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Road transport technology and climate change mitigation

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Executive summary

CUMULATIVE GLOBAL CARBON DIOXIDE (CO_2) EMISSIONS BETWEEN NOW and 2050 will strongly influence the extent of climate change by the end of this century[1]. Transport alone was responsible for around 23% of global energy-related CO_2 emissions in 2007[2]. Transport emissions could become even more significant as other sectors are decarbonised. The UK has committed to an 80% reduction in greenhouse gas (GHG) emissions by 2050. We therefore need as a matter of urgency to develop policies, technologies and infrastructure for the future delivery of transport services that are consistent with national and global emissions reduction goals.

Alternative, low-carbon fuel and energy sources and new powertrain technologies will be essential. Barriers to achieving global mitigation targets in transport are significant, and include the embryonic technological state of low-carbon alternatives, the likely rapid increase in the use of vehicles in developing economies, and the dependence of low-carbon vehicles on the still-evolving decarbonised energy supply and associated infrastructure.

How can we reduce road transport emissions?

(a) Rapidly reduce emissions from vehicles with conventional powertrains:

- **Improved vehicle efficiency.** Significant CO_2 reductions of perhaps 30% of the current fleet average could be achieved at relatively low cost with established technologies such as engine downsizing, lightweighting and selection of smaller vehicles[3]. We need to use significantly more best-in-class powertrains. Rebound effects from increased travel due to lower cost might partially offset the benefits, if measures are not taken to address them.

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Grantham Briefing Papers analyse climate change research linked to work at Imperial, setting it in the context of national and international policy and the future research agenda. This paper and other Grantham publications are available from **www.imperial.ac.uk/climatechange/publications**.

- **Improved efficiency of vehicle use.** Driving behaviour measures such as 'eco-driving' can reduce fuel consumption by around 10-15% at low cost[4], but require ongoing training. Speed limit enforcement and reduction could cut emissions quickly, but with mixed evidence on cost and acceptability.

- **Demand reduction** is challenging because of the economic and social opportunities that road transport provides, even though reduced demand may provide other benefits (e.g. improved air quality). Fuel price increases, though politically contentious, lead to modal shift, decreased travel and more efficient driving[4]. Land-use policies could lead to significantly reduced demand and modal shift in the medium to long term.

Significant CO_2 reductions could be achieved at relatively low cost with established technologies such as engine downsizing.

(b) Dramatically reduce the GHG intensity of fuels and accelerate the transition to low-carbon vehicles:

- **Hybridisation of the powertrain,** particularly for light duty vehicles, would open the door to a family of efficient and flexible options, albeit with higher capital costs for example internal combustion engine (ICE) hybrids, plug-in ICE hybrids, fuel cell hybrids and electric vehicles (EVs).

- The uptake of **electric vehicles** is critically dependent on the high cost of batteries, range limitations, and the trade-offs between them. About 93% of car trips in the UK are less than 25 miles, but motorists have become accustomed to a vehicle range of at least 200 miles. The cost, mass and volume of batteries to meet this requirement are at present relatively large. Plug-in hybrid electric vehicles (PHEVs) attempt to address this, but incur the extra costs of dual power sources. The CO_2 savings of electric vehicles and plug-in hybrids are strongly dependent on decarbonisation of the electricity grid.

- **Biofuels** could make a potentially significant contribution for all types of road transport, including hybrid and plug-in hybrid vehicles. Given likely supply limitations, their optimal transport use in the long term might be for long haul trucks/ buses and aviation, where alternatives to liquid fuels are not presently viable, and biofuels therefore represent the key low-carbon option. Crops grown in Europe could provide a substantial share of Europe's future transport fuels but issues of energy efficiency, CO_2 intensity of production, and land use change are complex, uncertain, and likely to be contested. This will therefore require careful consideration.

- **Hydrogen** offers the potential of a high energy density synthetic chemical fuel that can be flexibly produced from a variety of sources and consumed in fuel cells or ICEs. Cost-effective on-vehicle storage remains challenging and new infrastructure and low-carbon production systems would be needed.

(c) Develop smart infrastructure to support zero-carbon mobility:

- **Decarbonised smart electric grids and electric charging infrastructure** are critical to the realisation of low-carbon transport goals. Near-term choices about electrical generation, transmission and distribution will therefore determine the viability of mass adoption of PHEVs/EVs over the next several decades.

- **Low-carbon fuelling infrastructure.** Although liquid biofuels could use the same distribution and fuelling infrastructure as fossil fuels, the upstream agricultural and processing industries for producing sustainable biofuels are not yet well established. Hydrogen requires a completely new supply infrastructure and refuelling system.

- **More efficient interactive transport management and information systems** would help integrate different transport modes and underpin new business models for providing transport services and intelligent transport systems (ITS) such as vehicle-vehicle and vehicle-infrastructure communications to improve safety and network efficiency.

(d) Purposefully engineer cities and other spaces to support a near zero-carbon transport future:

- **An integrated systems approach,** linking urban planning and land use policies that directly influence transport demand with support for public and other transport systems will be critical to mitigate the expected rapid growth in transport emissions from newly industrialised economies such as China and India, and may be relevant in the UK in the longer term.

The main focus of this paper is on (a) and (b) and their implications. However, all dimensions of the mitigation strategy need to be progressed actively and in parallel in order to meet UK and global CO_2 reduction targets.

The technological transition path for the UK

Road transport presents particular challenges for emissions reduction and requires a step change in behaviour and technology. The scale of the challenge means that incremental improvements using existing technologies are not sufficient to meet the UK's 2050 targets. Taking passenger cars as an example, by 2025 the majority of cars will need to be best-in-class ICEs. By 2035, around half our cars will need to be EVs/PHEVs with a significant amount of grid decarbonisation (around 50%), and significant biofuel blending (around 30%) for the remaining non-electric vehicles. This assumes that 50% grid decarbonisation is possible, and that sufficient sustainable biofuels are available for passenger cars.

Beyond 2045, all vehicles must emit less CO_2 than a best-in-class fossil-fuelled ICE hybrid, which means that the majority of vehicles should be either EVs/PHEVs with an almost completely (75-100%) decarbonised electricity grid and/or substantial roll-out of sustainable biofuels (again, perhaps 75-100% blend). Such radical changes will require the availability of innovative technological options, and consistent political support and policies focused on the long term and across multiple sectors (e.g. vehicles, fuels and electricity supply).

Introduction

Transport is important in wealth creation and quality of life, enabling trade and social interaction through the movement of goods and people. It also has negative effects such as accidents and pollution, including carbon dioxide emissions. In 2007, transport (including shipping and aviation) was responsible for 6.6 gigatonnes of CO_2 emissions globally, 23% of all energy-related CO_2 emissions[5-6]. Emissions related to global transport could grow by 35% to 8.9 gigatonnes of CO_2 in 2030 under the International Energy Agency (IEA)'s baseline scenario, driven both by population and income growth. The tension between this projected growth and ambitious targets of 80% (UK) and 50% (global) reduction in GHG emissions by 2050 is starkly evident.

In addition to generating CO_2, transport—driven by internal combustion engines—is also responsible for small amounts of other GHG emissions including methane, nitrous oxide and fluorinated gases [7], as well as acoustic noise and significant local air pollution from SOx, NOx, carbon monoxide, volatile organic compounds, unburnt hydrocarbons and particulates, all of which affect health and the environment. Where combustion can be reduced or avoided entirely such as in electric and hybrid powertrains, or shifted to power stations where exhaust products can be cleaned up more effectively, the welfare and health benefits of low carbon transport—for example, better urban air quality—are immediately apparent and represent a strong selling point, independent of their impact on climate change[8].

The breakdown of domestic transport GHG emissions by transport mode in the UK is shown in Figure 1. About 73% of global transport-related CO_2 emissions in 2007 and 90% of domestic transport-related GHG emissions in the UK[9] were due to road transport, which will also be a major driver of domestic GHG emissions in the newly industrialised economies of China and India. By 2030, China could have more cars, trucks and buses than the USA has today[10]. Globally, car and light truck ownership are projected to increase from 700 million vehicles in 2005 to around 2 billion vehicles in 2050[6] —a huge challenge for reducing CO_2 emissions.

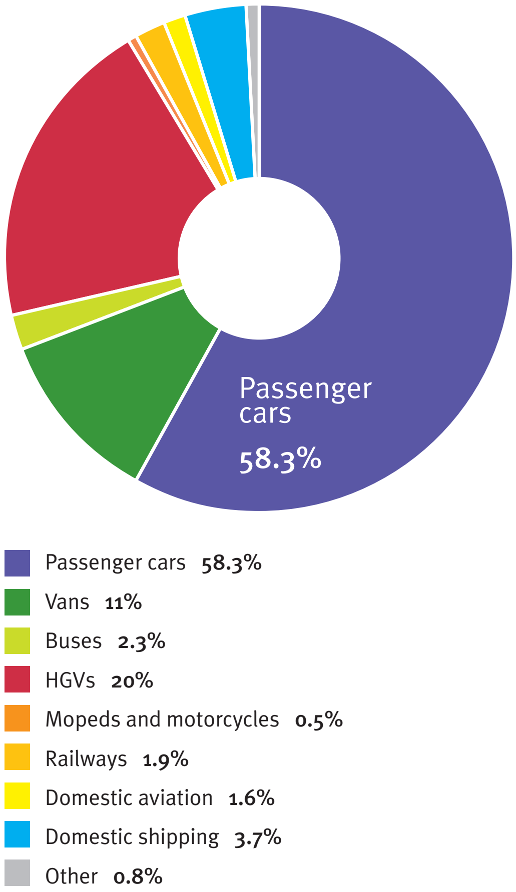

Figure 1. UK domestic transport GHG emissions 2007[9] excluding travel across borders.

Passenger cars make up the majority of the CO_2 emissions from UK domestic transport[9]. In 2009, over a third of emissions were due to business and commuting. Two-thirds of emissions came from trips of less than 25 miles. Journeys greater than 50 miles per day, although comprising just 3% of total car trips, were responsible for 22% of CO_2 emissions. Although only 5% of cars in the UK are company cars, these travel twice the annual vehicle mileage compared with private cars[11].

Vans and Heavy Goods Vehicles (HGVs) together make up a third of UK domestic transport CO_2 emissions and are a growing transport mode[9]. Growth in vehicle-kilometres for vans (i.e. light goods vehicles under 3.5 tonnes) in particular has been very rapid since 1990, whereas UK vehicle-kilometres for HGVs have been relatively stable over the past 20 years[12].

Buses comprise a small proportion of CO_2. Usage in the UK has increased slightly since 1990 but vehicle efficiencies have also been steadily increasing[13].

Technical review

Analytical structure

This briefing note identifies four key objectives for reducing the impact of road transport on climate change. Each has technical, policy and behavioural elements, and will have relevance on different timescales between now and 2050:

(a) **Achieve rapid reductions in emissions from vehicles with conventional powertrains.** This will be the main path for short to medium-term emissions reductions.

(b) **Reduce the CO_2 intensity of vehicle fuels dramatically and accelerate the transition to low-carbon vehicles.** In the medium to long-term this will be crucial to achieve reductions.

(c) **Develop smart infrastructure to support zero-carbon mobility.**

(d) **Engineer cities and other spaces to facilitate and support a near zero-carbon transport future.**

This is broadly in line with the 2007-2008 King Review of low carbon cars, commissioned by the UK Government. This suggested that we need cleaner fuels, more efficient vehicles, and smarter driver choices[3], although it did not address the impacts of land use and population growth on transport demands. These objectives also align with the recommendations of the UK Committee on Climate Change which in addition to suggesting better vehicles, fuels and driver choices, also considers reforms to the planning system[14].

Reducing emissions from conventional vehicles

The internal combustion engine (ICE) is widely available, mature and relatively inexpensive. However, most of the available energy in the fuel is converted to heat rather than work because of combustion inefficiencies, heat transfer from the engine block, wasted high temperature exhaust gases, friction, pumping and drivetrain losses. Typical vehicle engines have maximum fuel-to-shaft power efficiencies of approximately 35%[15]. Figure 2 shows the breakdown of best case energy conversion in a typical ICE vehicle[15-16]; in practice diverse engine configurations and sizes lead to the variations shown. At part load conditions, the efficiency will be much worse, which is why it is crucial that vehicle performance is evaluated over a drive cycle representing real conditions (see box about drive cycles).

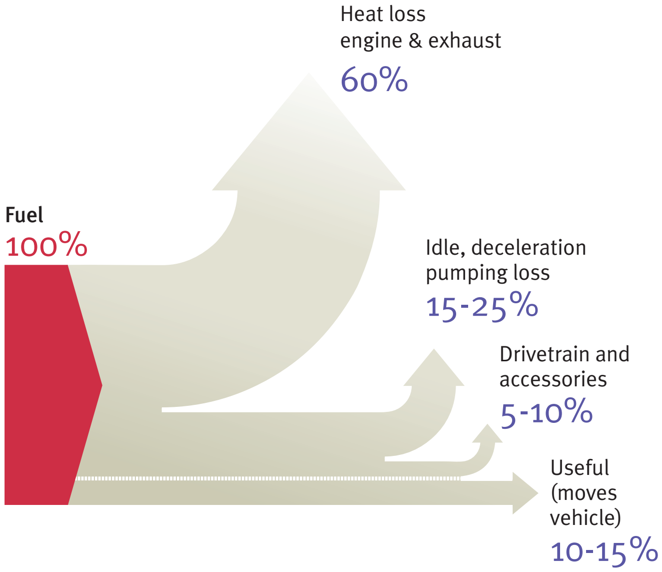

Figure 2. Typical best case energy flows in a standard-size ICE vehicle at steady state conditions

The poor energy conversion efficiency of ICEs has been accepted to date due to the ready availability and low cost of fossil fuels in most of the 20th century. Carbon dioxide emissions per vehicle-km for new passenger cars are typically in the region of 100 – 225 g CO_2/km. Vehicles such as buses and HGVs tend to be much larger in size, with higher mass, aerodynamic drag and rolling resistance. The engine therefore has to provide much more power and requires more fuel per km. The GHG emissions per vehicle-km are therefore larger (though not necessarily per passenger-km or kg-km), typically in the region of 700-1000 g CO_2/km for buses and HGVs[12]. Furthermore, buses and HGVs are used far more heavily than cars, often for most hours of most days, with buses typically having lower mileage than HGVs. Vans (light duty goods vehicles) also tend to be used more than

Box 1. Drive cycles

Vehicle fuel consumption and emissions are strongly affected by the drive cycle and other factors including the weather and state of maintenance. For pre-sales regulatory type approval, all cars in the EU are tested to ensure that their emissions are within a set of limits measured under standard conditions. A standard cycle, the New European Drive Cycle (NEDC), is used to produce benchmark tailpipe gCO_2/km values for 'urban', 'highway' and 'combined' driving conditions. Upstream CO_2 emissions are not accounted for. NEDC figures are now being used to enforce directives to reduce the CO_2 emissions from passenger vehicles. While this has been successful in providing a set of targets for the automotive industry, the NEDC underestimates real-world driving emissions by 15-50%[17]. Improved estimates can be made on the basis of alternative cycles such as the Combined Artemis Drive Cycle (CADC) developed to represent real-world driving behaviour on European roads[18].

Losses

	Relevance	Options	Improvement potential	Costs and barriers
Weight reduction (inertia)	Relevant in stop-start driving, for example in cities (urban and suburban driving)	(i) Reduce vehicle size (ii) Reduce chassis weight through re-design and new materials (composites, metal foams) (iii) Reduce powertrain weight (engine down-sizing, accessories)	**Cars:** 0.7% efficiency improvement for each 1% weight lost [15]; up to 10% savings possible[3]. **Trucks/vans:** Up to 7% improvement in fuel consumption per tonne-km[19]	**Costs:** £250-1500 for 10% weight reduction [3, 15] **Barriers:** Some evidence of a trend toward heavier, larger vehicles, perhaps due to comfort and safety concerns [3, 20]
Aerodynamics (drag)	Relevant at higher speeds (greater than 40 mph), e.g. intercity motorway driving.	(i) Reduce frontal area (e.g. by downsizing), (ii) Streamline body (iii) Redesign fairings, spoilers and grills, redesign underside	**Cars:** 3-7% improvement in fuel consumption [3, 15] **Trucks/vans:** 6-10% improvement in fuel consumption [19, 21] but variable with usage	**Costs:** Additional cost £3k for HGVs [21]. Cars: unknown. **Barriers:** HGVs—correct adjustment of fairings required; possible increased weight and loss of volume.
Rolling resistance	Relevant for all types of driving	(i) Use low rolling resistance (LRR) tyres (ii) Reduce weight (iii) Implement tyre pressure monitoring systems (TPMS) widely	**Cars:** 1-2% [15] **Trucks/vans:** 5-6% CO$_2$ benefit [19, 21]	**Costs:** Negligible, LRR tyres widely available at no additional cost **Barriers:** No significant ones; slightly reduced lifetime and traction, increased noise

Table 1: Vehicle tractive efficiency improvements (note all figures are approximate only)

cars, and have slightly higher CO$_2$ emissions due to their slightly larger size and less aerodynamic shapes. Substantial aggregate CO$_2$ emissions reductions can be made by vehicle technology improvements on high-utilisation vehicles.

The efficiency of conventional vehicles can be improved in a wide range of ways:

Air resistance, rolling resistance and vehicle mass. The powertrain converts energy in the fuel into the 'useful' motive or tractive energy at the wheels to move the vehicle. This tractive energy is used to overcome the vehicle's inertia when accelerating, the rolling resistance of the tyres, and the aerodynamic drag in order to maintain a steady speed; it also powers the auxiliaries (e.g. heating, ventilation, air-conditioning, pumps and power steering). Decreasing aerodynamic drag, inertia and rolling resistance therefore leads to efficiency gains irrespective of the fuel source or powertrain type. One key way to do this is through vehicle downsizing, which lowers weight (inertia), rolling resistance and frontal area (aerodynamic drag). However, this is challenging for HGVs and buses, which are required to be a certain size in order to carry sufficient freight or passengers. An alternative is light-weighting, which uses less dense materials such as metal foams and composites and decreases material volume by reducing wall thickness. Light materials such as composites remain high in cost and embodied energy and more difficult to repair than more conventional materials such as steel. A summary of the options and potential is shown in Table 1. Solar car racing and events such as the Shell Eco-marathon show these principles applied to the extreme, as do concept cars such as the Volkswagen L1 and Aptera.

Powertrain. Around 15% improvement in ICE efficiency is estimated to be possible, increasing to 20-30% or more if a hybrid configuration is used[3, 22]. Table 2 shows possible options (excluding hybridisation), which can be combined to some extent. Many of these are already available in vehicles that can be purchased today and are variously branded by manufacturers, for example VW Bluemotion, BMW EfficientDynamics or Renault Eco2. On average, these cars achieve CO$_2$ emissions reductions of about 18% over a similarly sized vehicle with the same sized engine (based on data from the UK Vehicle Certification Agency[23]). Powertrain savings may be multiplied if the engine can be downsized, because smaller engines exhibit lower friction and pumping losses; performance can be maintained by turbocharging the downsized engine[24]. Diesel engines have higher efficiencies than petrol engines but are more expensive and require exhaust after-treatment systems for NOx, particulates and other pollutant emissions[3]. There is a tailpipe CO$_2$ minimum 'plateau' for conventional fossil-fuelled internal combustion engine (ICE) powertrains, estimated to be 80-90 g CO$_2$/km for the best diesel ICE cars[25]. To exceed this limit using ICEs requires hybridisation and/or biofuels.

Improvement	Losses affected	Description	Improvement potential	Costs and barriers
Engine downsizing	• Friction losses • Pumping loss • Idle loss • Reduced weight	Engine downsizing without performance penalty through enhanced boost (turbo-charged; supercharged – mechanical or electrical) or some types of hybridisation. Applicable to all ICEs.	**Cars:** Modest downsize with turbocharging gives a 5-7.5% fuel economy benefit[15]. Large CO_2 reduction (30-40%) possible with extreme downsizing[24].	**Cars:** Modest downsizing using turbocharging costs $120-690[15]. Diesels more expensive than gasoline.
Exhaust gas energy recovery	• Exhaust loss	Thermo-electric devices, secondary cycles or turbo-generators recover some of the energy lost as heat in the exhaust stream [22]. With a turbine, it is possible to make better use of the exhaust energy by tuning the device to recover unsteady flow energy[26].	**Cars:** 6-10 % efficiency increase using turbo-generator[27] **HGVs**: 3-5% cycle fuel consumption decrease with 40 kW electric turbo compound[28]	**Cars:** unknown **HGVs:** $2000-3400 cost for electric turbo compound system[28]. Power electronics are a large cost.
Improved combustion	• Unburnt fuel • Thermo-dynamic losses	Direct injection, increased compression ratios and wider lean burn power ranges give some improvement. Greater improvement with advanced combustion processes, e.g. homogeneous charge compression ignition (HCCI).	HCCI could give 50% improvement in engine efficiency at part load compared to spark ignition engines and 30% compared to compression ignition engines [22]	HCCI: $263-685[15] for cars; but technical challenges remain in controlling HCCI over varying operating conditions. Direct injection: $122-525.
Variable valve timing (VVT)	• Off-design loss	A control improvement. Camless (actuator driven valves) engine remains a future possibility.	Cars: 0.5-4% [15], 5-7% [3]	Cars: $169-322[15]
Auto stop/start with improved alternator controls	• Idle loss • Auxiliaries • Deceleration loss	Engine turned off if vehicle stopped for more than a few seconds; requires driver interaction (e.g. gearbox in neutral). Alternator is engaged (loaded) during braking, coasting or decelerating only.	Cars: 7.5% [15], 3-7% [3]	Cars: ~$600[15], £100-450[3]
Kinetic energy recovery system (KERS)	• Deceleration loss: significant in urban driving.	Every time a car brakes, kinetic energy (KE) is wasted. A hydraulic system or a flywheel (about 70% round trip efficiency) or electric system (about 50% round trip efficiency) can recover some of this.	About 20% CO2 saving using flywheel system[29]. Urban drive of 3.5t electric van showed recovered KE was 15%[30].	Car-based flywheel KERS, around $1500 in mass production
Transmission improvements	• Transmission loss	Some improvement for manual gear-boxes, e.g. dual clutch and low engine rpm gear ratios. Greater improvements for automatic (e.g. CVT and magnetic	Cars: 4-5%[3]	Cars: £400-600[3]

Table 2: Improvements to ICE powertrains (focusing on light duty vehicles)

Improving efficiency of vehicle use. Vehicle energy consumption does not scale linearly with vehicle speed, meaning it is affected directly by driving styles, congestion and route choice. Driver training and network management interventions, such as adjusting traffic light controls to optimise traffic flow, can have a significant impact. Benefits tend to result from reducing the intensity and number of acceleration phases.

'Eco-driving'[31] reduces fuel consumption by encouraging smooth driving in response to the conditions and the performance envelope of the vehicle, with in-vehicle ‘eco-driving support’ devices now being included in some vehicles. This approach is most effective for conventional ICE vehicles, with improvements of 10-15% possible at low cost[4]. However, ongoing training is required for maximum benefits.

In urban areas, co-ordinated traffic signal control can lead to about 8% reduction in emissions from the whole fleet[32]. Widespread implementation is currently limited by a lack of tools to provide feedback to the traffic management system on the environmental performance of the network; this is being addressed by current research[33]. Enforcement of motorway speed limits could lead to 2-3% reduction of total road transport emissions in the short term[4], but evidence on costs is mixed, and such restrictions may be politically challenging to implement.

Travel demand management combines improved traveller information with pricing/charging policies to increase network efficiency by shifting travel demand to reduce peak loads and avoid or reduce congestion[4]. Car clubs offer an opportunity to promote the use of cleaner vehicles and to disconnect vehicle use from vehicle ownership. Clubs tend to reduce CO$_2$ by choosing best-in-class vehicles, and by having better planned trips[34]. In the UK, however, institutional and behavioural barriers remain, with the business case being difficult outside densely populated areas. Governments could provide incentives to encourage car clubs, for example by supplying seed funding, extending scrappage schemes and applying congestion charging in a way that favours car clubs.

Induced travel and rebound effects. A side-effect of improved vehicle efficiencies, decreased congestion and/or increased road

Measure	Key influencing factors	UK Potential, cost, challenges	Evidence base
Reducing demand for travel	•Absolute and relative travel costs •Land use and destination choice •Economic growth •Road pricing	Evidence that fuel price increases lead to decreased travel, modal shift and more efficient driving.	Medium to strong, but evidence on tele-working inconclusive (lack of data, possible rebound effects)
Modal shift to walking and cycling	•Improved safety and convenience •Penalising car use (e.g. by congestion charging)	6% per year CO2 savings if UK cycling was at a comparable level to leading European countries, plus health benefits	Good. No systematic cost estimates.
Support for public transport	•Availability of convenient, affordable public transport •Land use patterns •Measures to restrict car use	Requires large expansion in capacity to have significant impact—i.e. may only feel positive effects in long term. Increasing occupancy of under-utilized services is crucial	Complex, some disagreement. Lack of evidence on costs of investment in terms of reduced CO2 emissions
Car clubs	•Availability of designated car club parking spaces •Population density of area and ratio of members to cars	Car clubs can reduce total car miles driven. They require congestion charging exemptions, seed funding and sufficient daytime usage.	Need more research on the potential for car clubs, carbon cost effectiveness and how to attract a wider user-base and support periods of peak use
Travel plans (school/ work)	•Parking and other charges	6-30% reduced car usage usually by shift to non-motorised modes. £30-500/ tonne carbon.	More evidence on costs and co-benefits required
Congestion charging	•Revenue neutrality vs. revenue raising •Public transport and alternatives	Congestion charging has a significant impact, resulting in reduced traffic, more efficient driving, increased occupancy and modal shift.	Political acceptability debate
Road pricing	•Revenue neutrality vs. revenue raising	Significant potential and could be cost effective	Evidence is mixed; lack of actual data. Debate around political acceptability

Table 3: Measures for road transport demand reduction and lower carbon choices[4]

capacity is the corresponding reduction in the cost of travel. There is clear evidence[4] that this will lead to an increase in trip-making and in distances travelled and thus erode a proportion (around 20-40%) of the benefits. Policies such as road pricing, pedestrianisation and parking policies could help mitigate this effect.

Demand reduction. The choice of different transport modes and total distance travelled are strongly influenced by the feasible times and costs required to complete a journey and by land use policies, which affect the density and layout of urban spaces[11]. There are distinct differences between low-density North American cities and (currently) less private car-dependent, higher density Western European and Asian cities[35]. A number of measures reviewed in detail in a recent UK Energy Research Centre report[4] can lead to demand reduction in road transport. Table 3 summarises some of the findings of this report regarding travel choices.

If vehicle occupancy can be increased through car-pooling, ride-sharing or more effective aggregation of public transport demand, then the CO_2 emitted per passenger-km can be substantially reduced. For example, changing a car journey from single to dual occupancy almost halves this figure, on the premise that the shared trip is a journey that would otherwise be made as two trips. Services to promote ride-sharing/car-sharing are primarily based on matching travellers with similar trips. There have been several recent innovations through the development of co-operative mobility systems, where vehicles are equipped with positioning and communications technologies to allow vehicle-to-vehicle and vehicle-to-infrastructure communication, such as the EU CVIS project. Ride sharing can be successfully integrated with other systems such as park and ride. Dedicated road space, such as High Occupancy Vehicle (HOV) lanes, is a way to encourage lift sharing. However, it is difficult to quantify the effectiveness of these interventions accurately. Evidence suggests that there may be congestion or under-utilisation of HOV lanes and possible rebound effects[4].

Low-carbon vehicles

Hybrid vehicles. These combine an ICE with an electrical machine and energy storage such as batteries. In a parallel hybrid vehicle (Figure 3), the ICE and electric motor operate on the same drive shaft; either or both can power the vehicle. In a series hybrid (Figure 4), the motor drives the vehicle using electricity from either the batteries and/or a small ICE, which operates as an auxiliary power unit driving a generator. A ‘combined’ hybrid allows operation in either mode. Efficiency is increased by regenerative braking, controlling the ICE to run at more efficient operating points, and implementing stop/start to remove idle losses[36]. Additionally, engine downsizing may be possible. Because a wide variety of power flows is possible, optimal control becomes complex.

HGVs, vans and buses can also be hybridised. This will be beneficial for urban delivery fleets and urban buses, which are characterised by very transient drive cycles. Hybrid buses are already used in London, exhibiting about 30% reduction in fuel consumption[37]. Long-haul (inter-city) HGVs and buses benefit less from hybridisation, although smaller modifications, such as auto engine stop/start or electric turbo assist or new exhaust gas energy recovery systems, could be beneficial (Table 2).

Benefits: Experimental measurements[38] on hybrid vehicles show significant fuel economy benefits of 40-60% in urban (stop-start) driving below 95 kph. At highway speeds, hybrids perform similarly to conventional, efficient diesels. Combined urban and highway driving would expect to provide typical benefits of 15-30% in fuel economy[3, 22], depending on the comparison baseline. The extra complexity increases the energy required (and therefore CO_2 emitted) during manufacture, but the impacts of this are greatly surpassed by the CO_2 emissions savings achieved during use, resulting in overall lower lifecycle CO_2 emissions compared with conventional vehicles[39].

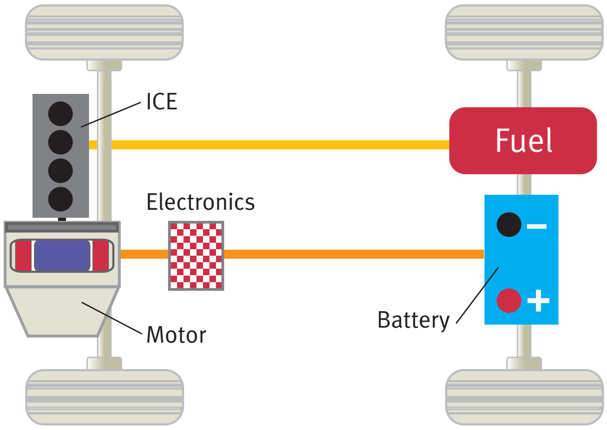

Figure 3: Parallel hybrid (e.g. Honda Insight)

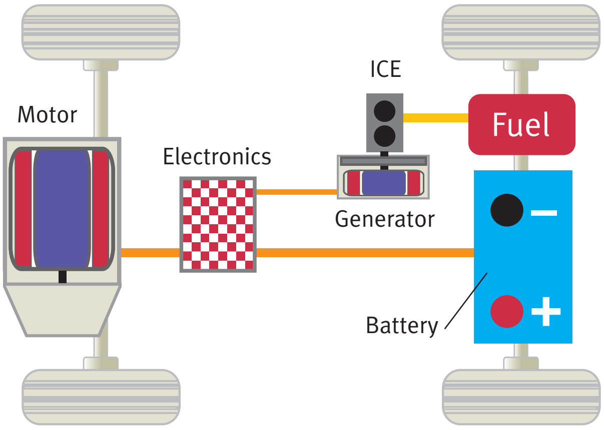

Figure 4: Series hybrid (e.g. Chevrolet Volt)

Diagrams adapted from Ricardo plc with permission

Costs and barriers: A hybrid requires an ICE and one or two powerful electric motors/generators. Since motors cost about the same per kilowatt as ICEs, this is a large capital cost increase. Batteries and power electronics are also a substantial cost.

Plug-in hybrid vehicles. PHEVs are hybrid vehicles that can be charged by plugging them directly into the electricity grid, and that run in purely electric drive mode within the maximum range of the energy storage. The naming convention for these vehicles shows how far each will run on electricity alone: for example, a PHEV40 can run for 40 kilometres. A recent study showed PHEV30s would allow 48% of passenger car-km currently driven in the UK to be driven in all-electric mode; PHEV50s, 63% and PHEV70s, 72% [40]. The calculation of the CO_2 emissions would depend on the amount of fuel versus electricity used as well as the carbon intensity of the grid (see page 11). A variety of PHEV operating modes in different combinations are possible:

- *Charge depleting mode:* all-electric operation, with ICE turned off
- *Charge sustaining mode:* battery state of charge stays within a narrow band (this is the same operating mode used in non-plug-in hybrids)
- *Blended mode:* charge-depleting mode, but with ICE contributing at high speeds or high loads

PHEV architectures are most likely to benefit cars, and perhaps vans and some buses. The high usage of long-haul HGVs and coaches does not lend these vehicles to being plugged in. Battery pack size, space and volume constraints, high capital cost and need for fast charging all deter this option.

Benefits: Potentially very low or zero CO_2 emissions are possible in all-electric mode if the electricity is supplied from a low- or zero-carbon source. Plug-in hybrids mitigate many of the challenges that face electric vehicles, such as ‘range anxiety’ and to some extent, cost (because a relatively small battery pack is needed). The idea of using a small ICE as a range extender offers a large amount of flexibility, bridging the gap between conventional ICE and electric vehicles.

Costs and barriers: Capital cost remains a major challenge, due to larger battery packs. Charging infrastructure also needs to be established (as for EVs); however there is significant potential for home and workplace charging.

Electric vehicles. These consist only of batteries, power electronics and motors. From a mechanical and control perspective they are typically simpler than hybrids, PHEVs and conventional ICE vehicles. A recent study[40] showed that suburban rather than urban areas may be more important for targeting early adopters of EVs/PHEVs. This is because suburban households tend to commute to work by car, and have higher disposable incomes and garages with recharging facilities. Slow charging overnight could be implemented in household garages more cheaply and conveniently than in public parking spaces. On this basis, and depending on patterns of ownership, over 50% of current car-km in the UK could be driven with EVs based on the residential (and workplace) infrastructure available today[40].

Range-extended electric vehicles extend their range by activating a small ICE-generator unit, like a series architecture PHEV with a heavily downsized auxiliary power unit.

Benefits: Electric vehicles offer high powertrain efficiency, regenerative braking and zero tailpipe emissions. Carbon emissions depend on power source (see next section). Electricity is a flexible ‘fuel’ that can be generated from a wide variety of sources. The SRZero (Figure 5), has a predicted energy usage of 150 Wh/km

Figure 5. The SRZero, an electric sports car built by engineers from Imperial College London

on the NEDC drive cycle; for comparison, the fuel energy usage of an efficient petrol ICE vehicle is about 550 Wh/km (assuming 50 mpg).

There is evidence that traffic-related air pollution may directly exacerbate asthma[41] and therefore decarbonising passenger vehicle transport by using electric and hybrid vehicles could deliver very significant co-benefits for society by improving urban air pollution.

Costs and barriers: The primary barrier for EVs is capital cost. Current battery cell prices of around $500-800+/kWh are prohibitive. Although it is technically possible to achieve a range of more than 300 km, at current costs this will be too expensive for the mass market. Other barriers include battery energy density and durability (see Box 2 below), charging times and infrastructure. Single-phase mains UK electricity sockets are limited to a maximum power level of about 3 kW, so an overnight charge from a normal socket allows a maximum energy storage of 24 kWh, giving a range of 100-150 km, assuming energy use of 15-25 kWh/100 km[42] and an 8-hour charging time. High power, high current fast charging (40-200 kW) could reduce charging times to less than 15 minutes, but fast chargers are expensive and require sufficient local grid capacity. Degradation of battery life through fast charging is also a concern. Battery swapping has been suggested, but may have drawbacks such as high cost and compromised vehicle packaging design.

Box 2. Batteries

Lithium batteries are the de facto standard rechargeable cells for vehicles, having at least five times higher energy density than lead acid batteries, although still substantially lower energy density than liquid fuels. Cost is a key challenge: in order for PHEVs/EVs to compete on cost with ICE vehicles, substantial research and development is required to reduce cell price to a more desirable $300-400/kWh[43]. In addition to cost and energy density (kWh/kg and kWh/litre), other aspects also need development including durability (number of cycles), environmental impact (use of rare materials, energy intensity of manufacture), and cell/pack monitoring and management. There is some contention over the long-term availability of lithium, the majority of which presently comes from South America. Despite this, a recent report estimates that lithium supply is unlikely to be a constraint given the reserves available and diversity of future battery chemistries[44]. Recycling of lithium as well as other materials such as cobalt is possible, with reasonable efficiencies[45].

At the cell level, fundamental scientific breakthroughs are required in new electrolyte chemistries and electrode materials such as manganese and iron for future batteries. Nano-structured materials and organic materials have further potential for exploitation[45]. An interesting possibility is the solid-state rechargeable lithium-air battery, which has been demonstrated in research labs[46] and could provide a 5-10 times increase in energy density over current technology, but challenges remain. In the future, chemistries other than lithium, such as magnesium-sulphur, may also have potential[45].

Fuel cell vehicles (FCVs) are electric powertrain vehicles that use a fuel cell as the primary power source. Fuel cells can also be used as range extenders for EVs or auxiliary power units for HGVs. FCVs could be designed to emit zero tailpipe CO_2, although the well-to-wheel emissions depend on the fuel feedstock and processing route. Fuel cells convert chemical fuel (such as hydrogen, methanol or natural gas) into electricity efficiently through a chemical reaction. Various different types are available such as proton exchange membrane fuel cells and solid oxide fuel cells. They may be key technologies in a low-carbon transport system, as chemical fuels will always play an important role. Fuel cells, batteries and/or supercapacitors—short-term, high-power density electrical energy storage devices—are complementary and could be combined into a hybrid vehicle configuration, resulting in lower lifecycle costs compared with a pure EV or pure FCV[47]. The challenge at present is to develop fuel cells that can compete on cost with ICEs.

Alternative low-carbon fuels and energy sources

Fossil fuels, particularly conventional oil, have been by far the most dominant energy source for transport due to their high energy density, and relatively low cost for much of the 20th century. By definition, any finite resource will eventually run out. Before this happens, there will be a period when demand consistently exceeds supply, leading to exploitation of harder-to-obtain or lower-grade resources. In this scenario oil prices are likely to be higher than historical averages, with significant price volatility[2]. Concerns have recently been raised that the extraction rate of crude oil may reach a plateau or decline before 2020[48-50]. There is considerable debate about the timing and implications of this, but the magnitude of the possible impacts could be large. This introduces a high degree of uncertainty both in demand projections and in technology and policy options. It highlights the importance of energy security considerations alongside carbon emissions as a strong driver for change in road transport.

Ultimately, unless we switch from fossil to alternative fuels, we will not be able to reduce vehicle-related CO_2 emissions below ~80 gCO_2/km for a typical small passenger car[25]. Gaseous fossil hydrocarbons such as compressed natural gas and liquefied petroleum gas do give CO_2 reductions, but these are relatively modest and therefore are not discussed in this paper. Fossil-fuelled vehicles with onboard carbon capture are not presently practical: it would seem preferable to undertake carbon capture centrally and use either electricity or hydrogen at the vehicle.

This leaves only three options: low carbon electricity, biofuels or synthetic chemical fuels such as hydrocarbons, alcohols or

	Low carbon electricity	Sustainable, low carbon biofuels	Low carbon hydrogen
Benefits	(i) Flexibility of supply options. (ii) Opportunity for local generation. (iii) Use of vehicle batteries as dispatchable loads in a smart grid with large amount of renewable electricity generation facilitates low cost integration of renewables into the grid, although overall costs and benefits are uncertain. (iv) Reduced local air pollution by displacing ICE-based transport.	(i) Sustainably produced biofuels have high energy density and can be transported and distributed easily. (ii) Potentially very low GHG emissions. (iii) Some fuels give superior performance in ICEs. (iv) Approximately 46-80% of the projected transport demand in 2020 in the EU could be met with biofuels grown in the EU [52-53].	(i) A high energy density synthetic chemical fuel. (ii) Flexibility of supply options. (iii) Opportunity for distributed production. (iv) Transportable by pipeline.
Barriers	(i) Decarbonising the grid is a formidable challenge, although it is central to the UK's climate change mitigation policy[12]. (ii) High take-up of electric vehicles could increase load on the electrical grid if measures are not taken to distribute the load and avoid the evening peak.	Concern about: (i) deforestation (ii) actual GHG benefits (iii) competition with food (iv) uncertainty over land availability and how to allocate land for different uses. Strong, comprehensive and mandatory global policies required to ensure production is sustainable and does not lead to deforestation, especially in tropical areas [51].	(i) Must be sourced from a low-carbon/decarbonised supply. (ii) Low total production efficiency if produced from electricity. (iii) Supply infrastructure would need to be built. (iv) On-vehicle storage could be improved. (v) Significant cost challenges remain for fuel cell development.

Table 4: Summary of low carbon fuel options

hydrogen, which must be produced using some net energy input and may or may not give an overall CO_2 reduction. These options are summarised in Table 4. (No attempt has been made to evaluate the cost of each option as the large uncertainties surrounding these are outside the scope of this briefing note.) Alternative fuels such as biofuels, electricity and hydrogen could contribute about half of transport fuels globally by 2050[6]. However, electricity generation is not presently low enough in CO_2 emissions to have a large impact; much greater roll-out of low-CO_2 options such as wind or nuclear is required. There is uncertainty surrounding the impacts of biofuels[51], but if they can be sustainably produced, then they could play a significant role in transport, although their use may need to be prioritised for trucks, ships and aircraft.

Low-carbon electricity has potential to become a significant transport 'fuel', or 'energy vector'. To meet the target of an 80% CO_2 reduction by 2050, electricity supply in the UK would have to be decarbonised [12]. This is a formidable challenge but several options exist for providing low-carbon electricity. Whatever the portfolio in 2050, it will require intelligent electricity grid systems ('smart grids') to absorb large intermittent renewable capacity while constraining investment costs. Strong complementarities exist between smart electricity grids and electric transport options: PHEVs and EVs can act as dispatchable loads and hence could have a role in grid balancing. This is an important service currently provided by adjusting the power output of fossil-fuelled power stations. An extension of this is the 'vehicle to grid' system, where vehicles are not just treated as dispatchable loads but as general distributed energy storage, able to supply energy to local loads in the home or to the grid for use in short term balancing. However, the effects of this on battery durability are uncertain.

There is uncertainty surrounding the impact of large numbers of EV/PHEVs on generating capacity. Conversion of the entire current UK light duty vehicle fleet to electric vehicles could increase electricity consumption by about 15% over current levels and increase peak system power required by 36% [54]. However, by using smart grids or delay timers to ensure that most charging occurs during off-peak periods (e.g. at night) when there is surplus available capacity, peak power requirement would reduce significantly, with benefits to the local grid even at low penetration levels [54-55] and lower CO_2 emissions. A large number of grid-connected vehicles could increase the flexibility of the grid to absorb larger amounts of wind power generation, which is a major challenge for future electricity systems.

The calculation of CO_2 emissions attributed to vehicles running on electricity is not straightforward, because it depends on which generator is turned on to meet the increased demand when an additional load is connected to the network. In the short term it is the CO_2 emissions associated with these marginal generators that should be used to assess the impact of an incremental change in electrical consumption rather than the average grid CO_2 mix. In the longer term (decades), investment in new power generation assets could take into account charging requirements for EVs and therefore calculation of CO_2 emissions is more uncertain. Average and marginal factors vary substantially with time of day and season. However, the mean marginal emissions factor is 0.67 $kgCO_2/kWh$ ±10%, which is around 35% higher than the average emissions factor[56]. Between about 12am and 5am this drops to around 0.6 $kgCO_2/kWh$. The mean marginal emissions factor could remain relatively high in the UK for the next 10 years, with a drop to about 0.6 $kgCO_2/kWh$ expected after 2016 when the EU Large Combustion Plant Directive is enforced, and a further drop to around 0.51 $kgCO_2/kWh$ by 2020-2025 as further plant is replaced[56]. This means that an efficient EV today emits about 90-100 gCO_2/km assuming energy usage of 0.15 kWh/km on average (decreasing to 90 gCO_2/km from 2016 and about 77 gCO_2/km in 2020-2025), which is only slightly less than the best of what is currently available on the market for normal ICE vehicles (see previous section on vehicle powertrains). Clearly, substantial grid decarbonisation of the marginal plant, and/or dispatch of EVs as loads, is required in order for EVs and PHEVs to achieve a low or zero carbon transport system.

Biofuels such as biodiesel and bioethanol could have a large impact on road transport CO_2 emissions and are attractive because of their similarity to fossil fuels. Strong growth in use of first generation biofuels up to 2008 led to concerns about food prices, deforestation and actual GHG emissions. This resulted in the Gallagher Review[51], which suggested that the evidence about biofuels is sometimes inconsistent or limited, and given the uncertainties, roll-out should be slowed down until adequate controls are in place. The review suggested sufficient land is available until 2020 to meet European demand without negative impacts, but the long-term potential is very uncertain. Conclusions from the Gallagher Review are supported by the Committee on Climate Change[12].

In Europe, agronomists have shown [53] that by 2030, a substantial amount of existing agricultural land could be accessed for feedstocks. The amount of land available in the UK is small, so the UK will have to import most biofuels, with careful consideration of the source, processing and associated GHG emissions. However there is significant UK potential to produce transport fuel from waste [57]. The sustainability of biofuel production is strongly dependent on the specific feedstock and production system used and the value of the co-products. The Gallagher Review recommended targeting marginal and idle land and ensuring full use is made of waste and non-crop feedstocks; the review also recommended that specific incentives should be provided for advanced second generation processing technologies (e.g. for lignocellulosics), which are currently immature and expensive, but which should become the primary focus of future developments in biofuels.

Hydrogen, like electricity, must be produced from some other energy or fuel source. Hydrogen can be consumed in ICEs and fuel cells, the latter having typically higher efficiencies. There is some contention over the role of hydrogen in future transport; it has been suggested that if the dominant available energy source is decarbonised renewable electricity, a largely electric system would have much higher 'well-to-wheel' efficiencies [42, 58-59] and therefore be more attractive.

However, if a chemical fuel feedstock is available, hydrogen can be produced very efficiently, for example by using chemical looping cycles with carbon capture at source[60]. Additionally, there are other novel production routes for hydrogen that offer potential, such as solar hydrogen (photoelectrolysis) or biological hydrogen production using algae. In order for hydrogen to become established as a transport fuel it may first need to penetrate niche transport markets such as urban buses and other centrally fuelled fleets.

The UK technological transition path

The challenge is to achieve substantial reductions in emissions using conventional technologies, while laying the foundation for their replacement over the succeeding decades. Figure 6 visualizes in simple terms the required European-wide fleet average tailpipe emissions from the current value towards an 80+% reduction by 2050, using a typical light duty car as an example. The United Kingdom historically has had and still continues to have worse fleet emissions than the European average [12].

By 2025 the majority of passenger vehicles in use need to be best-in-class ICEs, typically using diesel technology but also allowing for advanced spark ignition solutions. Without electrification or hybridisation, biofuels are likely required in order to achieve vehicle emissions better than 80 gCO_2/km[25]. However, this presumes that sustainable biofuels will be available in sufficient quantity that passenger cars can be fuelled in addition to priority uses such as HGVs, aviation and shipping. At present, this is very uncertain. By 2035, about half of vehicles will need to be EVs/PHEVs with a significant amount of grid decarbonisation (around 50%) as well as significant biofuel blending (around 30%). Beyond 2045, all vehicles must emit less CO_2 than a best-in-class fossil-fuelled ICE hybrid, suggesting that the majority of vehicles should be EVs/PHEVs with an almost completely (75-100%) decarbonised electricity grid and substantial roll-out of biofuels (again, perhaps 75-100% blend).

This scenario represents a challenging set of timelines. While many efficiency improvements pay for themselves in reduced fuel costs, the alternative fuels, new infrastructures and some of the types of powertrain required for low-carbon road transport are presently expensive compared with conventional fossil-fuel ICEs. It therefore seems unlikely that these radical transformations can be achieved without significant changes to the current industry and market structure and policy framework.

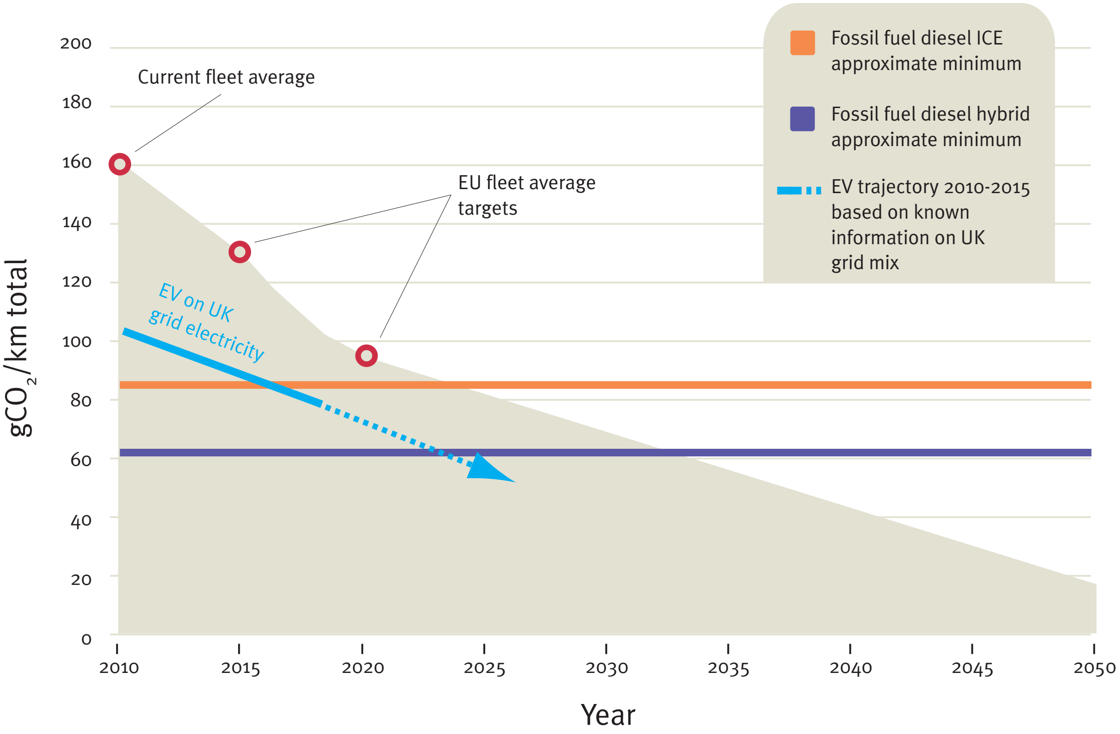

Figure 6: European passenger car tailpipe CO_2 trajectories (limits are shown for a typical 4-seater C-class vehicle e.g. VW Golf)

Policy and economic context

Achieving rapid reductions in emissions from vehicles with conventional powertrains

The mass market presently places a low priority on 'green motoring', seeing it as largely irrelevant[3, 40]. Providing clear comparative information about the fuel cost savings of efficient vehicles, reinforced by manufacturer advertising could mitigate this, although resulting CO_2 reduction could be small[4]. In the longer term, there is scope to reconfigure road space, change land use policies and re-engineer infrastructure to support demand reductions and modal shift, all of which may contribute to reduced CO_2 emissions. However, to achieve substantial changes in the short term, consideration needs to be given to additional policy measures to encourage consumers to switch to more efficient vehicles, including:

Fiscal measures. The majority of consumers apply high discount rates when purchasing vehicles, i.e. they tend to be concerned primarily with the capital cost, and short-sighted about other costs. Stable policies such as long-term subsidies and discounts in circulation taxes (vehicle duty) for best-in-class efficient vehicles could counteract this [4]. However, evidence on circulation and company car taxes is mixed, and the difference between taxes for efficient versus inefficient vehicles may need to be very large to have a substantial effect. Fuel costs plays a part, but vehicle travel and fuel use are relatively price inelastic, meaning it could take a substantial increase in price to cause a significant reduction in demand [61].

Emissions polices and efficiency standards. The European Union has some of the most demanding vehicle CO_2 emissions policies in the world, although many of the targets currently under discussion are not yet mandatory in law. There remains substantial potential for further emissions reductions but policy must be mandatory, sustained, progressive, enforceable and enforced[4]. Given the fuel price inelasticity mentioned above, there is a case for regulation to impose an upper absolute limit on individual vehicle emissions irrespective of the fleet average emissions. The upper limit might be reduced over time in line with the fleet average.

Current emissions methodologies focus exclusively on vehicle tailpipe (exhaust) emissions and ignore upstream CO_2 from the oil well to the vehicle fuel tank. As road transport begins to use a greater variety of fuels, CO_2 emissions will need to be measured in a more holistic fashion, including every processing step in the chain (i.e. 'well-to-wheels'), to ensure comparability. In the longer term, lifecycle emissions including energy used in manufacture should also be included [3].

Many UK car journeys are for business and commuting purposes, and of these many are made by public sector workers[9]. Therefore, alongside emissions policies and fiscal measures, public sector vehicle procurement could have a big impact by creating strong demand for more efficient vehicles and therefore increasing production volumes, in turn reducing costs.

The above-mentioned measures are aimed at encouraging a switch to more efficient vehicles at the point of vehicle purchase. However, the efficiency of vehicles already in use (which may not be replaced for some time), must also be addressed. Scrappage schemes may encourage drivers to purchase more fuel-efficient vehicles. Primarily however, this will take place through education programmes to improve driving and encourage 'eco-driving', which may include changing the curriculum for driving tests. Such measures can have a positive impact at low cost.

Accelerating the transition to low-carbon vehicles and fuels

Many of the measures discussed in the preceding section, particularly emissions policies and fiscal measures, could also play a large part in influencing the adoption of very low-carbon vehicles and fuels in the medium term. Additionally, because such vehicles are likely to be more expensive (in capital cost terms) at present than conventional technology—but with possibly lower fuel costs—innovative financing models such as leasing schemes could help to encourage uptake. Car clubs are an innovative way to arrange short term ‘pay as you go’ leasing.

> Radical change will require long-term political support and policies across multiple sectors.

In order to create the market for design and manufacture of new very low carbon powertrain technologies, two key issues must be addressed. First, international standards for design and interoperability must be agreed. At present there is a lack of European and global standardisation in areas such as battery pack manufacture and testing; recharging connectors, sockets and interfaces; drive cycles and holistic CO_2 measurement. This could hinder development of electric and hybrid vehicles[62] if not addressed in the near term. Second, a key issue for industry is the length of time that it takes to design and produce new vehicles - typically of the order of a decade for a completely new design. Appropriate policies need to be established now to demonstrate the long-term commitment to the development of these kinds of vehicles.

Particular considerations apply when contemplating biofuels and electricity as transport energy sources:

Biofuels. Strong policies are required for the sustainable use of available land for production; governments should be prepared to forsake biofuel blending targets if sustainability standards are not met[51]. To overcome cost barriers, a realistic carbon tax with a lower limit is crucial. Stability of policies for farmers planting crops and for biorefineries is important to enable the transition to biofuels. Changes in land use, which are difficult to predict, must be dealt with in an integrated fashion by considering all land use holistically.

Electricity. Decarbonisation of the grid is an urgent challenge if PHEVs and EVs are to be a major component of efforts to reduce GHG emissions in the long-term, despite other benefits.

Another key challenge will be how to establish and regulate fuel pricing structures across different networks (e.g. electricity and transport). There are many potentially problematic interactions, for example, at present, taxation of fuel at the pump is relatively straightforward; if the fuel is electricity, the taxation could become much more complex.

Research agenda

Conventional ICE vehicles. The key technical development opportunities for internal combustion engines are reduction of losses, improved combustion, engine downsizing, boosting methods, exhaust energy recovery and redesign of engines for use as range extenders, as well as light-weighting and other vehicle improvements.

Low-carbon vehicles. In order to achieve widespread adoption of hybrid, plug-in hybrid and electric vehicles, energy storage systems such as batteries require significant fundamental scientific breakthroughs to reduce costs and increase durability, energy density and power density. Battery packaging, monitoring and management systems also require development. Supercapacitors offer possibilities for high power density storage and require cost reduction and breakthroughs in the same way as batteries. Such vehicles also require improvements to be made in the areas of motors and power electronics. These are mature technologies with high efficiencies, but significant cost reduction and optimisation is required for them to become more competitive compared with ICEs.

Fuel cells are still an embryonic technology. Again, cost reduction is key, with clear routes to delivery required. Operating proton exchange membrane fuel cells at higher temperatures could significantly improve future prospects and deliver the breakthrough needed for low cost commercialisation. Solid oxide fuel cells may be suitable for transport applications as range extenders; they operate at higher temperatures, use cheaper catalysts and materials, and do not require high purity hydrogen.

Real world validation. Technological developments as well as behavioural interventions must be validated in ‘real world’ usage by measuring vehicle and emissions data. At present, such evaluation of real-world data is lacking. Initiatives in sensor networks in conjunction with space-based metrology techniques have a major role to play here, permitting emissions reduction potential to be assessed alongside other transport network management priorities.

Smart infrastructure to support zero-carbon mobility. Integration of energy decisions across sectors and the possibilities for overall system benefits through co-operative system-wide management is an important area of research. Systems research to model the adoption and use of new vehicle technologies is required, exploring the interactions between engineering design, policy, economics and consumer choices. Technologies, services, systems and policies that are developed alongside one another have great potential to deliver cross-sector reductions in CO_2

emissions. For example, 'smart grids' are crucial for the controlled roll-out of EVs/PHEVs with a greater proportion of renewable energy in the electricity grid. However, ongoing work is required at high spatial and temporal resolution to understand the interactions between vehicles, the grid and other devices such as heat pumps and CHP systems.

Conclusion

Road transport presents particular challenges for emissions reduction and requires a step change in our behaviour and technology. The scale of the challenge means that incremental improvements using existing technologies will not be enough to meet 2050 targets. The UK government proposes a target to reduce domestic transport emissions by 14% on 2008 levels by 2020[9, 63], which requires immediate action. However, much deeper reductions in transport emissions will be required in the longer term to meet the UK's legally binding target to cut GHG emissions by 80% by 2050 compared with 1990 levels. Radical change in this area will require consistent political support and policies focused on the long term, across multiple sectors (e.g. vehicles, fuels and electricity supply).

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