vehicle emission standards in road transport were largely responsible for a 60% cut in NO_x over the same period, and UK emissions of PM_{10} hydrocarbons declined by 58%. Yet despite such improvements, NO_x and particulate emissions remain a source of serious concern, with levels in many UK cities short of acceptable health standards. Some 60% of UK local authorities now have Air Quality Management Areas in an attempt to address this issue. In the USA, despite California's stringent emission standards for cars, air quality for the 14 million inhabitants of the Los Angeles basin currently fails to meet federal standards on around 130 days each year (though this is an improvement on the 226 days on which it failed back in 1988).

In emerging economies, where emission standards are less developed, air pollution remains very severe. In Mexico City the summer smog can be so bad that industrial plants are ordered to cut production and schoolchildren are given the month off. For the 2008 Olympics, Beijing famously banned almost half the city's cars for the duration of the games. In China as a whole, air pollution is estimated to cause around 750 000 deaths annually, making this a very politically sensitive subject (McGregor, 2007).

Transport's carbon dioxide

Even were local air-quality emissions from transport to be successfully addressed, there is a second major issue: the emission of carbon dioxide (CO_2) from fossil fuels, and the contribution of this and other 'greenhouse' gases to climate change.

Despite a number of international agreements and actions, CO_2 emissions from transport have continued to rise in all countries. This issue was highlighted in the 2006 UK Stern Report (Stern, 2006), where it was noted that between the base measurement year of 1990 and 2002, transport was the fastest growing source of carbon emissions in the rich and developed group of Organisation for Economic Co-operation and Development (OECD) countries (25% growth), and the second fastest growing sector in non-OECD countries (36% growth). Trends indicate that rather than declining over the next 40 years, transport CO_2 emissions will grow – particularly in non-OECD countries, whose share of global emissions is anticipated to increase from one third to one half by 2030.

In the UK, the recession in 2009 prevented the quantity of transport emissions in that year from rising compared to 1990. However, with other sectors having cut CO_2 emissions, the *proportion* of emissions coming from transport rose from 15.6% in 1990 to 21.7% in 2009. This share is similar in other EU countries. Over 90% of the UK's transport CO_2 emissions come from road transport (Table 2). Passenger cars remain the biggest source of CO_2, but road freight emissions are significant and those from light vans have risen substantially. Rail produces only 1.7% of transport's CO_2 emissions, despite recent substantial rises in passenger-kilometres and freight carried.

Table 2 UK CO_2 emissions by source, 1990 and 2009

Source	Emissions /Mt CO_2	
	1990	2009
Domestic civil aviation	1.4	2.0
Passenger cars	73.1	70.9
Light duty vehicles (vans)	9.4	15.3

Buses	3.8	5.3
Lorries	24.0	21.0
Mopeds and motorcycles	0.6	0.6
LPG emissions (all vehicles)	0.0	0.3
Other (road vehicle engines)	0.3	0.1
Railways	2.1	2.1
Domestic shipping	1.8	1.5
Military aircraft and naval shipping	5.3	2.5
Other transport	0.3	0.5
Transport total	**122.1**	**122.2**
Total UK CO_2 emissions	**781.6**	**563.6**
Transport as percentage of total CO_2	**15.6%**	**21.7%**

Source: Department of Energy & Climate Change (2011)

CO_2 emissions from aviation have also grown by 40%. Domestic aviation remains a small contributor, but these figures (in accordance with international accounting methods) exclude international aviation. If international aviation is included then aviation accounts for nearly a quarter of all transport's CO_2 emissions. The 2004 Transport Policy White Paper (Department for Transport, 2004) noted that because emissions at altitude have a greater global warming effect, these now represent 11% of the UK's total climate change impact.

However, although it was important to first consider CO_2 emissions from all types of transport, the focus in this free course will be on surface transport. There is a particular emphasis on travel by car, which – as mentioned above – accounts for a very large proportion of CO_2 emissions.

3 Petrol and diesel engines

The vast majority of the world's road vehicles are powered by petrol and diesel **internal combustion engines (ICEs)**, so I will start by looking at this technology, the emissions involved and ways that these emissions could be reduced.

Petrol engines

The petrol-fuelled spark-ignition engine is characterised by the use of a spark plug to initiate the combustion process. The engine uses a piston which is driven up and down inside a cylinder and connected to the drive section by a rotating crankshaft. At the top of the engine there is a cylinder head containing a number of valves controlling the flow of gas in and out. The four 'strokes' are: induction, compression, power and exhaust. An animation of this process can be found on the Animated Engines website. As is explained in the animation, on the induction stroke a small amount of fuel and air is drawn into a cylinder through the open inlet valve, which then closes. On the next stroke this mixture is then compressed into a smaller volume. This reduction in volume is a rather critical factor called the compression ratio. In a modern car it is about 9:1, i.e. the fuel/air mixture is squeezed into one-ninth of its original volume, creating a highly inflammable mixture. This is then ignited using an electric spark on a sparking plug. The gases then burn very rapidly reaching a high temperature (750 °C or more) and expand, pushing down the piston on the power stroke. Finally, on the exhaust stroke, the burnt gases are pushed out into the exhaust system through the open exhaust valve. The whole cycle then repeats.Higher compression ratios of 13:1 or more are possible using petrol, with careful engine design or by the use of fuels with a high octane rating, such as ethanol, methanol, natural gas or hydrogen. These can allow a higher combustion temperature and increased engine efficiency.

Diesel engines

The **diesel engine** works using the same four-stroke cycle as the petrol engine, but with two major differences involving the air–fuel mixture and injection systems (again, see the Animated Engines website). In the diesel engine, only the air is compressed in the cylinder instead of an air–fuel mixture, and at the end of the compression stroke, the fuel is directly injected into the combustion chamber by a fuel injection pump. A typical compression ratio of 20:1 is used, which is sufficient to raise the air temperature to over 400 °C. Once the diesel fuel is injected into the cylinder, it immediately vaporizes and spontaneously ignites.

Modern diesel engines tend to use direct-injection fuel-delivery systems, as they can be closely controlled by the use of computerized engine management systems.

In general, the fuel efficiency of a diesel engine is higher than that of a petrol engine. This is primarily due to the fact that the combustion temperature (and pressure) within a diesel engine is higher than in a petrol power unit. This increases the engine's efficiency according to Carnot's equation for a perfect heat engine. The higher combustion temperature also leads to different exhaust emission profiles between vehicles with a petrol engine and those with a diesel engine, which will be considered when I cover emissions in Section 4. In addition, although diesel fuel has almost the same energy content per kilogram as petrol, it is denser and so contains more energy per litre.For further details on petrol and diesel engines see Chapter 8 of Everett et al (2012).

Petrol and diesel vehicle energy efficiency

In a diesel engine about 32% of the heat energy is delivered to the crankshaft, whereas in a petrol engine only about 24% becomes delivered work (Everett et al, 2012). As this kinetic energy is delivered to the wheels via the mechanical drive-train, energy is 'lost' owing to friction between the transmission components and to aerodynamic drag of the vehicle. As a result, in theory only about 24% of diesel fuel's energy ends up being used for moving the car; in the case of petrol this figure is only 18%. In practice, the actual values found vary enormously with the vehicle type and with the driving conditions. ICEs are particularly inefficient in slow stop/start urban motoring and in situations of high acceleration; they work most efficiently running at a constant speed (e.g. on motorways).

If we consider how much of the fuel's energy is actually used to move the payload (as opposed to the whole vehicle), the situation is even worse. Only around 1–2% of the fuel's energy is used to move the vehicle's occupants.

Activity 2 (self-assessment)

List the key differences between petrol and diesel engines.

Provide your answer...

Answer

Petrol engines:

- compression ratio around 9:1 (up to 13:1 max.)
- relatively low temperature and pressure
- overall efficiency about 18%.

Diesel engines:

- compression ratio around 20:1
- direct injection of fuel
- relatively high temperature and pressure
- overall efficiency about 24%.

4 Petrol and diesel emissions

Petrol (known as gasoline or 'gas' in the USA) and diesel are refined from crude petroleum. More energy is required to 'crack' crude petroleum to produce shorter chains of hydrocarbons, which is why diesel needs less energy to refine than petrol (only about half as much).

Internationally, there has been a trend towards introducing cleaner conventional fuels through the removal of lead, sulfur and other additives and impurities. Lead was added as an **octane rating** improver, but owing to proven health risks (particularly its effect on the mental development of young children), leaded fuels have been phased out in most developed countries and have been banned in the EU since 2000.

European fuel specifications have also led to reduced sulfur content. Fuels that meet these requirements include ultra-low sulfur diesel (ULSD) and ultra-low sulfur petrol (ULSP). Since 2005, all petrol and diesel fuels sold in the EU have had to qualify as ULSD or ULSP, with a maximum sulfur content of 50 ppmv – whereas previous specifications allowed up to 500 ppmv sulfur content. Going even further than this, 'sulfur-free' petrol and diesel (which in practice means a maximum of 10 ppmv) has been required in the EU since 2009.

Recall that 'ppmv' stands for 'parts per million by volume'.

Emissions in use, manufacture and disposal

Conventional road transport leads to environmental pollution as a result of vehicle and fuel manufacture, the vehicles in use and the disposal of scrap vehicles. These impacts can be assessed using **life-cycle analysis**, which traces all the environmental impacts of a product – from the extraction and processing of raw materials through to manufacture and delivery of the product, its use and what happens at the end of its life. For petrol- and diesel-engine cars, the energy consumed in use (vehicles in operation) makes up most of the impact (see Figure A.2 and also studies such as Teufel et al., 1993; Mildenberger and Khare, 2000; Ecolane, 2006; Concawe, 2007; and Patterson et al., 2011). Therefore this free course focuses on the emissions associated with vehicle operation, which includes fuel production as well as use on the road.

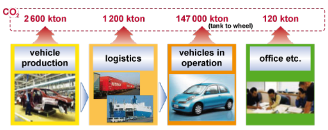

Figure 2 Typical car life-cycle emissions

There are also environmental impacts associated with road construction, road maintenance and the development of the transport and fuel-supply infrastructure. All these other impacts are important, but here I will concentrate on the energy used for the vehicle operations themselves.

4.1 Fuel performance

Within an internal combustion engine (ICE), chemical processes take place between the hydrocarbons (HCs) of the fossil fuel, the fuel additives and the gases that naturally occur in the atmosphere – predominantly oxygen and nitrogen. These processes include complete and partial oxidation of the fuel, which produces carbon dioxide (CO_2), water (H_2O) and carbon monoxide (CO). Nitrogen from the air is also oxidized to nitrogen oxides (NO_x). Partially burned and unburned fuel in the exhaust gases forms a complex cocktail of volatile organic compounds (VOCs) together with small particles of matter ('particulates' or PM). Tropospheric (low-level) ozone (O_3) is produced by the chemical action of sunlight on the VOCs and subsequent reaction of the products with oxygen in the air. In those countries that still permit the use of 'leaded' petrol, lead (Pb) is also emitted with the exhaust gases.

Petrol and diesel engines differ in their relative emissions performances, with petrol vehicles producing fewer NO_x and particulate emissions, and diesel vehicles producing less CO_2 per kilometre. The relatively high combustion temperatures attained in a diesel engine explain both diesel's higher NO_x emissions (NO_x production is predominantly associated with reaction temperature) and its lower CO_2 emissions (due to the engine's higher efficiency). Levels of particulates up to 10 micrometres in size (termed PM_{10}) are also higher for diesel, although recent technical improvements are set to almost match petrol engine performance.

Figure 3 compares average petrol and diesel emissions from a typical passenger car with an engine size in the 1.5 to 2.0 litre range. These are measured in laboratory conditions, over a defined driving cycle that represents a mix of urban and longer-distance inter-urban car journeys.

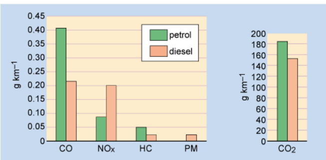

Figure 3 Vehicle emissions for a typical car

Source: Vehicle Certification Agency, 2006

Note the relative levels of CO, NO_x, PM and CO_2. To some extent, the emission profiles of petrol and diesel illustrate the general tendency for different conventional technologies to 'trade off' emissions against each other. In this case, local air-quality pollutants (NO_x, PM) are traded off against global ones (CO_2).

It should also be noted that, particularly for fuel consumption and CO_2 emissions, on-road performance will be worse than the test cycle. A Dutch study (Linterink and Bos, 2010) showed that actual CO_2 emissions and fuel consumption were 20–40% worse than the test figures. This is important as we consider emission reduction technologies, which are always quoted in terms of standard test results. Actual performance in the real world tends to be at least 20% poorer than in the laboratory tests.

4.2 Technologies and standards

During the last 30 years, as well as fuel formulations, several technological advances have significantly reduced the emissions from ICE vehicles. One of the most important developments in emission-control technology has been the introduction of the three-way catalytic converter for spark ignition engines (see Box 1). This technology was first used in the USA in the 1970s so that vehicles would conform to the US Clean Air Act, one of the first regulations that limited pollution from mobile (and stationary) sources. Since then, these catalyst systems have done much to improve air quality in the USA, Japan and Europe. More recently, diesel particulate filters (DPFs) have also been increasingly used to reduce emissions of particulates. These are a porous ceramic filter, normally with flow through walls, whereby the diesel exhaust gases flow through the filter trapping all of the particulates.

Box 1 Catalytic converters

Catalytic converters are an important type of 'end-of-pipe' technology that reduces emissions of CO, NO_x and unburned HCs from the exhausts of petrol-engine vehicles (and are hence known as 'three-way' catalysts). Catalytic converters use a mixture of platinum, palladium and rhodium metals as their active components. In the presence of excess air, these catalysts promote chemical reactions that convert emissions to less harmful gases. The catalysts are applied to a high-surface-area support structure (within the exhaust pipe) through which the exhaust gases are made to flow.

A catalytic converter unit is protected in a steel or other metal canister located within the vehicle's exhaust pipe. Most systems have to meet stringent durability requirements, including working for 100 000 km or 5 years – whichever occurs first.

Catalytic converters do have some inherent drawbacks. They are relatively ineffective before the 'light-off' temperature is reached, which means that they are inactive during short trips. Also, they tend to slightly increase fuel consumption (and hence CO_2 emissions). The precious metals in the converters can also be poisoned by certain fuel components such as lead and sulfur, which is why the use of catalysts has been dependent on the availability of lead-free and ultra-low sulfur fuels.

As in the USA and Japan, legislation in Europe continues to be tightened for vehicle emissions (see Table A.2) and has been highly successful in reducing some of the pollutants associated with road transport. Key European legislation for passenger cars has been the 'Euro' standards, introduced periodically from 1992; similar limits have been introduced for light commercial vehicles (vans) and heavy-duty vehicles (the latter specified in terms of grams per kWh of engine output).

Table 3 European emissions limits for passenger cars (grams per km)

Standard	Year	Petrol					Diesel				
		CO	HC	NO_x	HC $+NO_x$	PM	CO	HC	NO_x	HC $+NO_x$	PM
Euro 1	1992	2.72	–	–	0.97	–	2.72	–	–	0.97	0.14
Euro 2	1996	2.20	–	–	0.5	–	1.0	–	–	0.7	0.08
Euro 3	2000	2.30	0.20	0.15	–	–	0.64	–	0.50	0.56	0.05

Euro 4	2005	1.0	0.10	0.08	–	–	0.50	–	0.25	0.30	0.025
Euro 5	2009	1.0	0.10	0.06	–	0.005	0.50	–	0.18	0.23	0.005
Euro 6	2014	1.0	0.10	0.06	–	0.005	0.50	–	0.08	0.17	0.005

Note: all emissions are as measured under test using the New European Driving Cycle (NEDC).

Source: data taken from DieselNet, 2011 (latest figures)

Activity 3 (self-assessment)

Is it possible to be conclusive as to whether, in general, petrol or diesel cars produce the lowest amount of emissions?

Provide your answer...

Answer

This depends on which pollutant is chosen, but in general diesel now outperforms petrol on most pollutants and, as has already been noted, also has lower CO_2 emissions per kilometre.

4.3 CO_2 regulation

For petrol and diesel cars, CO_2 emissions are directly related to the fuel economy of a vehicle. Until recently, carbon dioxide emissions from vehicles were 'unregulated emissions', subject only to voluntary industry agreements. This changed in 2009 when the European Commission's car CO_2 emissions regulation (EC443/2009) set a sales-weighted CO_2 target for new passenger cars. The regulation specifies an average target of 130 g km^{-1} by 2015 (a 9.8% reduction on the 2010 level), proceeding to an average of 95 g km^{-1} by 2020.

Manufacturers will face significant fines if they fail to achieve their targets. These fines will be at a set rate per gram, multiplied by the number of cars registered. The fine rate will be €5 for the first gram over target, €15 for the second gram, €25 for the third gram and €95 for the fourth and any subsequent grams over target. So a manufacturer selling 1.5 million cars with an average CO_2 emissions level of 131 g km^{-1} in 2015 will face a fine of €7.5m; if their level is 132 g km^{-1} they will pay an additional €15 per car, taking the fine up to €30m; and so on. This system is being phased in from 2012 and will be fully operational, with fines, from 2015.

There is also the temporary provision of supercredits for cars emitting 50 g km^{-1} or less. These very low-carbon cars will be multiplied up in the overall calculation, and so reduce the overall average for a manufacturer. They will be calculated as being equal to 3.5 cars each in 2012 and 2013, 2.5 cars in 2014, 1.5 cars in 2015 and then normally thereafter. This is to encourage car manufacturers to develop and promote these ultra low-carbon cars sooner rather than later. Certain innovative CO_2-reducing technologies will also be granted credits.

In practice, in 2010 the average test CO_2 emissions level of cars registered in the EU was 140 g km^{-1}. In 2010, the UK average new car test CO_2 emissions level was slightly above the EU average, at 144 g km^{-1}, but this had dropped substantially from 190 g km^{-1} in 1997 and was at 165 g km^{-1} as recently as 2007 (Figure 4). In 2011 the UK average dropped further, to 138.1 g km^{-1}.

As previously mentioned, all emissions and fuel consumption are as measured under test using the New European Driving Cycle (NEDC) and do not reflect real-world driving.

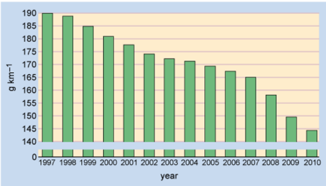

Figure 4 UK average new car test CO_2 emissions, 1997–2010

Source: redrawn from SMMT, 2011, p. 5 (Chart 2)

It appears that the EU target of achieving an average new car test figure of 130 g km^{-1} by 2015 is a real possibility, although this does depend on consumers being willing to accept smaller cars overall. However, there are also counter-trends: there is demand for more extra features within the vehicle such as air conditioning, heated seats, electric windows, auto-defrosting and on-board navigation, which all require energy to operate and can result in increased vehicle weight. In addition, the number of cars is increasing, as is peak engine power and the distance driven.

This all helps to explain the substantial gap between the reduction in new car test CO_2 figures and total CO_2 emissions from the car sector as a whole. For example, compared to 1997, in 2009 the UK's new car test CO_2 emissions were over 20% lower but the amount of CO_2 coming from UK cars as a whole had only dropped by 7%. There is a time-lag effect as the new, more fuel-efficient cars are introduced and old cars scrapped. But in addition to this, behavioural factors are seriously eroding the vehicle improvements.

Activity 4 (exploratory)

The UK has a legally-binding target to reduce all CO_2 emissions by 80% by the year 2050, compared to 1990 emission levels. Would an 80% reduction in the car fleet's test CO_2 emissions achieve this? If not, why not and what is needed to achieve an actual, real reduction to this level in CO_2 emissions from cars?

Provide your answer...

Discussion

The CO_2 emission performance of a car fleet is only part of what makes up the total emissions from the car sector. The total will be a function of the actual (not test) CO_2 emissions per kilometre multiplied by the number of cars and the total distance driven (see Potter, 2007). So if the number of cars owned increases and the distance driven increases, an 80% cut in emissions per car will result in a less than 80% cut overall. The extra cars and driving behaviour counterbalance the reduction per car/km. This is why transport policies need to address both vehicle technologies and behavioural factors, with the latter affecting the distance driven and the mode choice (between car, train, bus, walk or cycle).

Broadly, looking at the historical data on reduction in test car CO_2 emissions and reduction of CO_2 emissions from cars as a whole, technical improvements need to deliver twice the overall CO_2 reduction target to allow for on-road conditions and growth in travel and car use. Expressed in terms of test CO_2 emissions, in 1990 (the base year for the calculations) the EU average for cars was around 190 g km^{-1}. An 80% cut suggests a target of 38 g km^{-1}, but if car ownership and distance driven both increase then to get a real overall cut of 80% in CO_2 emissions, a test figure of about 20 g km^{-1} would have to be achieved.

Now, having looked at some of the issues around controlling and regulating the emissions of conventional petrol and diesel road vehicles, the rest of this free course will focus on ways in which these emissions can be reduced further: by improving existing technology, by using alternative fuels or by switching to electric vehicles. Each of these options has its own advantages and problems, as you will see.

5 Cleaner conventional car technologies

Vehicle emission legislation has been one of the strongest factors stimulating car manufacturers and their suppliers to develop less-polluting engines. Technology improvements to date include more efficient engine designs, new tail-pipe emission controls and electronic management systems, together with improved sensing devices to monitor the state of the engine and exhaust.

Up to around 2007, the main focus was on meeting the increasingly stringent EU emission standards (and the parallel air-quality emission standards in the USA and Japan). In addition to development of the three-way catalytic converter, much work has been conducted to develop new exhaust emission control systems for petrol and diesel engines. Hover your mouse over the different areas of the diagram in Figure A.5 to learn more about the functions that have been implemented in each area.

Interactive content is not available in this format.

Figure 5 Functions to minimize particulate emissions

Source: based on Piock, 2011

A crucial technology is the diesel particulate filter (DPF). This has been used to meet the substantial cuts in particulate matter required under the Euro 4 and 5 regulations for diesel engines, as well as programmes in other countries (e.g. Mexico City started a programme for particulate filters to be retrofitted to diesel lorries in 2003).

A particulate filter is a complex system containing a filter to trap the soot, an active fuelling strategy that helps burn the trapped particles and a control system to monitor the soot level, initiating combustion of the particulates when required. For heavy-duty engines, particulate emission control devices include oxidation catalysts ('one-way' catalysts) and continuously regenerating traps (CRTs). A CRTs is a diesel particulate filter system which traps the particulate and then combusts the particulate completely under controlled circumstances. The combustion (or regeneration) is carried out by a reactive gas or agent in the presence of oxygen. These devices are now fitted as standard and are proven to reduce particulates by up to 90%. Other 'after-treatment' units that are designed to reduce NO_x are also being fitted to meet the latest heavy-duty diesel standards (Euro 5 and 6); these include exhaust gas recirculation (EGR) systems and selective catalytic reduction (SCR) systems.

Activity 5 (self-assessment)

Using the data shown in Figure 6 (which is a repeat of Figure 4), calculate the percentage improvement in test CO_2 emissions between:

a. 1997 and 2007
b. 2007 and 2010.

Note any particular contrast in the rate of change.

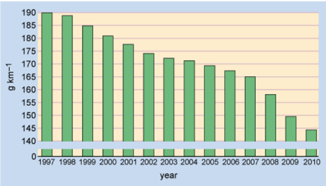

Figure 6 UK average new car test CO_2 emissions, 1997–2010

Source: redrawn from SMMT, 2011, p. 5 (Chart 2)

Answer

a. For the ten years between 1997 and 2007, the percentage improvement was (190 − 165)/190 × 100 = 13%.

b. For the three years between 2007 and 2010, the percentage improvement was (165 − 144)/165 × 100 = 13%.

Up until 2007, there was only a gradual improvement in new car test CO_2 emissions (and also fuel economy). In the ten years from 1997 to 2007, test CO_2 emissions were cut by 13%. Yet in only three years to 2010, CO_2 emissions were cut by a further 13%. The change from the poorly enforced voluntary agreement of the 1990s to the EU regulations and prospective fines of the 2009 regulations seems to have spurred real action from the car industry to improve fuel economy and cut CO_2 emissions.

5.1 Low CO_2 technologies

In the last few years, all major car manufacturers have introduced models with substantially improved fuel economy and consequent reductions in CO_2 emissions. In some companies these have been branded as an 'eco' variant range (e.g. Ford's ECOnetic, Volkswagen's BlueMotion and Skoda's GreenLine among others). Note that fuel economy and CO_2 emissions go hand in hand: since, in petrol and diesel vehicles, CO_2 emissions are a function of the fuel used, better fuel economy technologies for petrol and diesel cars also improve CO_2 emissions. (The alternative approach of switching cars to fuels with a lower carbon content will be considered in Section 5.2 and later in this free course.)

Key technologies include the following:

- Optimization of the engine for enhanced fuel efficiency
- Auto start/stop – the automatic switching-off of the car's engine when it idles (e.g. waiting in queues or at traffic lights). This can improve fuel consumption by up to 10% in urban driving (see Volkswagen's explanation of Start-Stop for further details).
- Recapturing waste energy through regenerative braking to charge the battery (thus cutting the need for the ICE to generate electric power).
- Tyres with a low rolling resistance.
- Driver information technologies – these include a Shift Indicator Light, to alert drivers to when they can reduce fuel consumption by shifting to a higher gear; and Eco Mode, a driver information system to encourage a more economical driving style.
- Aerodynamics – including body streamlining, radiator grilles, underbody panels and spoilers designed to reduce drag (see pp. 283–4 of Everett et al, 2012, for details).

Cars incorporating these technologies achieve test CO_2 emissions for a family hatchback car in the range 80–100 g km^{-1}. As noted previously, actual CO_2 emissions and fuel consumption are 20–40% worse than such test figures; as Activity A.5 revealed, a 2050 sustainability target of 20 g km^{-1} for test CO_2 emissions is needed.

Video 1 is a three-minute clip from the motoring programme *Fifth Gear* that provides an accessible and practical review of this type of car.

If you are reading this course as an ebook, you can access this video here: [Fifth Gear Web TV - Ford Focus Econetic Video Diary]

5.2 Hybrid vehicles

Drive-train 'hybridization' is a further way to improve the fuel efficiency of ICE vehicles. Petrol–electric hybrids were initially introduced in the late 1990s by Toyota and Honda, and are now offered by several car manufacturers. By February 2011, sales of Toyota's Prius (Figure 7) had reached 3 million worldwide; in the USA, hybrids have around a 3% share of new car sales. By 2012, around a million hybrids were being sold worldwide annually (of which about 15 000 were bought in the UK). With the introduction of many new models, sales are expected to increase significantly over the next few years.

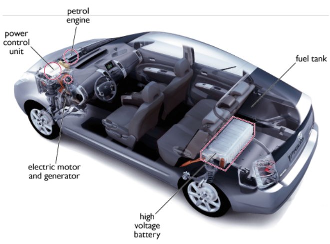

Figure 7 Cutaway of a Toyota Prius

The principle underlying all hybrid vehicles is the use of a rechargeable battery as an energy buffer that enables the main ICE to be operated at close to maximum efficiency. The electric engine is used at low speeds and to assist acceleration – situations when ICEs are least fuel efficient. The battery is charged by the ICE when the engine loading is low. This means that the ICE is used more efficiently and so fuel economy improves. The use of an on-board battery also enables better use of regenerative braking and start/stop than in a conventional petrol or diesel car.

Overall, hybrids reduce fuel consumption through a combination of the following:

- reducing wasted energy during idle/low output, generally by turning off the internal combustion engine
- recapturing waste energy through regenerative braking
- allowing the internal combustion engine to run at greater efficiency by letting the electric motor take over for key engine loadings.

Current models of family hatchback hybrid, such as the Prius and the Lexus CT, have CO_2 emissions in the 89–94 g km^{-1} range. A comparable standard petrol car would have emissions of around 130–160 g km^{-1}, and a diesel around 110–140 g km^{-1}, with 'eco' diesels somewhat less (e.g. the Ford Focus Ecotronic at 99 g km^{-1}). Higher-performance sports saloon hybrids (e.g. the Lexus IS) achieve 135 g km^{-1}, again much lower than a standard petrol or diesel equivalent.

Overall, hybrids cut CO_2 emissions by around a third compared with the best equivalent non-hybrid car, and by up to 20% compared with 'eco' diesels. When they were first introduced, hybrid cars did cost more to buy than a diesel or petrol equivalent, but with volume production the price difference has been narrowed.

A development of the hybrid design, that makes less use of the ICE by incorporating the plug-in technology of an all-electric vehicle, will be considered in Section 7.2.

The scope of emission reduction

A limiting factor to reducing CO_2 emissions from petrol and diesel cars is the carbon intensity of the fuel used. Whatever is done to improve fuel efficiency, there is a limit set by the fact that petroleum-based fuel is carbon intensive. As already mentioned, in the long term – to 2050 – an 80% reduction in CO_2 emissions is being sought. However, the improvements to petrol and diesel cars that have been discussed so far, though substantial, are limited by the chemistry of the fuel itself as well as by the thermodynamic efficiency limits of combustion.

To date, improvements to petrol and diesel car designs and the introduction of hybrid vehicles have put us on a path towards the EU-regulated targets of 130 g km^{-1} by 2015 and 95 g km^{-1} by 2020. However, even the best petroleum-based technologies cannot reach the sustainability target we have identified of 20 g km^{-1} (unless all cars become much smaller, slower and lighter – more akin to a scooter!). The sections that follow will therefore look at some alternatives to petrol and diesel engines.

6 Lower-carbon fuels

CNG and LPG vehicles

An alternative approach to cutting CO_2 emissions by improving fuel efficiency in petrol and diesel cars is the use of transport fuels with a lower carbon content. There have been a number of developments of 'alternative fuel' ICE vehicles. Two fuels in particular, compressed natural gas (CNG) and liquefied petroleum gas (LPG), have come to be widely used.

CNG vehicles (for details see this link on CNG and LPG vehicles) have been utilized in a number of countries for many years, with Argentina, Brazil, Pakistan, Italy and India operating the largest fleets. The Argentinean government in particular were early promoters of the fuel, partly in response to severe air-pollution problems in Buenos Aires, and partly to conserve their own supplies of oil for export to earn foreign currency (International Energy Agency, 1999). However, it is for air-quality emission improvements that CNG and LPG technologies have mainly been adopted.

For heavy-duty vehicles such as buses (Figure 8), compared to diesel, using CNG or LPG achieves reductions of around two-thirds for both NO_x and particulates. Emissions of hydrocarbons are reduced by well over 50% for LPG, but are significantly higher for heavy-duty CNG vehicles. However, most of these HC emissions are composed of methane that can be almost eliminated from exhaust gases by the use of methane catalyst systems.

Figure 8 LPG bus in Strasbourg, with fuel tanks on the roof

For light-duty vehicles, most local air-quality pollutants are significantly reduced by using LPG or CNG. Compared to a petrol car, NO_x is reduced by at least a third and particulates are virtually eliminated. Hydrocarbons are also reduced in LPG vehicles, but the presence of non-combusted methane in the exhaust gases can be a problem, as methane is a powerful greenhouse gas.

For cars, CNG and LPG vehicles achieve a 10–20% reduction of fuel life cycle CO_2 emissions compared to petrol cars, but little improvement compared to diesel cars or hybrids. Fuel life cycle analysis is a technique to assess the environmental impacts associated with all the stages of a fuel's life from extraction (oil or gas wells) through processing, distribution and use.

Although they are still in use around the world, interest in CNG and LPG cars has waned as the latest technologies applied to petrol and diesel engines have largely matched the emissions performance of LPG and CNG vehicles. For heavy vehicles such as lorries and buses, CNG and LPG remain competitive, although hybrid diesel–electric buses are making serious inroads to this market.

Overall, although CNG and LPG can cut CO_2 emissions, because they are derived from fossil fuels they do not represent a path that can radically reduce transport's carbon intensity.

Biofuels

With there being a limit to the carbon reductions achievable from petrol, diesel, CNG and LPG, attention has shifted towards fuels that can be used in ICEs and that have substantially lower CO_2 emissions. The most significant developments have been in liquid biofuels: renewable fuels that can be produced by the fermentation of energy crops or from vegetable oils or animal fats. Such fuels can reduce the transport sector's dependence on fossil fuels and potentially achieve major cuts in greenhouse gas emissions, since the crops used are part of the natural carbon cycle.

Biofuels can come from a wide number of sources, and include:

- **bioethanol**, an alcohol that can be produced from virtually any fermentable source of sugar
- **methanol**, an alcohol that is largely produced from natural gas, but that can also be produced from biomass
- **biodiesel**, which is most commonly produced from energy crops such as oilseed rape or recycled vegetable oils; the use of waste oil as feedstock is particularly beneficial, as there is little additional CO_2 generated in the production of the fuel
- **biogas**, which is gas produced from biological processes (e.g. from an anaerobic digester); this can be used in vehicles adapted for CNG (Figure 9).

For further information see 'Biofuel types' in Department for Transport, 2012a; U.S. Department of Energy, 2011; 'Methanol' and 'Renewable Natural Gas' in U.S. Department of Energy, 2012; and CPL Press, 2009.

Figure 9 A dual-fuel bus running on gas from a landfill site: originally powered entirely by diesel, the Mercedes-Benz engine has been adapted to run for 60–80% of the time on biomethane

Practical use

The most common way to introduce biofuels has been as a 5% blend with mineral petrol or diesel. This requires no adaptation to a vehicle's engine or fuel system, but only results in a small cut in emissions.

High percentage blend alcohol fuels require modified engines – for instance, flex-fuel vehicles are able to run on fuel consisting of up to 85% alcohol blended with petrol (known as E85). As alcohol has a relatively low energy density (per unit volume), this also means that such vehicles require much larger fuel tanks than petrol vehicles.

While high percentage blend biodiesel fuels can be used in some older conventional diesel engines, there is an issue of increased corrosion of rubber seals and piping, so replacement with non-rubber alternatives is advised. Biodiesel has only a slightly lower energy density than mineral diesel, so standard-size fuel tanks are fine, although fuel consumption is about 5% worse.

A number of countries have introduced policies to promote biofuels. During the 1970s and 1980s, ethanol produced from sugar cane was vigorously promoted in Brazil (Figure 10), both as a response to a slump in the global price of sugar and to reduce the country's dependence on foreign oil imports.

Figure 10 Filling a car with sugar-cane-derived ethanol in Brazil

In the USA, energy security concerns in the wake of the 1970s oil crisis led to the serious development of ethanol production from energy crops (particularly maize). This was accelerated following the Energy Policy Act of 1994, and in 2005 the USA overtook Brazil as the world's largest ethanol producer. However, unlike ethanol derived from sugar cane, which has significant carbon benefits, 'corn ethanol' can lead to an increase in fuel life cycle CO_2 emissions – this is detailed on the next page.

In Europe, the EU Biofuels Directive of May 2003 stipulated the replacement of 5.75% of all transport fossil fuels (petrol and diesel) with biofuels by 2010. In order to comply with this directive, in 2008 the UK introduced the Renewable Transport Fuels Obligation specifying that the amount of biofuel in UK petrol and diesel increase annually to around 5% (by volume) by April 2013 and remain at that level for subsequent years (see 'Renewable Transport Fuels Obligation' in Department for Transport, 2012a).

Activity 6 (exploratory)

What has motivated the adoption of the alternative fuels considered so far (both biofuels and CNG/LPG)? Is it energy security, energy shortage, local air-quality emissions, climate change emissions or something else?

Provide your answer...

Discussion

Energy security and economic reasons seem to have played a major role in the initial development of many alternative fuels. In some instances, particularly the use of CNG in heavy vehicles, local air-quality emissions have also been important. The approaches that seem to have had most support are those that address a combination of these factors.

Environmental impacts

Compared to conventional fossil fuels, CO, HCs and particulates are generally reduced for the E85 mix (85% ethanol and 15% petrol), M85 methanol blends and pure-alcohol fuels. Air-quality emissions for biodiesel are also reduced when compared to mineral diesel – comparative tests suggest that particulate emissions are 10–15% lower than with ultra-low sulfur mineral diesel. Biodiesel's low sulfur content also allows the use of advanced emission control systems, which can further reduce particulates. However, some pollutants are increased when using biofuels, including higher NO_x for biodiesel.

The great promise of biofuels is their potential to be carbon neutral, as all the CO_2 emitted during the processing and use of the fuel is theoretically balanced by CO_2 absorption from the atmosphere during the fuel crop's growth. However, in practice this is rarely the case, as the process of growing the biomass requires the input of fossil fuels for fertilizers, harvesting, crop processing and fuel distribution. The actual extent of greenhouse gas emissions is therefore strongly dependent on the type of energy crop grown and the fuel processing used.

For example, in Brazil – where sugar cane is used as the feedstock for ethanol production (Figure 11) – large amounts of bagasse (the woody fibres that remain after the juice is extracted from the cane) are used to provide the process heat energy. As a result, the average energy ratio of ethanol output to fossil fuel input is of the order of six, i.e. six units of energy are produced for each unit input. Therefore, on a fuel life cycle basis, carbon emissions are significantly reduced – by up to 90%. This contrasts with the net energy ratio for corn-derived ethanol from the USA, which in some cases can be negative (i.e. the fossil fuel required to produce the ethanol is greater than the energy value of the final product).

Figure 11 Harvesting sugar cane

Similarly, the results of life-cycle analysis of greenhouse gas emissions for biodiesel depend on the production processes employed. For biodiesel produced from waste oil, there is a substantial CO_2 reducing effect – often by as much as 85%. For rapeseed biodiesel, the carbon benefits are around 40%, taking into account upstream emissions from the production of fertilizer (Concawe, 2007).

Biogas produced from a food waste anaerobic digester also has clear environmental benefits. This is set to be an increasing source of biogas, as there is a UK programme to build anaerobic digesters to reduce waste sent to landfill sites (see TheBioenergy-Site, 2009).

Overall, it appears that if the right sort of biofuel and production system is used then this is a potentially sustainable transport technology.

Activity 7 (self-assessment)

What is the carbon-reduction potential of biofuels?

Provide your answer...

Answer

Biofuels present a complex picture. If produced in the right way, some biofuels can be very carbon efficient; others are not.

Even for fuels that have a good carbon-reducing potential, there is an issue around the amount of biofuel produced (e.g. the level of CO_2 emitted from waste oil or biogas is very good, but only a limited amount of these fuels is available).

Problems

The analysis so far suggests that the right sort of biofuel could yield a significant reduction in CO_2 emissions from transport vehicles. However, since around 2007 there have been serious criticisms of biofuels in terms of:

- diversion of productive land from growing food
- destruction of rainforest for palm oil production
- rich firms driving poor people off their land to convert it to fuel crops (Figure 12).

An example of such criticism is the online BBC News report 'Will biofuel leave the poor hungry?' (Ayre, 2007).

Figure 12 The biofuel dilemma

In January 2008 the EU announced that they were rethinking their biofuel programme due to environmental and social concerns, and new guidelines were issued to ensure that EU targets are not damaging. At the same time, the UK House of Commons Environmental Audit Committee raised similar concerns and called for a moratorium on biofuel targets. In 2009 the UK Renewable Transport Fuels Obligation target for 2010/11 was cut from 5% to 3.5%, although it is still aiming for 5% by 2013 (Renewable Fuels Agency, 2009).

A 2011 Nuffield Report (Nuffield Council on Bioethics, 2011, p. xxv) advocated the potential benefits of biofuels, but recommended that they should be subject to a certification scheme to ensure that biofuels:

- are not produced at the expense of human rights
- are environmentally sustainable
- contribute to an overall reduction of greenhouse gases (as you have seen, some currently increase greenhouse gases)
- adhere to fair trade principles
- have costs and benefits that can be distributed in an equitable way.

Potential

Second-generation biofuels

As biofuels have developed, there has emerged the need to address wider strategic issues around their production. Currently we largely produce 'first-generation' biofuels, made from the fruit starch or grain of a plant. Producing such crops for biofuels results, to some degree or another, in the problems outlined on the previous page.

Such problems may be addressed by 'second-generation' biofuels that are only just emerging. These include products such as cellulosic ethanol, biohydrogen and wood diesel, which are produced from agricultural residue and waste materials. Crucially, they do not directly compete with food production, nor do they require the destruction of natural habitats to expand.

Using current technologies we do produce some biofuels from waste sources, such as processing used cooking oil and biogas, but this is only available in very small amounts. If agricultural waste and refuse were used to make biofuels, this could lead to large-scale production that might replace 20% of current transport fuels. By using waste, such fuels have the potential to reduce CO_2 emissions by up to 90%.

However, at the moment the technology of producing second-generation biofuel from waste is not fully developed and the costs are high.

If you wish to explore this issue further, a useful online review of biofuel issues is provided on the explainthatstuff website.

Third-generation biofuels

The long-term solution for biofuels could be production using microalgae (Dragone et al., 2010) – see also Figure 13 and Video 2 below. Algae can produce very large volumes of feedstock for biodiesel and bioethanol much more efficiently than production from plants. It can also use land not suitable for agriculture. The process could be undertaken sustainably and so cut CO_2 emissions by 90% compared to current transport fuels.

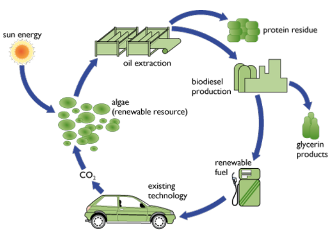

Figure 13 Microalgae biofuel production

If you are reading this course as an ebook, you can access this video here: Biofuel Production using Microalgae

However, several important cost, scientific and technical barriers remain to be overcome before the large-scale production of microalgae-derived biofuels can become a commercial reality.

Activity 8 (self-assessment)

Briefly summarize the prospect for biofuels.

Provide your answer...

Answer

Overall, biofuels as currently produced (with certain exceptions) make a limited contribution to cutting transport's CO_2 emissions. However, in the long term – despite limitations and serious issues around current biofuel production – advanced, third-generation biofuels could represent a permanent sustainable fuel solution.

7 Electric vehicles

Battery electric vehicles

The concept of third-generation biofuels is to cut or eliminate pollutants in the fuel production process. This fuel-switch approach also includes policies to promote electric and hydrogen vehicles, which enable pollutants to be reduced either during manufacture (e.g. in generating electricity at power stations/hydrogen at refineries) or by using renewable sources of energy that produce little pollution at all. The move towards such a fuel-shift strategy thus brings together action to cut transport's local and global environmental impacts. It is also one that has the potential to link to the powerful political driver of energy security.

Although the use of batteries and electric drive in hybrid cars is now mainstream, an entirely electrically powered car requires the storage of large amounts of energy on board the vehicle. One way to do this is, of course, in batteries. Older types of battery electric vehicle (BEV) used lead acid batteries, but most current electric vehicle designs use lithium-ion (Li-Ion) and lithium-polymer (Li-Poly) traction batteries. These have a much higher energy density (100–125 W per kg), providing a significant improvement in driving performance and vehicle range.

First-generation electric vehicles used direct current (dc) motors, but more recent cars convert the direct current to alternating current (ac) using an inverter, which then drives an induction motor. These vehicles have increased efficiency, have a higher specific power (per kg) and require less maintenance.

Until recently, BEVs were only available in small numbers as variants of ICE cars (e.g. the Peugeot 106 electric car, manufactured from 1995–2003). A dedicated BEV design, the REVA G-Wiz micro car (legally classed as a 'quadricycle'), was launched in 2001 and has secured a small niche market, selling 4000 vehicles worldwide by 2011. Renault's recently launched 'Twizzy' is also an electric 'quadricycle'.

More significantly, since 2010 a number of dedicated high-performance BEVs have been launched commercially, including the Mitsubishi iMiEV, the electric Smart, Nissan's Leaf (Figure 14), the Peugeot iOn, Renault's Fluence and the Teslar Roadstar 210 kph sports car. The Mitsubishi iMiEV EV technology website provides a good overview of key features of modern BEVs; if you wish, you can also follow this link to find BEVs available in the UK.

Figure 14 A Nissan Leaf charging from a public point in Milton Keynes at the car's national UK launch in spring 2011; by January 2012, global sales of the Leaf had exceeded 20 000

One of the main concerns about BEVs is that they only have about a 160 km (100 mile) range and that in most cases recharging is slow (6–8 hours). They also cost about a third more than a comparable ICE car, although much-reduced running costs counteract the high initial purchase price.

Promoting battery electric vehicles

The commercial launch of a range of BEV designs is part of a UK government/industry partnership approach that envisages a long-term transition to a low-carbon transport future in which cleaner internal combustion technologies are joined by an initial widespread uptake of battery electric vehicles and then 'plug-in' hybrids, followed later by hydrogen fuel cell vehicles (New Automotive Innovation and Growth Team (NAIGT), 2009). Similar programmes have taken place in France, Germany, Spain and the USA. Figure 15 shows the technology uptake 'roadmap' from the 2009 NAIGT report.

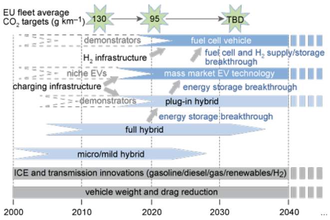

Figure 15 Product development roadmap

Source: redrawn from New Automotive Innovation and Growth Team, 2009, p. 45

Note that this roadmap envisages that BEVs will only initially have a niche market, which will pave the way to mass-market EVs from 2020 onwards. The roadmap includes EU fleet average targets for CO_2 emissions, but does not indicate a target beyond 2020.

This long-term strategy is supported by government programmes to encourage the uptake of BEVs. These have included, up to 2015, purchase subsidies (worth up to £5000) to help overcome the high initial cost of battery electric cars, and a programme to provide recharging infrastructure through grants to local authorities. The full UK programme is coordinated by the Office for Low Emission Vehicles. (For further information, see 'Plug-in Car Grant' and 'Recharging infrastructure' in Department for Transport, 2012b).

Activity 9 (exploratory)

BEVs are a good illustration of the different cost structure of low-carbon vehicles. Table A.3 shows some key costs of the Nissan Leaf BEV and a comparable ICE car – the Ford Focus diesel.

Table A.3 Cost comparison of an electric car and a diesel counterpart

	Nissan Leaf (electric)	Ford Focus (diesel)
Purchase price	£24 000 (after £5000 subsidy)	£19 500
Annual car tax	£0	£125
Annual fuel costs*	£230	£1100
Average annual parking and toll charges	£80	£180

Annual insurance	£280	£550
Annual interest on purchase loan	£600	£490

* Assuming 10 000 miles/16 000 km a year

If someone chose to buy a Leaf instead of a Focus, how long would it take for the lower running costs to repay the higher purchase cost?

Discussion

The Leaf costs £4500 more to buy than the Focus (even taking into account the £5000 purchase subsidy). The annual savings amount to £1255. Therefore the payback period is four years for these savings to repay that higher initial cost.

Without the (temporary) purchase subsidy, the Leaf would cost £9500 more than the Focus, pushing the payback period up to eight years. The chances are that the car would have been sold by then, so other financial factors – such as resale price and, possibly, battery replacement – would come into play.

This cost structure means that low-carbon vehicles can only have a relatively small price premium if they are to be financially competitive.

Despite the purchase subsidy that has cut the price of a BEV to around £24 000, there has been a slow uptake of these grants in the UK. Grants became available from January 2011, with £43m allocated until 31 March 2012 – enough to support the purchase of 8600 cars – yet in 2011, only a little over a thousand grants were made. The market launch of plug-in hybrids, considered next, may increase the rate of grant uptake; the scheme has now been widened to include electric vans and will run to 2015.

'Plug-in' electric/petrol hybrid

As you saw in Section 5.2, hybrid vehicles use a battery and electric engine to improve the fuel efficiency of their internal combustion engine. They only run on electric power alone for limited slow-speed manoeuvring. 'Plug-in hybrid electric vehicles' (PHEVs) use this hybrid configuration to operate more on electric power. They thus have a larger battery than ordinary hybrid cars, with some running for 50 kilometres (30 miles) or more before the ICE cuts in; the ICE then runs as an efficient generator to provide power for the car's electric motors.

A key advantage of this configuration is that it overcomes the range limitation of a BEV while still allowing the car to run entirely on electricity for shorter trips. A further advantage is that these cars have the potential to be even more efficient than conventional hybrids, because (when used) the ICE runs at closer to its maximum efficiency.

The term 'plug-in hybrid electric vehicle' can lead to confusion between such cars and ordinary hybrids, and the term 'extended-range electric vehicle' is now also used to describe this technology. You should now watch Video 3, which explains how a plug-in hybrid works. This features the Opel/Vauxhall Ampera (Figure 16) which, under its US branding as the Chevrolet Volt, was the first extended-range electric vehicle to market: it was launched in the USA in 2011. About 25 000 US sales are expected in 2012, and Vauxhall also anticipates selling up to 3000 Amperas in the UK during 2012, largely to fleet buyers.

Video content is not available in this format.
Video 3 How a plug-in hybrid works

Figure 16 The Volt/Ampera

The Ampera can travel around 60 kilometres (possibly up to 80 km if driven carefully) on its lithium-ion battery pack before the ICE cuts in. At £30 000 the Ampera is an expensive car for its class, but it qualifies for the £5000 UK plug-in grant. As with all low-carbon vehicles, there is a price premium that is counterbalanced by lower fuel costs. However, comparable ICE cars cost around £20 000 (or less).

The Toyota Prius plug-in is to be launched in the UK in late 2012, with a UK price about the same as the Ampera. The Prius plug-in (Toyota prefer the term 'plug-in') also uses a high energy density lithium-ion battery, but one that is smaller than the battery used in the Volt/Ampera; thus its range on electricity alone is only 20 kilometres (12.5 miles).

The Prius plug-in has official test CO_2 emissions of 59 g km^{-1} (compared to 89 g km^{-1} for a regular hybrid Prius). The Ampera, with its longer battery range, is rated at 42 g km^{-1} CO_2. However, the actual emissions will depend very much on the mix of electric and ICE driving undertaken.

Further plug-in/extended-range EVs are due for market launch soon, and are viewed as having both the potential for high market penetration and the technical potential to achieve very low carbon emissions. For example, Volkswagen's XL1 two-seater electric/diesel PHEV concept car has a combined test fuel consumption of 0.9 litre per 100 km and test CO_2 emissions of 24 g km^{-1}. This achievement by a concept vehicle design is impressive, but for the car fleet as a whole the emission rate would be higher, as this design would fall at the bottom end of the range of vehicle sizes. Were a range of plug-in/extended-range EVs to be available, and assuming a certain amount of overall downsizing, a CO_2 emissions fleet average of around 45 g km^{-1} might be achievable.

This emission rate could be further improved if this technology were combined with low-carbon biofuels. This would overcome both the disadvantages of BEVs and the current limited supply of sustainable biofuels. Moreover, it would further lower CO_2 emissions as both the electricity and the biofuel could, potentially, be produced in a decarbonized form.

Fuel cell vehicles

A **fuel cell vehicle (FCV)** is an electric car, but instead of using a battery, energy is stored as hydrogen and a **fuel cell** converts that hydrogen into electricity to run the electric motor. A small battery is also used as an energy store for regenerative braking. The general design of an FCV is shown in Figure 17.

Interactive content is not available in this format.
Figure 17 Layout for Honda Clarity fuel cell car

Hydrogen fuel cells are widely viewed as the eventual future technology that will power cars and other vehicles, and are the technology to which the NAIGT roadmap leads. As a fuel, hydrogen has the highest energy-to-weight ratio of all fuels, with 1 kg of hydrogen containing the same amount of energy as 2.5 kg of natural gas or 2.7 kg of petrol. This is in stark contrast to the low energy density storage of even the best batteries.

Like electricity, hydrogen can be manufactured in a wide variety of ways. Although today it is largely produced using natural gas as feedstock, hydrogen can be manufactured using renewable energy through the electrolysis of water. (For details of how fuel cells work see Everett et al 2012, pp. 587–91).

Hydrogen can be used in an ICE vehicle (an option explored by car manufacturer BMW), but it is largely being developed for use with fuel cells to power an electric motor. Fuel cells convert chemical energy directly into electrical energy, with the only by-products being water and heat. There are no pollutants emitted in use.

Most fuel cells consist of two electrodes, an 'anode' and a 'cathode', which are separated by an electrolyte that allows the transfer of ions. When the reactants are fed into the cell, chemical reactions occur between the fuel/oxidant and the electrolyte. The main charge carriers (usually H^+) cross the electrolyte and the electrons are transferred via an external circuit. The electric current produced can be used to drive a motor. This is demonstrated in the fuel cell animation provided by the U.S. Department of Energy.

There are a number of types of fuel cell, but the polymer electrolyte membrane (PEM) fuel cell is the type best suited to transport traction purposes. Individual fuel cells designed for use in vehicles each produce a power output of under 150 watts. Larger outputs are achieved by assembling cells in series or parallel to form a 'stack'. Fuel cells are able to achieve higher conversion efficiencies than heat engines, and efficiencies of up to 80% have been demonstrated in the laboratory – though in practical vehicle use, 45% is the sort of efficiency achieved. For further details, see the Howstuffworks basics on fuel cells.

As with biofuels and BEVs, fuel cell cars are an example of an approach towards shifting to a fuel that has the potential to be produced sustainably – but rather than the fuel being stored as electricity, as in a BEV's battery, it is stored in a hydrogen tank, with the hydrogen converted to electricity using the fuel cell.

FCVs in practice

Interest in fuel cells for road transport developed with the rise in environmental concerns around transport in the 1980s and 1990s. Most of the major vehicle manufacturers have produced prototype FCVs; in addition, new companies have emerged that specialize in the manufacture of fuel cell systems. One such company is Ballard Power Systems, which in the 1990s collaborated with DaimlerChrysler and Ford to make the world's first fuel cell bus and the demonstration NECAR (New Electric Car).

A large number of prototypes and demonstration cars have been developed in the last 20 years. Recent examples of near-production vehicles include the Honda FCX Clarity, the Toyota FCHV-adv and the Mercedes-Benz F-Cell. Altogether, these various demonstration FCVs have driven around 3 million kilometres in trials.

Several car manufacturers have announced plans to introduce a production model of a fuel cell car from 2015, but there have been previous announcements of a similar kind, with launch dates being subsequently postponed. Policy assumptions are that FCVs will not be widely available until around 2025–2030. There remain several issues to address, including the following:

- *Costs* – like all low-carbon vehicles, there is a price premium for FCVs. A 2015 launch price of US$50 000 is being mentioned for the Honda Clarity, although this will include a company subsidy.
- *On-board storage* – although hydrogen contains three times more energy per *weight* than petrol, it contains only a third of the energy per *volume*, making on-vehicle storage bulky. Hence the large tank shown in the diagram of the Honda Clarity (Figure A.17) and the need for very space-efficient designs.
- *Hydrogen losses in on-board storage* – some gas is vented and lost in storage on the vehicle.
- *Fuel cell stack durability* – this is currently about half of what is needed for commercialization. Durability has increased substantially over the past few years, to 120 000 km, but needs to be closer to a 250 000 km lifetime.
- *Refuelling infrastructure* – this is an even bigger issue than for BEVs (which only need limited public charging points, as electricity is readily available in homes and workplaces). Hydrogen refuelling will require a whole new system, with only a handful of refuelling points currently available globally. It is estimated that it would cost at least a billion euros to create a hydrogen refuelling network for Germany alone.
- *Source of hydrogen* – producing hydrogen from non-fossil sources (biomass, wind, nuclear) has a limited potential and is expensive. The 2007 Concawe report suggested that the more efficient use of renewables would be through direct use as electricity rather than to manufacture hydrogen.

The last point is crucial and raises doubts as to whether hydrogen fuel cell cars are a viable route to low-carbon transport. For example, if you started with a renewable source of energy such as biogas, this could be compressed and directly used in a CNG or CNG/electric hybrid car. To be used in an FCV, the gas would have to be processed (reformed or used to power electrolysis) into hydrogen, compressed and pumped into a tank for fuelling a car. There are energy losses at each stage and in storage. Thus although the energy efficiency in *use* in an FCV is better than in an ICE or hybrid car, the *overall* energy loss is greater.

Activity 10 (exploratory)

Work out the energy losses for the following fuel supply chains from renewable fuel to powering an engine.

a. Renewable electricity → hydrogen by electrolysis → fuel cell → electric power to drivetrain
b. Biogas → electricity → hydrogen by electrolysis → fuel cell → electric power to drivetrain
c. Biogas → ICE vehicle → power to drivetrain
d. Biogas → ICE hybrid vehicle → power to drivetrain

Take a starting index of 1.0 and assume the following:

- generating electricity from biogas is at 60% efficiency
- electrolysis is at 65% efficiency
- compression and distribution losses for hydrogen are 10% (i.e. 90% efficiency)
- fuel cells operate at 45% efficiency

- a CNG ICE vehicle operates at 30% efficiency
- a CNG ICE hybrid vehicle operates at 35% efficiency.

Discussion

The energy efficiency chains are as follows.

a. Renewable electricity (1.0) → hydrogen by electrolysis (1.0 × 65% = 0.65) → hydrogen to car (0.65 × 90% = 0.59) → fuel cell (0.59 × 45% = 0.26) → electric power to drivetrain (0.26)

   Energy loss: 74%

b. Biogas (1.0) → electricity (1.0 × 60% = 0.60) → hydrogen by electrolysis (0.60 × 65% = 0.39) → hydrogen to car (0.39 × 90% = 0.35) → fuel cell (0.35 × 45% = 0.16) → electric power to drivetrain (0.16)

   Energy loss: 84%

c. Biogas (1.0) → ICE vehicle (1.0 × 30% = 0.30) → power to drivetrain (0.30)

   Energy loss: 70%

d. Biogas (1.0) → ICE hybrid vehicle (1.0 × 35% = 0.35) → power to drivetrain (0.35)

   Energy loss: 65%

The long fuel conversion chains result in serious energy losses, with 70–85% of the energy being lost. This supports the case for renewable fuels to be used as directly as possible.

Getting FCVs established

The mainstream industry approach towards fuel cell vehicles does suggest that although some vehicles may be available in the next few years, the widespread use of fuel cell cars is at least a decade (if not more) away. One approach is to introduce FCVs for fleets, with buses and delivery vehicles being obvious pioneer applications. The problem of tank size is less acute for larger vehicles, and these fleets can be served by dedicated fuelling and maintenance depots, overcoming the refuelling problem.

Global demonstration programmes of fuel cell buses include the EU CUTE (Clean Urban Transport for Europe) project that ran from 2005–2007, closely followed by the HyFLEET: CUTE project (2006–2009) that tested 33 Mercedes-Benz Citaro fuel cell buses in 10 cities worldwide, including London – see Figure 18. Following this experience, London now operates ten fuel cell buses serviced by its own hydrogen fuelling station (if you wish, follow the link for details). The year 2011 also saw the opening of the UK's first public hydrogen station at the Honda manufacturing facility in Swindon, part of the planned Hydrogen Highway along the M4 (this BBC report and video clip present a somewhat optimistic view that ignores fuel manufacturing and distribution issues, but explains well how hydrogen fuelling works).

Figure 18 A Mercedes-Benz Citaro fuel cell bus in service in London during the CUTE demonstration (the hydrogen tanks are on the bus roof)

Another approach to getting FCVs established is to redesign the system whereby people obtain a car to one that better suits FCVs. To some extent, manufacturers have already done this for BEVs – for example, by leasing cars and batteries to address the problem of high initial cost. One company has sought to take this approach by designing both the car (Figure 19) and the way cars are provided to overcome the usual FCV problems. This is the small UK company, Riversimple, whose founder explains their philosophy in Video 4.

Figure 19 The Riversimple concept vehicle

If you are reading this course as an ebook, you can access this video here:
The Open Source Hydrogen Car

Riversimple's open source and collaborative approach has produced an energy-efficient and lightweight concept design that only requires a small fuel cell stack and a small hydrogen tank to provide a range of 380 km (240 miles) – see Riversimple (2010) and Figure 20. This keeps the costs low, with life cycle CO_2 emissions of 31 g km^{-1} from hydrogen manufactured conventionally from natural gas. This design, with its emphasis on energy efficiency, does not require major improvements in the production of hydrogen to cut CO_2 emissions, and so helps to overcome the Cancawe (2007) criticisms about hydrogen production. In other words, this design seeks to overcome the problem of losses in the long fuel conversion chain.

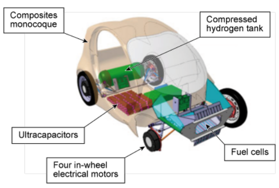

Figure 20 Riversimple cutaway diagram

However, it is not just the car design that is optimized for fuel cells. The design of the business model for how customers obtain the car is also new (Thackara, 2010). People buy not a car but a mobility service. The monthly lease (much like that for a mobile phone) will cover all costs including vehicle maintenance, insurance and fuel deliveries. This overcomes the fuel supply problem to users and also means that Riversimple, not its customers, bears any risks involved in being a pioneer (so customers don't need to worry about uncertain resale value, or if the vehicle or fuel cells have a major failure). Customers will interact with Riversimple and its user community through a personalized digital interface accessed from the car, on their computer or via their mobile phone. In this way they will be able to manage their account, request maintenance, ask questions, order fuel and so on.

At the time of writing, we have yet to see how successful this individual company, the car design and the new business model will be – a 30-car trial of both the cars and the leasing model will commence in Leicester in 2012. However, this example shows that it is not only the vehicle technology that needs to change in order for us to move towards sustainable transport: the way in which we obtain mobility also needs to change.

Models of wider transport service packages are being developed that include not only access to cars but access to train, bus and other travel services as well. Examples include the GO-OP car, bus and rail cooperative, and Mobility car share in Switzerland. These models also have beneficial impacts on travel behaviour, because their pricing structure encourages travel by bus and train, or more efficient travel in general.

8 Decarbonized transport

Environmental performance of low-carbon vehicles

We are entering a time when a whole range of new transport technologies and fuels is becoming available. Each of these, alone or in combination, has the potential to reduce CO_2 emissions to some degree or another. Those based on fossil fuels (petrol, diesel, CNG and LPG) have a more limited potential because of the high carbon intensity of the feedstock fuel. The CO_2 reduction potential of biofuels, electricity and hydrogen depends crucially on how the fuel in question is produced. In addition, some technologies (particularly those involving batteries) have issues around the low energy intensity of storage.

As noted earlier, life-cycle analysis indicates that the main environmental impact of petrol and diesel cars (some 70% or more) comes from their use of fuel. Yet for low-carbon vehicles the situation is different; CO_2 from the production of the vehicle and manufacture of the fuel accounts for a higher proportion of emissions, with actual fuel in use accounting for a lower proportion.

Critics of hybrid, electric and fuel cell vehicles have focused on the higher embodied energy and CO_2 emissions in the production of these vehicles and their fuel production and storage systems. A lot of claims and counterclaims have appeared in the technical and popular media. This issue was addressed in a recent LCA of different vehicle technologies (Patterson et al., 2011), the overall results of which are shown in Figure 21.

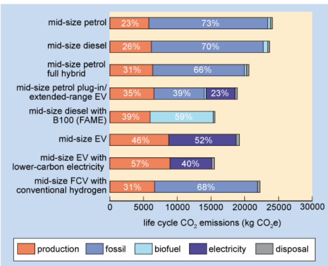

Figure 21 Life cycle CO_2 emissions of different vehicle technologies

Source: redrawn from diagrams on pages 49, 50 and 51 of Patterson et al., 2011

Key points are as follows.

- The proportion of emissions coming from the production of the vehicle and its fuels rises from around 25% for petrol/diesel to 31% for hybrids and fuel cell vehicles, to 35% for plug-in/extended-range EVs and 46% for EVs.
- The rise in production CO_2 emissions for hybrids, EVs and plug-in/extended-range EVs is more than counterbalanced by a cut in the fuel emissions in use.
- The overall result is only a modest cut in overall CO_2 emissions (about 20%) for hybrids, plug-in/extended-range EVs and BEVs.
- There is a substantial cut in overall CO_2 emissions (nearly 40%) for BEVs using low-carbon electricity; likewise for appropriately sourced biodiesel cars.

- Fuel cell cars provide a very small improvement in CO_2 emissions compared to petrol/diesel cars.

According to this LCA analysis, a typical medium-sized family car powered by petrol or diesel will produce around 24 tonnes of CO_2 during its life cycle, while a hybrid will produce 21 tonnes. A comparable BEV will produce around 18 tonnes, which can be cut to just over 16 tonnes if lower-carbon electricity is sourced; an appropriately sourced biodiesel car also produces around 16 tonnes.

Decarbonisation potential

This LCA raises a second point. Critics have pointed out that the production of electricity and hydrogen today is highly dependent on fossil fuels, and that these technologies simply shift rather than eliminate CO_2 emissions. This is reflected in the vehicle technologies LCA, which assumes a current mix of primary fuels for electricity (500 g CO_2 per kWh) and that hydrogen is produced from natural gas. The 2011 study also notes the effect of decarbonizing energy production, making the following points.

- Reducing the carbon intensity of electricity from the present 500 g CO_2 per kWh to 310 g CO_2 per kWh would cut the total emissions produced by BEVs from 18 tonnes to 15 tonnes.
- Biofuels could also cut car emissions significantly.
- If hydrogen were produced from renewable sources (such as the wind turbines shown in Figure 22), its carbon intensity would be reduced by up to 90% (which would cut total lifetime emissions for a fuel cell vehicle down to about 9 tonnes of CO_2). However, as noted earlier, this may not be the most efficient use of renewable energy.

Figure 22 Wind turbines

This illustrates the crucial point about whether these production systems can be decarbonized or not. Fuels based on oil can only cut CO_2 emissions by increasing efficiency (carbon capture is only viable in large plants – not on vehicles in use). Electricity and biofuel production can be decarbonized. Decarbonizing hydrogen is problematic if a long conversion chain is involved (see Activity 7.2).

This situation, of the low-carbon technologies providing only a limited improvement under current conditions, is something that is common at the early stages of a new technology or design. When first introduced, a new design may only just about match the performance of the incumbent design; yet it may have a much greater development potential, and it is the realization of that potential that is important. Critics (often with vested interests) focus on the present performance rather than on the future potential.

This LCA leads on to suggest that 'winning combinations' could be important. I have separately looked at biofuels and electricity, and both have issues around decarbonising production. Plug-in/extended-range EVs could combine decarbonized fuels from both sources. Overall, rather than being just a step towards another transport technology, if combined with cleaner liquid ICE fuels then they could represent a long-term sustainable vehicle technology in their own right. This is possibly a path that is less fraught than the one for BEVs and fuel cell vehicles, with their associated problems of long fuel conversion chains, range limitations and the need (particularly in the case of fuel cell vehicles) for new fuel supply networks.

Conclusion

The UK is seeking an 80% cut in transport's CO_2 emissions by 2050. This means that, allowing for behavioural factors, the fleet vehicle average test CO_2 emissions will need to be around 20 g km^{-1}.

Improving the fuel economy of petrol- and diesel-engined cars will not produce a sufficiently radical improvement. It could possibly result in a fleet average of around 70–80 grams of CO_2 per kilometre, but developments based upon mineral oil fuels and gas cannot realistically get much lower. Plug-in/extended-range EVs could have the potential to move to a fleet average of around 45 grams of CO_2 per kilometre, but this will depend on the carbon content of the electricity used.

This leads us towards the use of fuels with a lower carbon content than mineral oil, and here a range of choices open out. CNG and LPG do not offer sufficient improvement and are becoming sidelined. However, three fuels – biofuels, electricity and (possibly) hydrogen – could be produced from renewable or low-carbon primary sources.

In its current state, biofuel production needs to be optimized to cut CO_2 emissions and also not to have indirect negative impacts. Biofuels could potentially reduce CO_2 emissions to the target amount, but there is an insufficient supply of such 'first-generation' biofuels for transport needs. However, second- and third-generation biofuels offer the potential for the production of a large amount of low-carbon fuel.

Activity 11 (exploratory)

On the basis of this free course, make a list of the key issues that affect the introduction of biofuels, electric and hydrogen vehicles.

Provide your answer...

Discussion

Your list is likely to contain a variety of issues. As noted above, biofuels need to shift to second- and third-generation fuels to avoid the problems of indirect environmental and social/economic impacts, and also to ensure sufficient supply.

BEVs depend crucially on the decarbonization of both electricity production and the production of the vehicles and batteries themselves, but if this were to occur then it would represent a possible path towards a car with CO_2 emissions of 20 g km^{-1}. However, a crucial user barrier is that the purchase cost of electric (and hydrogen) vehicles is high compared to that of petrol and diesel cars.

Like BEVs, hydrogen fuel cell cars depend on fuel production decarbonization, this time of hydrogen. Hydrogen also faces problems of storage and distribution infrastructure. It may be that vehicles are not the best use of hydrogen and decarbonized electricity owing to the large losses in the fuel conversion chain. For these reasons, hydrogen cars may only be a viable path to low CO_2 emissions if the technology can be incorporated into a new service system that delivers significant energy efficiency gains. Optimized service designs such as that developed by Riversimple can achieve CO_2 emissions of around 30 g km^{-1}, but a fleet average would probably be more like that for plug-in/extended-range EVs (about 45 g km^{-1}).

Hybrid technologies could help to optimize each fuel. Indeed, biofuel plug-in/extended-range EVs could be an important development, and have the potential to out-compete both BEV and hydrogen fuel cell technologies.

A further key point emerging from this examination of more sustainable transport technologies is the need to link technological developments to behavioural factors. To achieve transport sustainability, it could be necessary to change the way we obtain and use cars and mobility. Thus not only are new technologies emerging, but new mobility business models are as well. These may involve car leasing models, such as the one being trialled by Riversimple, but might extend to more radical service models – for instance, a car/mobility club in which people are not financially locked in to the use of one car, but receive an integrated service package that allows them use of different cars depending on what kind of trip they are making, as well as providing for bus, train and bike use.

Overall, we may be on the verge of a time of experimentation and competition between transport technologies, and also a time of experimentation and competition in how mobility is provided. How all this will be resolved is unclear. Today, traditional ways of buying and using cars are deeply entrenched in our culture. This has constrained the technical approaches to cutting transport's environmental impacts. However, in the future a more systemic design approach could become possible – and may in fact be inevitable if sustainable transport is to become a reality.

References

Ayre, M. (2007) 'Will biofuel leave the poor hungry?', *BBC News* [online], 3 October, http://news.bbc.co.uk/1/hi/business/7026105.stm (accessed 16 January 2012).

Berridge, C. (2010) *Hydrogen as a Fuel for Vehicles*, PhD Thesis, The Open University.

Boak, J. (2007) 'CO_2 release from in-situ production of shale oil from the Green River formation in the Western United States', *27th Oil Shale Symposium*, Colorado School of Mines, 15–17 October; also available online at http://www.ceri-mines.org/documents/27symposium/papers/ma15-1boak.pdf (accessed 16 January 2012).

Brandt, A.R. and Unnasch, S. (2010) 'Energy intensity and greenhouse gas emissions from thermal enhanced oil recovery', *Energy & Fuels*, vol. 24, no. 8, pp. 4581–9; also available online at http://pubs.acs.org/doi/abs/10.1021/ef100410f (accessed 5 March 2012).

Concawe (2007) 'Well-to-Wheels analysis of future automotive fuels and powertrains in the European context', *TANK-TO-WHEELS Report Version 2c*, European Commission Joint Research Centre, March.

CPL Press (2009) *Biomethane for use as a transport fuel* [online], European Biofuels Technology Platform, http://www.biofuelstp.eu/biogas.html (accessed 26 March 2012).

Department of Energy & Climate Change (2011) '2009 final UK figures', *UK Emissions Statistics* [online], http://www.decc.gov.uk/en/content/cms/statistics/climate_stats/gg_emissions/uk_emissions/uk_emissions.aspx (accessed 16 January 2012).

Department for Transport (2004) *White Paper: The Future of Transport: a network for 2030 London*, Cmd 6234, London, Department for Transport.

Department for Transport (2012a) *Biofuels* [online], http://www.dft.gov.uk/topics/sustainable/biofuels/ (accessed 26 March 2012).

Department for Transport (2012b) *Ultra-low emission vehicles* [online], http://www.dft.gov.uk/topics/sustainable/olev/ (accessed 26 March 2012).

DieselNet (2011) *Emission Standards >> European Union >> Cars and Light Trucks* [online], ECOpoint Inc., http://www.dieselnet.com/standards/eu/ld.php (accessed 16 January 2012).

Dragone, G., Fernandes, B., Vicente, A.A. and Teixeira, J.A. (2010) 'Third generation biofuels from microalgae' in Méndez-Vilas, A. (ed.) *Current Research, Technology and Education Topics in Applied Microbiology and Microbial Biotechnology* (vol. 2), Badajoz, Spain, Formatex; also available online at http://www.formatex.org/microbiology2/chapters2.html (accessed 5 March 2012).

Ecolane (2006) *Life Cycle Assessment of Vehicle Fuels and Technologies – Final Report* [online], March, http://www.ecolane.co.uk/projectspublications.php (accessed 16 January 2012).

Energy Independence and Security Act (2007) US Congress; also available online at http://www.epa.gov/lawsregs/laws/eisa.html (accessed 16 January 2012).

Everett, B., Boyle, G., Peake, S. and Ramage, J. (eds) (2012) *Energy Systems and Sustainability: Power for a Sustainable Future* (2nd edn), Milton Keynes, The Open University/Oxford, Oxford University Press.

International Energy Agency (1999) *Implementation Barriers of Alternative Transport Fuels*, IEA/AFIS and Innas BV.

Linterink, N.E. and Bos, B. (2010) *Passenger car CO_2 emissions in tests and in the real world – an analysis of business user data*, TNO Report MON-RPT-2010-001/14, Delft, the Netherlands, Dutch Ministry of Housing, Spatial Planning and the Environment.

McGregor, R. (2007) '750,000 a year killed by Chinese pollution', *Financial Times* [online], 2 July, http://www.ft.com/cms/s/0/8f40e248-28c7-11dc-af78-000b5df10621.html#axzz1lLGHiycH (accessed 3 February 2012).

Mildenberger, U. and Khare, A. (2000) 'Planning for an environment-friendly car', *Technovation*, vol. 20, no. 4, pp. 205–14.

National Atmospheric Emissions Inventory (2011) *Air Quality Pollutant Inventories for England, Scotland, Wales and Northern Ireland*: *1990 – 2009*, Didcot, AEA Group.

New Automotive Innovation and Growth Team (2009) *An Independent Report on the Future of the Automotive Industry in the UK* [online], Crown Copyright, Department for Business, Enterprise & Regulatory Reform, UK, http://www.bis.gov.uk/files/file51139.pdf (accessed 16 January 2012).

Nuffield Council on Bioethics (2011) *Biofuels: Ethical Issues*, London, Nuffield Foundation; also available online at http://www.nuffieldbioethics.org/biofuels-0 (accessed 16 January 2012).

Patterson, J., Alexander, M. and Gurr, A. (2011) *Preparing for a Life Cycle CO_2 Measure*, report for the Low Carbon Vehicle Partnership, London, Ricardo/Low Carbon Vehicle Partnership; also available online at http://www.lowcvp.org.uk/assets/reports/RD11_124801_5%20-%20LowCVP%20-%

20Life%20Cycle%20CO2%20Measure%20-%20Final%20Report.pdf (accessed 16 January 2012).

Piock, W., Hoffmann, G., Berndorfer, A., Salemi, P. and Fusshoeller, B. (2011) *Strategies Towards Meeting Future Particulate Matter Emission Requirements in Homogeneous Gasoline Direct Injection Engines*, SAE 2011 World Congress & Exhibition, April, Detroit, MI.

Potter, S. (2007) 'Exploring approaches towards a sustainable transport system', *International Journal of Sustainable Transportation*, vol. 1, no. 2, pp. 115–31.

Potter, S. and Bailey, I. (2008) 'Transport and the environment' in Knowles, R., Shaw, J. and Docherty, I. (eds) *Transport Geographies*, Oxford, Blackwell.

Renewable Fuels Agency (2009) *About the RTFO* [online], http://webarchive.nationalarchives.gov.uk/20110407094507/http://renewablefuelsagency.gov.uk/aboutthertfo (accessed 14 February 2012).

Riversimple (2010) *The network electric powertrain* [online], http://www.riversimple.com/Content.aspx?key=f29e068d-82aa-4145-9e13-33d451027e02&mode=menu (accessed 26 March 2012).

SMMT (2011) *New Car* CO_2 *Report 2011*, London, Society of Motor Manufacturers and Traders; also available online at http://www.smmt.co.uk/wp-content/uploads/SMMT_New_Car_CO2_Report_2011.pdf (accessed 16 January 2012).

Stern, N. (2006) *Stern Review: The Economics of Climate Change*, London, HM Treasury and Cabinet Office.

Teufel, D., Bauer, P., Lippolt, R. and Schmitt, K. (1993) *OeKO-Bilanzen von Fahrzeugen* (2nd extended edn), Heidelberg, Umwelt-und Prognose-Institut Heidelberg e.V.

Thackara, J. (2010) 'Is an Environmentally Neutral Car Possible?', post in his blog on *Design Observer Blogs* [online], http://observersroom.designobserver.com/johnthackara/post/is-an-environmentally-neutral-car-possible/22708/ (accessed 26 March 2012).

TheBioenergySite (2009) *UK Commitment to Anaerobic Digestion* [online], 5M Enterprises Ltd, http://www.thebioenergysite.com/articles/378/uk-commitment-to-anaerobic-digestion (accessed 26 March 2012).

U.S. Department of Energy (2011) 'Biodiesel', *Alternative & Advanced Fuels* [online], Alternative Fuels & Advanced Vehicles Data Center, http://www.afdc.energy.gov/afdc/fuels/biodiesel.html (accessed 26 March 2012).

U.S. Department of Energy (2012) 'Emerging Alternative Fuels', *Alternative & Advanced Fuels* [online], Alternative Fuels & Advanced Vehicles Data Center, http://www.afdc.energy.gov/afdc/fuels/emerging.html (accessed 26 March 2012).

Vehicle Certification Agency (2006) http://www.dft.gov.uk/vca/index.asp (accessed 26 March 2012).

Further reading

If you would like to learn more about energy systems we suggest the textbook “Energy Systems and Sustainability, Power for a Sustainable Future” by Everett, B., Boyle, G., Peake, S. and Ramage, J. (2012) (2nd edition, Oxford University Press).

If you are interested in transport then you might find these interesting: “Unsustainable Transport: City Transport in the New Century: The Transport Crisis” by D Banister (2005, New Edition, Routledge).

Acknowledgements

All third party content in this course is not subject to Creative Commons licensing. This includes the content acknowledged below and all third party figures (with source information) and videos which links are provided for ease of access only.

Course image: Petras Gagilas in Flickr made available under Creative Commons Attribution-NonCommercial-ShareAlike 2.0 Licence.

The material acknowledged below is Proprietary, used under licence and not subject to Creative Commons licensing.

Grateful acknowledgement is made to the following:

Figure 2: Nissan calculation from Nissan Green Program 2010 www.nissan-global.com

Figure 5: adapted from figure 4 in 'Strategies Towards Meeting Future Particulate Matter Emission Requirements in Homogeneous Gasoline Direct Injection Engines'(Walter Piock, Guy Hoffmann, Axel Berndorfer, Patick Salemi and Bernd Fusshoeller, Delphi Powertrain Systems), Luxembourg © SAE International 2011

Figure 7: http://www.toyota.com

Figures 8, 9, 18, 22: courtesy of Stephen Potter

Figure 10: photographer Joel Creed/ © http://Ecoscene.com

Figure 11: © Patrick Laverdant/iStockphoto.com

Figure 12: © unknown

Figure 13: http://www.itbhuglobal.org

Figure 14: photograph of Nissan Leaf by Steven Lines, Milton Keynes Council

Figure 16: photograph (Joe Mills, course team) of Opel Volt Ampera www.opel-ampera.com

Figure 17: American Honda Motor Co, Inc.

Figures 19, 20: http://www.riversimple.com

Audio 1: Thanks go to Professor Stephen Potter (Open University), Professor Dermott Roddy (University of Newcastle), Professor Andrew Weller (University of Oxford). Post production The Hall; produced by Clear Focus Productions. © The Open University 2012.

Every effort has been made to contact copyright owners. If any have been inadvertently overlooked, the publishers will be pleased to make the necessary arrangements at the first opportunity.

Creative Commons link:

Don't miss out:

If reading this text has inspired you to learn more, you may be interested in joining the millions of people who discover our free learning resources and qualifications by visiting The Open University - www.open.edu/openlearn/free-courses