Smith School of Enterprise and the Environment

University of Oxford

Future of Mobility Roadmap

Ways to Reduce Emissions While Keeping Mobile

PUBLISHING INFORMATION

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EXECUTIVE SUMMARY

Transport is the second largest greenhouse gas (GHG) emitter by sector and will play a key role in achieving emissions reduction targets. The dependence of the transport sector on fossil fuels, namely crude oil, has led to two main problems: the **input problem** of dwindling conventional crude oil reserves and the **output problem** of increasing GHG emissions. The central **challenge** is how to reduce GHG emissions without reducing human mobility.

Land transportation is responsible for 11% of global GHG emissions. A number of changes to current methods can offer a reduction in GHG emissions.

- In the short-term, **turbocharging** and a **simple down-scaling,** in combination with weight reduction, can bring significant benefits.
- In the medium-term, **hybrid systems**, those using internal combustion engines and regenerative electric systems such as the Toyota Prius, offer significant savings and will accelerate the evolution to a purely electric drivetrain.
- **Purely electric vehicles** are not zero emission vehicles, due to electricity production and hydrogen generation. Such technologies will be important forms of **low carbon transport** in the long term.
- Plug-in electric vehicles are restricted by **battery technology**, fuel cell systems are limited by **power density** of the unit and both systems are challenged by the **limited material availability**.
- First generation biofuels, those derived from food stocks, have **proved the viability** of such fuels, but remain a localised solution, as in Brazil.
- Second generation biofuels synthesised from inedible cellulosic biomass have the potential to be **true low carbon** fuels but are constrained by land availability.
- Algae based fuels **show promise** as they overcome land use and food security issues, but they require the development of large scale production to be viable.
- Both electric and diesel rail systems have **low operating emissions,** but high embedded infrastructure costs and lack route flexibility.

Air transportation is responsible for 2-3% of GHG emissions, but the IPCC estimates that the total impact from aviation is 2-4 times greater due to various indirect effects.

- Technical changes, such as improvements to propulsions systems and the reduction of aerodynamic drag could reduce emissions by **up to 50%**, in the short-term.
- However, the rate of uptake of new technologies is **restricted by fleet lifetimes**.
- Longer term developments require a change to the current aircraft architecture from 'tube and wing' to **'flying wing' systems**, offering a 32% cut in GHG through drag reduction alone.
- **Biofuels** could reduce emissions, but aviation faces competition from the road sector.
- Operational improvements, such as **Air Traffic Control**, could be the 'low hanging fruit' for GHG emissions reduction from aviation.

Sea or maritime transportation accounts for 3% of global GHG emissions, while transporting 70% of the world's cargo by volume. This sector has the **lowest emission per tonne kilometre** of all modes considered here.

- Through both technical and operational change, GHG reductions of **up to 75%** are possible in the medium to long-term.

Behavioural Change is needed to encourage low carbon transport and a combination of top-down and bottom-up policies are required.

- Top-down methods include **command and control** policies, such as regulation and **incentive** based policies, for example taxes and charges.
- Top-down methods are not efficient from an economic perspective but are effective when drastic changes in activity are required.
- Bottom-up methods or **complementary policies** can be used in combination with top-down methods.
- Complementary policies fall into one of three broad categories: **physical** policies, **soft** policies and **knowledge** policies.
- Bottom-up methods are **economically efficient**, but do not always achieve their full potential for change.

From this we have drawn the following recommendations:

- **Downscale** the car fleet for emission reduction in the short-term.
- **Hybrid systems** for medium-term and **purely electric systems** are the long-term solution.
- As a 'drop-in' technology, **biofuels** offer a solution to both the input and output problems. Food security, land use and mass manufacture must be overcome before widespread use is possible.
- Minimise car use by shifting users to more **suitable modes**.
- Investment in infrastructure is **crucial**.
- A combination of **physical, soft and knowledge** policies must be applied within an integrated framework to direct consumers to low carbon transport modes.

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"If we shift the source of our energy and change our transportation systems, there's no question that we can solve the climate change crisis."

Al Gore

Nobel Prize laureate and former U.S. Vice President

at the inaugural The Times-Smith School World Forum on Enterprise and the Environment, Oxford, United Kingdom, July 2009.

1 INTRODUCTION

Soon after the Industrial Revolution, the transportation of people and goods was revolutionised by the invention of the internal combustion engine[1] and the mass manufacture of automobiles. Initially, these automobiles were fuelled with plant-derived alcohols or oils that had a limited capacity to service large demands. The abundance of petroleum, derived from crude oil, soon put these early fuels out of business. Since then, the availability of cheap, readily available fuel combined with affordable, mass-produced vehicles has radically changed the face of the earth[2].

Cars have become ubiquitous in the developed world and are increasingly used in the developing world, providing many with cheap, reliable transport. Currently, there are more than one billion cars on earth and forecasts suggest we will soon reach the two billion mark due to rapidly increasing car ownership in the emerging markets[2].

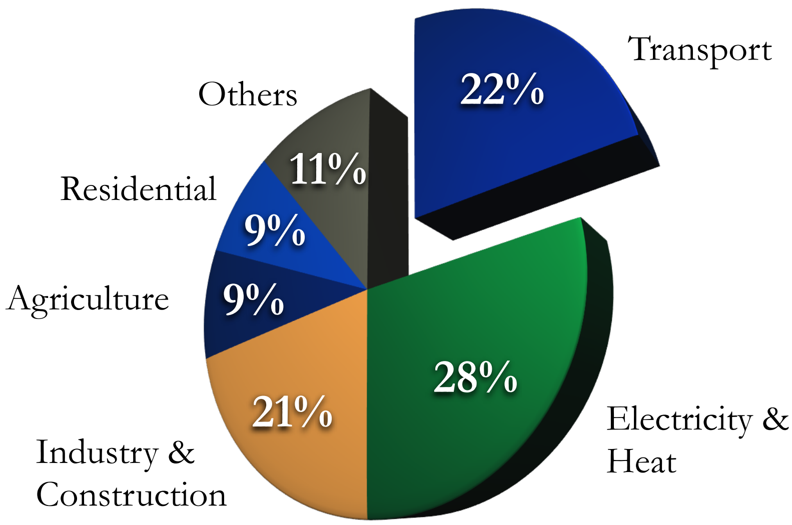
Subsequent to the spread of the automobile, improved aviation technology, relying on crude oil derived kerosene, further enhanced our mobility, effectively shrinking the world. Intercontinental travel became possible in hours as opposed to weeks and even the trade of perishable goods between hemispheres started to flourish. Aviation in combination with telecommunications and the fall of borders, played a critical role in the foundation of today's globalised society[3].

The transport revolution has not only changed our way of life, but has also significantly contributed to global economic development, human welfare and technological development[4]. This enhanced mobility of goods and humans has, on the other hand, left us with a severe addiction to crude oil. Today more than 90% of transport fuels are derived from this commodity[2]. Consequently, energy security concerns deeply influence geopolitics, as crude oil supply is inextricably tied to economic activity and development[5]. These concerns have been raised by potential oil shortages due to depleting oil reserves, which will eventually lead to increased oil prices. Recently, unease over the looming climate change induced by anthropogenic greenhouse gases (GHG) emissions[6, 7] has intensified this discussion[8, 9] as the transport sector is the second largest emitter of GHGs in the industrialised world (figure 1.1). The crude oil addicted transportation culture has two main problems, declining fuel supply – **the input problem** – and increasing GHG emissions - **the output problem**.

1.1 The Input Problem

In the transport sector the fuel mix has been dominated by fuels derived from so-called light crude oil, which is accessible and cheap to produce. In recent years, concerns have grown over the capacity for crude oil reserves to service rising demands[2, 10-14]. These reserves can roughly be classified as conventional resources such as light crude and unconventional resources such as tar sands and heavy oil. The status of conventional oil reserves is obscured by a lack of binding

Figure 1.1: Greenhouse-gas emission in the European Union by sector (2007)



Source: European Environment Agency, http://dataservice.eea.europa.eu/

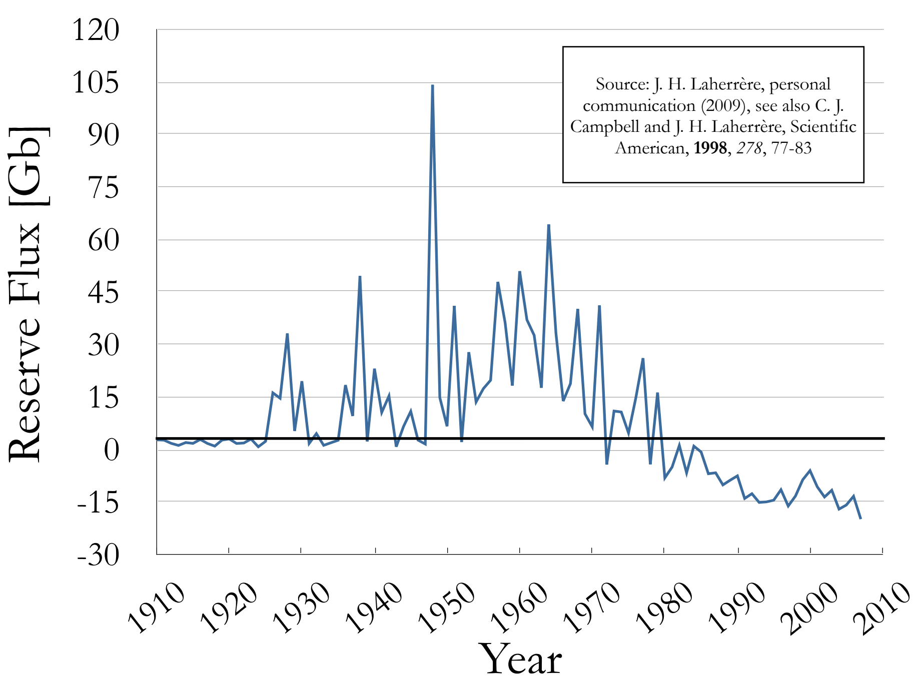
international standards that define conventional oil (reserve volume and grade)[11-13, 15], by intentional misreporting to suit political or financial agendas[11, 16, 17] and by inherent technical uncertainty[15, 18]. Most data in the public domain originates from reporting agencies such as the World Oil Journal or the Oil and Gas Journal, which is then reproduced by information agencies (for example the International Energy Agency or the Energy Information Administration). Data on individual fields may also be purchased from scouting companies, which is generally considered the most accurate by independent authors and academic institutions[12]. Reporting and information agencies estimate that there is between 1,184 Gb (giga barrels) and 1,342 Gb[19, 20] in world oil reserves. Independent authors and academic institutions are more conservative and estimate conventional oil reserves at between 800 Gb and 900 Gb[11-13, 21-24]. At current demand, conventional oil reserves are forecast to run out by 2035. It should be noted, however, that reserve-production ratios are not sensitive to declining production rates, even if the net amount produced over an extended period remains the same.

Oil reserves are defined as the fraction of oil resources that can be commercially and technically recovered at the current market price[15]. Best practice assessment demands that estimated reserve volumes should be stated together with a 50% probability (2P) of achieving the specified volume to limit inherent assessment uncertainty[11, 25-27]. This uncertainty is increased by ambiguity over the point at which sub-commercial resources can be reclassified as commercially exploitable reserves - the price-reserve relationship[28]. Moreover, data from reporting agencies are inconsistent on the inclusion of Canadian tar sands in world reserve estimates[20] and usually report sub-commercial reserves prematurely[11]. If data presented by information and reporting agencies is amended to reflect conventional 2P reserves, and account for widely acknowledged false additions, figures become consistent with those quoted from independent institutions.

In the context of rising liquid fuels demand, it is necessary to consider the effect that limited conventional oil resources may have on the liquid fuels' mix. Figure 1.2 gives a history of the flux of oil entering and exiting the conventional global oil reserve inventory, based on backdated 2P data.

Data below the zero flux axis indicates periods of net withdrawal from reserves. This first occurred in 1972 and has consistently occurred since 1980, indicating that conventional oil reserves have been in decline since then. This is in sharp contrast to figures published by reporting and information agencies that indicate oil reserves are continuously rising. Since records show that the peak of conventional oil discovery occurred in the early 1960's[29], it is unlikely that many significant and accessible conventional oil fields remain to be found. The World Energy Outlook 2008 estimates that the world's producing oil fields are declining at such a rate that by 2020, only 50% of liquid fuel

Figure 1.2: Oil flux entering and exiting the global conventional oil reserve



demand will be serviced by reserves that are in production today. Shortages in supply of conventional oil would most likely be closed by using unconventional oil. The major drawback of unconventional reserves is that they consume more energy to extract and convert to usable liquid fuels; consequently, fuels derived from these sources have a higher carbon footprint, *i.e.* the same amount of fuel burnt would result in a larger amount of GHGs formed. Rising fuel demand and higher emissions per volume of fuel thus multiplies overall emissions from the transport sector and we conclude that *unconventional reserves could mitigate the input problem, but they exacerbate the output problem.*

1.2 The Output Problem

Temperature levels on the earth's surface have risen by between 0.74 ± 0.18°C over the last 100 years, according to the Intergovernmental Panel on Climate Change (IPCC)[30]. A further increase of between 1.1 and 6.4 °C is likely this century[30] as it is likely the rate of warming will double[31]. Accelerated climate change is largely attributable to anthropogenic GHG emissions – carbon dioxide (CO_2), methane (CH_4), and nitrous oxides (NO_x)[7, 32-34]. Since the Industrial Revolution, the combustion of fossil fuels has caused atmospheric CO_2 concentrations to rise by 36%[35]. The atmosphere is heated through the absorption of infrared radiation by GHGs[7, 36]. Consequently, higher atmospheric GHG concentrations accelerates the rate of warming. The current level of atmospheric GHG concentrations is equivalent to 430 parts per million (ppm) of CO_2, so-called CO_2 equivalents ($CO_{2(eq)}$), compared to 280 ppm before the industrial revolution[34]. If GHG emissions stagnate at the current level, atmospheric GHG concentrations will still reach 550 ppm $CO_{2(eq)}$ by mid-century, which is double pre-industrial levels. If we continue with business as usual and emit GHGs at a higher rate, we could reach 550 ppm of $CO_{2(eq)}$ by 2035[34].

The consequences of anthropogenic climate change are wide ranging: glacial retreat and the melting of Arctic ice means sea levels are likely to rise by between 0.18 to 0.59 metres by the end of the century, putting at risk those living near coasts[30]. Rainfall patterns are also likely to change, extreme weather events could become more frequent, water scarcity will increase in many regions and crop yields will fall. The spread of diseases, such as malaria and dengue fever, could accelerate, potentially causing turmoil in large parts of the developing world[37].

With regards to economic consequences, the Stern Review[34] has warned that the '…costs of extreme weather alone could reach 0.5% – 1% of world Gross Domestic Product (GDP) *per annum* by the middle of the century, and will keep rising if the world continues to warm'. The same report says that '…climate change [under business as usual conditions], will reduce welfare by an amount equivalent to a reduction in consumption *per capita* of between 5% and 20%'[34]. Moreover, studies by Barker have shown that the costs of mitigating and preventing the worst environmental effects of climate change will be insignificant compared to the risks and potential costs of an unhindered and unmitigated climate change[38].

This potential threat has lead to international environmental treaties such as the Kyoto Protocol to the UNFCC, which aims to stabilise GHG concentrations by reducing emissions. In order to comply with the GHG emissions targets set out in the Kyoto Protocol, countries have to reduce the emissions intensity of all sectors, especially sectors such as transport. However, reducing GHG emissions from the transport sector without decreasing human mobility remains a non-trivial **challenge**.

1.3 The Challenge

Economic activity and, consequently, the societal welfare are intrinsically linked to the mobility of humans and the transportation of goods. Reducing emissions from the transport sector by reducing mobility will have dire consequences for the global economy. The aim of this study is to assess technologies and policies that have the potential to reduce emissions from the transport sector while enhancing human mobility. The problem will be addressed from multiple perspectives aiming at a transformation of the transportation sector by taking an integrated approach. Technological innovations that have the potential to reduce GHG emissions in the transport sector are assessed. These innovations encompass advancement in vehicle design and drivetrain engineering and alternative fuels. We focus on ways to use our current fuels more efficiently in the short-term and the possibility of replacing fossil fuels in the medium and long-term. Special attention is paid to energy and food security as well as to scarce commodities. In parallel, this study focuses on legislative interventions and policy levers that can support these technological innovations. The study identifies desirable interventions, which meet the twin objectives of enhancing human mobility and minimising adverse effects on the environment. A roadmap for the renovation of our transport system can hence be a significant **benefit** for our society.

1.4 The Benefit

The impact of greenhouse gases is not the only problem caused by transport. Vehicles emit toxic local pollutants, such as nitrous and sulphur oxides, volatile organic compounds, carbon monoxide and soot, which cause asthma and other respiratory diseases and produce acid rain that destroys forests. Although the emission levels of these pollutants in developed countries have been reduced significantly through technologies such as advanced combustion and exhaust treatment systems as well as low sulphur fuels[39, 40], those in the developing countries remain high[41]. Noise from busy streets as well as landing and departing aircraft can affect humans and wildlife. In other words, improving our transport systems would reap many environmental benefits, while green technologies could create jobs in underdeveloped areas. Previous revolutions such as the transformation of our communication system in the 1990's have had a tremendous impact on economic growth. Last but not least, the relief from the current crude oil addiction could ease geopolitical tensions.

This study is divided into three broad areas: **land**, **air** and **sea** transport, weighted and ordered by their contribution to overall transport emissions. We focus on technologies and policies and deliberately neglect transport management, such as logistics, air traffic control, rail and road management, as these more dynamic processes will be addressed in a subsequent Smith School of the Enterprise and the Environment study.

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2 LAND

Land transport is the largest contributor to the transport sector's greenhouse gas emissions. This chapter considers ways to reduce these emissions while maintaining and enhancing mobility. It begins by focusing on passenger cars, noting that the biggest impact can be made by getting consumers to drive less and to buy smaller vehicles with smaller engines. The chapter goes on to look at technological improvements that can be made to internal combustion engine vehicles (ICEVs) to reduce CO_2 emissions and the contribution that alternative drivetrains can make, including hybrid-electric vehicles (HEVs), plug-in hybrid-electric vehicles (PHEVs), fuel cell vehicles (FCVs), and battery electric vehicles (BEVs). Major alternative fuels that can be or are already being used in existing ICEVs such as ethanol and biodiesel derived from biomass, synthetic fuels produced from coal, natural gas and biomass, and compressed natural gas (CNG) are evaluated and compared with conventional fuels in terms of resource constraints and environmental impacts, including the effects of land-use change. Looking to the potential fuels of tomorrow, the possibility of a transition to a hydrogen economy is assessed, looking at the current state of affairs and the challenges such a transition faces. Rail as a potential low carbon transport mode is also briefly reviewed. Transport technology and alternative fuels alone, however, will be insufficient, at least in the short to medium-term, to substantially reduce greenhouse gas emissions. Economic policy measures that could bring about consumer behavioural changes towards more sustainable transport choices are discussed.

2.1 Road Vehicle Technology

Road transport is one of the largest and fastest-growing contributors to increased greenhouse gas concentrations and the associated climate change[1, 2]. Globally, passenger cars[3] alone emit more than 6% of anthropogenic carbon dioxide (CO_2)[2], the most abundant greenhouse gas[4], along with other pollutants. Incomplete combustion from internal combustion engine vehicles (ICEVs) running on petroleum-based fuels (petrol and diesel) produces particulate matter and carbon monoxide (CO), as well as toxic nitrogen oxides (NO_x) and volatile organic compounds (VOCs) that are the precursors of smog[5]. Improved combustion, particulate filters, and catalytic after-treatment systems such as three-way catalytic converters have helped to improve urban air quality and reduce smog hazards[6], mitigating the associated health concerns[7] and ICEVs can be expected to continue to improve with increasingly stringent fuel efficiency regulations. With the economic growth of China and India, the number of passenger cars expected to double to two billion in the next two decades[8]. Therefore advanced vehicle technologies are needed that can greatly reduce or eliminate automotive pollutant emissions and CO_2 emissions.

This chapter examines two such alternative technologies: fuel cell vehicles (FCVs), which run on hydrogen and convert chemical energy directly into electrical energy; and battery electric vehicles (BEVs), which run from onboard batteries that are charged with grid electricity. Because of their higher efficiency, both FCVs and BEVs require less energy to operate than ICEVs. With no tailpipe emissions, they offer the possibility of being *de facto* zero emissions vehicles if they get their energy from low carbon sources such as nuclear and renewable sources. This chapter begins, however, with a note on the importance of changing consumer behaviour regarding vehicle choice and use patterns instead of simply relying on technological 'fixes'. The chapter then moves on to technological improvements that could be made to reduce ICEV CO_2 emissions, as well as a brief look at two other alternative technologies: hybrid-electric vehicles and plug-in hybrid-electric vehicles. The chapter then summarises the advantages and disadvantages of the main types of fuel cells and provides an assessment of their relative promise for automotive applications. It concludes that although a number of prototype FCVs have been produced and the technology is continually improving, problems of cost, durability, and power density remain serious challenges to commercial viability. The chapter then looks at BEVs, focusing particularly on a Smith School of Enterprise and the Environment study on the well-to-wheel CO_2 emissions (emissions from initial energy extraction to ultimate consumption) from three production BEVs – the Tesla Roadster, TH!NK city, and REVA G-Wiz i – when run in the US, the UK, and France. The study compares these figures with well-to-wheel emissions data for a selection ICEVs and HEVs and shows the massive reductions in fleet CO_2 emissions that could be achieved with the introduction of large numbers of BEVs, provided the electricity grid is also decarbonised. The study also considers the increase in electricity demand that a BEV fleet would bring, as well as the effect of regional differences in the carbonisation level of the electricity grid.

Before focusing on FCVs and BEVs, we will briefly outline other more immediate ways of reducing CO_2 emissions from light-duty road vehicles. The most significant impact that can be made in reducing CO_2 emissions from automobiles in the coming decades is reducing the average weight and engine size of vehicles. Consumers can influence manufacturers to produce smaller vehicles by opting not to buy larger, heavier vehicles with higher CO_2 emissions. For example, consider table 2.1, which shows the differences in CO_2 emissions produced by a range of

“Diesel cars are highly polluting.”

Table 2.1: Comparison of tank-to-wheels CO_2 emissions from a range of vehicles produced by a single manufacturer

Class	CO_2 emissions (g/km)[9]
Supermini	88
Small family	118
Family	142
Coupe	146
Compact executive	165
Executive	176
Estate	191
Open-top	210
MPV	244
Luxury	284

vehicles available from a single major manufacturer.

Consumers clearly have a range of smaller vehicles with smaller engines from which to choose. They should be further encouraged and incentivised to make such choices, as well as to drive less and make more use of alternative, less-carbon-intensive means of transportation (see section 6).

Apart from these measures, a number of technological innovations to reduce CO_2 emissions can and are being made to conventional automobiles. Indeed, since improvements in ICEV technology have the shortest lead time, these incremental improvements will have the biggest impact on greenhouse gas emissions reductions in the next two decades[10]. Reducing greenhouse gas emissions from ICEVs can be achieved by using alternative fuels such as biofuels (see section 2.2) or reducing the amount of energy the vehicles consume. Decreasing energy consumption can be accomplished by reducing acceleration resistance and rolling resistance. This can be achieved by using lightweight materials such as high-strength steel, aluminium, and plastic composites, making the engine smaller, and/or making the vehicle smaller. Reducing rolling resistance through advanced tyre technologies; and reducing aerodynamic resistance, or drag, by making cars more aerodynamic also contributes to energy saving[11]. Most importantly, vehicles should become smaller, as attempting to reduce energy use while keeping cars the same size is very expensive[11].

Reducing vehicle energy use beyond the above requires moving past ICEVs and incorporating electric or hybrid-electric powertrains. Besides FCVs and BEVs, options include hybrid-electric vehicles (HEVs) and plug-in hybrid-electric vehicles (PHEVs), which run both on petrol or diesel in an internal combustion engine (ICE) and grid electricity in an electric motor. HEVs[12-16] have been the first to be mass produced, first with the Toyota Prius in 1997[17]. HEVs combine the high energy density of ICEVs, with the high efficiency and no idling losses of BEVs. ‘Mild’ HEVs shut off when idling but are still propelled by an ICE, while full hybrids have a smaller ICE and run on an electric motor during most stop-and-go (urban) driving. Full hybrids are more efficient than ICEVs because they have no idling losses, they capture and reuse some of the energy used in braking (regenerative braking), their electric motors are more efficient than ICEs, and their ICE operates primarily during highway driving, where it is more efficient[11]. PHEVs[18-22] are a variant of HEVs that have been on the market since the end of 2008 when BYD launched production of its F3DM model in China[23].

One of the key challenges for the growth of BEVs, HEVs, and PHEVs is battery technology. Although batteries are widely used in small-scale electric appliances, the electrification of vehicles raises an entirely new set of challenges. Compared to petrol and diesel, current electric battery technology is heavier (affecting vehicle performance), requires more space (reducing passenger comfort and vehicle functionality), and demands longer refuelling times (reducing operational convenience). Although BEVs have thus faced major barriers to reaching a mass market, there is a large range of battery technologies under development that show promise in addressing some of these challenges (Table 2.2).

BEVs on the market today have a range between 80 km for lead acid batteries (0.23 km/L) and 320 km for lithium ion (Li-ion) technology (0.72 km/L)[30]. Increasing range using current technologies demands larger, heavier batteries that compromise other aspects of vehicle performance and functionality. For this reason, vehicle use patterns and intended application play a significant role in choice of battery technology. HEVs require batteries with an extended cycle life to accommodate frequent discharge-recharge cycles and good power characteristics for acceleration[31]. In contrast, BEV battery design emphasises the need for greater power and usable energy capacity to increase vehicle range[31].

While current battery technology has the capacity to satisfy acceleration and range targets independently, no technology has the capacity to meet targets for both criteria simultaneously[31]. Many industry experts believe a step change in battery technology is required for BEVs and HEVs to gain a viable place in the market[32]. In general, BEVs demand good range and rapid electricity release to ensure good acceleration properties, while acceleration alone is more important for HEVs. Based on

- Today's diesel cars meet the most stringent requirements created by the California Air Resources Board.

Table 2.2: A comparison of battery technologies for HEV and BEVs

Type	Energy density (Wh/kg)[24-26]	Peak Power (W/kg)[24-26]	Energy Efficiency (%)[24, 26]	Cycle life[24, 27]	Cost ($/kWh) [27]	LCA score (high is poor)[26]	Advantages[27-29]	Disadvantages[28-29]
Lead-acid (Industrial vehicles)	35-50	150-400	>80	500-1000	100	503	Mature, proven technology	Limited to industrial vehicles, little scope for improvement, low performance, not suitable for BEVs or HEVs
Nickel-cadmium	50-60	80-150	75	800-1350	>550	544	Mature technology	Toxicity and safety issues, low performance
Nickel-metal hydride (Toyota Prius, common in other HEVs)	70-95	200-300	70	750-1350	530 (unlikely to decrease)	491	Proven technology, safe, longevity in calendar and lifecycle, suitable for low-performance PHEVs	Little scope for improvement and future cost reductions
Sodium-nickel chloride (Renault Twingo, fleet car)	90-120	130-160	80-95	1000-1200	$240/kWh	234	Suitable for fleet cars though still in development phase, low cost	High operating temperature, must be heated before use, insufficient power density for BEV and PHEV
Lithium-ion (Tesla Roadster)	80-130	200-300	>90	1000-3200	>800 (likely to decrease significantly)	278	Only battery that shows promise to achieve performance goals for HEVs and BEVs, low material cost	Safety, needs to be use within operating limits to avoid damage, need sophisticated management system, relatively short calender life

specific energy and power alone, Li-ion batteries outperform all other available technologies, although nickel metal hydride (Ni-MH) batteries will continue to contend for a place in the BEV and HEV market over the next decade. It should also be noted that lead acid batteries provide a cheap alternative for low performance industrial vehicles such as fork lifts, but are not suitable for cars.

In general, Ni-MH batteries are more durable and have better safety characteristics than Li-ion batteries. Whilst they are cheaper to produce, Ni-MH batteries are a more mature technology with limited scope for improvement. A key drawback of Ni-MH technology is that its lifecycle impact remains problematic with limited recycling, processing, and disposal possibilities[33]. Although Ni-MH technology does not achieve specific energy densities attained by Li-ion batteries, this is of less importance for HEV technology. Ni-MH batteries currently have widespread commercial application in the Toyota Prius HEV.

Table 2.2 shows that Li-ion batteries have greater specific energy density (100-150 Wh/kg) and power than Ni-MH batteries. To put this figure into context, the chemical energy in petrol is theoretically equivalent to an electrical energy density of 12,700 Wh/kg. This greatly affects the performance of BEVs compared to internal combustion engine cars. For example, the most advanced Li-ion battery technology currently in use in the Tesla Roadster, weighs 450 kg and contains about 53 kWh of energy, equivalent to only 8 litres of petrol[34]. Li-ion technology is immature with significant development expected in production costs, improved performance, and mitigated safety concerns[27]. Current Li-ion technology performs very well over the complete life cycle and is not restricted by commodity scarcity (see table 2.2). For these reasons Li-ion batteries are likely to play a greater role in future BEV and HEV markets. The success of electric vehicles is contingent upon the performance of battery technologies, which is constrained by inherent tradeoffs between power, energy, longevity, safety, and cost[27]. At the moment no single battery technology satisfies all these criteria for either PHEV or BEV use.

Although there is a CO_2 emissions premium for HEVs and PHEVs compared to ICEVs due to the production of their batteries, their average cradle-to-grave CO_2 emissions, the total emissions from vehicle production, use, and disposal are still lower than those of ICEVs[20]. To gain the most CO_2 reduction benefit from HEVs and PHEVs, however, they should be driven in such a way that the ICE is used as little as possible. For HEVs, this means stop-and-go city driving because the ICE is shut off during standstill instead of idling, and because the electric motor is powered in part by regenerative braking; for PHEVs, this means short-distance driving up to the capacity of the grid-powered battery, so that the PHEV can operate essentially as a BEV. When this is compared to average US driving patterns, where only 30-40% of kilometres driven could be run on electricity stored in the battery rather than petrol from the ICE[35], it is clear that the usage pattern determines the CO2 reduction potential of HEVs and PHEVs. This is underlined by a comparison by *Popular Mechanics* in 2008, which found that the Toyota Prius (a HEV) and the VW Jetta (a diesel ICEV) have essentially the same fuel efficiency in highway driving[36]. If a consumer will not primarily be driving in urban conditions, a smaller diesel ICEV would be better for CO_2 emissions reductions than a HEV or PHEV.

We end this introductory section with a brief comparison of the efficiency of current vehicle-propulsion technologies. The efficiency of current petrol engines is 20-30%[37], and diesel engines are 35-45%[35, 38]. Slight improvements in well-to-wheel efficiency of petrol engines of 6-15% are possible within the next decade[39]. Electric motors are approximately 90% efficient[40], and PEM fuel cells are 40-60% efficient[41]. However, the well-to-wheel efficiency of BEVs and FCVs depends greatly on how the vehicle fuel (electricity and hydrogen, respectively) is produced. For example, when running on electricity generated from coal, natural gas, or a typical electricity grid, a BEV's well-to-wheel efficiency is only 30% or less; but when running on electricity generated from renewable sources, Campanari *et al.* report that the well-to-wheel efficiency can be more than 60%[40]. Campanari *et al.* also report, however, that the best efficiency that can be reached by a FCV is approximately 22%, when it is run on direct hydrogen from electrolysis or natural gas reforming powered by renewable energy[42]. HEVs and PHEVs, however, are 30-40% more efficient than ICEVs and they offer the best interim step toward commercially successful purely electric vehicles[11,13]. Though, improvements in battery capacity, durability and cost are required in order for them to compete with current ICEVs.

Fuel Cell Vehicles

Fuel cells convert hydrogen fuel and oxygen from the air into water, producing electricity in the process. By converting chemical energy directly into electrical energy, fuel cells skip the inefficient intermediate conversions to thermal and kinetic energy found in ICEs. Although first demonstrated 170 years ago[43], only recently has it been possible to use fuel cells in vehicle drivetrains[44]. Fuel cells offer the transportation sector the promise of decreased dependence on fossil fuels, low or zero tailpipe emissions, and high efficiency. Fuel cells produce much less waste heat and consequently offer a much higher theoretical efficiency. Unlike batteries, fuel cells can run continuously with sufficient input of reactants (fuel and oxidant). Fuel cells run best on pure or reformed hydrogen[45, 46] but some can operate directly on alternative fuels such as methanol or hydrocarbons[47].

Many prototype fuel cell automobiles have been produced[48-51]. The existing technical challenges make it more likely that the initial market uptake will be for fleet vehicles such as buses, which often use a single refuelling station and can store larger quantities of hydrogen on board. Limited trials of hydrogen buses have been carried out in cities such as Chicago, Vancouver, Beijing, Aichi, Perth, and 10 European cities in the EU-funded Fuel Cell Bus Club[52, 53]. Additional early introduction of FCV may be through niche markets such as forklift trucks and airport ground-support vehicles. Perhaps the most ambitious planned uptake is Iceland's announcement in 1998 that it would use its vast hydroelectric and geothermal power resources to create the world's first hydrogen economy by as early as 2030[54, 55] (see section 2.2).

Principal Fuel Cell Types

Fuel cells are typically classified according to the electrolyte (that is, the electric conductor) that they use:

- Polymer electrolyte membrane fuel cell, or proton exchange membrane fuel cell (PEMFC) [56-58]
- Alkaline fuel cell (AFC)[59, 60]
- Phosphoric acid fuel cell (PAFC)[61, 62]
- Solid oxide fuel cell (SOFC)[47, 63, 64]
- Molten carbonate fuel cell (MCFC)[65, 66]

These principal types of fuel cells are compared in table 2.3, with an assessment of their suitability for automotive applications.

Two other examples of fuel cells undergoing further research are biological fuel cells and direct alcohol fuel cells. Biological fuel cells (for example, microbial fuel cells[72, 73] and enzyme-based fuel cells [74]) are significantly cheaper than the above, but their power density is orders of magnitude less, ruling them out for almost all practical applications for the time being. Direct alcohol fuel cells (DAFCs) are a type of PEMFC because they use a polymer electrolyte membrane, though they can run on fuels such as methanol[75], ethanol[76], and ethylene glycol [77]. The most developed DAFC is the direct methanol fuel cell (DMFC)[75], which has the advantage of running on a fuel that is readily available and easily stored compared to hydrogen. With a lower operating efficiency and a lower power density than hydrogen PEMFCs, DAFCs are suited for portable electronics applications instead of automobiles[75].

General Advantages and Limitations

The widely differing materials, cell design, electrochemistry, and operating temperature of the different fuel cells in table 2.3 bring about important advantages and disadvantages. On the plus side, because they can be run on a variety of feedstocks, such as hydrogen, hydrocarbons, and alcohols, fuel cells offer the potential to decrease dependence on fossil fuels and increase energy security. Fuel cell emissions are also lower than those of ICEs – in fact, emissions of SO_x, NO_x, and particulates are virtually zero. If running on pure hydrogen, emissions of greenhouse gases like CO_2 are low or zero at the point of use, but the method of hydrogen production must be taken into account[78] (see section 2.2). If running on a hydrocarbon fuel, CO_2 will be produced, though less than for an ICE because of the greater efficiency of fuel cells. Fuel cells are also about twice as efficient as ICEs, at 40-60% – a number that may reach 80% in the future[37] – and they more efficient at partial load, which is the typical running condition for automobiles. Because of their scalability of power, fuel cells are suited to a wide range of applications, from mobile phones and laptops to power plants. In vehicles, fuel cells could be sized to provide all the power required, only the base load, only the recharging of batteries, or only an auxiliary power unit.

Despite great progress in recent years, FCVs continue to face significant challenges particularly with durability. An ICE automobile must be durable and reliable, able to withstand large changes in temperature and humidity, and to withstand load cycling (acceleration and deceleration) with minimal performance degradation (3-5%) over a lifetime of 5000 hours[79]. Fuel cells cannot yet achieve this, with undesired reactions, corrosive electrolytes in some cases, and high operating temperatures prematurely degrading performance. Fuel is another complicating factor. Fuel cells work most efficiently using hydrogen[47], which is not widely available, is difficult to store, and has low volumetric energy density. This means vehicles must have large, heavy tanks to store the hydrogen[80]. The alternative is to reform other hydrocarbon fuels into hydrogen onboard the vehicle, but this is complex, expensive, and reduces the overall vehicle efficiency due to inefficiencies in the reforming process[81]. Kobayashi *et al.* estimates a 30-50% loss in vehicle efficiency

Table 2.3.: Comparison of principal fuel cell types

	PEMFC	AFC	PAFC	MCFC	SOFC
Electrolyte	Flexible polymer membrane	$KOH_{(aq)}$	$H_3PO_{4(aq)}$ in porous silicon carbide matrix	Molten alkali metal carbonate in porous matrix	Ceramic (yttria-stabilised zirconia)
Operating temperature (°C)	80	60-220 (typically 70)	200	650	500-1000
Catalyst	Pt	Pt (anode), Ni (anode and cathode)	Pt	Ni (Ni alloy at anode, NiO at cathode)	Perovskites (ceramic) (Ni cermet at anode, La-based compounds at cathode)
Fuel compatibility	H_2, methanol (see direct methanol fuel cell, below)	H_2	H_2	H_2, hydrocarbons (e.g., CH_4)	H_2, hydrocarbons (e.g., CH_4), CO
Reformer	External reformer required if H_2 unavailable	No (reformate fuels cannot be used because of presence of CO_2)	External reformer required if H_2 unavailable	Internal (thermally integrated)	Internal (thermally integrated)
Main poison	CO, S	CO_2, CO	CO (tolerance 1-2%), S	S	S
Electrical efficiency (%) [37]	40-60	45-60	35-45	45-60	45-55
Power density (mW/cm^2) [38]	100-1000 [38]	150-400	150-300	100-300	250-350
Power range (kW) [38]	0.001-1000	1-100	50-1000	100-100,000	10-100,000
Advantages	Low operating temperature; best power density; rapid start-up (best start-stop cycling)	Extremely low-cost electrolyte; often do not need Pt catalyst at cathode	Relatively low-cost electrolyte; technology is mature; high reliability	Do not need Pt catalyst; fuel flexibility (external reforming not required); high-quality waste heat	Do not need Pt catalyst; fuel flexibility; relatively high power density; high-quality waste heat
Disadvantages	Catalyst, membrane, and ancillary components are expensive [40]; waste heat rejection is difficult [41]; catalyst is susceptible to poisoning [24]	Requires pure H_2 and O_2; waste heat rejection is difficult; electrolyte is corrosive	Catalyst is expensive; catalyst susceptible to poisoning; electrolyte is corrosive; electrolyte must be replenished occasionally	Materials relatively expensive because of high operating temperature; electrolyte is corrosive; lower durability; very long start-up time	Materials relatively expensive because of high operating temperature; lower durability; long start-up time
Most promising applications	Portable electronics, automotive, stationary power	Suited only for auxiliary power in space applications	Stationary power	Stationary power	Stationary power
Suitable for commercial automotive applications?	Yes	Not at present, particularly because of need for pure H_2 and O_2; development has stagnated	Not at present, because power density is low and because electrolyte freezes at 42°C; further development has focused on stationary applications	No, because of very long start-up time (tens of hours); further development has been only for stationary applications	Possibly for automotive auxiliary power units (APUs) [42]

> - As well as the problems with the hydrogen economy, there are also not enough raw materials available to replace all internal combustion engines with fuel cells.

with onboard fuel reformation[35]. Even when running on direct hydrogen, CO must be removed from the fuel[82, 83] in fuel cells that contain platinum catalysts, to avoid catalyst poisoning[71]. The biggest current limitation, however, is the cost of fuel cell systems. Compared to a cost of just US$30 per kW for a mass produced ICEs[79](500,000 units), an 80 kW automotive PEMFC system operating on direct hydrogen costs approximately US$75 per kW[84-86], though such production levels appear to be many years away, The cost increases for low volumes, such as those found in initial proof of concept and evaluation vehicles, with costs nearer to US$700-800 per kW[84]. The major cost in fuel cell systems is the relatively large amount of platinum needed for catalysis. The price of platinum on the London Platinum and Palladium Market was US$45,150 per kilogram, as of 10 September 2009, although in the last two years this has varied from a low of US $26,660 to a high of US$77,320[87].

Assessment

PEMFCs and SOFCs offer the best prospects for eventual wide commercial application, although for automotive applications, PEMFCs appear best positioned for commercialisation and currently receive the most attention from major automobile manufacturers[88-98]. Indeed, more than 90% of FCVs on the road since 2000 have used PEMFCs[99]. Crucially, only PEMFCs currently meet the power density target of 800-900 mW/cm^2 required for automotive applications[100] (see table 2.3). PEMFCs' low operating temperature, relatively high power density (and consequent compactness), and rapid start-up make them superior to SOFCs for automotive applications. The PEMFC operating temperature (80°C) is limited by the need for water to be present in the electrolyte membrane, although research is being undertaken on novel polymer electrolytes for PEMFCs that do not require water, allowing the operating temperatures to rise as high as 200°C[47, 101, 102]. The higher operating temperature mitigates some of the disadvantages of current PEMFCs – namely, reaction kinetics improve (that is, reactions occur more quickly and effectively), CO poisoning is reduced, and heat rejection improves. The lack of low-cost CO-tolerant catalysts remains a major challenge for PEMFC commercialisation, so high-temperature PEMFCs may offer some promise.

SOFCs offer two major advantages over PEMFCs: no need for a platinum catalyst (see section 5.1) and greater fuel flexibility without the need for external reforming. SOFCs' high operating temperatures and consequent lower durability and long start-up time, however, pose significant hurdles to use in automotive applications[64]. Advances in materials, however, have made it possible to create intermediate-temperature (IT) SOFCs, which operate at 500-750°C[47]. The lower operating temperature of IT-SOFCs, and consequently the faster start-up time, greater durability, and lower-cost materials, makes this technology a possible candidate for automotive applications[47]. IT-SOFCs offer greater efficiency, fuel flexibility, and tolerance of impurities than PEMFCs, and unlike PEMFCs, they do not require external fuel reforming when run on fuels other than pure hydrogen. IT-SOFCs face the challenge, however, of reduced activity for oxygen reduction at the cathode (that is, poorer performance in the absence of a catalyst) compared to high-temperature SOFCs[103]. Because of their still-relatively-long start-up time and bulkiness compared to PEMFCs, however, IT-SOFCs in the automotive sector might be suitable only as auxiliary power units (APUs), such as for refrigeration units in heavy-duty lorries[44].

FCVs are not yet ready for wide commercialisation, not only due to the difficulties in fuel cell technology, but also because of the difficulties with storing, transporting, and distributing hydrogen fuel (see section 2.2). In 2007, the total number of light-duty FCVs deployed worldwide was approximately 800, with an additional 3000 niche vehicles such as forklifts, motorcycles, and marine craft[86]. Writing in 2004, Schäfer *et al.* predicted a market-competitive light-duty FCV would be available in approximately 15 years, but that major fleet penetration could take *more than 50 years*[104]. As of 2008, Daimler, Ford, GM, Honda, Hyundai, and Toyota had announced plans to commercialise FCVs anywhere from 2012 to 2025[86]. To get to this stage, however, breakthroughs in materials and fabrication methods, rather than incremental change, will be needed. For PEMFCs, a particular challenge is catalyst cost reduction. The search for non-platinum catalysts has been ongoing for more than 40 years. At low temperatures and running on hydrogen, reformate (that is hydrogen produced from other chemical compounds), or methanol, platinum-based catalysts remain the most active[105]. One could potentially use a greater amount of a cheaper (non-noble element), less active catalyst, but the acidic environment of PEMFCs prevents the use of non-noble metals[100]. Another option is to reduce platinum loading, but this reduces catalyst durability [106].

The need for alternative catalysts is also driven by limitations on the availability of platinum. Platinum catalysts in automobiles already consume approximately half of the platinum sold globally each year[107]. Borgwardt[108] concludes that even under the most favourable circumstances, and with the US auto industry consuming as much platinum as is currently consumed by the global auto industry, a complete transition of the US vehicle fleet to FCVs would take *approximately 66 years*. The effect this would have on the price of platinum would exacerbate the existing problem of making fuel cells more cost-competitive with other technologies (see section 5.1). Unless breakthroughs are made, however, low-temperature fuel cells will continue to require platinum catalysts for the foreseeable future.

Fuel cells continue to offer promise in automotive applications, with designs, materials, components, and fabrication methods continually evolving. But technological breakthroughs will be needed before fuel cells can become commercially viable. Significant advancements are needed in durability, reliability, power density, and hydrogen production and storage methods (see section 2.2). If they are to become more than simply a niche technology, fuel cells will need to become competitive with ICEVs on cost and convenience, and massive investment will need to be made in hydrogen distribution infrastructure.

Electric Vehicles

Electric passenger cars were first produced in the late 19th century, but after being overtaken by ICEVs when the limitations of BEVs became clear, BEVs were not produced again commercially in appreciable numbers until the 1990’s[11]. Major automobile manufacturers began to produce BEVs to comply with the California government’s Zero Emission Vehicle (ZEV) regulation of 1990[109]. Manufacturers such as Chrysler, Ford, GM, Honda, Nissan, and Toyota produced BEV models in limited numbers from the mid-1990’s[110], but as of 2007, there were only 4200 electric passenger cars in the US[111] and 1200 in the UK[112]. Many major automobile manufacturers, however, have announced plans to have BEVs on the market between 2010 and 2012[113-118].

Although progress has been made in recent years on some of the challenges facing BEVs, hurdles remain. Because of their relatively low use of fuel, BEVs are cheaper to operate than ICEVs and HEVs. The price of electricity versus that of petrol and diesel varies greatly by country, but for the OECD in 2007, the average price of residential electricity was 55% higher per unit of energy than the retail price of regular unleaded petrol, and 20% higher than that of diesel[119, 120]. However, the upfront cost of purchase is still high due to the battery cost and the small scale of production[121]. Battery charging can often be done overnight, but BEVs take significantly longer to refuel than ICEVs (hours compared to minutes)[122-124]. Although there are notable exceptions and rapid improvements are being made, to date most BEVs have had limited range compared to conventional ICEVs[123-125]. (Examples of cost, battery charging time, and driving range, along with other parameters, are shown for three production BEVs in table 2.4.)

Most significantly, however, while BEVs may help to

Table 2.4: Characteristics of BEVs included in the Smith School Study

	Tesla Roadster	THINK city	REVA G-Wiz i
Driving range, combined city/highway (km)	~354	175	80 (city only)
Top speed (km/h)	201	100	80
Peak power (kW)	185	30	13
Motor type	3-phase AC induction[127]	3-phase AC induction[128]	3-phase AC induction
Battery type	Li-ion	Sodium or Li-ion	Lead acid[129]
Battery capacity (kWh)	~53[130]	28.3	9.6
Battery charging time (h), 0-100% state of charge	3.5-48 d	13	8
Battery weight (kg)	450	245-260	~300[131]
Total kerb weight (kg)	1238[132]	1397	700
Base price (US$) e	109 000[127]	~34 000[133]	~14 000[134]

a All data are from [125], except where noted.
b All data are from [123], except where noted.
c All data are from [124], except where noted.
d The charging time is 3.5 hours using Tesla’s High Power Connector; 8 hours using its 240-V Mobile Connector, the highest-power portable charging option; and 37-48 hours using its 120-V Mobile Connector[122].
e Base price in the US, Norway, and the UK, respectively. The Tesla Roadster costs £94 000 (with VAT) in the UK and €89 000 (without VAT) in France and the rest of the euro area.

- They are in operations but not in construction and charging.

decrease dependence on foreign oil, they have, to date, generally not decreased dependence on fossil fuels[25]. BEVs can become *de facto* zero emissions vehicles if they use electricity generated entirely from renewable sources such as hydroelectric, solar, or wind power, or from nuclear power[40], but the potential of BEVs to reduce greenhouse gas emissions depends entirely on the fuel mix used in the electricity generation that charges the vehicles' batteries, which can vary widely from country to country, and within countries. The US's largest source of fuel for electricity generation is coal, for example, while in Canada it is hydroelectric, in Russia it is natural gas, and in France it is nuclear[126]. Consequently, the emissions from electricity generation, and thus the indirect CO_2 emissions from BEV use, vary widely from country to country. A Smith School of Enterprise and the Environment study on electricity usage for a selection of BEVs and the associated well-to-wheel emissions of CO_2 showed that increasing the proportion of BEVs in passenger car fleets can help to greatly reduce these emissions. The study analysed the well-to-wheel CO_2 emissions from three production BEVs when run in three major industrialised countries in which the national electricity grid is fed by different mixes of renewable and fossil fuel sources: the US, the UK, and France, where the largest share in the fuel mix is coal, natural gas, and nuclear, respectively. The vehicles used as examples of current production BEVs were the Tesla Roadster, from Tesla Motors of San Carlos, California; the TH!NK city, from Think of Aurskog, Norway; and the REVAi (marketed in the UK and referred to herein as the G-Wiz i), from REVA Electric Car Company of Bangalore, India. Table 2.4 compares some of the key characteristics of each of the BEVs.

The amount of electricity generation required to run each of BEVs in the three countries was calculated inclusive of transmission and distribution losses and battery charging inefficiency, along with the average CO_2 emissions from electricity generation in the same countries. In France, emissions from electricity generation are only 86 g/kWh[135, 136], compared to 605 g/kWh in the US[137, 138] and 541 g/kWh in the UK[139, 140]. These figures can be interpreted in part through the share of electricity in each country that is generated from fossil fuels. Only 10% of France's net electricity generation comes from the combustion of fossil fuels[135], while in the US it is 71%[137] and in the UK, 77%[141-143]. The well-to-wheel CO_2 emissions for the three BEVs considered in this study were calculated and compared to those of a selection of ICEVs and HEVs, as well as the emissions of the existing passenger car fleet in each country and its hypothetical replacement: a BEV fleet with the average electricity generation requirements of the three BEVs considered in this analysis. The results are shown in table 2.5.

As can be seen from table 2.5, the fuel mix in the national electricity grid is the overwhelming factor in determining the indirect CO_2 emissions from electric vehicles. While in the US and the UK, the emissions for the TH!NK city and the Tesla Roadster are not appreciably lower than those of the most efficient small diesel cars, in France, where 78%[135] of electricity is generated from nuclear fission (which produces no CO_2 emissions), substantial emissions reductions from passenger cars could be realised if a large part of the existing fleet passenger car fleet were replaced with BEVs.

Table 2.5 also underlines that the BEVs emit less CO_2 than comparable ICEVs or HEVs. The Tesla Roadster's emissions, for example, are higher than those of some of the ICEVs and HEVs listed in the table when run in the UK and the US, but it fares well against comparable ICEVs such as the Lotus Elise and the Porsche Boxster, both of which have well-to-wheel emissions approximately double those of the Tesla Roadster in the US. Running in France, all three BEVs come far ahead of the most efficient ICEVs and HEVs, and only the lowest-emitting ICEVs and HEVs, the Smart fortwo cdi and the Toyota Prius T3, emit less than the TH!NK city running in the US. Considering fleet emissions, table 2.5 further demonstrates that if the entire passenger car fleet in each country were replaced with an electric fleet composed of equal parts of the three BEVs considered in this study, the hypothetical BEV fleets would produce, compared to the existing fleets, 91% less CO_2 emissions in France, 60% less in the US, and 51% less in the UK.

The reason the BEVs emit less CO_2 than the ICEVs and the HEVs is their superior fuel efficiency. Even though the average efficiency of electricity generation and supply to end users in the US, the UK, and France is only 33%[137, 140, 141, 165], about the same as an efficient diesel engine[166] the BEVs' lower use of fuel means their emissions are lower than comparable ICEVs or HEVs. Even if the BEVs in this study were to run in states or regions where electricity is generated almost entirely from coal, such as West Virginia in the US (98% coal[167]), the CO_2 emissions associated with BEV use would still be less than those from the average new ICEV in each country. For example, the Tesla Roadster, running solely on coal-generated electricity, would have indirect CO_2 emissions of 198 g/km[123-125, 130, 135, 137, 140, 141, 144-151, 159], compared to 215 g/km for passenger cars from the 2006 model year in the US [144, 152-157, 168].

Replacing a large part of the ICEV fleet with BEVs would require a number of considerations. i) It may be difficult to get consumers to move to smaller cars such as the TH!NK city and REVA G-Wiz i, particularly in the US, where SUVs, minivans, and pickup trucks make up more than 40% of the entire

Table 2.5. Comparison of well-to-wheels CO_2 emissions for BEVs by country and a selection of ICEVs and HEVs, as well as the hypothetical BEV fleets and the existing national fleets

UNITED STATES

Make	Model[b,c]	Class	emissions ($g\ CO_2/km$)[d]	Sources[f]
REVA	**G-Wiz i**	**Quadricycle**	**92**	[illegible]
Gordon Murray Designs	T.25 (petrol)	Supermini	93	
Smart (Daimler)	fortwo cdi (diesel)	Supermini	103	
Toyota	Prius T3 (HEV)	Small family	105	
Hypothetical US BEV fleet			**112**	[illegible]
THINK	**city**	**City car**	**114**	[illegible]
SEAT (Volkswagen)	Ibiza Ecomotive (diesel; manual)	Supermini	117	
Volkswagen	Polo BlueMotion (diesel; manual)	Supermini	117	
Toyota	iQ	Supermini	117/130	
Smart (Daimler)	fortwo (petrol)	Supermini	121-146 *	
Honda	Civic Hybrid (HEV)	Small family	128	
Tesla	**Roadster**	**Open-top**	**128**	[illegible]
Mini (BMW)	Cooper D Clubman (diesel)	Estate	128/160	
Mini (BMW)	Cooper Clubman	Estate	155/187	
Lotus	Elise (manual)	Open-top	245	
Porsche	Boxster (manual)	Open-top	261	
Existing US fleet (2006)			**275**	[94, 95-98]

UNITED KINGDOM

Make	Model[b,c]	Class	emissions ($g\ CO_2/km$)[d]	Sources[f]
REVA	**G-Wiz i**	**Quadricycle**	**83**	[illegible]
Gordon Murray Designs	T.25 (petrol)	Supermini	93	
Hypothetical UK BEV fleet			*107*	[illegible]
THINK	**city**	**City car**	**103**	[illegible]
Smart (Daimler)	fortwo cdi (diesel)	Supermini	103	
Toyota	Prius T3 (HEV)	Small family	105	
Tesla	**Roadster**	**Open-top**	**136**	[illegible]
SEAT (Volkswagen)	Ibiza Ecomotive (diesel;manual)	Supermini	117	
Volkswagen	Polo BlueMotion (diesel;manual)	Supermini	117	
Toyota	iQ	Supermini	117/130	
Smart (Daimler)	fortwo (petrol)	Supermini	121-146 *	
Honda	Civic Hybrid (HEV)	Small family	128	
Mini (BMW)	Cooper D Clubman (diesel)	Estate	128/160	
Mini (BMW)	Cooper Clubman	Estate	155/187	
Existing UK fleet (2006)			*204*	[illegible]
Lotus	Elise (manual)	Open-top	245	
Porsche	Boxster (manual)	Open-top	261	

FRANCE

Make	Model[b,c]	Class	emissions ($g\ CO_2/km$)[d]	Sources[f]
REVA	**G-Wiz i**	**Quadricycle**	**15**	[illegible]
Hypothetical French BEV fleet			*18*	[illegible]
THINK	**city**	**City car**	**19**	[illegible]
Tesla	**Roadster**	**Open-top**	**21**	[illegible]
Gordon Murray Designs	T.25 (petrol)	Supermini	93	
Smart (Daimler)	fortwo cdi (diesel)	Supermini	103	
Toyota	Prius T3 (HEV)	Small family	105	
SEAT (Volkswagen)	Ibiza Ecomotive (diesel; manual)	Supermini	117	
Volkswagen	Polo BlueMotion (diesel; manual)	Supermini	117	
Toyota	iQ	Supermini	117/130	
Smart (Daimler)	fortwo (petrol)	Supermini	121-146 *	
Honda	Civic Hybrid (HEV)	Small family	128	
Mini (BMW)	Cooper D Clubman (diesel)	Estate	128/160	
Mini (BMW)	Cooper Clubman	Estate	155/187	
Existing French fleet (2006)			*210*	[illegible]
Lotus	Elise (manual)	Open-top	245	
Porsche	Boxster (manual)	Open-top	261	

[a] The 2009 model year is used for all.
[b] The fuel is petrol except where noted.
[c] The gear box is automatic except where noted.
[d] Where two values are given the lower is for manual and the upper is for automatic.
[e] The figure varies according to engine power and tyre size options.
[f] Sources for the ICEVs and HEVs are [9, 144, 152, 158, 159].

highway vehicle fleet[153]. ii) Because of the large batteries required, BEVs are still more expensive than comparable ICEVs, despite tax credits and other incentives (see table 2.4). iii) The average vehicle lifetime in the US, for example, is about 15 years[169], meaning that major fleet penetration, under the best circumstances, would take many years. iv) Emissions reductions from taking ICEVs off the roads would be partially offset by increased emissions from power plants, although controlling emissions from a few thousand power plants may be easier than controlling emissions from millions of automobile tailpipes. v) If the entire fleet in each country were replaced with an electric fleet composed of equal parts of the three BEVs considered in this study, the increase in net electricity consumption would be 12% in the US[137, 153], 20% in the UK[141, 160], and 15% in France[135, 164].

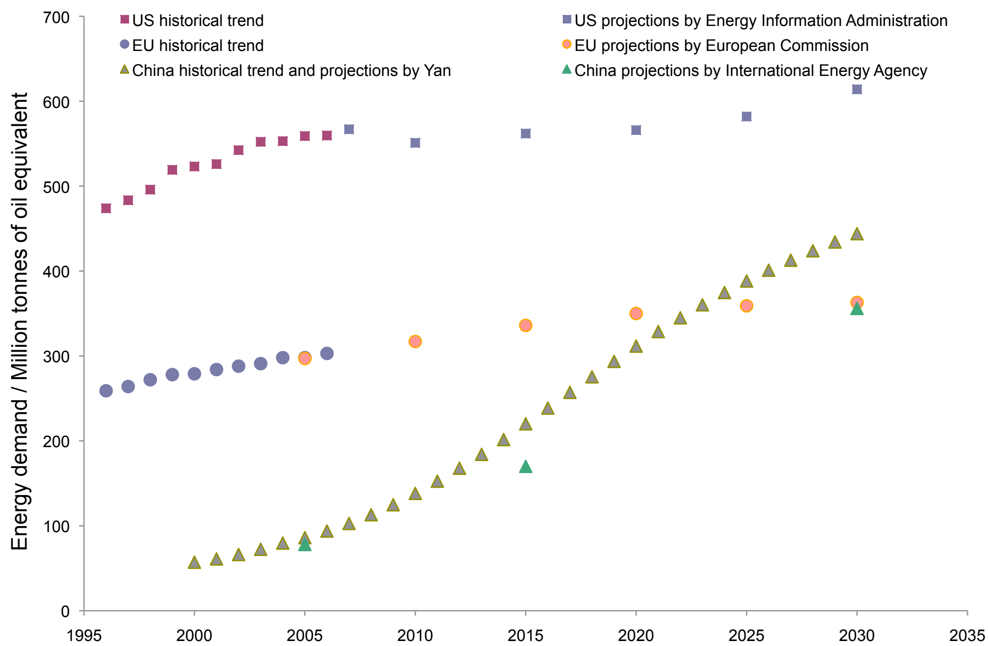
The study found that at least half of the additional electricity demand could be met by charging vehicles overnight when demand is lower, without needing to increase overnight production levels above annual daytime averages and without needing to increase power plant capacity[170]. But an increase in demand for charging BEVs, if it happens, would come gradually, over many years, and extra capacity could be added over time. BEVs could also potentially return to the grid excess electricity stored in their batteries during times of peak load and replace it with electricity in off-peak hours[171]. Indeed, the total electrical capacity of the hypothetical BEV fleets in each country, as defined above, would be at least 10 times the total installed capacity of electrical power plants in each country[123-125, 153, 164, 172, 173].

Analysis of three production BEVs has shown that they can reduce well-to-wheel CO_2 emissions over the existing passenger car fleet by more than 90%. But despite their advantages, the number of BEVs on the road remains small. Therefore, BEVs should be promoted, particularly in areas where electricity generation has the lowest carbon intensity. The production of new electricity generation capacity will affect the carbon intensity level of the electricity grids and the potential for BEVs to reduce CO_2 emissions. Further investment will be needed in BEV battery technology to increase the driving range and to decrease the vehicle weight and cost. Those who cannot yet afford a BEV would do well to drive a fuel-efficient ICEV or HEV like those shown in table 2.5. Continued improvement in ICEV technology will remain essential, as ICEVs will continue to dominate vehicle sales for the foreseeable future.

2.2 Fuels

The transport sector currently depends almost entirely on petroleum-based fuels, conventional petrol and diesel, consuming 60% of global oil production[174]. This section focuses on fuels for road transport, which consumes more than 80% of the total transportation energy use[175-177]. Figure 2.1 shows the historical trends and business-as-usual projections up to 2030 for energy demand from road vehicles in the three largest economies. Although a full-scale transition to BEVs or FCVs is desirable, it is not likely to happen for many decades

Figure 2.1: Historical trends and business-as-usual projections up to 2030 for energy demand from road vehicles in the three largest economies[175, 177-180]



considering the required technological breakthroughs, infrastructure development, and timescale for major fleet penetration[104]. The development of alternative fuels for ICEVs has been progressing at an increasing speed in recent years, driven by concerns over energy security, volatile oil prices, local air pollution, and global warming. Alternatives that could enter the market substantially in the next two to three decades include petrol and diesel produced from unconventional oil; ethanol and biodiesel derived from biomass; synthetic liquid fuels produced from coal, natural gas, and biomass; and compressed natural gas (CNG)[11]. An overview of these fuels is provided here and a brief examination of a possible hydrogen economy, in which hydrogen could potentially replace all other transportation fuels by the end of this century, is considered at the end of this section.

Biofuels

Ethanol and biodiesel are currently the most predominant liquid biofuels. Utilising the existing petrol infrastructure, ethanol can be used in blends of up to 10% by volume with conventional petrol (E10) in existing spark-ignition ICEVs. Use of any higher level of blends would require changes in vehicles and fuel infrastructure. Flexible-fuel vehicles (FFVs) in the US are capable of running on up to 85% volume blends with petrol (E85) and those in Brazil are able to cope with pure ethanol [181]. Global production of ethanol reached 46 billion litres in 2007, representing about 4% of petrol demand, and could reach 125 billion litres by 2020 if targets set by governments in America, Asia, and Europe are met[182]. Ethanol is produced mainly from grain and sugar crops grown on agricultural land (see table 2.6). Promising feedstocks for future development include cassava[183], sweet sorghum[184], and cellulosic biomass such as agricultural and forestry residues, perennial grasses, municipal solid waste (MSW), and algal residues. Biodiesel can be used in the form of blends with conventional diesel in existing compression-ignition ICEVs with no major modification to the engine/fuel systems and utilising the existing diesel infrastructure. Global production of biodiesel reached around 10 billion litres in 2007[185], while the potential is believed to be far larger than the present production level (see table 2.7). Biodiesel (fatty acid methyl ester) is currently produced mainly from edible oil crops such as rapeseed in the EU, soybean in the US and South America, and palm in Southeast Asia[186]. Promising feedstocks for future development include jatropha [187] and algae[188], mainly because of their high yields.

Production of petroleum fuels from unconventional oil, most notably oil sands in Canada, has been increasing rapidly in recent years and is expected to grow to a similar level to biofuel production by 2030 [180]. Synthetic fuels can be produced from coal, natural gas, and biomass via the Fischer-Tropsch process, also known as coal-to-liquids (CTL), gas-to-liquids (GTL) and biomass-to-liquids (BTL), respectively. Synthetic fuels have similar characteristics to conventional fuels and can be used in existing vehicles and infrastructure. CTL plants in South Africa and GTL plants in Malaysia have been in operation for years and the first commercial-scale BTL plant in the world is about to start operation[11]. Some believe BTL is even more promising than ethanol because of the compatibility to existing vehicles and infrastructure[190]. It is projected by the EIA that China will be the largest CTL producer by 2030 with annual production capacity of 31-70 billion litres[191].

Millions of CNG vehicles are currently in use worldwide, driven primarily by the stated desire to reduce urban air pollution or dependence on imported oil[192]. It is unlikely, however, that CNG vehicles will enter the private vehicle market on a large scale due to the lack of CNG supply and distribution infrastructure. Fleet vehicles such as

Table 2.6: Ethanol feedstocks, yield and land use in major producing countries, 2006/2007[182]

Country	Feedstocks	Ethanol yield (per ha)	Arable land (Total area M ha)	Ethanol share (%)
Brazil	Sugarcane (100%)	6641	59	5.1
USA	Corn (98%)	3770	174	3.8
	Sorghum (2%)	1365		
China	Corn (70%)	2011	143	0.7
	Wheat (30%)	1730		
EU-27	Wheat (48%)	1702	114	0.6
	Sugar beet (29%)	5145		
Canada	Corn (70%)	3460	46	0.6
	Wheat (30%)	1075		

- Depending on the carbon emissions from land-use change, corn ethanol could produce up to twice the carbon cost of conventional petrol.

Table 2.7: Top 10 countries in terms of annual biodiesel production potential[189]

Country	Feedstocks
Malaysia	14.54
Indonesia	7.60
Argentina	5.36
USA	3.21
Brazil	2.57
Netherlands	2.50
Germany	2.02
Philippines	1.23
Belgium	1.21
Spain	1.07

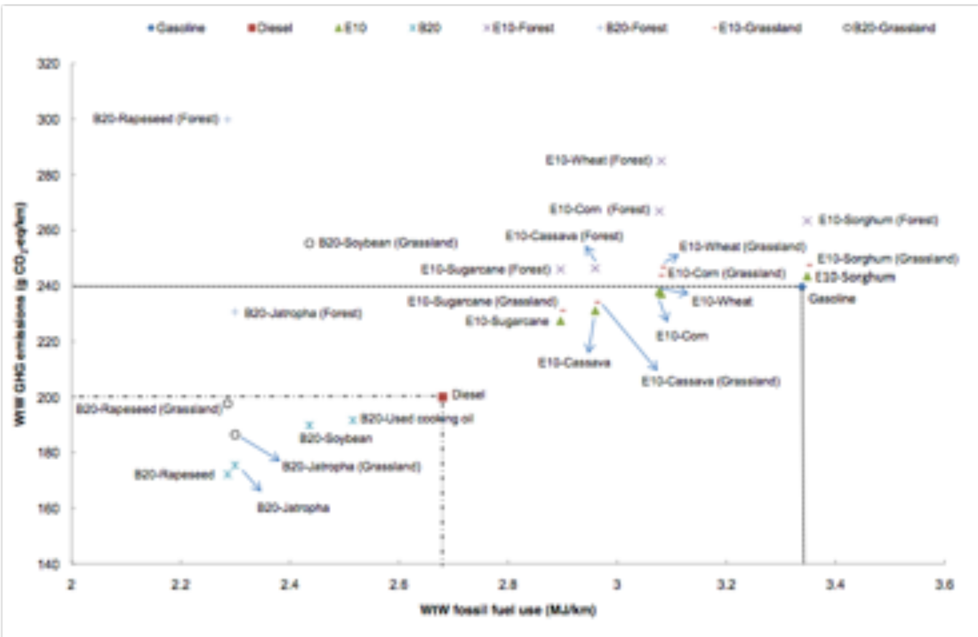
urban buses and taxis are more suitable for CNG utilisation[193].

The higher octane number and the presence of oxygen enable ethanol to be operated at higher compression ratios and combusted more completely than conventional petrol, and hence achieve higher thermal efficiencies and generally lower criteria pollutant emissions[194, 195]. Despite the weight penalty due to the lower energy density of ethanol, vehicles operating on ethanol blends have better fuel efficiencies than those operating on conventional petrol[196]. Similarly, biodiesel can achieve higher thermal efficiencies (MJ/km) and significantly lower criteria pollutant emissions (except nitrogen oxide emissions, or NO_x) without affecting engine performance when compared with conventional diesel, because of the combustion-enhancing oxygen in the fuel[194, 197]. Synthetic fuels are also reported to have similar engine performance and much lower criteria pollutant emissions (except CO emissions) than conventional fuels[198-200]. CNG has lower CO and particulate matter emissions, but higher HC and NO_x emissions than petrol[191, 201], which poses a problem in areas with very strict pollutant emission restrictions, such as California.

Over the whole life cycle, whether or not and to what degree an alternative fuel can reduce greenhouse gas (GHG) emissions depends on a variety of factors, but most importantly, feedstock, location, process energy mix, and land-use change [202-206]. Conventional diesel and CNG can achieve only moderate reductions in GHG emissions over conventional petrol[191, 203], while GTL, petroleum products from unconventional oil, and CTL (even when coupled with carbon capture and storage) result in greater GHG emissions[11, 191, 202].

Most first-generation biofuels (food crop-based biofuels) appear to have the potential to reduce GHG emissions when land-use impacts are excluded [202]. For instance, it is reported that ethanol produced from corn in the US[207, 208] and cassava in China[209, 210] could moderately reduce GHG emissions, while ethanol produced from sugarcane in Brazil[211, 212], cassava in Thailand[213], wheat in France[203], biodiesel produced from soybean in the US[208, 214], rapeseed in the EU[215, 216], and palm oil in Southeast Asia[217, 218] could substantially reduce GHG emissions. In some cases, no GHG reduction was observed for biofuels such as corn ethanol in China because of the relatively low feedstock productivity and the heavy reliance on coal[203]. When land-use change is taken into account, these

Figure 2.2: Life cycle fossil fuel use and GHG emissions 'per vehicle kilometre travelled' for biofuels and synthetic fuels in the US[202]



first-generation biofuels have significantly higher GHG emissions than conventional fuels due to substantial biomass and soil carbon release if carbon-rich land such as forest is cleared to grow the feedstocks (so-called carbon debt)[202, 219, 220]. It could take decades or centuries to offset these upfront carbon emissions by substituting conventional fuels with biofuels. Furthermore, additional impacts could also include soil erosion and biodiversity loss[220]. This may still happen indirectly when the existing croplands are devoted to first-generation biofuel production and land is cleared to compensate for the reduced production of food or feed (so-called indirect land-use change) [221]. In other words, conserving the existing forest and restoring forest on cropland not used for food production could achieve greater GHG mitigation than first-generation biofuels as well as additional environmental benefits[222]. Corn ethanol in particular, is being increasingly questioned and even criticised because corn production causes more soil erosion and uses more nitrogen fertiliser, insecticides and herbicides than any other crop grown[223]. Given the scarcity of arable land and the increasing demand for food, the potential for the production and use of first-generation biofuels is limited[181].

Second-generation biofuels, including ethanol derived from perennial grasses[207, 224, 225], crop residues[225, 226] and municipal solid waste (MSW)[227, 228], biodiesel produced from jatropha[210] and algae [229] and BTL produced from perennial grasses and forestry residues[230], present exciting opportunities for reducing GHG emissions without significantly competing with food production for arable land. It should be noted that although biofuels derived from crop residues and MSW do not induce land-use change, those from dedicated feedstocks do. Consequently, second-generation biofuels could induce either a significant carbon release or substantial carbon sequestration (depending on where the feedstocks are grown)[202, 220, 231]. A comparison of the lifecycle fossil fuel use and GHG emissions for biofuels and synthetic fuels in the US is shown in figure 2.2. Nevertheless, even the highly promising second-generation biofuels are unlikely to supply a major portion of the global transportation energy demand, mainly because of constraints such as suitable land available to grow dedicated feedstocks[232] and the amount of agricultural residues that can be recovered without jeopardising soil quality[233]. There are concerns that the increasing availability of alternative fuels might reduce the prices of conventional fuels and hence result in a so-called rebound effect[220, 234]. Policy options that could prevent such rebound effect will be discussed in section 2.5. One important objective of alternative fuel promotion is to reduce dependence on fossil energy, oil in particular. Although all of the alternatives discussed here could dramatically reduce oil use, most of them still largely rely on other forms of fossil energy such as coal and natural gas[191, 203] and only second-generation biofuels appear to be able to reduce fossil energy use to a large extent[202]. The production of biofuels requires large amounts of water inputs and hence concerns over competing for water with food production and even water security by large-scale biofuel expansion are increasing in recent years [235-238]. Compared with fossil energy, biofuels usually have water requirements that are several times of magnitude higher (see table 2.8).

There are a number of social effects: Promotion of biofuels could provide employment and economic development in rural areas especially of developing countries. However, the upward price pressure on US domestic crop prices from January 2002 to June 2002 was aggravated by rising energy prices, the weakening US dollar, which accounted for 25%-30% of the price increase and the increasing demand for biofuels. The expansion of biofuel production and the related issues of low grain stocks, vast land-use shift, export bans and speculative trading accounted for approximately 70% of the observed price increase[239]. Moreover, cellulosic biomass might divert much-needed research investment away from food crops[239]. Promotion of alternative fuels needs substantial government subsidy because their costs are higher than conventional fuels, with the exception of Brazilian sugarcane ethanol, which has achieved economic competitiveness with petrol[240]. Production of biofuels in developing countries might thus induce substantial financial burdens[241]. Biofuels produced from feedstocks such as corn ethanol, could result in much larger health costs than their petroleum counterparts[242].

A thorough evaluation of alternative fuels will have to go beyond energy use and GHG analysis and include their full environmental and societal effects [242-244]. It is unlikely that one alternative fuel could become superior to the others on all dimensions in the foreseeable future (see table 2.9 for our best judgements). Some first-generation biofuels such as sugarcane ethanol in Brazil, cassava ethanol in China and palm oil biodiesel in Southeast Asia, could be successful as local solutions as they can provide energy security to some extent and promote economic development and hence improve standards of living in rural areas. Large-scale expansion at the cost of arable land or natural habitat should however be avoided. Liquid fuels produced from unconventional oil, coal and natural gas could immediately contribute to liquid fuel supply, but will increase the GHG emissions. Nevertheless, a general consensus seems to be emerging that biofuels are important and necessary to meet the energy and climate challenges and future

- Second-generation biofuels do not compete with food, they come from inedible cellulose.

Table 2.8: Water requirements for biofuels and fossil energy[235, 236]

		m^3/GJ
Ethanol	Sugar beet	59
	Sugar beet	108
	Corn	110
	Cassava	125
	Wheat	211
	Sorghum	419
Biodiesel	Soybean	394
	Rapeseed	409
	Jatropha	574
Fossil Energy	Coal	0.2
	Natural gas	0.1
	Crude oil	1.1

success in biofuel development will have to rely on the second-generation biofuels produced in a sustainable manner, *i.e.* ethanol and BTL derived from agricultural and forestry residues, municipal and industrial solid waste, perennial grasses grown on degraded, abandoned and marginal agricultural lands as well as algae biomass[181, 190, 245, 246].

Hydrogen

Hydrogen and fuel cells (see section 2.1) have the potential to transform road transport to carbon neutrality, provided that the hydrogen is produced without indirect CO_2 emissions. Many have been predicting a hydrogen economy for years[247, 248], touting hydrogen as a key energy solution for the coming century. The impetus is the possibility of increasing energy security and reducing CO_2 emissions by decreasing the use of fossil fuels. A hydrogen economy, however, is by no means inevitable. The extent of movement to hydrogen depends on huge investments in infrastructure, energy markets, developments in electricity generation, and massive advances in the technology of fuel cell vehicles (FCVs) (see section 2.1), which is likely to be the crucial technology of a hydrogen economy. This section examines the current status of hydrogen production, storage, and distribution technology from the point of view of transport, assessing the prospects and challenges for a possible hydrogen energy future.

Hydrogen is the most abundant element in the universe and the third most abundant in Earth's crust. On Earth, however, hydrogen almost always occurs in compounds and to isolate it is energy intensive. Hydrogen can be produced from both renewable and non-renewable resources via a variety of processes. These are at different stages of development and with different opportunities and challenges. Currently, over 95% of the world's hydrogen is produced by reforming hydrocarbons [249], most commonly steam reforming[250], autothermal reforming[251], and partial oxidation[252]. The most popular feedstocks are natural gas (48% of total production), oil (30%), and coal (18%)[249], which all produce CO_2 as a by-product, but reforming can also be done using renewable sources such as renewable oils[253]. Steam reformation is currently the cheapest, most efficient, and most common method of producing hydrogen. Research is being undertaken on other forms of reformation, including solar-thermal reforming[254], which could provide increased efficiency and reduced CO_2 emissions, and plasma reforming[255, 256], which could provide a more efficient means of hydrocarbon fuel reforming onboard the vehicle.

The electricity for electrolysis (decomposition by an electric current, in this case to produce hydrogen) usually comes from the combustion of fossil fuels [257], but electrolysis is low carbon if using electricity produced from nuclear or renewable sources[258]. Researchers are investigating the use of nuclear[259], solar[260], and geothermal energy[261] to make possible high-temperature electrolysis, which would require less electricity than conventional electrolysis and also be less expensive[80].

Hydrogen can also potentially be produced by a number of other methods, including splitting water thermochemically[262] and by photoelectrolysis[263]; high-temperature pyrolysis[264]; from ammonia[265]; biological hydrogen production[266, 267], such as biophotosynthesis using algae and cyanobacteria, fermentation of wet biomass by bacteria, and photodecomposition of organic compounds by photosynthetic bacteria; gasification of biomass[267, 268]; combustion of metals (such as aluminium and magnesium) in water[269]; and gasification of coal[270].

A huge infrastructure would need to be built to produce hydrogen on the scale required by a large fleet of vehicles[271], and it will need to be done at far lesser cost than is currently possible. For the short-term, reformation remains the most likely source of hydrogen for large-scale production, and it is likely to continue to use primarily fossil fuels. Electrolysis is a well-developed method for small-scale, local production of hydrogen and could therefore reduce the need for a separate hydrogen infrastructure. Other methods of hydrogen production are limited in scale and are at an early stage of development, so it is difficult to assess the likelihood of their commercialisation. All have at least one considerable drawback, including high cost, low efficiency, or low energy density.

Table 2.9: Performance of various fuel/propulsion options compared with conventional petrol or diesel powered ICEV[a]

Propulsion system	Fuel	Feedstock (Location)	Food	Water	Land use impact[b]	Local air pollution	Global warming	Fossil fuel depletion	Compatibility to existing vehicles & infrastructure[c]
SI ICE	Ethanol	Wheat (EU)	---	---	---	+	++	++	--/=
		Corn (US, China)	---	---	---	+	+	+	--/=
		Sugarcane (Brazil)	-	---	--	+	+++	+++	--/=
		Cassava (China, Southeast Asia)	-	---	--	+	++	++	--/=
		Cellulose	=	-	++/=/--	+	+++	+++	--/=
CI ICE	Biodiesel	Rapeseed (EU)	--	---	---	++	++	++	=
		Soybean (US, South America)	--	---	---	++	++	++	=
		Palm (Southeast Asia)	--	---	--	++	+++	+++	=
		Jatropha	=	---	++/-	++	++	++	=
		Algae	=	=	=	++	?	?	=
SI/CI ICE	Petrol/Diesel	Unconventional oil	=	-	=	=	--	--	=
SI/CI ICE	CTL	Coal	=	-	=	+++	---	---	=
SI/CI ICE	GTL	Natural gas	=	-	=	+++	--	--	=
SI/CI ICE	BTL	Cellulose	=	-	++/=/--	+++	++	+++	=
SI ICE	CNG	Natural gas	=	+	=	+	+	+	--
FC	Hydrogen	Coal	=	=	=	+++	=	+	---
		Natural gas	=	+	=	+++	+	+	---
		Cellulose	=	-	++/=/--	+++	+++	+++	---
		Grid electricity (US, China)	=	-	=	+++	---	---	---
		Solar	=	++	?	+++	+++	+++	---
		Nuclear	=	++	=	+++	+++	+++	---

Note: a, +, ++ and +++ represent the option is slightly better, better, and significantly better, respectively; -, -- and --- represent the option is slightly worse, worse, and significantly worse, respectively; = represents the option about the same; ? represents unknown. b, land use impact for cellulose and jatropha depend on where they are grown. c, compatibility for ethanol depends on the level of blends.

One of the chief problems of storing hydrogen is its low volumetric energy density. Vehicle applications will require a tank that achieves approximately the same driving range as the petrol or diesel tank it replaces, without being much larger or heavier. Table 2.10 compares the energy density of some common fuels to those of possible hydrogen storage options. Storage methods should be safe, low-weight, low-cost, and have a high energy density. Such a method does not yet exist[80]. Potential storage options include compressed gas, liquid hydrogen, hydrides, and carbon-based storage. Hydrogen's low energy density means gaseous storage onboard vehicles must be at high pressure. Containing the required pressure requires strong tanks, which are very heavy if made of metal. Composite vessels are now available, which are lighter and stronger, although more expensive, than metallic cylinders. Compression consumes about 20% of the energy in the hydrogen[272], greatly reducing the well-to-wheel efficiency for FCVs.

Cryogenic liquid hydrogen, stored at temperatures lower than 253°C requires a lower pressure and smaller volume than compressed gaseous hydrogen to store the same amount of energy and can thus be transported more efficiently. Like compressed gas, liquid hydrogen is also a relatively mature technology, but maintaining the low temperature is challenging and requires an expensive, heavily insulated tank. Liquid hydrogen production also has a high energy requirement, using up to 40% of the energy content of the fuel[80], and is significantly more expensive to produce than compressed hydrogen or petrol and diesel. Finally, although liquid hydrogen is denser than compressed gaseous hydrogen, the tank must still be 3.5 times larger (excluding the size of external insulation) than a conventional fuel tank to store the same amount of energy[41]. Nonetheless, concept vehicles have been produced that run on liquid hydrogen, such as the BMW H2R race car[273], and liquid hydrogen buses which were tested in London as part of the CUTE fuel cell bus programme[41].

Storing hydrogen in metal and chemical hydrides[274] and carbon-based nanostructures[105, 275] has been the focus of much research, as such materials are in solid form and do not require high pressures or low temperatures. To compete with conventional vehicle fuels, however, they will need to have a lower cost and a higher storage density.

None of the technologies described above can yet compete with petroleum and meet all the needs for automotive applications. Compressed gaseous hydrogen and liquid hydrogen are energy-intensive to produce and come with safety concerns[276, 277]. Hydrides and carbon nanoconfigurations offer some promise, but remain at an early stage of development. Major breakthroughs are needed to create storage systems that are smaller, lighter, cheaper, safer, more efficient, and more convenient than the current options.

Table 2.10. Energy density of common fuels and possible hydrogen storage options

Fuel	Energy density (kWh/dm^3)[80]
Diesel	10.6
Petrol	9.5
Coal	7.6
Liquid natural gas	5.6
NH_3BH_3 [a]	5.5
Methanol	4.4
Wood	3.0
Liquid hydrogen	2.37
Natural gas (200 bar)	2.3
Li-ion battery	1.69
Gaseous hydrogen (200 bar)	0.53

[a] NH_3BH_3 (ammonia borane) is a chemical hydride (*vide infra*).

Distributing hydrogen from the point of production to vehicle fuelling stations will require massive infrastructure investments, depending on the scale of hydrogen use. The principal options for delivery of hydrogen to fuelling stations are by truck or pipeline. Current long-distance transport of hydrogen is done in liquid form. Trucks can carry approximately six times as much hydrogen in the liquid phase as in the gaseous phase[79]. Pipelines[278, 279] would be more efficient still, but they would require a great capital cost, and trucks would still be needed to deliver hydrogen from production facility to pipeline and from pipeline to fuelling station. Furthermore, pumping over long distances consumes a large amount of energy in relation to the energy content of the gas delivered. Based on current technology, therefore, regional production and local distribution would be most likely[41].

Networks of fuelling stations will be critical for the uptake of FCVs. According to Fuel Cells 2000, there are currently nearly 200 hydrogen fuel stations across the globe, mostly in the US[280]. A few hydrogen highways have already begun. California designated its Interstate motorway network the 'California Hydrogen Highway Network' in 2004[281] and aim to have fuelling stations approximately every 30 to 35 kilometres by the time FCVs are commercialised. In Canada there is the British Columbia Hydrogen Highway[282] that runs from Vancouver to Whistler, and to Victoria, using Hythane (a blend of 20% hydrogen and 80% natural gas[283]) as an interim fuel. Linde, the largest supplier of hydrogen in Germany, has proposed an 1800km ring of hydrogen fuelling stations around Germany, at an estimated cost of no more than €30 million [284].

Hydrogen used as fuel for FCVs has the potential to completely remove CO_2 emissions from motor vehicles. Moreover, the diversity of possible feedstocks and production techniques promises to increase energy security. At present, however, formidable challenges remain. The existing energy infrastructure is entrenched and will be difficult and expensive to displace. Hydrogen's success, however, crucially relies on FCVs, which require a cost reduction of a factor of 20 at least, in order to be competitive with ICEVs[41]. The high cost of fuel cells suitable for road vehicles is due to the significant quantities of expensive platinum incorporated in them (see section 2.1); a large-scale manufacturing of fuel cells could in addition increase the price of this commodity considerably (see section 5.1). Widespread market penetration of FCVs is therefore unlikely until 2050 or later, and even optimists estimate that it will take at least 20 years[41]. Breakthroughs in production and storage methods will be needed if a hydrogen economy is to become a reality. Hydrogen must also be delivered in a more efficient way, and one that is cost-competitive with petroleum.

The shape that a hydrogen economy may take will depend on the cost of competing fuels. Fossil fuel production will eventually peak, causing prices to rise to a point where alternative fuels may become economically viable. Combined with concerns over climate change and energy security, this may eventually lead to a change in energy production. Hydrogen from non-carbon sources may then come to play an important role. The timescale, however, will be long, as new energy technologies are usually introduced over decades.

In the near-term, hydrogen production will use the existing infrastructure. It will mostly be produced locally on a small scale from fossil fuel reformation or electrolysis from grid electricity, mostly to fuel fleet FCVs such as buses and taxis that use a single refuelling point. International agreements and national regulations on the use of hydrogen as a transport fuel will need to be established. Collaboration like that of the International Partnership for the Hydrogen Economy[285], the European Union Fuel Cells and Hydrogen Joint Technology Initiative[286], and the International Energy Agency (IEA) Hydrogen Implementing Agreement[287] will need to expand and continue.

In the medium-term, local and regional hydrogen highways may be created, but the drawbacks compared to petroleum and ICEVs and the capital costs of hydrogen infrastructure will remain too great for major fleet penetration of FCVs. More energy for electrolysis may come from renewable sources, but nuclear power may become the dominant source of energy for large-scale carbon-free hydrogen production. Carbon capture and storage may be implemented in power plants and hydrogen production facilities that use fossil fuels. Generation of hydrogen in remote areas may take place by home-based electrolysis[79].

Widespread use of hydrogen in transport is unlikely except perhaps in the long-term, after 2050[41, 104, 108, 288, 289]. If demand for hydrogen grows, larger distribution networks, including pipelines, may be created, first around cities and then gradually moving out to rural areas. Renewable sources of energy may be more developed and therefore make electrolysis powered by them the preferred option for hydrogen production. Current energy practises are highly entrenched, but they can be dislodged over decades if the technology matures and the cost decreases significantly. The transition to a hydrogen economy, if made at all, will be over the long-term and will most likely be difficult and costly. But the possibility remains that, by the end of the century, production of hydrogen from renewable sources of energy may virtually eliminate CO_2 from motor vehicles and make hydrogen the clean energy carrier of the future.

2.3 Rail

Rail transport has several distinct advantages over air and road transport, such as lower operating emissions, higher carrying capacities, and in many cases greater passenger comfort and convenience[290, 291]. For example a diesel Class 220 Voyager has emissions of 31 g per seat km and electric Class 373 Eurostar has emissions of 24 g per seat km using the current UK electricity generation mix. However, an important issue is load factor, or the utilisation of carrying capacity. For cars additional passengers increase the efficiency of the vehicle, for example a family of four in an average car would emit 26 g of CO_2 per km, comparable with rail. For rail, under-utilisation of carrying capacity leads to significant increases in CO_2 emissions per passenger km. For a load factor of 52%, the current average on the Virgin Trains network the class 220 emits 42 g per passenger km. The same is true for electric rail, the Eurostars 67% load factor equates to an emission of 21 g of CO_2 per passenger km. From a single passenger point of view, for example a businessman travelling for work, rail compares well with cars (European wide average of 105 g per km)[292] and aircraft (European average 227 g per km), but if you take the single journey, a car is by far the most efficient, 105 g per km compared to 17.8 kg per km for rail.

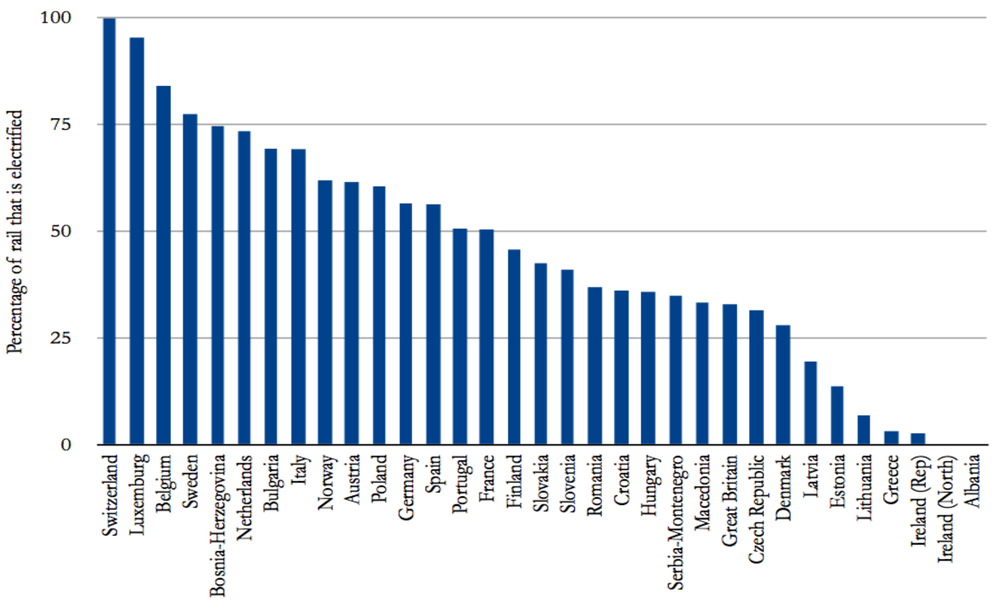
- Currently, they cannot replace crude-oil-derived fuels due to limited land suitable for production.

Whilst it seems obvious that an increase in rail use will help reach reach emissions targets, rail does face some inherent challenges that restrict its place in the transport sector. Central to these challenges are high up-front capital infrastructure costs and the carbon debt incurred during the construction process. Premature investment may also risk 'lock-in' to obsolete technologies and routes, since the lifetime of a rail project is commonly greater than 60 years. The level of inflexibility implicit in rail travel often requires goods and passengers to transfer services several times to reach their final destination. This reduces usability and threatens any modal shift towards a new investment[290]. Such a threat could also diminish the environmental and economic performance of a particular project over time[293].

A number of studies have been commissioned into improving the efficiency of rail transport. These have identified that in the short-term, there are a number of easily achievable changes that offer significant savings with a short payback time. For example, a study by the Association of Train Operating Companies (ATOC) indicates up to 15% of traction electricity is consumed when trains are stabled. When this is extrapolated across the entire electric network, it results in waste of approximately 321,000MWh or 190,000 tonnes of CO_2 annually [294,295]. This can be prevented through isolating the train from the supply or, on some more modern units, by software modifications. A direct analogy to electric stabling loads is the reduction of diesel idling, which wastes approximately 36.1 million litres of fuel or 96,000 tonnes of CO_2 annually. This can be reduced through a number of changes to the current systems, with the costs being quickly recovered in reduced energy costs[295]. Significant savings can also be quickly achieved through operational changes. By the application of efficient driving techniques and train regulation, studies have indicated that energy savings of 5-15% are possible by designing routes using energy efficient speeds, coasting boards, driver training and other methods. Using an average value of a 7.5% saving, this equates to 141,000MWh and 33.5 million litres of diesel or approximately 180,000 tonnes of CO_2 annually[295]. Another energy saving option is to tailor the train size, by splitting units according to demand. Most services are dictated by the size of the peak service, running at 20-50% capacity during the day. Preliminary analysis of timetables for third rail fleets in London alone indicate as much as 280,000 MWh or 170,000 tonnes of CO_2 could be saved. Whilst splitting units is a simple solution it creates some issues such as increased staffing costs, reliability issues, timetabling due to inherent delay, stabling space and stabling locations[295].

In the longer-term, efficiency improvements lie mainly in technical changes. This is due to the life of the fleet (30+ years) and the long gestation period for infrastructural changes. Perhaps the most obvious step is to remove diesel use by electrifying the network. In the United Kingdom, 38% of passenger kilometres are performed by diesel traction over the 66% of the un-electrified network [296]. If the entire rail network was electrified at a cost of approximately €18 billion[297], savings of approximately 12 million tonnes of CO_2, over a 50 year period, would be possible[298]. These savings would alter depending on the UK energy generation mix, which is expected to be decarbonised in the future.

Figure 2.3: Electric rail as a percentage of total rail transport by country[310]



Due to the high cost of electrifying the complete rail network, using replacement fuels instead of diesel on low use lines is an attractive proposition. A number of fuels have been identified as possible long-term replacements for diesel traction. Biofuels, both first and second generation, are obvious candidates for rail use, as with road and air transport. They offer all the previously covered environmental benefits (see section 2.2) and are expected to provide a significant percentage of diesel fuel use in future. The use of pure biodiesel is under investigation in India and Germany[299]. A 20% biodiesel mix would offer carbon savings of approximately 400,000 tonnes of CO_2 at 2008 use levels[299]. However, the issues identified for road transportation are also applicable. The use of gas, both natural and bio-gas has been investigated as both fuels offer considerably lower emissions. They require significant changes in infrastructure and require the involvement and acceptance of the engine manufactures so they are unlikely to be adopted by the rail industry[299]. The use of hydrogen as a energy source has also been considered and a number of demonstrator units have been produced[300]. The challenges in the use of hydrogen as a fuel source for the rail industry are similar to those faced by the road transport sector (see section 2.2,) such as the lower energy density and the required infrastructural changes. It is therefore unlikely that hydrogen will be used on the rail network in the foreseeable future, though use as auxiliary power units to reduce idling is a possibility [301]. Fuel additives have been offered for a number of years and claim up to a 20% improvement in overall efficiency. With a conservative value of a 4% fuel saving equates to 28.9 million litre or 75,000 tonnes of CO_2 saved annually[302]. Additives require more research into long-term effects before network wide roll-out.

The use of hybrid drive systems are another option for reducing the impact of diesel trains[303]. Using an approach similar to the Toyota Prius, onboard batteries receive power from regenerative braking and diesel engines, which also provide some tractive effort. This stored electric power is then used to provide the majority of the tractive effort. As with road transportation, battery technology is the main constraint. Fuel burn could be reduced by 10% overall or 45.9 million litres or 10%, equating to 123,000 tonnes of CO_2. Energy regeneration from braking can be used by non-hybrid drive systems. This is achieved by either feeding back to the grid or to onboard storage in flywheels, superconductors or batteries[304]. These technologies offer a 25% saving for electrical multiple units and 15% for diesel electric multiple units, which equates to 200,000 tonnes of CO_2 saved annually. Technical issues with this method include onboard storage methods and the required infrastructure for the return to the grid [295]. Assuming that the whole network would not be electrified, a combined diesel/electric drive would allow units to use cleaner electric drive on the electrified network and diesel elsewhere. This could save 100 million km of diesel driven traction resulting in 49.7million litres of fuel saved, but would increase the electric load by 195,000 MWh, giving an overall saving approximately 130,000 tonnes of CO_2. It should be noted that some savings would be offset by increased weight of the dual drive system and increased electrification of the network would also reduce the savings[295].

Another method to improve the efficiency of diesel systems is the use of intelligent control on modern distributed power trains. Diesel Multiple Units (DMUs) have significant tractive power redundancy and intelligent control of the engines would minimise the losses due to this. Initial calculations have shown a possible saving of 15.4 million litres of fuel (40,000t of CO_2) with a three year pay-back rate for the alterations[295]. Further efficiencies in onboard power can be gained by the reduction of heating and cooling loads. In extreme conditions, up to 80% of auxiliary energy consumption is used in conditioning the passenger environment. This can be achieved through a number of actions including reducing solar loading and reduction of interior temperatures by 1-2°. Such alterations offer fleet wide savings of 115,000 MWh and 18.5 million litres of diesel, equating to 120,000 tonnes of CO_2 annually[295].

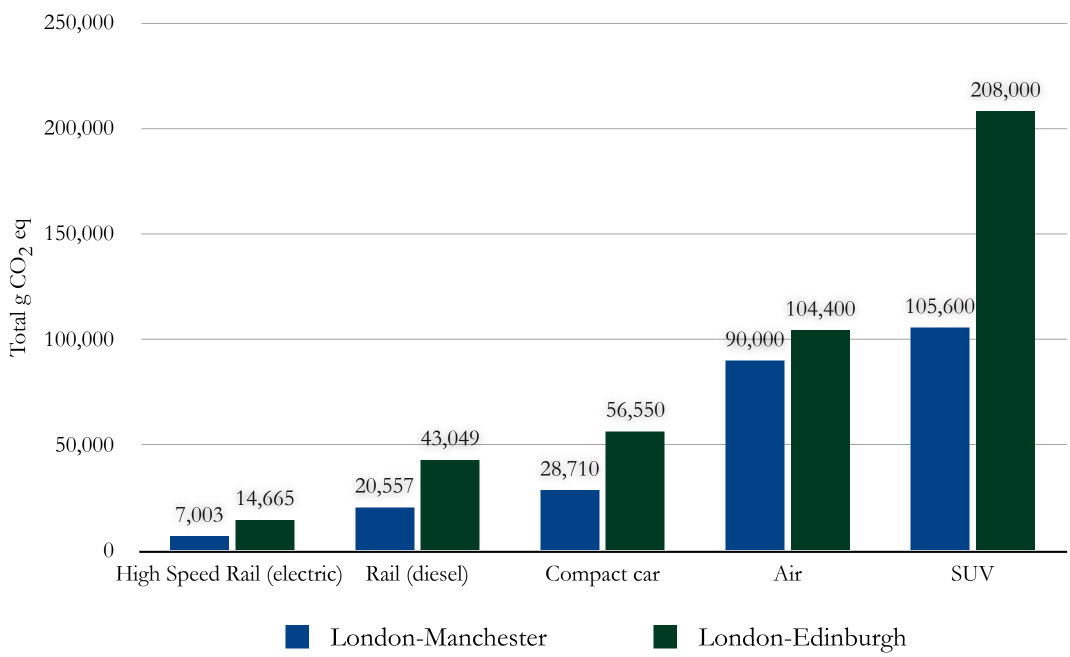
Other areas that offer significant savings are in weight reduction and aerodynamic improvements. Whilst both these methods could be retrofitted, it is more likely that they would be applied at the design stage of new vehicles. Fitting bogie skirts and other aerodynamic aids could deliver a 10% drag reduction, saving 35,000 MWh and 7.5 million litres of diesel across the network, reducing overall emissions by 40,000 tonnes CO_2[295]. There have been developments in the materials used in unit construction, as has occurred in aviation. Today, it is common for rail bodies to be constructed mainly of aluminium and there is an increasing use of composites for cabin parts, thus reducing overall weight. An example of this are the units in contention for the replacement Thameslink units. Both, the Bombardier Aventra and Siemens Desiro, utilise lightweight aluminium alloys, which in combination with other technologies offer an energy saving of approximately 50% over the 1980's generation Class 319 currently used[305,306]. As a rough approximation, a two tonne reduction in the average vehicle mass, which reduces inertia and grade resistance, would equate to a saving of 55,000 MWh and 8.8 million litres of diesel – 60,000 tonnes of CO_2 per year over the UK network[295]. Not only do lightweight vehicles save energy in operation, they have a reduced impact on the infrastructure leading to lower maintenance cost and engineering issues.

The furthest development of lightweight rail vehicles are 'light rail' systems, commonly known as Rapid Transit Systems or Super Trams. These operate usually in private right of way situations, but can, where necessary, share right of way with road vehicles. These light weight systems are slower than traditional heavy rail (70-80 mph compared to 100+ mph) and do not have to meet such high levels of crashworthiness. They are more efficient, have lower infrastructure costs and requirements and are generally applied to urban mass transit systems. There is also a move toward smaller scale lightweight systems, such as automatic people movers, which contain smaller numbers of passengers, but run in a dedicated guideway[307]. There are a number of smaller 'tweaks' available to improve energy efficiency in rail systems, such as reduction in light levels, low resistance conductor rails and selected switching of transformers which offer saving in the region of 125,000t of CO_2 per annum. The cost of these procedures for a defined network wide replacement program is prohibitive, but the systems should be replaced with these as and when required for maintenance reasons.

Combining all of these technologies and discounting full electrification and other systems where the savings are not so clear (hybrid diesel electric drives) could offer a possible overall saving of 50% of current energy, and therefore carbon emissions. Comparing this with current average car passenger km (160 g/km) and current state of the art (87 g/km) shows electric rail could have a CO_2 emission per passenger km some 15% of current car average and 30% of current systems. However as rail has a share of approximately 1.9% of domestic transport emissions in the UK even a full roll-out of these technologies would have a limited impact on the overall emissions from the transport sector[308].

Advances in high-speed electric rail, however, have expanded the context in which rail presents as a viable transport option for a modal shift away from aviation. Challenges faced by high-speed electric rail in the UK must be considered within the context of alternative transport modes over varying distances. Emissions from cars (SUV and compact), rail, and air travel have been quantified for a hypothetical middle distance domestic journey (London to Manchester) and long distance domestic journey (London to Edinburgh) in Figure 2.4. It should be noted that a detailed environmental analysis requires a full lifecycle assessment which is beyond the scope of this report. Reasonable qualitative conclusions, however, may be drawn from comparing operating emissions per passenger kilometre and determining how the inclusion of additional emissions would affect results. In all cases, only direct emissions from operation have been considered that include well-to-tank and tank-to-wake. Indirect emissions, which

Figure 2.4: Direct emissions from relevant transport modes for middle London-Manchester) and long (London-Edinburgh) distance domestic journey scenarios.



Myth - “Policy X is the only solution.”

include embodied emissions produced during construction, have not been included in all cases.

Figure 2.4 illustrates the benefit of high-speed rail from an emissions point of view over all other transport modes considered. It should be noted that calculations were based on figures quoted in HS2S [311] and an average carbon content of UK electricity of 430 g CO_2eq/kWh[312], which is expected to decrease with investment in low carbon electricity generation technologies. It is also relevant to appreciate that embodied emissions are significant for rail infrastructure[313], although it is expected that emissions parity (the point at which the embodied emissions debt is paid off and any additional use results in a net emissions saving) will occur well within the first half an estimated 60 year project life time. Values in Figure 2.4 also assume occupancy rates of 67% for high speed rail, 52% for diesel rail, 75% for air travel, and that cars only have a single driver. Potential error from occupancy assumptions and excluding embodied emissions from calculations could feasibly increase the quoted estimate by a factor of four, although the inclusion of such amendments would not change the central conclusion that high speed rail outperforms all other selected transport modes from an emissions point of view.

Currently the lowest emitting compact cars produce 87 g CO_2eq per kilometre[314], which was used to calculate road transport emissions in Figure 2.4. Values given assume single occupancy that may lead to an overestimation of total emissions, although this would be offset by the exclusion of embodied infrastructure and congestion emissions in calculations. Compact cars would still not compete with high-speed rail on an emissions basis if high occupancy is assumed.

Emissions per kilometre from short haul air travel is highly sensitive to landing take-off cycles (LTOs). Very short flights, as modelled by the London-Manchester route (about 300 km), are characterised by high emissions at 225 g CO_2 per passenger kilometre, while medium distance domestic flights from London to Edinburgh emit less at 135 g CO_2 per passenger kilometre[315]. The effect of LTOs is that net emissions vary marginally (by approximately 15%) over very short to medium distance domestic flights, which further supports the case for domestic high-speed rail. Embodied emissions and radiative forcing (which may increase the global warming impact of high altitude emissions by 2 to 4 times) have not been taken into consideration, and would further increase the global warming impact of air transport. 4x4 SUVs may emit up to 320 g CO_2eq per kilometre that makes performance significantly worse than all other modes of travel considered, based on single passenger occupancy.

Over very short distances (100 km to 200 km) high speed rail infrastructure costs and embodied emissions represent a greater share of the total over the life cycle, and therefore it is more likely to make economic and environmental sense to invest in suburban commuter, high-speed intercity trains or upgrade bus transport systems. This is also supported by the fact that bus transport is intrinsically more flexible than rail, and provides a more user-friendly option over short distances. Middle and long distance domestic travel scenarios that include short haul flights both show that high-speed rail performs better than any other alternative according to any metric. It should also be noted that a rail line from London to Edinburgh would transit at Leicester, Sheffield, and Manchester, meaning that the benefits of developing a London-Edinburgh line would include the double-dividend of a high-speed service to these major centres. Additional services would also promote a greater modal shift towards a high-speed rail service, thereby further improving environmental and economic performance. Conversely, it would be expected that a comparable diesel rail service would not attract the same modal shift, possibly compromising emissions benefits and economic performance.

Germany and France have shown that efficient high-speed rail networks can reduce domestic flights while increasing mobility and reducing GHG emissions. High-speed electric rail also has great scope to improve in the future. Reducing the carbon content of grid electricity and onboard electricity generation through photovoltaic’s can further mitigate the GHG impact of trains[316]. Twin deck trains also offer the potential to increase passenger numbers by 40% while only marginally increasing energy demands[317]. Furthermore, the inevitable increase in the cost of liquid fuels and carbon prices in the future strengthens the economic case to invest in high-speed rail in the UK as a priority.

2.4 Economic policy

An efficient mobility model for the future must take into account the true costs of transport and the regulatory framework needed to create incentives for people to make sustainable transport choices. In order to achieve this, economic instruments can be used to correct road transport externalities. These include environmental and road damage, accidents, congestion and oil dependence. From an economic point of view, the two types of instruments for reducing the negative impact of transport externalities are command-and-control and incentive based policies.

Command-and-control (CAC) policies are governmental regulations that force consumers and producers to change their behaviour. They are the

- As with technology, there is no 'silver bullet' policy to tackle climate change; a mix of top-down, bottom-up, and market-based measures are required.

type of instrument most favoured by policy makers in terms of feasibility and effectiveness. These policies are not efficient, as even in a context of perfect information when the regulation or standard is set at the optimal level, the target is not achieved at the minimum cost, and worse yet, the social costs could exceed the potential benefits. Despite not being efficient, a number of CAC policies implemented in road transport have achieved what they set out to accomplish.

Fuel standards, a very common CAC policy, are standards that countries impose on motor vehicle fuels. A notable example is the ban on lead in petrol, which has been implemented virtually all over the world as of 2009. Lead had been used as an additive since the 1920's. It was a pollutant of great concern, mainly due to its effects on children's brains and was therefore phased out and finally banned in most countries. In the US, for example, the Environmental Protection Agency (US EPA) started a lead phase-down program in 1973, with the objective of reducing the lead content in petrol Although this was mainly a CAC policy, it was complemented with a form of credit trading, an early ancestor of cap-and-trade. By 1995, unleaded petrol sales accounted for 99% of the petrol market in the US[320]. Meanwhile, the UK also introduced regulations on the lead allowed in petrol. Unleaded petrol was first sold in the UK in 1986 and by the end of 1999 a final ban was imposed on leaded petrol[321]. Most developed countries followed similar paths in the 1980's and 1990's. In addition to national programs, the United Nations Environment Program led a campaign to eliminate leaded petrol completely everywhere in the world and as of 2009 very few countries still use it.

Fuel standards are widely used in many (mainly developed) countries and have reduced the emissions of benzene, sulphur dioxide and other harmful pollutants. Much less common are regulations on CO_2 emissions from fuel. One exception is the Low Carbon Fuel Standard, introduced by the state of California in 2007. The Low Carbon Fuel Standard requires fuel providers to reduce GHG emissions of the fuel they sell. The programme intends to achieve a 10% reduction in the carbon intensity of transport fuels by 2020.

Vehicle standards are CAC policies that typically regulate vehicle safety, tailpipe emissions and fuel efficiency. In general, different countries set their own vehicle standards, although the EU sets standards for all its members. Typically, safety standards set front and side impact tests which vehicles have to pass before they are introduced into the market. There are also regulations regarding compulsory fitting of head-restraints and seat-belts, and on the minimum depth of tyre treads, brakes, and annual safety checks[322]. In general, safety standards have become more stringent over time and newer vehicles tend to be safer than older ones.

One prominent example of a CAC policy relating to tailpipe emissions is that of catalytic converters. These were first introduced in new cars in the US in 1975 in order to reduce the toxicity of emissions from internal combustion engines. The converters also facilitated the compliance with the Clean Air Act of 1970, according to which all new vehicles sold in the US from 1975 onwards had to meet US EPA standards on hydrocarbons, nitrogen oxides and CO emissions[323]. The EU made catalytic converters mandatory in new cars with the Council Directive 91/441/EEC of 26 June 1991, which called for measures to be taken against air pollution by emissions from motor vehicles[324, 325]. The main systems of vehicle emission standards are those from the US and the EU. Having said that, most developed countries (and some developing ones), including Australia, China, Japan, Switzerland, South Korea and Taiwan have implemented some type of fuel economy or CO_2 standard[326], although in many instances they closely follow (or import) the standards in place in the US or Europe[327]. In general, when a country or group of countries adopts a standard, this standard applies to new vehicles sold, rather than to those already on the road. The US was the first country in the world to set standards for vehicle emissions[328]. Under the North American Free Trade Agreement (NAFTA) these standards were later also adopted by Canada and Mexico[327].

There are a number of landmarks that have shaped the development of vehicle emissions standards and fuel economy around the world. One important such landmark was the introduction of the Corporate Average Fuel Economy (CAFE) in the US, enacted by Congress in 1975 and still in place as of 2009. The purpose of CAFE is to reduce energy consumption by increasing the fuel economy of cars and vans. Regulating CAFE is the responsibility of the US National Highway Traffic Safety Administration (US NHTSA) and the US EPA. The US NHTSA sets fuel economy standards for cars and vans sold in the US, and the US EPA calculates the average fuel economy for each manufacturer[329]. Typically, a manufacturer can meet the standard by producing fewer large vehicles and more small vehicles or by improving the mileage of all of the vehicles it produces.

CAFE standards in the US have typically been 'technology-forcing' as opposed to 'technology-following'[327]. Technology-forcing standards are standards set at a level which, although feasible, remains to be demonstrated in practice, and in the case of the US, have pushed technological advances forward.

Although consumers may regard CAFE as a good policy, it has been seen as an inefficient CAC policy for two reasons: i) it encourages excess investment in fuel efficiency and distorts the mix of large and small vehicles[330]; and ii) it is less cost effective than fuel taxes at reducing petrol consumption because by lowering fuel costs per km driven it increases vehicle use[331-335]. Referring to standards in general, although not necessarily to CAFE standards in particular[336], shows that more stringent standards for new vehicles prolongs the retention of old, high emission ones and as a result aggregate emissions may increase in the short run.

CAFE standards could have been tightened periodically since they were implemented. In practice, however, CAFE standards for cars have remained the same since 1990, and are, as of 2009, still 27.5 miles per gallon (11.7 km per litre). CAFE standards for vans have indeed been tightened, albeit in very small increments. They are 23.1 miles per gallon (9.8 km per litre) and 23.5 miles per gallon (10 km per litre) for the years 2009 and 2010 respectively.

Portney *et al.*[337] show that higher real petrol prices together with new standards in the US had a substantial combined impact on fuel economy. They point out that new car and new van fuel economy rose by over 30 and 35% respectively between 1978 and 1982. At that point fuel prices decreased and yet fuel economy continued to increase, very likely as a result of the CAFE program. However, the increase in the share of vans[338], subject to less stringent standards, meant that the combined new vehicle average fuel economy declined 6% between 1987 and 2002. This increase in the share of vans is a direct impact from CAFE[330, 335]. As of 2007, vans accounted for half of new passenger vehicle sales in the US[335].

On 19 May 2009, President Barack Obama announced new tighter CAFE standards, covering models for the period 2012 to 2016 and reaching an average of 35.5 miles per gallon (15 km per litre) by 2016[339]. Portney *et al.*[337] warn that, although tightening CAFE standards may reduce fuel consumption and CO_2 emissions, they will also reduce the cost of driving and thus create a stronger incentive to drive. The external cost of the 'rebound effect' of additional driving could be as large as the benefits from CAFE. However the rebound effect has recently halved in the US due to rising incomes and diminished significance of fuel costs[340].

Until the 1980's, vehicle emissions regulations in Europe were designed by the Economic Commission for Europe, to be later adopted and enforced by individual countries, and were typically much less stringent than US standards, as they had to be agreed by so many countries[327]. Europe wide regulation came with the Consolidated Emissions Directive 91/441/EEC, which was adopted by the Ministers of the European Community in June 1991, made effective from 1 July 1992 for new models and from 31 December 1992 for all production[327]. Since then emission standards have been adopted at a European level without the need for unanimous agreement from all countries.

Like in the US, EU standards increase their stringency with time. As of 2009, emissions of nitrogen oxide, hydrocarbons, CO and particulate matter are regulated for cars, vans, lorries and for other vehicle types. While CAFE standards in the US regulate fuel economy and in doing so, CO_2 emissions, the EU still lacked similar legislation until recently. Europe relied on voluntary changes and information campaigns to reduce CO_2 emissions from the road transport sector, which failed to produce any substantial CO_2 emissions reductions.

However, in 2007 the European Commission finally proposed mandatory reductions of emissions of CO_2 to reach a target of 130 grams of CO_2 per km for the average new car fleet, through improvements in vehicle motor technology, and a further reduction of 10 grams of CO_2 per km by other technological improvements and by an increased use of biofuels [341]. In December 2008, the European Parliament voted to adopt the regulation[342]. Heavier cars are allowed higher emissions than lighter cars, while preserving the overall fleet average. The requirements will be phased in, starting with 65% of each manufacturer's newly registered cars having to comply, increasing to 100% from 2015 onwards[342]. In order to maintain the diversity of the car market, the CO_2 emissions targets are defined according to the vehicles mass, so different vehicle sizes are subject to different targets. Also, manufacturers are allowed to form pools so that the average emissions of the pool as a whole do not exceed the target emissions for the pool[341]. Other CAC policies include restrictions on vehicle circulation, vehicle ownership, parking, and emissions in certain areas or on certain days.

An example of restrictions based on emissions is the **Low Emission Zone** (LEZ) in London. The zone which can broadly be defined as the area inside the M25 motorway, covering most of Greater London, was implemented in February 2008. Vehicles driving on the M25 without entering Greater London are not subject to the emission limits. The main objective of the scheme is to deter the most polluting diesel vehicles from driving inside Greater London. The regulation includes diesel lorries, buses, coaches, large vans and minibuses. It also includes a number of other specialist vehicles, such as for example, breakdown and recovery vehicles, gritters and road sweepers. Cars, motorcycles and small vans are not included in the LEZ. The scheme operates 24 hours a day, seven days a week, every day of the year (Transport for London website).

Restrictions to circulation have been widely implemented in towns and cities throughout the world. It is very common to see pedestrianisation of streets, which are closed to traffic at all or some times of the day. It is also common to see streets where only public transport and taxis can circulate. This type of CAC policy is equitable, in the sense that it affects all drivers and does not differentiate by their willingness to pay for using the road (i.e. by their ability to pay). Many (historic) towns in Europe have such types of areas. In general, they do not harm the local economy, but rather, create a better environment for shoppers in the area. A pedestrianisation scheme in Oxford, UK, was implemented in 1999. An evaluation found there was a reduction of 17% in the number of car trips to the centre, but such reduction did not affect overall visitor numbers. Another type of road space rationing has been to restrict certain licence plates from circulating. Such a policy can be found in cities like Athens, where cars with even (odd) number plates are allowed to drive on even (odd) days only. The problem with this type of policy is that even if the final number of vehicles using the road as a result of this type of policy was optimal from an economic point of view, there is no guarantee that the most efficient trips, with the highest marginal benefit (made by those drivers with the highest willingness to pay) would be the ones taking place [343]. A similar scheme was implemented in Mexico City in 1989 to control air pollution from cars. The *Hoy No Circula*[344] programme bans most drivers from using their vehicles one weekday per week on the basis of the last digit of the vehicle's licence plate. The restrictions apply Monday to Friday, from 5:00 a.m. to 10:00 p.m. and affect most residential and commercial vehicles. Taxis, buses, and emergency vehicles (police cars, ambulances, and fire engines), commercial vehicles operating with liquid propane gas and commercial vehicles transporting perishable goods are all exempt. Davis[345] measures the effect of the driving restrictions on air quality and finds no evidence of the restrictions having improved air quality. He finds evidence of the restrictions having led to an increase in the total number of vehicles in circulation as well as a change in composition towards high-emissions vehicles. Eskeland and Feyzioglu[346] find that many households bought an additional car to be able to drive on any day of the week and the amount of driving increased. The use of old cars also increased as well as weekend driving.

Another way of controlling vehicle use is through **restrictions on vehicle ownership**. The only example of a direct quantity control of this sort is the Vehicle Quota System (VQS), a policy implemented in Singapore in 1990. Prospective vehicle owners are required to purchase a Certificate of Entitlement (COE), which is a licence that lasts ten years, except for taxis, for which it lasts seven. The government sets a quota on COEs for different vehicle categories a year in advance, in May each year. The allocation of COEs is done through open auction. When a person submits a bid (something which is done electronically) the current successful price is known and the person can adjust his bid. As the number of bids usually exceeds the set quota, there are usually unsuccessful bidders.

Parking restrictions can indirectly reduce traffic levels, and in doing so reduce most traffic externalities. Parking as an activity entails costs because parked vehicles use public space, for which there is an opportunity cost, as the land used for parking could be used for something else[343]. Verhoef *et al.* shows that under strict assumptions quantitative restrictions on parking, a CAC policy, can achieve the optimal volume of traffic in terms of marginal congestion costs and marginal parking costs, just as they would with an incentive based (IB) policy[343]. However, they point out that there would be no guarantee that the most valuable trips would be the ones that are realised. They also note that under quantity restrictions on parking, a market for parking permits could develop spontaneously, as drivers would try to secure parking for the most valuable trips. Finally, reducing the number of parking spaces available, could result in more congestion, as more drivers would spend time looking for an available parking slot[347, 348].

To conclude our brief discussion on CAC policies, it should be highlighted that CAC is not efficient from an economic point of view because even when the standard is set at the optimal level, it is not achieved at minimum cost. Despite that, CAC is the most widely used type of instrument in the road transport sector. The most prominent examples are fuel and vehicle standards, which are used in virtually every country in the world. There are also some less widespread regulations, which include parking restrictions, the Low Emission Zone in London, restrictions on vehicle circulation and the restrictions on vehicle ownership in Singapore. The success of these measures varies, but in general they are all perceived as equitable by the motoring public, only because they do not involve payments, which tend to hit harder on the poorer.

IB policies are designed to mimic in some way the functioning of the market. They provide financial incentives to consumers and producers to alter their behaviour. They can be further categorised into price and quantity control strategies. Price controls tend to be taxes, charges or fees, but can also take the form of subsidies, given that a foregone subsidy can have a similar impact to that of a tax. Quantity controls are systems of tradeable permits, where a cap is imposed by the regulator and permits can be traded among economic agents. The main advantage of IB policies (both price and quantity controls) over CAC ones is their cost effectiveness. Producers or consumers with low costs of abatement tend to reduce the amount of externality they generate, rather than buy permits or pay taxes. Those with high costs of abatement choose to buy permits or pay taxes. The cost of reducing the externality is thus minimised compared to the more direct regulatory approach of setting standards. Standards oblige everyone to reduce their generation of externalities to the level fixed by the regulator, regardless of how costly abatement for each firm or individual is.

The use of revenues generated through IB road transport policies, those that correct externalities, have impacts on social welfare and equity and is an important determinant of the political acceptability of these policies. In general, using these revenues to reduce distortionary taxes increases the efficiency of the system, and investing them in the transport sector increases equity. Taxes and charges have been widely implemented in the road transport sector around the world, both in developed and developing countries. Their effectiveness as corrective instruments, however, depends on the link between the externality they are targeting and the tax or charge itself.

With the exception of the inter-refinery averaging and banking of credits that were instituted by the US Environmental Protection Agency in the 1980's to facilitate the phase-out of leaded petrol in the US, tradeable permits have not been implemented in the road transport sector anywhere in the world to date. Although tradeable permits would in principle incentivise the development of fuel-efficient and alternative fuel vehicles, there are a number of potential problems relating to their implementation: i) auctioned permits would awake public and political opposition, whereas grandfathered permits would deprive governments of revenues, which could be allocated to reducing distortionary taxes or for investment in research and development of new technologies; ii) permits with shorter life would have higher tradeability, but also transaction costs, and permits with longer life would have greater uncertainty about future prices; iii) including road transport in a much larger scheme, such as the EU ETS, would achieve reductions in emissions, although not necessarily in road transport. Designing a separate system would guarantee emission reductions in road transport, but not necessarily in other sectors with lower abatement costs.

Taxes and charges on road transport are used extensively throughout the developing and developed world. From an economic point of view, Pigouvian fiscal measures can correct externalities and achieve efficient levels of traffic and therefore congestion and emissions. This has not historically been the reason for the introduction of taxes and charges, which have existed before any concerns regarding externalities in general, and climate change in particular, were raised. Governments need funds, not just to build and maintain roads, but also to provide other public goods and services. Road transport has increasingly become an excellent source of revenues, regardless of any consideration of negative externalities. Road taxes and charges have helped to reduce excessive levels of negative externalities. This is not to say that they have been designed to reduce them or that they have reduced them to their efficient levels. Road taxes and charges include taxes on purchase and ownership of a vehicle, taxes on usage of a vehicle, parking charges and pay-as-you-drive insurance.

Many European countries levy a vehicle **registration tax**, based on the pre-tax price, fuel consumption, cylinder capacity, vehicle length, CO_2 and/or other emissions[349]. Registration taxes are typically charged when the vehicle is registered for the first time. The exceptions are Belgium and Italy, where the registration tax is levied every time the vehicle changes ownership[350]. Registration taxes exhibit great variation across countries, with Denmark, Ireland, Malta and Norway imposing the highest registration taxes in Europe[351]. Ryan *et al.* conducted a study for the EU-15 and found that registration taxes are significant in purchasing decisions[352]. This is especially true regarding the decision of whether to buy a petrol or diesel car when the specificities of each country are ignored. When such country fixed effects are included in the model, they stop being significant[352]. It was also found that registration taxes are not significant in changing average vehicle CO_2 emissions and highlights the fact that registration taxes in the EU are levied mainly on cars. On commercial vehicles such taxes apply at reduced rates, if at all. As it has very high ownership taxes, the case of Singapore is worth highlighting. On top of the COE described above, motorists need to pay the Additional Registration Fee (ARF). The ARF is an *ad valorem* duty on a vehicle's open market value payable by buyers of new motor vehicles, in addition to an administrative fee, referred to as the Basic Registration Fee[353]. The ARF rate was raised through the 1970's, reaching 125% in 1978 and 150% in 1980[354]. However, as the ARF rate rose, it discouraged existing vehicle owners from replacing their cars and encouraged new car buyers to buy used cars. Concerned with a stock of aging vehicles, when the applicable ARF rate was raised to 100% in 1975, the government introduced a Preferential Additional Registration Fee (PARF). This was to counterbalance the disincentives on vehicle renewal.

The purchaser of a new vehicle paid a substantially lower PARF rate if he de-registered an old vehicle (i.e. by exporting or scrapping it) of the same engine category at the time of his new purchase. Since 1997, the PARF has been amended to a system where the applicable discount is a function of the age of the vehicle to be de-registered[355]. Vehicles older than ten years no longer qualify for PARF treatment.

Annual ownership taxes, sometimes also called **annual circulation taxes** or **vehicle excise duties**, are usually levied on private and commercial vehicles in most countries. In Europe, the criteria to set these taxes vary across countries. For cars, these include cylinder capacity, fuel efficiency, vehicle age, gross weight, CO_2 and/or other emissions. For commercial vehicles, which tend to be heavier and therefore damage roads more, the duty depend mainly on weight and axles, although noise and CO_2 and/or other emissions are also used[349]. Some European countries do not levy any annual tax including the Czech Republic, Estonia, France, Lithuania, Poland, Slovenia and Slovakia[349]. Ryan *et al.* found that annual ownership taxes, in contrast with registration taxes, show a strong impact on total new car sales in Europe[352]. Consumers seem to be more sensitive to taxes they will pay every year for as long as they own the vehicle than to one-off registration taxes.

Another way of providing incentives is to give **subsidies to efficient vehicles and feebates**. A showcase example of this type of subsidies is the 'Ecoauto Rebate Program', which was run in Canada between March 2007 and March 2009. The idea behind it was to encourage Canadians to buy new fuel efficient vehicles. Eligible vehicles included cars with a fuel efficiency of 6.5 litres per 100 km or better, vans with fuel efficiency of 8.3 litres per 100 km or better, and flex-fuel vehicles, running on a combination of petrol and ethanol, with a combined fuel consumption rating of 13 litres per km or better [8]. During the two years that the program operated, applicants who purchased or leased (12 months or more) eligible vehicles from model-years 2006 to 2008, could apply for and receive rebates ranging from CA$1000 to CA$2000 (US$925 to US$1,850) [358]. By the time the program finished it had issued over 167,000 rebates, amounting to CA$187.7 million (Transport Canada website). The rebate was combined with a tax on fuel inefficient vehicles, the Green Levy, which started at CA$1,000 for vehicles with fuel (in)efficiency of between 13 and 14 litres per 100 km. This increased in CA$1,000 steps for every litre in consumption up to 16 litres per 100 km, at which point the tax was capped and all vehicles using 16 litres per 100 km or more paid a maximum tax of CA$4,000[356]. The impact of the program on new vehicle purchases and emissions has not yet been published by the Canadian Government and therefore it is difficult to assess its success.

A number of European and other countries have **scrappage schemes** in place. In December 2007 France introduced a system of bonuses and penalties on the purchase of new vehicles with a bonus between €200 and €5000 on vehicles emitting less than 130 grams of CO_2 per km and penalties between €200 and €2,600 for vehicles emitting more than 160 grams of CO_2 per km. The system also included a 'super-bonus', a scrappage scheme offering an additional incentive of €300 for scrapping a car more than fifteen years old. In December 2008, as part of an economic stimulus program the policy was reviewed, the 'super-bonus' was increased to €1,000 and the scheme was extended to include the scrapping of cars more than ten years old and the purchase of new vehicles emitting less than 160 grams of CO_2 per km. The maximum total bonus under the revised scheme is €2,000, which would be attained by replacing an old vehicle by one emitting less than 100 grams of CO_2 per km[359]. In Germany there is an incentive of €2,500 for scrapping cars older than nine years and buying new fuel efficient cars, which satisfy Euro 4 criteria on emissions[360].

A similar scheme was launched in the UK on 18th May 2009 and will last until the end of February 2010, or until the £300 million (€346m; US$482m) funding is exhausted. The scheme offers an incentive of £2,000 (€2,307; US$3,212) to scrap a car over ten years old and buy a new one. In this scheme £1,000 of the incentive is provided by the government and £1,000 from the vehicle manufacturer. The scheme is mainly intended to provide a short-term boost to the demand for cars and does not specify any restrictions on the new car's CO_2 emissions[361].

Other European countries, including Austria, Cyprus, Italy, Luxemburg, Portugal, Romania, Slovakia, Spain and The Netherlands have also introduced scrappage schemes[362]. Although many of the scrappage schemes in Europe specify conditions regarding CO_2 emissions, the main reason for the proliferation of these incentives is the economic recession and its impact on the car industry.

While many countries in Europe have been keen to adopt scrappage schemes, they are not limited to Europe only. In the US, a scrappage scheme was introduced with the signing into law of the Consumer Assistance to Recycle and Save Act of 2009, by President Barack Obama in June 2009[329]. The Car Allowance Rebate System (CARS)[357] is an incentive scheme which aims to both stimulate car and lorry sales, while also removing older and less fuel efficient vehicles from the roads. The scheme offers an incentive of either US$3,500 or US$4,500 for the purchase or long-term lease (minimum 5 years) of a new vehicle, when an old vehicle is traded in[364]. The incentive depends on the type of vehicle and the difference in fuel economy between the new vehicle and the one traded in. The car or van traded in must be 25 years old or newer and have a combined city/trunk road fuel economy of 7.7 litres per km or less[365]. The scheme was scheduled to run until 1st November 2009, or until the US$1 billion allocated to it by the federal government ran out[329]. The inital US$1 billion was exhausted by 30th July 2009 and Congress approved another US$2 billion, of which US$2.877 billion was allocated by the closure of the scheme on 25th August 2009.

The Japanese government's stimulus package approved by the Cabinet in April 2009 includes a scrappage scheme as well as incentives for the purchase of environmentally friendly vehicles with no scrapping requirements. The vehicle replacement incentive scheme applies to cars and mini-vehicles as well as lorries, requiring the scrapped vehicles to be at least 13 years old. For cars in the standard and small categories the subsidy upon replacement of an old car by one meeting the 2010 fuel efficiency standards is ¥250,000 (US$2,588)[366] per vehicle (Japan Automobile Manufacturers' Association website).

Taxes on usage of a vehicle including **carbon taxes**, are proxies for emission taxes. A carbon tax is a tax on the carbon content of the fuel in question or on the estimated CO_2 emitted in the fuel combustion process. There are some countries in Europe that have implemented a carbon tax, but the efforts have never been coordinated or agreed at EU level. These countries are Finland, which introduced a carbon tax in 1990, Sweden and Norway in 1991, the Netherlands in 1992, Denmark in 1993[367] and Italy in 1999.

Although most countries argue that these carbon taxes have decreased CO_2 emissions to some extent [365], the carbon tax component of the petrol and diesel duties have not made them significantly different from those applied in other countries. In July 2008 British Columbia in Canada implemented a carbon tax. It started at CA$10 ($9.40)[369] per tonne of carbon dioxide equivalent (CO_2e)[370] and will rise by CA$5 per year reaching CA$30 in 2012. The petrol tax will then reach CA$0.0724 per litre [371], equivalent to €0.046, which represents a very small increase relative to the current tax component of €0.22.

Although **fuel taxes** were originally introduced as revenue raising instruments, they are now also increasingly being regarded as Pigouvian taxes to internalise road transport externalities. Virtually all countries have mechanisms in place for collecting fuel duties. Thus, in addition to being fairly effective and internalizing the global warming externality, they have the advantage of already being in place. In addition, they are easy to monitor and enforce, inexpensive to collect, and guarantee some level of price stability. They vary widely from one to another and no other product seems to be subject to such divergent treatment[372]. Mexico and the US, for example, have remarkably low petrol taxes, when compared to the rest of the OECD countries. Unsurprisingly there is not that much difference in the pre-tax price across countries, except, as expected, for Mexico. There is however, considerable variation regarding taxes. This is also the case in African countries[373]. It is puzzling that countries so close to each other geographically and some times members of the same economic community, have such variations in fuel duty rates across them.

Newbery points out that the European Commission aims at harmonising energy taxes within the EU and that a European approach to reducing emissions requires that each country and GHG source face the same charge per tonne of carbon[374]. The argument is perfectly reasonable from an economic point of view, since marginal abatement costs need to be equalised across polluters to achieve efficiency. The EU therefore faces the challenge of getting all its member states to agree on a uniform rate of petrol and diesel taxes. The next question is what this uniform rate ought to be. Should it be at the lower end, like the one applied in Greece, or at the higher end, as in the UK? If the revenue raising component of fuel taxes is the VAT, the fuel duty is left to cover the external costs from road transport that may be deemed worth internalizing through fuel duties. Parry and Small developed a model that estimates the optimal fuel tax and they calibrate such a model for the US and the UK[375]. The externalities they include are damage from CO_2 emissions and air pollution, congestion and accidents. They conclude that for the year 2000 the optimal petrol tax in the US would have been US$1.01 per US gallon[376], more than twice the actual rate for that year. The optimal petrol tax in the UK would have been US $1.34 per US gallon, slightly less than half the rate for that year. Newbery finds that the external costs of road damage, air pollution, global warming, water pollution and noise in the UK in 2000 amounted to £0.36 per litre of petrol[377-379]. Since the fuel duty in the UK for the year 2000 was £0.488 pence per litre [380] it can be concluded that the fuel duty more than covered those externalities. Both Parry and Small[380] and Newbery[377] conclude that the UK had a fuel duty that more than covered the environmental costs of petrol. The numbers could be easily updated to 2009 and the same conclusions would be reached. This kind of analysis would need to be done when trying to agree on a harmonised European rate of fuel duties.

It is worth keeping in mind that in the UK, and probably in other countries with comparable fuel tax rates, the global warming externality seems to have *already* been internalised. This would make substantial increases in tax rates inefficient from an economic point of view. CO_2 emissions from road transport in these countries are probably lower than they would have been had no such high taxes been in place[381]. However they still seem to be too high to meet the various commitments that different governments have adhered to. The only way to defend higher fuel tax rates would be to use a much higher shadow price of carbon. It is also worth bearing in mind that there are countries with significant scope to increase fuel taxes, especially when the idea of harmonisation is brought into the discussion.

Governments can also use taxes to incentivise motorists to switch to cleaner petrol, when this becomes available in the market. The main economic advantage of this type of tax is that they leave the user to decide how best to respond, rather than forcing him to choose one fuel. In the UK for example, the higher tax on leaded than on unleaded petrol, raised the proportion of motorists buying unleaded petrol from 5% in 1988 to 63% by 1993 [382]. Similarly, in Sweden the tax differential between leaded and unleaded petrol decreased the share of leaded petrol from 70% in 1986 to practically zero in 1994[383]. The differential duty in the UK on unleaded petrol and ultra-low sulphur petrol that followed is another example. The fuel duty on ultra-low sulphur petrol, which at the time was difficult to find at petrol stations, was cut down by £0.01 per litre in October 2000. In March 2001 it was further cut down by two pence. The prices at the pump was £0.782 and £0.759 per litre[380]. At that point most drivers switched from unleaded petrol to unleaded ultra-low sulphur petrol, and by 2006 unleaded petrol was eventually phased out.

Another type of charge in road transport is **congestion charging.** Although congestion charging has been advocated by transport economists for many decades its implementation has been limited. The main barriers are typically public and political opposition. As a result, there are only a few examples of congestion charging as of 2009. These include the Norwegian urban toll rings, the Singaporean electronic road pricing, the Stockholm congestion tax and the London congestion charge. There are also a number of toll highways around the world and high occupancy/toll lanes in the US. The Norwegian toll rings, very often cited in the road pricing literature as examples of congestion charging, were designed to generate revenues to finance infrastructure. The aim was not to manage traffic demand. Since the late 1980's to early 1990's a number of towns in Norway, including Oslo and Bergen amongst others, have tolls, usually surrounding the whole town rather than the city centre, with daily charges which never exceed NOK 20 (roughly £2 or €2.20) for cars and light vehicles [384]. All schemes in Norway have flat rates 24 hours a day every day, except for Namsos, where the scheme only operates Monday to Friday, from 6:00 a.m. to 6:00 p.m. Since the original aim of these toll rings was not to reduce traffic levels and congestion, the decrease in demand for car travel has been low, with estimates varying from zero to 10 % reduction. Similarly there have been no significant changes in private car occupancy rates or demand for public transport[385].

There are also a number of toll highways around the world. Although the only objective of many of these schemes is to generate revenue, some also aim at relieving congestion. Examples include the M6 Toll in England, the 407 Express Toll Route (ETR) in Toronto and a number of roads in major Australian cities, such as City Link in Melbourne and the Westlink M7 Toll Road in Sydney. In all these cases the toll highways are privately owned or managed. Drivers have the option of choosing between the toll road with a lower journey times and the publicly provided alternative with higher journey time. The M6 Toll in England is a parallel segment to the M6 motorway, which extends 27 miles (43 km)[386]. Drivers have the option of using the publicly provided alternative for free or using the toll road. Charging is done at toll plazas along the road or at the exit and is not electronic. The Highway 407 ETR in Toronto extends 67 miles (108 km) from Brock Road in Pickering in the east to the QEW/403 interchange near Hamilton in the west. The 407 ETR charges tolls electronically, based on distance driven. The City Link in Melbourne is a toll road in the centre of Melbourne in Australia, which extends 14 miles (22 km), from Tullamarine Freeway to the West Gate Freeway and the West Gate Freeway to the Monash Freeway. The system operates electronically and charges per trip made along the toll segment. The Westlink M7 Toll Road in Sydney extends 35 miles (40 km), connecting the M2, M4 and M5 motorways. It operates electronically and charges per distance driven.

High Occupancy Toll (HOT) lanes in the US are lanes where tolls are applied on low occupancy vehicles wanting to use lanes which are free to use for high occupancy vehicles (HOV). High occupancy is usually defined as vehicles with two or more occupants. The State Route 91 (SR-91) Express Lanes, which opened in December 1995, were the first practical example of congestion pricing in the US[387]. Although they were originally privately operated, in January 2003 their operation was taken over by the Orange County Transportation Authority. As of 2009 there are an additional seven HOT lane projects in operation in the US, which have been partly funded by the Value Pricing Pilot program or by its predecessor, the Congestion Pricing Pilot Program. Projects include segments of the I-15 in San Diego, California (implemented in 1996), the I-25 in Denver, Colorado (implemented in 2006), the I-394 in Minneapolis, Minnesota (implemented in 2005), the Katy Freeway (I-10) and the US 290 in Houston, Texas (implemented in 1998 and 2000 respectively), the I-15 in Salt Lake City, in Utah (implemented in 2006), and the SR 167 in King County, Seattle, Washington (implemented in 2008). The individual designs vary, and tolls range from 50 cents to US$9. In some cases tolls apply in the morning peak, in others in the afternoon peak and in others they change in real time with traffic demand. In this case, drivers are informed of the toll rate changes through variable message signs located in advance of the entry points.

In 1975, congestion pricing was implemented in Singapore. The system was a paper-based area licensing scheme (ALS). Vehicles had to purchase a licence and display it on their windscreen before entering the restricted zone (RZ). The charge was per day, not per entry, meaning that they could enter and leave the RZ an unlimited number of times during the day. The system was manually enforced by officers standing at the boundaries of the RZ, and was thus prone to error. In September 1998 Electronic Road Pricing (ERP) replaced the ALS. Rather than a licence to use the RZ, charges apply per-passage. The charging area is divided into central business districts (including the areas previously covered by ALS), where charging applies from 07:30 to 20:00, and expressways/outer ring roads, where charging applies Mondays to Saturdays from 07:30 to 21:30., except public holidays. Vehicles are charged automatically on an electronic card, which is inserted in an In-vehicle Unit, each time the vehicle crosses a gantry. If the charge cannot be deducted from the card, either because it is not properly inserted or because it does not have sufficient credit, a fine is issued to the vehicle owner. The Singaporean ERP is the most fine-tuned road pricing system in the world to date. Since charges vary with vehicle type, time of day and location of the gantry, and are only debited per passage, they incorporate a fair degree of differentiation.

More recently, a congestion charge was implemented in London. The London Congestion Charging Scheme (LCCS) was first introduced in February 2003 and later extended west in February 2007. All vehicles entering, leaving, driving or parking on a public road inside the Charging Zone (CZ) between 07:00 and 18:00 Monday to Friday, excluding public holidays, must pay £8 per day. The CZ is relatively small. It covers roughly 15 mi^2 (39 km^2), representing 2.4% of the total 617 mi^2 (1,579 km^2) of Greater London. No charge is made for driving on the roads that limit the CZ and there are two free corridors: one north to south, crossing roughly in the middle of the CZ, and another one north-west of the zone, east to west, as the diversion route would have been too long for drivers just wanting to cross a short segment of an A-road[388] that falls inside the CZ. The charging zone is set to shrink. The new Mayor of London, Boris Johnson, who took post in May 2008, conducted a public consultation on the Western Extension between September and October 2008, giving the public and stakeholders the options of keeping it, removing it or altering it. Following this consultation, in November that same year, he announced that the Western Extension would be removed, although not earlier than 2010. The LCCS is an unsophisticated flat charge, which does not differentiate by vehicle type or time of day. However, it achieved its objective of reducing car use. Although speeds increased in the first two years, they then started to deteriorate and by 2007 delays were back at pre-charging levels. The decrease in average speeds however, is not linked in any way to an increase in traffic but rather, to a reallocation of network space to buses, cyclists and pedestrians, plus the unfortunate timing of road works in central London.

The congestion tax in Stockholm was implemented in August 2007 with the objective of reducing traffic congestion and emissions. It is a cordon toll system, with a cordon that surrounds the entire Stockholm City, a total area of roughly 35.5 km^2. Each passage into or out of the area surrounded by the cordon costs SEK 10, 15 or 20 (roughly between £0.80 and £1.70 or €0.90 and €1.80)[389] depending on the time of day. The accumulated passages made by any vehicle during a particular day are aggregated and the vehicle owner is liable for either the sum of the charges or SEK 60, whichever is lower.

Parking charges can be divided into three groups: parking charges for using a space on a public road, charges for using a space in a private parking lot and charges for parking at the workplace. Except for the charges paid in privately provided spaces, which typically cover all costs of parking and even yield some profit to the owner, the other charges tend to be low or non-existent. Zatti discusses the effectiveness of the parking charges in the city of Pavia[390]. In Pavia, the parking charges are limited to a small area, the charges are modest and many categories of drivers are exempt from payment. He argues that these factors, together with the vast use of illegal parking, contribute to make parking fees in the city of Pavia a revenue instrument rather than an instrument to internalise externalities. In fact, the majority of the burden falls disproportionately on occasional visitors to the city.

The Transport Act 2000 (Acts of Parliament, 2000) gave local authorities in England and Wales powers to introduce workplace parking levies. However, as of August 2009, Nottingham City Council is the only local authority to have concrete proposals for a workplace parking levy, and the scheme will not start until specific regulations regarding workplace parking charges have been resolved[391]. Employers with more than ten parking spaces would be liable and the Council hopes that the policy will reduce peak-time congestion and encourage the use of an improved public transport system.

Pay-as-you-drive (PAYD) insurance differs from standard insurance in that the premium is dependent on the annual distance travelled. As in standard insurance, the premium can be conditioned on the driver's rating factor[392], which is a function of age, crash record and region[375]. The advantage of PAYD insurance over conventional insurance is that it price-discriminates more successfully between travellers on the basis of the distance they drive, which is correlated to their willingness to pay for insurance. As PAYD insurance reduces premiums for short distances driven, implementing such insurance schemes can be expected to reduce the number of uninsured drivers[375]. Parry reports that PAYD schemes are slowly emerging at state level in the US[375]. Oregon has offered insurance companies a state tax credit of US$100 per motorist for the first 10,000 motorists who take up a PAYD policy and Texas has passed legislation which allows insurance companies to offer PAYD. There are some limited examples in other countries, with some companies offering PAYD in Australia, Israel, the Netherlands and South Africa. It is not a widely spread practice yet, so there are not many implementation examples to report on or assess.

Without questioning the fact that to achieve efficiency, those who cause negative externalities should pay, we find sufficient evidence in the literature to demonstrate that many other policy instruments can be used in combination with taxes and permits in order to move towards a sustainable transport model. These other policy instruments broadly fall into three categories: physical policies, soft policies and knowledge policies. All three aim to bring about changes in consumers' and firms' behaviour, but in different ways. The first category includes policies with a physical infrastructure element: public transport, land use, walking and cycling, road construction and freight transport. Soft policies, on the other hand, are non-tangible aiming to bring about behavioural change by informing users about the consequences of their transport choices, and potentially persuading them to change their behaviour. These measures include car-sharing and car-pooling, teleworking and teleshopping, eco-driving, as well as general information and advertising campaigns. Finally, knowledge policies emphasise the important role of investment in research and development for a sustainable model of mobility for the future.

Physical Policies

An increase in the use of public transport, combined with a decrease in the use of private cars, can reduce traffic congestion and CO_2 emissions. Public transport fares are subsidised in most places, which can be justified by economies of scale and by the fact that public transport can reduce total road transport externalities. Policies to increase public transport use must be part of an integrated policy across different modes of transport, government objectives, needs of social groups and the coordinated action between the relevant government institutions. A sustainable model for transport policy also requires integration with land use policies, which can direct urban development towards a form that allows public transport as well as walking and cycling to be at the core of urban mobility.

There are a number of towns and cities in the world where public transport is heavily used. The share of public transport in commuting trips can indeed be very high. In London, for example, the share of trips made by public transport between 07:00 and 10:00 was 87% in 2002, before the London Congestion Charging Scheme was introduced, it increased to over 88% in 2003, after the charge had been implemented and to over 89% in 2006[321]. In Hong Kong the share of commuters using public transport was 74% in 1990[393]. The net revenues raised from the LCCS are used entirely to improve transport facilities in London. The focus has been mainly on bus services: of the £138 million (€153 million, US$201 million) raised from the scheme in 2008, £112 million (€124 million, US163 million) was spent on the bus route network, infrastructure and safety.

Singapore is another example of a successful implementation. Despite its world-class transport system, its rail and bus network operates entirely without government subsidies. Singapore has four main forms of public transport: bus, Mass Rapid Transit (MRT), Light Rapid Transit (LRT) and taxi, which account for 60% of all daily trips. Most of the services are operated by two private companies, which are regulated by the Public Transport Council who review quality (e.g. air-conditioning and seat belts in taxis) and fares. The Council also insists on physical (e.g. MRT-bus-taxi interchanges) and fare (e.g. smart-card) integration in order to make connections in public transport as seamless as possible. Although public transport is not subsidised, the government finances over three-quarters of the price of replacing operating assets: the operator is only required to pay the historical value of assets, so that less of an increase in fares is necessary[354,394]. The average cost for commuting trips by public transport is less than 2% of individual income, and therefore very affordable[395]. Even Singaporean taxis are very affordable and make up 11% of all travel[395].

While North America, an area tends to be associated with cars, there are success stories of cities that have 'overcome the dominant paradigm of automobile-based planning'[396]. Newman and Kenworthy[396] note that success stories such as Vancouver, Toronto and Portland are common in that the community managed to force planners to rethink their proposals of freeway construction. Gibson and Abbott[397] describe the problems of 'urban crisis' that Portland in Oregon faced before the crucial revitalisation plan of 1972 (the 'Downtown Plan'). The city centre, and especially retail, faced a bleak future with inadequate parking facilities and a bankrupt private bus system, as well as a new super-regional shopping centre. Addressing this threat, members from throughout the community started working together with city officials to develop integrated solutions for the problems faced by the city[397]. Key policies in the 1970's thus included replacing a six-lane riverside freeway at the edge of the city centre with a waterfront park. Plans for the construction of the Mt Hood Expressway through the city were abandoned, instead using the federal highway funds to construct a 15-mile light rail line[396, 397]. Notably, the number of passenger trips per person using public transport increased by 119% between 1970 and 1980[396].

This rail system has since been augmented with several additional light rail lines, including the Portland Streetcar in 2001 and the Interstate MAX in 2003[398]. The numerous light rail projects have been supplemented with a limitation of car access and planting of trees, together with the introduction of bus priority streets with high quality bus shelters. Newman and Kenworthy[396] also emphasise the role played by the business community in making the streets more attractive by helping to repave them and by furnishing them with seats, plants and sculptures.

Curitiba is another success story. In 1964 the Preliminary Urban Plan, later to become the Curitiba Master Plan, was commissioned by the public administration of Curitiba[399]. While the integration of land use and transport policy has since become widely accepted, the Curitiba Master Plan's integration of these principles was quite unusual at the time. The integrated approach viewed transport as a system linked to 'housing, land use, the road network, commercial development and recreational investments such as parks, green spaces and the preservation of historic sites'[399]. The transport network started operating in 1974 and is designed in a trunk and branch system. High-capacity buses serve the 'trunks' routes that radiate from the city centre. These 'trunk' routes have transfer stations at regular intervals allowing for interchange with the 'branches' of the system, i.e. the lower-demand feeder routes, as well as with the orbital inter-district routes. Interchanges do not require extra payment as tickets are integrated. The system, operated by ten bus companies under the regulation of municipal authorities, is entirely self-financed[399]. Curitiba's bus-based public transport system is characterised by a step-by-step approach of improvements. Rather than replacing the existing bus system with an underground or rail system, the first step was to establish an express bus system with dedicated bus lanes. This system, improved and extended over the years, provides 'a high-quality service comparable to an underground system at a much lower capital cost[399]'. This low cost allows the system to be financed entirely by passenger fees. Between 1974 and 1999 the transport network went from carrying 54,000 to an average of 1.3 million passengers transported daily, catering for 75% of the population with one of the highest patronage rates in the world[399]. Rabinovitch reports that a survey by the Bonilha Institute finds a modal shift amongst commuters to have occurred, with around 25% of commuters estimated to have switched from cars to public transport[399]. Smith and Raemakers note that whilst Curitiba is often upheld as a developing country success story due to its environmentally sustainable integration of land use and transport policy in a fast-growing city, this success may not be easy to emulate[400]. The institutional strength, policy co-ordination and in particular control over land allocation required to copy Curitiba's success tend to be lacking in other cities.

Not all transportation systems need to be motorised. Walking and cycling constitute an excellent alternative to on short distance trips within towns and cities. The policies which can incentivise walking and cycling include crime reduction to make streets safer, well-maintained and clean pavements, attractive street furniture, safe crossings with shorter waiting times, dedicated cycle paths, showers in offices and lower speed limits, to name but a few.

There are a number of cities that have implemented successful cycling policies. The Netherlands carried out the first and probably the most successful official bicycle policy in the world[401]. A typical Dutchman cycles 2.5 km daily, which is 25 times more than the average

Spaniard, Greek or American. Almost a quarter of longer-distance trips (4.5 km-6.4 km) are made by bicycle, compared to 1% in the UK.

The high cycling rates in the Netherlands are not a result of unaffordable motorised transport as GDP per capita was over US$52,000 (£35,600; €39,500) in 2008 according to the IMF. Its success came from a government policy adopted in 1975. This policy favoured the use of bicycles and introduced a fund for the construction of bicycle facilities in both urban and rural areas. Roughly €227 million (at 2004 prices) was spent over ten years[401]. The policy managed to reverse the fall in cycling rates and curtail a rapid expansion in car ownership[402].

There is no single prescription for the Netherlands' success, as although it is fortunate in terms of moderate climate, high population density and compact settlements, strong winds discourage cycling,[401]. Local municipalities and cities adopted policy packages aimed at encouraging cycling. Rietveld and Daniel claim that the most influential policy interventions were: reducing journey times by bicycle compared to car, reducing the number of stops and increasing car parking costs and safety[401]. All of these can be achieved by a combination of policies, such as separate cycle lanes and traffic calming measures.

Pucher and Buehler find that the success of Danish, Dutch and German cycling programs was due to similar policy packages[402]. Although overall Germany and Denmark have lower cycling rates, some cities, such as Copenhagen and Münster match the Dutch average. Germany tripled its cycle path network between 1976 and 1995. Like the Netherlands, many German cities invested in improving cycling safety, by separating car traffic from cyclists and integrating the cycling network to make cycling a practical mode of transport[403]. In fact, Germany, like the Netherlands, has brought down the fatality rate for cyclists by 60% since 1975. The German rate (25 per billion km travelled) almost matches the Dutch rate (17 per billion km travelled) and is much improved over the US (100 per billion km travelled), which has only reduced its fatality rate by 20% between 1975 and 1995[403].

Urban planners in the Colombian capital have not lagged behind their Dutch counterparts (who are their advisors) in attempting to transform Bogotá's transport in a modern and sustainable way. They introduced the following measures: building 300 km of cycle lanes (the most extensive in Latin America), connecting the lanes and pedestrian pathways to the new bus rapid transit system, building a 17 km (world's longest) pedestrian corridor, planting trees along cycling and walking lanes and restricting driving along 120 km of roads on Sundays to create a 'Cycle Way' . The total investment of US$178 million on bicycle improvements has increased the share of daily trips by bicycle from 0.9% to 4% over the past decade[404]. The entire policy package in Bogotá reduced the capital's CO levels by 28% between 1998 and 2002[405] and reduced travel times by 11%[391]. Interestingly, this new transport model was driven by the need to reduce poverty and promote social justice as opposed to environmental concerns[404, 406].

In August 2004 the Borough of Hammersmith and Fulham in London piloted a bicycle rental scheme, called OYBike. Similar small-scale schemes had already existed in Stockholm, Lyon, Frankfurt, Cologne and Munich. Bicycles were located at unmanned locking stations around the borough. After completing a registration process residents could hire bicycles on a per-hour or per-day basis. The scheme was not a particular success with research conducted by Noland and Ishaque suggesting that most trips with OYBike were made for leisure and recreation on sunnier days and weekends[407]. Users tended to substitute short walking trips by cycling, so the environmental impact of the program is probably quite small. The reason for the apparent lack of success is probably the lack of appropriate cycling infrastructure in London and frustrating payment facilities. Boris Johnson, the Mayor of London, is continuing the investment programme commenced by his predecessor, Ken Livingstone. In 2009 £111m will be spent on improving cycle lanes and parking in extensive Cycle Hire and Cycle Highways schemes. These will provide continuous cycling corridors criss-crossing central London and safety training.

In 2007, Paris and Barcelona rolled out two bicycle sharing programs, which were much larger in scope and ambition. The programmes introduced bicycle locking stations around the entire city: *Velib* operating over 20,600 bicycles in Paris and *Bicing* operating 3,000 in Barcelona. Paris achieved an extraordinary penetration of 135 citizens per bicycle [408]. The schemes are run by private companies, which introduced annual subscriptions, smart-card payment and reservation technologies. Economies of scale allowed prices to be drastically reduced to €1 (£0.90, US$1.30) per day in Paris, which compares to £8 (€9, US$12) per day charged by OYBike in London. *Velib* has become the face of sustainable Parisian transport. Full evaluations of the schemes are yet to be completed, but there are signs that commuters in Paris and Barcelona are moving from cars into *Velib* and *Bicing* to commute and complementing their use of public transport[401].

Road construction and expansion (in developed countries) increases, rather than decreases, congestion and ultimately induces higher levels of travel demand. The extra capacity reduces the general cost of travelling and the less expensive the travel, the more it will be demanded. Regarding freight modal shift, road transport is much more polluting than rail per tonne kilometre of goods transported and therefore a shift towards the latter is desirable. In developing countries rural areas are often extremely poorly connected to transport infrastructure in contrast to developed countries. The benefits of road construction can strongly outweigh the total costs, including environmental ones. The main challenge is to develop a solution to the problems arising from the combination of urbanisation and motorisation for which the integration of transport and land use policy will be key.

Soft Policies

Car sharing, car clubs, teleworking and teleshopping can potentially reduce CO_2 emissions and congestion, though evidence for this reduction is rather mixed as it is unclear whether these measures lead to overall reductions in road transport.

Eco-driving campaigns aim to inform and educate drivers in order to induce them to drive in a fuel-efficient and environmentally friendly way. There seems to be some consensus in the literature that eco-driving could lead to reductions in CO_2 emissions of around 10%. Information and education policies are necessary, but not sufficient, to trigger behavioural change. Similarly, advertising and marketing may go a long way in changing peoples behaviour. Goodwin[409, 410] also finds that family life changes trigger changes in behaviour. People whose lives are being changed by some important development (birth of a child, retirement, etc.) tend to respond more to changes in the relative attractiveness of different transport modes. Advertising campaigns promoting a modal shift towards public transport, for instance, may thus be more successful if targeted at people in the process of important life transitions.

Knowledge Policies

Research and development is crucial for developing sustainable and low carbon transport. It is essential that governments provide incentives to undertake research and development, so that new low carbon technologies in the transport sector can be demonstrated and applied on a large scale.

Policy Recommendations

Before moving on to specific policy recommendations it should be noted that the combination and integration of policies can lead to positive side effects and synergies. Policy integration is crucial in order to rise to the challenges we face in moving towards a sustainable mobility model. Thus, economic policies may successfully be combined with a number of other policy measures in order to achieve a model of sustainable transport. On the basis of our review, which considered economic theory and policy implementation of instruments to ameliorate road transport externalities, as well as complementary policy measures, such as physical policies, soft policies and knowledge policies, we offer the following policy recommendations.

Economic Policies

Regulations and standards are not efficient from an economic perspective, but they are excellent instruments under the following circumstances:

- If the level of an activity, such as emitting a lethal substance, needs to be drastically reduced or altogether eliminated;
- When the constraints faced by the regulator, such as public and political acceptability of incentive based measures, are severe;
- As complements to incentive based policies, as long as the two instruments - the command-and-control and the incentive based one - are not designed to achieve the same reduction in activity, as in that case the reduction would be beyond optimal.

In general, regulations on fuel composition and vehicle emissions have worked well, and are both feasible and effective instruments.

Given that incentive based policies are efficient from an economic point of view, but in reality, do not always fulfil their cost minimisation potential, we do not recommend widespread adoption of this type of instrument blindly. However, taxes, charges and permits are excellent instruments in the following cases:

- When the revenue generated from taxes or permit auctions by the government can be used to reduce distortionary taxes in the economy, such as income taxes, and/or be returned to the road transport sector in the form of investment in public transport or research and development of cleaner technologies;
- As a driver to change economic agents' behaviour, such as driving fewer km or increasing the use of public transport.

When faced with the choice between permits and taxes, governments may find that taxes are more practical and administratively easier to implement in the case of road transport. However, given the general current trend throughout the world to consider permits as an alternative to taxes, the time may be optimal to move towards tradable permits to internalise the external costs of CO_2 emissions, if only because they seem to be more acceptable. It should also be highlighted that, if a global carbon market emerged, with the participation of most countries and economic sectors, the price signals would make decisions easier at all levels (production and consumption, as well as investment), as well as targeting them towards lower carbon choices. Taxes and charges, on the other hand, should be used when there is a strong link between the tax or charge and the externality in question. Congestion charging and pay as you drive (PAYD) insurance, for instance, are good examples.

Other Sustainable Transport Policies

Rural and urban areas in developing and developed countries face a host of barriers to creating a sustainable mobility form. These barriers may be physical, such as inadequate public transport and infrastructure or low population densities, which are entrenching car dependency, there are also behavioural barriers, for instance the social status associated with car-ownership. Combining physical and soft policies, in the form of new integrated transport infrastructure, appropriate land use and information provision to the public, may help to overcome these barriers. Economic incentives and government support can accelerate the development of new transport technologies. Physical and soft policies, which are very cost efficient in reducing carbon emissions, can thus serve as a useful complement to economic policies. We offer the following context-specific policy recommendations.

Urban and Rural Transport in Developed Countries

Integrated transport policy is key to moving towards a more sustainable design of urban mobility. Providing safe and pleasant interchange facilities together with integrated ticketing and real-time passenger information can help make public transport more attractive and reduce some of its perceived disadvantages relative to the car. In order to meet urban mobility needs, a sustainable urban mobility concept must be multi-modal, integrating different modes of public transport, private cars, walking and cycling. For example, building cycling lanes to railway stations encourages people to make multi-modal commutes. Park-and-ride facilities can be effective at reducing congestion and pollution in the city centre. Mixed-use neighbourhood designs can reduce travel demands by locating facilities near people's homes.

Car use in the city can further be discouraged by parking restrictions and establishing car clubs, together with congestion charges. Combining these policies with information and advertising campaigns that promote more sustainable transport choices can help to bring about behavioural change and discourage unnecessary car use. Changing driving behaviour by informing people about eco-driving can also reduce CO_2 emissions in a very cost-effective way. Commuting traffic is central to the urban mobility challenge and thus teleworking could play a role in alleviating congestion.

Meeting the transport needs of rural populations in developed countries in a sustainable way faces the challenge of low population densities, making public transport provision less feasible. Moving towards more demand-based forms of public transport could help to ensure accessibility and combat social exclusion. Promoting walking and cycling can help break the habit of taking the car for short-distance journeys in small towns. Facilities, similar to those we suggested for cities, as well as pedestrianisation of streets, could serve well for that purpose. Teleworking may also reduce the need for commuting to the city to some extent.

Urban and Rural Transport in Developing Countries

Cities in developing countries face the particular problem of rapid urbanisation and motorisation, which cause and exacerbates the interlinked problems of congestion, pollution, safety and social exclusion.

Combining land use and public transport policy can help to direct growth towards a more sustainable urban form that can be served effectively by public transport services. Simple measures, such as establishing bus priority lanes, integrated ticketing and integrating public transport facilities with other modes of transport can be cost effective and play an important role in developing a sustainable transport network.

If increasing incomes are to be disconnected from increasing motorisation, public transport services need to be both affordable and desirable. Walking and cycling can play a key role in urban transport, especially for short distances. Improving the infrastructure for walking and cycling and enforcing the rights of these so-called 'vulnerable' road users can help to make these modes safer and more attractive. Crucially, rising to the challenge of developing a sustainable transport network requires both political will and institutional capability.

Rural areas of developing countries tend to be extremely inaccessible by transport. This is mainly due to the lack of paved roads, which are necessary for more efficient transport.

Therefore, in order to promote sustainable forms of transport, other than walking, governments must invest extensively into new roads and related infrastructure. This may have significant social benefits, as people find access to emergency healthcare, education and labour opportunities. On top of that, new roads will drastically reduce transport costs and promote trade, particularly in agricultural products, between rural and urban areas.

However, this policy recommendation, which stands in stark contrast to others because of its context, will not be at all sufficient to encourage sustainable transport in the future. Informal car sharing, which probably exists on a vast scale in the rural areas of developing countries, has the potential of turning into permanent formal car clubs.

Policymakers must approach the challenge of creating a sustainable mobility model for the future. Economic policies offer strong financial incentives for individuals to shift into low carbon transport modes and for firms to invest in energy-efficient transport technologies. Physical policies provide feasible and sustainable transport alternatives. Soft policies inform people about the consequences of their transport choices, and induce them to take up more sustainable options. Combining all these policy instruments in an integrated framework will reduce negative externalities from road transport in general, and CO_2 emissions in particular.

2.5 Conclusions

In the short-term, a significant impact can be made in CO_2 emissions from automobiles by a simple down-scaling the physical vehicle size and engine capacity. In the medium-term, alternative powertrain technologies such as HEVs and PHEVs offer the best interim steps by combining the advantages of ICEVs and battery electric vehicle (BEV). In the long-term it is envisaged that all electric drive vehicles will be the man source of transportation. These can be split into two distinct groups, fuel cell vehicles (FCV) and BEV. Of the fuel cell power polymer electrolyte membrane fuel cells (PEMFCs) offer the best prospect for use in automotive applications, but technological breakthroughs are required prior to fuel cells becoming commercially viable. Significant improvements will be needed in cost, durability, reliability, power density, hydrogen production and storage methods. Compared to fuel cell systems, BEVs offer more promise although limited ranges restrict their application. If the entire passenger car fleet were replaced with BEVs CO_2 emissions from passenger cars could be reduced by more than 50%, based on the current energy mix in the UK. If the UK grid decarbonised to the extent of France's grid, the emissions reduction could be more than 90%. Half of the increased electricity demand could be met by the current grid infrastructure, without increasing overnight production levels above annual daytime averages.

Further potential to reduce GHG emission for road transportation is from the application of alternative fuels. Liquid fuels produced from unconventional oil, coal and natural gas sources offer energy security, but have a significantly higher carbon footprint. Another source of non-fossil fuel for road transportation is biofuel. Most first-generation biofuels, most notably corn ethanol, offer only limited GHG benefits and when produced on a large scale will inevitably compete with food production or natural habitat for land, resulting in significant carbon debt directly or indirectly. However some first-generation biofuels such as Brazilian sugarcane ethanol, can be meaningful local solutions. Second-generation biofuels, such as those synthesised from inedible cellulosic biomass, can be produced in a sustainable manner and are truly low carbon fuels but are not currently commercially viable. Alternative fuels are unlikely to supply a major portion of the transportation fuel demand in the short-term but could become more significant in the medium to long-term. Hydrogen has the potential to eventually make transport carbon-neutral, but formidable economic and technological challenges remain. Widespread use of hydrogen requires massive investments in infrastructure, and the cost of hydrogen-fuelled FCVs must be vastly reduced. All current hydrogen production and storage methods have at least one considerable drawback, including high cost, low efficiency, or low energy density. Breakthroughs will be needed if a hydrogen economy is to become a reality.

Rail transport has low operating emissions but has a high up-front carbon debt during the infrastructure construction process. Occupation rates and travel distances could significantly affect the emissions performance for rail transport as opposed to other transport modes.

As with technology, economic policies also have an important role to play in reducing GHG emissions from transport. An efficient mobility model for the future must take into account the true costs of transport and its regulatory framework needs to create incentives for people to make sustainable transport choices. In order to achieve this, economic instruments can be used to correct road transport externalities such as environmental and road damage, accidents, congestion and oil dependence. CAC and incentive based policies can be used to reduce the negative impact of transport externalities. Physical policies, soft policies, and knowledge policies can be used in combination in an integrated framework with taxes and permits in order to move towards a sustainable transport model.

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[356] The average exchange rate over the period March 2007 - March 2009 was CA$1 = £0.5 = EU 0.65 = USD 0.93 (IMF Exchange Rate Query Tool).

[357] In the US this scheme is usually referred to as 'Cash for Clunkers'.

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[362] European Automobile Manufacturers' Association, Vehicle Scraping Schemes in the European Union. **2009**.

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[364] The requirements for work lories are different and the CARS Act limits the amount of funds that can be used to provide credits for purchases or leases of work lories to 7.5% of the funds available for the program.

[365] The average exchange rate over the period April - July 2009 was £1 = Y 152 = EU 1.14 = USD 1.57 (IMF Exchange Rate Query Tool).

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[377] D. M. Newbery, *Road User and Congestion Charges*, in Cnossen, S. (Ed.), *Theory and Practice of Excise Taxation Smoking*, Drinking, Gambling, Polluting, and Driving, Oxford: Oxford University Press, **2005**, *7*, 193-229.

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The aviation sector consumes 13% of all transportation fuels or 2-3% of total fossil fuels and therefore produces 2-3% of anthropogenic CO_2[1]. However, as aircraft fly at or near the stratosphere, the effect of altitude on various non-CO_2 emissions may increase the total impact on anthropogenic climate change significantly. In an attempt to quantify the climate impact of aircraft emissions, the IPCC has estimated that aviation's total climate impact is some 2-4 times that of its CO_2 emissions alone, excluding the potential impact of cirrus cloud enhancement[2]. The enhanced impact of aviation's emissions on climate change is illustrated by radiative forcing as shown in figure 3.1. Radiative forcing is defined as 'the change in net irradiance at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values' or approximately as the net change in irradiance at the tropopause[3]. The IPCC has produced a number of scenarios estimating what the overall contribution of aviation on climate change by 2050 if action is not taken. They calculate aviation's contribution will climb to 5% of the total, though the worst scenario is 15%[2]. Also, if other sectors achieve significant cuts in their own greenhouse gas emissions, aviation's share as a proportion of the remaining emissions could also rise.

The resultant emissions from the combustion of fossil fuels can be broken down to carbon dioxide (CO_2), oxides of nitrogen (NO_X), water vapour and particulates. Whilst the effect of CO_2 on climate change has already been discussed in section 1.2, other emissions such as NO_X, SO_X, particulates and water vapour effect the atmosphere differently due to distinct region of emissions from aviation, namely the stratosphere and troposphere. Their individual effects on global warming are as follows:

Oxides of Nitrogen

NO_X - nitric oxide and nitrogen dioxide - are formed during the combustion cycle of jet turbines. Whilst the understanding of the effects and impacts of NO_X is continuing, it is generally agreed that release of NO_X at cruise altitude and below increases the level of ozone present in the atmosphere. Increasing altitude is understood to increase NO_X effectiveness at producing ozone[2]. NO_X also leads to the breakdown of methane, another greenhouse gas (GHG), which results in a cooling effect. However, as aviation is concentrated in the northern latitudes (figure 3.2) and methane is spread throughout the atmosphere, there is a net overall gain in temperature due to increased ozone levels. The amount of NO_X produced is related to the quantity of fuel burned and the conditions within the engine. Whilst aircraft characteristics and operational practices do effect the NO_X emissions relating to fuel burn, the principle factor is the quality of the combustion within the aircraft engine.

Water Vapour

After CO_2, H_2O is the largest (by weight) emission of jet engines, and whilst this amount is insignificant when compared to the natural cycle, it is the location of the emissions within the stratosphere and troposphere which is an issue. Water vapour

Figure 3.1: Radiative forcing from aviation emissions (gases and aerosols) in 1992 as estimated by the IPCC[2]

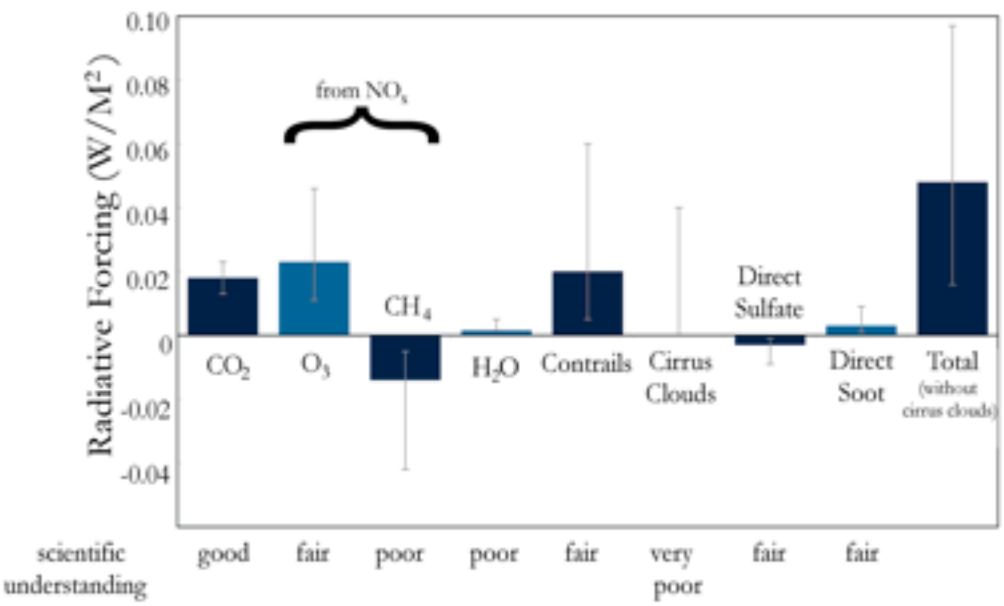
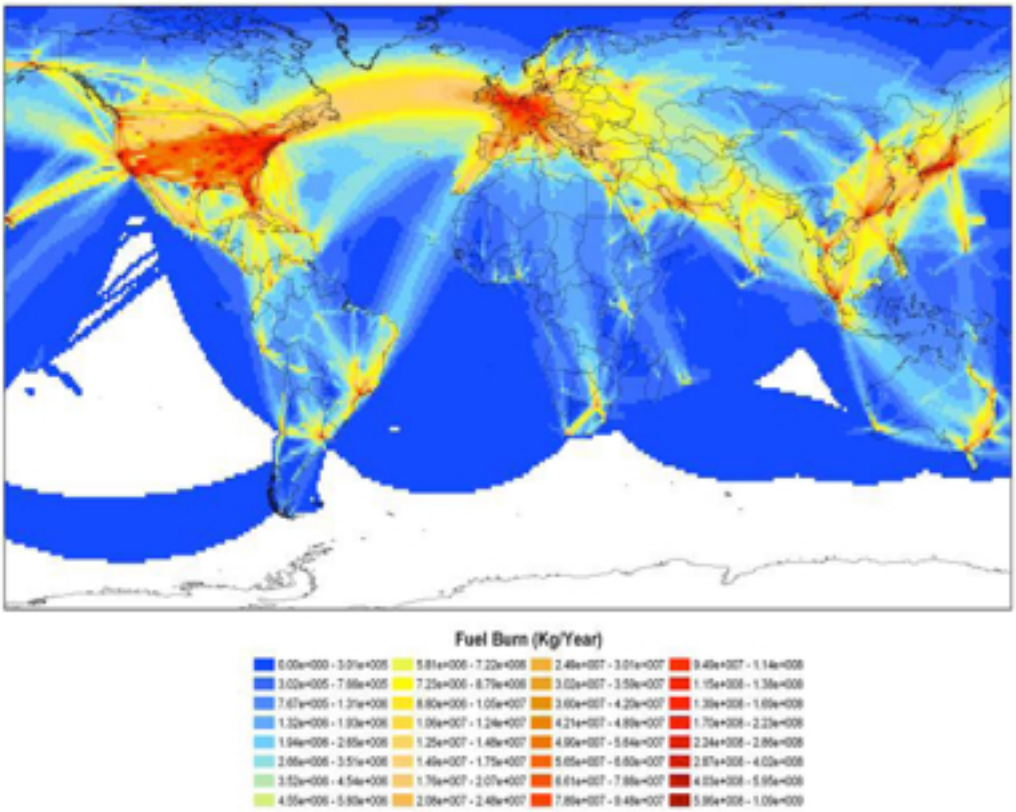


Figure 3.2: Geographical distribution of civil aviation activity, indicated by fuel burn in kg/year[4]



emissions and the associated cloud formations have large radiative effects on climate and directly influence tropospheric chemistry[5]. Water vapour resides in the troposphere for about 9 days and much longer in the stratosphere, ranging from months to years. As a result there is a possibility that aircraft emissions increase the ambient concentration. Any such increase could have two effects: i) a direct radiative effect with a consequent influence on climate, and ii) a chemical perturbation of stratospheric ozone both directly and through the potentially increased occurrence of polar stratospheric clouds at high latitudes[2].

Particulates

The atmospheric effects of the particulate emission from jet engines are similarly complex in nature. These particulates are sulphate and carbon (soot) based and are generated during the combustion of jet fuel. Aircraft engines actually emit a mixture of particles (including metal particles and chemi-ions) and gases (e.g., SO_2). These emissions evolve in the engine exhaust and the atmosphere to form a variety of particles, mainly composed of soot from incomplete combustion and sulphuric acid (H_2SO_4) from sulphur in the aviation fuel[2]. The potential effect of the emitted particles is to promote cloud and contrail formation in the stratosphere. The cloud formations can have both positive and detrimental effects on the climate. They can reflect the sunlight back into space and trap outgoing infra-red radiation from the earth's surface. With high level cloud formation the insulating effect on the infra-red radiation is much greater than the reflective effect resulting in a warming tendency[2]. Particles are also involved in the chemical balance of the atmosphere, as the sulphate layer in the stratosphere is critically important in determining the amount of NO_x hence effecting ozone[2].

Previous Studies

Due to aviation's position as the 'premier' technology and the heavy involvement with GHG emissions, a large body of work has, and is, being produced with respect to aviation's impact on the environment. A number of groups exist who have an interest in aviation and they have produced a number of reports and papers on various aspects of

- Due to aviations unique operating altitude, even water vapour can be detrimental to the environment.

aviation's impact on the environment and these groups range from intergovernmental organisations such as the United Nations (UN) and the European Union (EU) to lobby groups supporting their individual aims and beliefs. Some of these groups are discussed below, along with a selection of publications they have produced.

Intergovernmental Groups

International Civil Aviation Organisation (ICAO) is the UN agency concerned with international aviation. ICAO's current environmental activities are largely undertaken through the Committee on Aviation Environmental Protection (CAEP) in formulating new policies and adopting new standards on aircraft noise and aircraft engine emissions. About once a year, CAEP meets as a Steering Group to review and provide guidance on the progress of the activities of the working groups with each formal CAEP meeting producing a report with specific recommendations for the consideration of the ICAO Council[6-8]. Another UN agency, the Intergovernmental Panel of Climate Change (IPCC), is a scientific body which reviews and assesses the most recent scientific, technical and socio-economic information produced worldwide that is relevant to the understanding of climate change. The IPCC does not collect data nor conduct research but rather acts as a review body to ensure an objective and complete assessment of current information. The most significant report produced by the IPCC, with respect to aviation and the environment, was the 1999 special report 'Aviation and the global atmosphere' that assessed the effects of aircraft on climate and atmospheric ozone[2]. It was prepared in collaboration with the Scientific Assessment Panel to the Montreal Protocol on Substances that Deplete the Ozone Layer, in response to a request by the International Civil Aviation Organisation (ICAO). They found that there are a range of options to reduce the impact of aviation emissions, including changes in aircraft and engine technology, fuel, operational practices and regulatory and economic measures. These could be implemented either singly or in combination by the public and/or private sector. The EU has also launched a number of initiatives, committees and research packages to examine and combat climate change from aviation. It is pursuing three streams to reduce aviation's impact on the environment, namely: i) research and development for 'greener' technology, ii) modernised air traffic management systems and iii) market based measures. Research and development for greener technology is given high priority in the 7th Framework Programme for research funding, which consist of €51 billion over seven years. The flagship project is the 'Clean Sky' Joint Technology Initiative, which aims to reduce fuel consumption and CO_2 emissions by 50% per passenger kilometre, NO_X emissions by 80% and to reduce hydrocarbons and CO emissions by 50%. With the aim to reduce operational inefficiencies in European air traffic management is the Single European Sky (SES) legislation, which will reform the way air traffic management is organised in Europe. The SESAR initiative is the technological component of SES and one of the objectives is to reduce emissions by 10% per flight. The Commission has also decided to include aviation in the EU emissions trading scheme (ETS) from 2012 as a market based measure to reduce emissions.

National Groups

At a national level, most civil aviation authorities have environmental committees, as does the Federal Aviation Administration (FAA) and Civil Aviation Authority (CAA) in the United States and United Kingdom respectively. Both the FAA and CAA have developed significant programmes to investigate the possible reductions. For the FAA the Aviation Policy, Planning and Environment board leads the agency's strategic policy and planning efforts in the environment and energy arenas. It has a number of programs, initiatives and partnerships which research and report on various areas of aviation. These include aircraft technology (PARTNER), alternative fuels (CAAFI), operations (NextGen and SWIM) and environmental policy and market measures (EMS)[9]. The Environmental Research and Consultancy Department (ERCD) of the CAA carries out a range of activities in the field of aviation and the environment. Not only do national civil aviation authorities produce reports and policy on aviation and the environment, but numerous governmental departments produce white papers laying out government policy[10-14]. Governments may also commission independent reviews of various topics such as the Stern Review which looked at the economics of climate change[15]. The National Aeronautics and Space Administration (NASA) is the main US body for research into aviation. Its Aeronautics Research Mission Directorate (ARMD) works on cutting-edge, fundamental research in traditional aeronautical disciplines and emerging fields to help transform the air transportation system. ARMD is based around four program areas; the Fundamental Aeronautics Program, Airspace Systems Program, Aviation Safety Program and the Aeronautics Test Program. They lead much of the cutting edge research in aviation within the US and liaise between the major bodies such as the FAA and United States Air Force.

Industry Groups

Unsurprisingly, the aviation industry itself is also involved in research and the production of various reports. One such body is the Air Transport Action Group (ATAG), whose 60+ members which include major manufactures such as Airbus and Rolls-Royce, airports and some international bodies, such as International Air Transport Association (IATA). They have produced a number of reports covering the basics of aviation's impact on the environment, biofuels and the economics associated with aviation [16-18]. Of particular interest are the economic benefits of aviation, as they identify US$408 billion in direct benefits and US$3,557 billion in indirect and various catalytic impacts[18]. International Air Transport Association (IATA) is an international trade body that represents 93% of scheduled flights, some 230 airlines in total. IATA set up an industry committee ENCOM to advise the relevant IATA bodies on environmental matters, and act as the focal point in IATA on environmental issues. They publish a number of reports on a wide range of issues relating to aviation and the environment[19-21]. There are also a number of regional associations, such as Air Transport Association of America, Sustainable Aviation and global airline alliances, such as Oneworld and Star Alliance who produce reports and guidelines for their members and the public.

Academic Institutes

There are a large number of academic institutes that have aviation and the environment themed research centres or members of partnership groups. Significant centres and research projects include Omega, a publicly funded partnership led by Manchester Metropolitan University with University of Cambridge, Cranfield University and a number of other partners. Omega offers impartial, innovative and topical insights into the environmental effects of the air transport industry and sustainability solutions [22]. Tyndall Climate Research Centre is an organisation based in the United Kingdom that brings together scientists, economists, engineers and social scientists to 'research, assess and communicate from a distinct trans-disciplinary perspective, the options to mitigate, and the necessities to adapt to, climate change, and to integrate these into the global, UK and local contexts of sustainable development'. They have published a range of articles on aviation and the environment looking at policy and technology solutions to the issues at hand [23-25]. The Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER) is a leading aviation cooperative research organisation, and an FAA/NASA/Transport Canada-sponsored Centre of Excellence. As with the previously mentioned groups, PARTNER fosters breakthrough technological, operational, policy, and workforce advances for the betterment of mobility and the environment. The organisation's operational headquarters is at the Massachusetts Institute of Technology (MIT); Professor Ian Waitz, head of the MIT Aeronautics and Astronautics Department, is the director. The group has currently 32 projects running covering every aspect of aviation from 'en-route traffic optimisation to reduce environmental impact' to 'assessment of the impact of reduced vertical separation'[26-28]. Stockholm Environment Institute (SEI) is an independent international research institute engaged in environment and development issues at local, national, regional and global policy levels since 1989. Its goal is to bring about change for sustainable development by bridging science and policy to provide integrated analysis that supports decision makers. The SEI has produced a significant number of papers in the areas of Climate and Energy, Future Sustainability, Policy & Institutions, Risk, Livelihoods and Vulnerability and others, with a number of aviation specific articles produced[29, 30]. These are just a small selection of the institutes and publications currently on offer from the academic sector. Individual universities have their own programmes running such as the Silent Aircraft Initiative at the university of Cambridge[31]. There have also been a number of books published on the subject of aviation and the environment, looking at various trends, issues and possible solutions over a wide range of scenarios[32, 33].

There also exist a number of lobby groups that produce reports that support their claims, as either for or against aviation. As they are far from impartial their work has therefore not been included within this report.

3.1 Aircraft Technology

What can be done in order to reduce the emissions from aircraft? If we consider the formula below for aircraft fuel efficiency[34]:

$$FE = \eta_0 \left(\frac{Lift}{Drag} \right) \left(\frac{W_{PL}}{W_{PL} + W_{fuel} + W_0} \right)$$

Where FE is the fuel efficiency of the aircraft, η_0 is the engine fuel consumption, W_{PL} is the payload weight, W_{fuel} is the weight of fuel and W_0 is the structural weight. For an aircraft carrying a given load over a given range there are three methods to increase the fuel efficiency of the aircraft; i) by increasing the efficiency of the engines, ii) increasing the aerodynamic efficiency of the aircraft (lift/drag) and iii) reducing the structural weight (W_O). However, it is not as straight forward as that. Take for instance reducing the engine fuel consumption. As an approximation, the efficiency of a jet turbine can be simplified to the product of its thermodynamic efficiency and its propulsive efficiency. The thermodynamic efficiency of the engine is the percentage of chemical energy of the fuel that is converted into kinetic energy of the airflow moving through the engine. Propulsive efficiency is the percentage of this kinetic energy that is used in providing usable thrust for the aircraft and is illustrated by the mass flow of an engine.

Were we to increase the operating temperature within the engine, one of two things would occur. Firstly, with all other things kept constant, either the materials used would have to withstand higher temperatures or the level of cooling flows would have to increase, which reduces the propulsive efficiency. Even if we could use higher temperature this has an effect on NO_x emissions, as hotter engines produce more NO_x. The same goes for propulsive efficiency. Increasing fan sizes to increase the mass flow of air results in a more efficient engine, but, when fitted onto aircraft they increases the drag, lowering the aerodynamic efficiency as well as weighing more. Aerodynamic developments can weigh more, due to extra structure require, thus negating any benefit. The 'balancing act' doesn't stop there, the designed use of aircraft also impacts on their efficiency. Long haul aircraft have similar carbon emissions per passenger kilometre to short haul (figure 3.3). While you would assume that with greater cruise distances and carrying capacity long haul aircraft would be much more efficient than short haul aircraft, due to the weight of fuel carried to travel the extra distance the benefit is not so obvious.

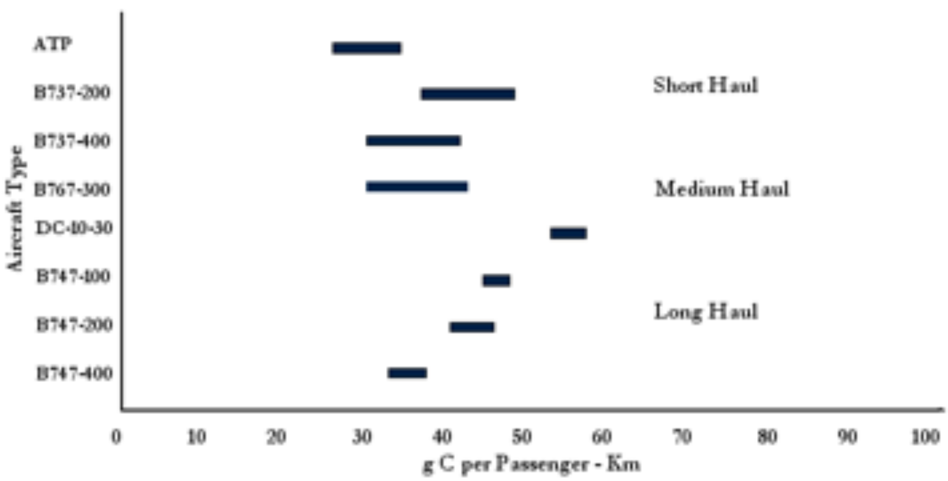
For the purpose of this report, we will consider the three identified technology areas individually and assume that these benefits can be implemented without significant impact on other areas. This is an important assumption, as the level of complication in trying to estimate the knock-on effects of implementing certain technologies is beyond the scope of this report and requires detailed study.

Going Forward

The most obvious target for the reduction of emissions in aviation are the engines, or propulsion systems. These are the source of the various GHG emissions, and development here will therefore have an obvious effect on aviation's environmental impact. Most modern commercial aircraft operate using high by-pass turbo-fan engines. These engines are the current state of the art in a propulsion system first developed by Sir Frank Whittle in 1941 [35]. The jet engine has become the preferred method of propulsion in aviation, due to their reliability and performance. The principle of operation of jet engines is relatively simple. The air is sucked through the front of the turbine by the intake stage (figure 3.4). This is then compressed by the compressor stage up to 40 times the ambient air pressure[36]. The high pressure air is then mixed with fuel in the combustion chamber and ignited. The heated air expands, sending a jet of gas exiting the engine through the turbine and exhaust, producing thrust.

As stated earlier a simplification of jet engine efficiency is the product of its thermodynamic efficiency and it propulsive efficiency. In order to improve the thermodynamic efficiency of an engine, either the temperatures or the pressure ratio (the total pressure ratio across the engine) has to be increased. These two options have a number of knock-on effects within the engine. Firstly, by raising the temperature within the engine, either the amount of cooling which occurs (to maintain the integrity of the parts) or the temperature the materials can

Figure 3.3: Carbon emissions for different aircraft types, based on British Airways fleet of 1997-98[2]



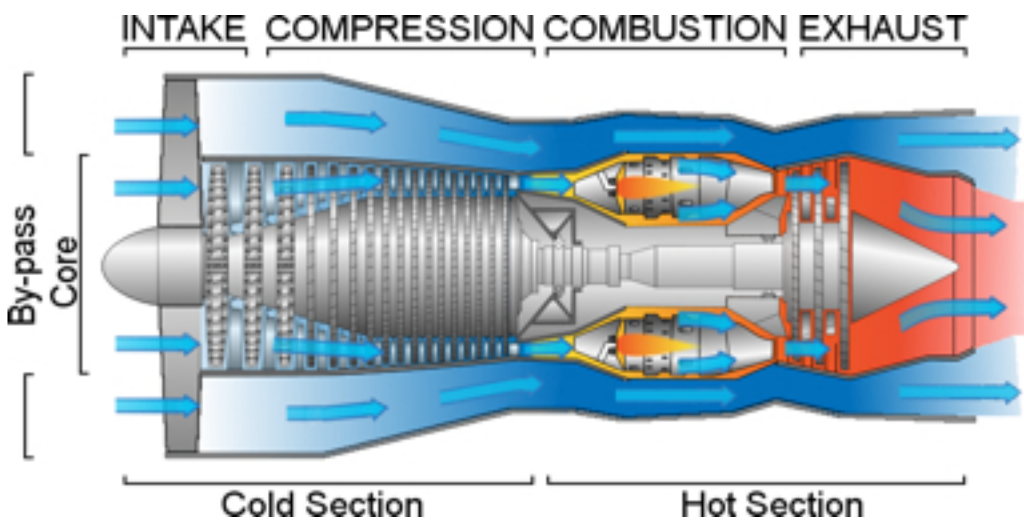
withstand must increase. To increase the level of cooling within the engine requires a reduction in the mass flow, and therefore the propulsive efficiency of the engine. This is because the air used for cooling (also known as secondary flows) is removed from the main gas flow prior to the combustor stage. Secondary flows can result in a 4-6% decrease in power and an increase in specific fuel consumption (SFC - mass of fuel burnt per second per unit of thrust) by 3-5%[37]. Therefore the main area of research in improving the thermodynamic efficiency of engines is within the field of material science. Novel materials such super alloys and ceramics are undergoing significant research in the hope of increasing the working temperatures within turbine engines[38-40]. Of all these technologies ceramic matrix composites have the greatest potential to improve the thermodynamic efficiency of engines by allowing an approximate temperature increase of 300°C (from 1200°C to 1500°C) which would equate to a 6-8% reduction in SFC[41].

There is a much greater scope for improvement in the development of propulsive efficiency *i.e.* increasing the mass flow of the engine. These can stem from minor tweaks within the internal gas flows to wholesale changes to the overall architecture of the engine. The major manufacturers have two main development strands in operation, the first being an optimisation of the current technology (high by-pass fans), and the other being developing new architectures. An example of the optimisation route is General Electric's (GE) GEnx, a high by-pass ratio turbo fan which features a number of advanced technologies, such as composite fan blades and thermally activated tip clearance technology. GE claims that it will offer a 15% reduction in SFC[42, 43]. Another evolution of current designs is in development by CFM International (an alliance between GE and SEMCA). Their Leap-X advanced engine features a new composite fan, an advanced compressor design, next-generation TAPS (twin-annular, pre-swirl) combustor technology and next-generation turbine technologies based on developments from Project TECH56[44]. The Leap-X is predicted to enter service by 2016 and offer a 16% reduction in fuel use[45].

A more significant change in the turbine system is being investigated by Pratt and Whitney with the PW1000G. As development from the earlier PW8000, which itself was an extension of the PW6000, the PW1000G represents more than 10 years of research and over US$350 million in development costs by Pratt & Whitney. The engine's fan, which produces most of the thrust, is driven through a reduction gearbox, rather than being directly connected to the rest of the engine. As fans operate best at slower speeds, and compressors and turbines run more efficiently at higher speeds, the gear box allows the fan, compressors, and turbines all to achieve their most efficient operating speeds, leading to a quieter engine with better fuel burn and fewer parts to maintain. The PW1000G is currently undergoing testing and is expected to offer double digit savings to SFC when launched in 2013[46, 47].

Of the companies developing new architecture for engines, both Rolls-Royce and CFM International are investigating unducted fan or open rotor engines. These were first demonstrated by GE with the GE36 UDF in the late 1980's, and are the logical step in increasing the by-pass ratio of aero engines [48]. By removing the ducting that surrounds the engine, the mass flow of air that can be moved by the engine increases significantly, thus increasing the propulsive efficiency. They suffer from a number of issues, such as increased noise and vibration, but

Figure 3.4: Simplified schematic of a low by-pass fan jet engine indicating the various stages, sections and gas flow paths



> - 4.5% of global economic output can be attributed to civil aviation. Can we do without $3.5 trillion ,the approximate GDP of India?

they are undergoing significant development in order to overcome these issues. CFM also plans to use its Leap-X as 'foundational' technology for an open rotor design which will offer a 26% improvement in SFC over today's engines when launched in 2016[49]. Rolls-Royce is developing open rotor architecture as part of an EU wide framework development program. They are developing both geared and direct drive systems with an aim of a 7% improvement in ACARE (*Advisory Council for Aeronautics Research in Europe*) targets by 2020[50, 51].

It is believed that development of the gas turbine engines will continue for another 25-30 years, culminating in what NASA identifies as the intelligent engine[52]. Once this stage is reached, there are a number of possibilities in changes to aircraft propulsion systems. NASA predicts that once gas turbines have reached their pinnacle of design, with ultra high by-pass unducted fan, intelligent engines (integral adaptive controls and smart systems that change the engine setup to its optimum automatically), that the next set will be an engine configuration revolution. This will be characterised by innovative vectored propulsion systems which will lead to smart engine operations and distributed engine systems. These distributed engine and exhaust concepts will be integral to the aircraft structure, not only improving engine efficiency but also reducing the levels of parasitic drag (drag produced by non-lift creating components), resulting in a 8-10% increase in propulsive efficiency of the aircraft[53, 54].

Losing Weight

Whilst wings produce lift and engines produce thrust, the structure of an aircraft provides the carrying capacity or the 'usefulness'. A measure of the efficiency of aircraft structures can be found by dividing the operating empty weight (OEW – the weight of an aircraft ready to fly but without payload and fuel) by its maximum take-off weight (MTOW). The historical development of this ratio is displayed in figure 3.5 and shows a limited improvement in structural efficiency. Prior to 2000, the lack of development in this area could be explained by the use of aluminium as the main structural material up to, and including, the Boeing 777 (where it composes of 70% of the structure by weight). However the Boeing 787 (and to a lesser extent the Airbus A380) consists of a significant percentage of composite by weight, yet still exhibits an OEW/MTOW ratio of approximately 0.5. This suggests that advances in structural design are being traded for improvements in other areas, such as aerodynamic design and passenger comfort[55]. This has however not stopped or slowed the development of new materials offering increases in specific strength, and therefore a like for like reduction in the mass of parts in aircraft structures. Such developments in metallics include: 'new' materials, such as aluminium-lithium alloys and next generation super alloys; development of current materials such as improvements to the mechanical properties of aluminium-copper alloys, which have been used since the Wright brothers; as well as new structures such as lattice and laminate structures [56-59]. One area that has seen a huge level of research and investment is composite materials. Developments include materials nearly in service such as ceramic matrix composites (which offer higher operating temperatures at a lower weight) to materials still at a laboratory stage, such as nanocomposites[60, 61].

Ceasing Resistance

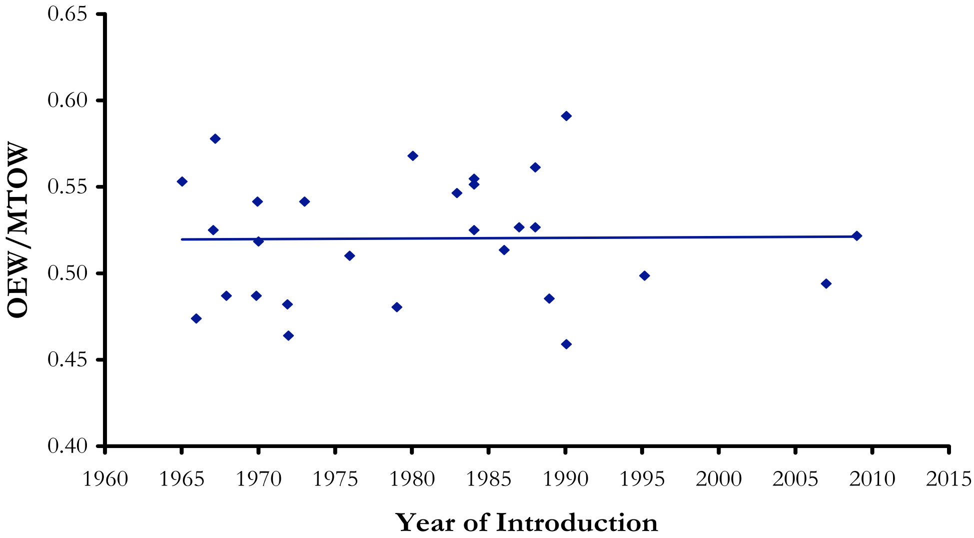
The two remaining forces active on an aircraft in straight and level flight are lift and drag. These two forces are related, as it is not possible to produce lift without inducing drag. As a fluid or gas flows past the surface of a body, it exerts a force on it. Lift is the component of this force that is perpendicular to the flow direction and drag is the force parallel to the flow direction. The total amount of drag on aircraft is a combination of lift induced drag (approximately 21%), skin friction drag (approximately 50%), interference drag (9%), wave drag (9%), roughness (5%) and miscellaneous other sources (3%)[62].

Lift induced drag is caused by air-flows round the length of the wing creating vortices along the wing trailing edge. The lift induced drag can be limited by carefully tapered wings, winglets and wing fences. Developments at NASA, such as distributed propulsion and active flow control, could help reduce or even prevent these occurring[53, 62].

Skin friction drag is caused by the interaction between the aircraft's skin and gas flowing around it and is directly related to the wetted surface (the area of the body that is in contact with the fluid). Drag due to skin friction rises with the square of velocity and is caused by turbulence in the boundary layer (the layer of fluid immediately next to the bonding surface). In a technique similar to the active control of flows within the jet turbine intakes (as discussed earlier), it is also possible to manipulate the boundary layer to prevent turbulence. This is done by either energising or de-energising the boundary layer over the wing in order to induce a laminar flow. Either by gas injection or removal, or inserting either mechanical or plasma actuators into the flow achieve this. Computational fluid dynamics modelling suggests that skin friction can be reduced by between 20-70%[63, 64].

Interference drag is caused by vortices being induced in the flow of air. Whenever two surfaces

Figure 3.5: Historical trends in structural efficiency



meet at a sharp angle on an object, the airflow has a tendency to form a vortex which causes drag on the object, and the resulting low pressure area behind the object also contributes. Therefore, the primary method of reducing interference drag is eliminating sharp angles by adding fairings which smooth out any sharp angles on the aircraft. Wave drag is caused by the formation of shock waves due to flows reaching supersonic speeds, which can occur even if the aircraft is travelling subsonically. Drag due to roughness is removed by a number of methods, such as laser and friction stir welding, which produces large panels with a smooth surface, devoid of rivet heads. These panels also have the advantage of being lighter than traditional riveted sections[65]. Another technique is the application of silicon paint which offers a 2-3% reduction in drag but has maintenance issues[66].

The levels of drag on modern aircraft are due to the tube and wing design which have surfaces that produce drag but do not contribute to lift. A number of proposals have been presented to overcome this, but the most radical and most promising is the blended wing body (BWB), or flying wing approach. The flying wing approach removes anything not necessary for flying, such as the fuselage and tail, resulting in an aircraft design with the highest possible aerodynamic efficiency. The removal of tail surfaces and engine pylons can result in a 33% reduction in surface area, producing a corresponding reduction in skin friction drag and resulting in a 32% reduction in fuel burn in an aircraft carrying over 500 passengers[67, 68]. By combining this design with advanced distributed propulsion, the exhaust of which would 'fill' the wake produced at the wings trailing edge, reducing the induced drag. Studies show that this results in a reduction of the take-off gross weight by 5.4% and a 7.8% reduction in fuel weight[68, 69]. The BWB also offers a significant reduction in noise as the engines are located on the upper surface, so the airframe deflects the noise. Also the BWB aircraft has no slotted trailing edge flaps present which are also a major source of noise generation[70]. However the BWB design has a number of issues to be overcome, not least of all is passenger acceptance of windowless designs and the problems of pressurising its non-cylindrical shape.

3.2 Aviation Fuel

It is not just the technology of aircraft that is envisaged to, and requires, changing. The fuel or energy source converted within the propulsion system must also alter. The current reliance on crude oil based fuels must end for two reasons; i) the ever-increasing global energy consumption will continue to drain global reserves of crude oil and ii) the increasing demand for reduction in GHG emissions. Due to the extreme conditions during operation, the energy density and demanding prerequisites with regards to the combustibility the spectrum of potential aviation energy sources is narrower than in road transportation (see section 2.2).

Of these alternatives, a drop-in low carbon fuel, which include fuels derived from biological feedstocks manufactured using the Fischer Tropsch process or via hydrogenation of oils, are preferred [71]. A number of flight tests have recently occurred and are detailed in table 3.1. The first test was undertaken in February 2008 by Virgin Atlantic in a Boeing 747 powered by GE engines. Here an 80:20 mix of Jet A1 and a palm oil/babassu nut fuel was used[72]. The flight took some criticism as palm oil is suspected of being an unsustainable product that competes with food production and is a source of deforestation[73]. However, the flight gave some

important data on burning biofuels in modern commercial engines allowing for the later tests to occur. The next flight test used a fuel derived from jatropha which is neither a food source nor competes with food for land use and is seen as a possible significant source of liquid fuel[74]. The following month an algae based biofuel was tested in one engine of a Continental 737-800 with a CFM-56 engine. It flew a blend of algae and jatropha oil in a 50:50 mix with Jet A1. The biofuelled engine burned less fuel than the conventionally fuelled engine showing that mixing biofuels has no detrimental effects on performance[75]. The final flight test used a fuel derived mainly from Camelina (Camelina 84%, jatropha 16% and algae less than 1%) in a Japan Airlines 747-300[76]. Camelina is of interest as it can be grown in rotation with wheat, in temperate climates. With the aim of proceeding with certification of these fuels, the FAA has instigated the Commercial Aviation Alternative Fuels Initiative (CAAFI). They take a holistic approach in developing standards for generic feedstock, allowing industry to decide which feed is relevant in their specific regions. Their goal is certification for generic biofuel/jet A1 blend by 2010, and 100% biofuel by 2013.

Synthetic fuels, as for instance a 100% coal to liquid produced by SASOL of South Africa, are already used in aviation, although their current benefit to reducing emissions is minimal, as the process is heavily carbon intensive. Alternatively with carbon capture and storage such fuels have an overall lower CO_2 cost that Jet A1[77].

Some research suggests that the best energy source for aviation will require a move away from crude and crude like fuels, NASA is investigating hydrogen sources, both as a fuel for 'traditional' turbines and for fuel cell based propulsion[78, 79]. As well as the issues of hydrogen production, storage and the vast level of resources already attributed to hydrocarbon based energy in the aviation sector, hydrogen as an aviation energy source has a number of issues that must be addressed. The first of these is the low density of hydrogen requiring about four times the volume of storage as Jet-A1. This leads to lower aerodynamic efficiency and a lower level of wing loading at take-off reducing the effectiveness of an aircraft. The other main issue is the need for cryogenic storage of the hydrogen fuel. Whilst the low temperature of hydrogen is beneficial in cooling various critical components of aero-engines and storage in well insulated, light weight, sealed cryogenic fuel containment is not insurmountable, it is the flight specific issues of cyclic loading during repeat take-off and landing and retaining its thermodynamic effectiveness through the 15+ year life cycle of the aircraft that is the main challenge[80]. The use of hydrogen with fuel cells has all these issues and more, with an increase in energy density of fuel cells of a factor of 20 of that of the current state of the art required for large commercial passenger aircraft, though single seat private aircraft and APU systems are currently feasible[81].

Nuclear power as an aviation fuel source has long been proposed. The USAF initiated the Nuclear Energy for the Propulsion of Aircraft (NEPA) to develop long range and high performance aircraft in 1946, which was replaced by the Aircraft Nuclear Power (ANP) program in 1951. ANP consider two designs, direct and indirect turbojets. Both of which used the heat generated by the nuclear reactor to replace the heat generated in the combustion chamber of the jet engine. The direct system fed the compressed air through the nuclear core whilst the

Table 3.1 Comparison of various biological feedstocks' with coal and crude

Feed Stock	Certification	Test date	Current Global Production [84, 85]	Forecast Global production in 5 years	Region	Competes with Food?	g CO_2 per MJ [77, 86-88]	CO_2 sequestration g per MJ [89]	Approx. Barrel per ha [85, 90-92]
Palm Oil		Feb '08	57.7 million tonnes		Tropical	Yes	139	70	40
Babassu Nut	2010 for generic biofuel/Jet A1 Blend 2013 for 100% biofuel	Feb '08	7 Million tonnes	15 million tonnes	Tropical	Yes			0.8-2.4
Jatropha		Dec '08		$80 per barrel		No	22	70	13
Algae		Jan '09			Any	No	35	70	75-575
Camelina		Jan '09		100-200 million gallons	Temperate	No	13		4
Soya bean					Temperate	Yes	289	70	4
Coal	50% blend Jet A1 Aug '09		8.6bn litres a year		N/A	N/A	91* 195	0	
Crude	Yes		7 million barrels a day	8 million Barrels a day	N/A	N/A	85	0	

* With CCS

Myth -
"We'll all be flying around in nuclear powered aircraft."

indirect system used coolant fluid to transfer the heat. Neither of these systems powered an aircraft in flight, although some developments in the necessary technology were achieved. There are three main issues with nuclear power: i) weight, ii) safety and iii) public perception. Early designs required a five tonne reactor, which is not dissimilar to current engine weights, but in addition nearly 50 tonnes of shielding. Also, the worry of accidents releasing nuclear material, radioactive emissions and the proliferation of nuclear material are significant concerns. Moreover, as the issue of ground-based nuclear power for electricity generation face considerable opposition in the public sphere, one can only postulate on the level of hostility to nuclear powered aircraft. Whilst some experts believe that nuclear power should be seriously considered for aviation, this report agrees with other findings that nuclear power in aviation is unlikely in the foreseeable future[82, 83].

3.3 Aviation Policy

Air Traffic Management is defined in the ICAO Global Air Traffic Management Operational Concept as 'The dynamic, integrated management of air traffic and airspace – safely, economically, and efficiently – through the provision of facilities and seamless services in collaboration with all parties.' However the current system is full of inefficiencies. The IPCC report 'Aviation and the Global Atmosphere' indicates there is 12% inefficiency in air traffic management globally. This results in US $13.5 billion in wasted costs and 73 million tonnes of CO_2[2]. As early as 1983, the ICAO Council had identified that the existing air navigation system and its subsystems suffered from technical, operational, procedural, economic and implementation shortcomings. In addition to these technical issues, it was identified that the conventional airspace organisation is based largely on national rather than international requirements, reducing the efficiency of routing and metrological information. The report also identified limited airport capacity as an issue, resulting in congestion and delays, with every minute of flying time resulting in an average 160kg of CO_2 [93]. Not only was it regional routing where issues were identified, but also existing worldwide fixed route structure often imposes mileage penalties, compared to the most economic routes (generally great-circle routes). Studies on penalties to air traffic associated with the European ATS Route Network alone suggest that air traffic management related problems add an average of about 9-10% to the flight track distance of all European flights *en route* and in terminal manoeuvring areas[94]. Lack of international coordination in the development of ground ATC systems exacerbates these problems. Examples include inconsistent separation standards in radar and non-radar airspace and operation at less than optimum flight levels in oceanic airspace as a result of communication deficiencies. The IPCC also identified the limited presentation, accuracy and timeliness of meteorological information as an issue which impacts long-range flight planning. The final area identified is the implementation of restrictions on the use of airspace for a variety of reasons, including technological limitations, political considerations, security, and environmental concerns. Significant regions of airspace are permanently reserved or restricted, thereby forcing civil air transport to circumnavigate these areas. This varies significantly from region to region, with the EU applying the flexible use of airspace (FUA) concept where airspace is assigned on user requirement[94].

In order to meet these issues, large scale investment is being undertaken around the world in advanced air traffic control systems. The EU (Single European Sky), the US (NextGen) and Asia (ASPIRE) are all planning advanced ATC systems that will allow the use of FUA, capable of tripling capacity by 2025 and the ability to maximise routings for fuel efficiency. User Preferred Routes (UPR) allow aircraft to make use of prevailing winds or to route away from head winds. Airservice Australia estimates 48 tonnes of CO_2 per day are saved by limited flexi-track use in their airspace. Studies on replacing of the fixed routes on the Central East Pacific routes with user preferred routes showed an average reduction of 10 minutes flight time[95]. Continuous Decent Approaches (CDA) where the aircraft has a smooth glide-path when coming into land, as opposed to the traditional stepped approach, would also be possible with improved ATC. This has the benefit of reducing noise (as the aircraft stays higher for longer) and fuel burn (the stepped approach requires thrust during the level portions of the approach). One study at Louisville International Airport showed up to a 6.5 dB noise reduction and 250kg of fuel saving was possible[96]. The developments in technological systems that would be required for advanced ATC in avionic systems, satellite based positioning and high bandwidth communication systems would allow not only greater accuracy in the positioning of aircraft but also a greater flow of information to aid in flight planning.

However, these large scale international systems are not the only operational changes which can reduce aviation's impact on the environment. Airlines and manufacturers are looking closely at all aspects of aircraft in order to reduce fuel burn. From the application of silicon paints (or no paint in the case of American Airlines) to reduce drag, the use of advanced engine washing (P&W claims to have achieved a 1.2% reduction in fuel burn from their atomised closed loop engine washing system) to using advanced materials to reduce galley trolley weight (Emirates saves nearly 500kg on the A380).

- Whilst serious studies have and are being undertaken, nuclear power is unlikley to be ever anything more that a ground based power generation system.

Another method of reducing aviation's emissions is a market based system, where the emissions are given an economic value thereby providing incentive to reduce them. A central authority (usually a government or international body) sets a limit (or cap) on the amount of a pollutant that can be emitted, companies or other groups are issued emissions permits and are required to hold an equivalent number of allowances (or credits) which represent the right to emit a specific amount. The total amount of allowances and credits cannot exceed the cap, limiting total emissions to that level. Companies that need to increase their emissions allowance must buy credits from those who pollute less. The transfer of allowances is referred to as a trade, hence a 'cap-and-trade' scheme (see section 2.4). In effect, the buyer is paying a charge for polluting, while the seller is being rewarded for having reduced emissions by more than was needed. Thus, in theory, those who can easily reduce emissions most cheaply will do so, achieving the pollution reduction at the lowest possible cost to society[97]. The European Union Emission Trading System (EU-ETS) is the largest multi-national, emissions trading scheme in the world[98], and is a major pillar of EU climate policy. In the first phase of EU-ETS (2005-2007), included some 12,000 installations, representing approximately 40% of EU CO_2 emissions, covering energy activities (combustion installations with a rated thermal input exceeding 20 MW, mineral oil refineries, coke ovens), production and processing of ferrous metals, mineral industry (cement clinker, glass and ceramic bricks) and pulp, paper and board activities. Aviation will be included in the second phase (2008-2012) from 2012 onwards. Whilst some airlines support inclusion in to the trading scheme (British Airways, Easyjet, Air France-KLM) some oppose it (IATA, Ryanair). The main issue raised by those who oppose aviation's inclusion into EU-ETS include that the unilateral nature of it is unworkable and breaks the Chicago Convention governing international air travel and that the EU has no right to claim a carbon charge over areas for which it has no jurisdiction. The Chicago Convention mentions customs duties (article 24), non-discriminatory regulations and charges (articles 11 and 15) and sovereignty (article 1), none of which apply to the EU-ETS. It is not a customs excise or navigation charge, it is none discriminatory and does not count for movements which start and terminate outside of the EU so it is not extra-territorial. IATA also claims that it is unnecessary as fuel costs are a driving concern for airlines already, they do not need a secondary charge. The final line is that there is more effective measures available, for example, single sky which offers a 12% improvement in efficiency. All these arguments are moot however, as Directive 2008/101/EC was published in November 2008 which includes aviation in the scheme.

3.4 Conclusions

So where does that leave us? In this section two main areas of development in aviation technology have been identified, those achievable in the short-term, which are an evolution of current technology and those in the long-term, which require fundamental changes in the architecture of aircraft and their operation. If we look at the short-term options (approximately 5 years time) and what impacts these will have on commercial aviation? If first we consider propulsion, reduction of secondary flows and increasing engine temperatures could lead to a 5% and 8% reduction in SFC respectively, this makes the claims of the main manufacturers in producing engines with 15% reduction in SFC realistic[37, 41, 43, 45]. If we assume that the claims made by the producers of various biofuels (using biomass feedstocks) and with ASTM producing a certification process by 2013 as claimed by CAAFI, then our short-term option aircraft could be feasibly flying on a 95-5 mix of Jet-A1 and biofuel. Assuming biofuel would come from a mix of second generation sources (from camelina, jatropha and algae) a mean value of 23g of CO_2 per MJ, or a 70% reduction over crude oil jet fuel leads to a 3.5% reduction in CO_2 emissions from fuel alone[77]. If we then look at aerodynamic efficiency, historical improvements have seen a 0.4% increase per year which would continue without significant changes to aircraft design, equating to a 2% increase in efficiency[55]. Any structural improvements leading to weight reduction are currently being used for improvements in other areas, such as in flight entertainment. If we assume that the current demand for greater fuel efficiency in aircraft out weighs the consumer demand for entertainment, then a 5% improvement in this area would not be un-achievable by the use of composite materials and novel structures. Whilst the report has not covered the possible improvements due to operational efficiencies, such as continuous decent arrivals, preferential flight paths, tailored levels of portable water and digitisation of paper goods on board aircraft, will go some way towards the 12% improvement the IPCC suggest is possible, offering a 2.5% decrease in fuel consumption[2]. All of these add up a 28% reduction in CO_2 emissions from today's current crop of aircraft.

There is a delay in this new technology reaching the airline fleet. If we assume that all of these developments are included instantly (which is impossible) in new aircraft, then what effect will this 28% reduction in CO_2 emissions per aircraft equate to by 2014? Using Airbus' global market forecast of 718 new aircraft per year of which 68% are replacements of older aircraft, this gives a total of 16,905 aircraft flying by 2014[99]. Of these 3,590 would be of the 'new' type equating to an overall 6% drop in CO_2 emissions over the fleet, compared with 'old' aircraft, assuming that only the 'new' type are bought. It should also be noted that the total overall emissions would rise by approximately 1% over 2009 levels due to an increase in the fleet size of 1,155 aircraft. These calculations do not include the freight fleet, which usually consists of older former passenger aircraft with higher emissions. This illustrates the slow 'time to market' of new technology in aviation due to the longevity of the aircraft. Moreover, there are also issues with acceptance and safety, but recent increased use of composites suggests that the manufacturers are more willing to investigate new areas.

In the case of long-term developments, not only do these have technical issues, but also consumer challenges to overcome. The most promising update to aviation technology, the blended wing body, would most likely have to be a windowless design. This would have significant problems with passenger acceptance. Assuming that in 40 years time the best case scenario has occurred, a blended wing body aircraft (a possible 32% reduction in fuel burn) carrying 800+ passengers using distributed propulsion (a further 8-10% increase in propulsive efficiency), active boundary layer control (up to 70% reduction in skin friction drag), 100% biofuel (a possible 85% reduction in CO_2 emissions) and a fully integrated global air traffic management system (13% increase in efficiency) will produce an aircraft producing minimal levels of CO_2 emissions, between 60% and 95% reduction in current technology, mainly from the use of biofuel. However, the likelihood of the best case scenario occurring is slim, resulting from the demand from road transportation for biofuels, the various challenges faced by the technologies, as well as the financial risk of developing new aircraft and overcoming consumer perceptions.

These delays in the uptake of new technology suggests the 'low hanging fruit' in aviation may be changes in policy, particularly improvements in air traffic control. The technology for both NextGen and Single European Sky will need to be retrofittable, allowing fleet-wide roll-out much sooner than any significant technological change in propulsion or airframe architecture. Also a requirement for such technology to be utilised in any commercial aircraft flying within European or US airspace would force the majority of the world commercial fleet to fit such technology. However it should be noted that these changes are neither straight forward or cheap but they do offer a significant step change in aviation technology.

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4 SEA

Driven by emerging developing countries and transitional economies the demand for sea-borne trade continues to grow. The annual average growth rate is estimated to be 3.1% over the last three decades and continues to grow, fuelled by the world economy and increasing international mercantile trade[1]. During 2007, the world's gross domestic product (GDP) grew by 3.8%, while world merchandise exports grew by 5.5%, suggesting that the growth in maritime trade will continue. The shipping industry is estimated to have carried 80% of global trade by volume, over 51,200 billion tonne-km in 2008 alone[1, 2]. During the course of this, a billion tonnes of CO_2 was emitted, approximately 3% of global emissions[3]. It is not only CO_2 emissions from exhaust gasses that shipping releases but also refrigerant and volatile organic compounds (VOC) in conjunction with the transport of crude oil. The volume of CO_2 emissions released from sea cargoes is directly linked to the amount of marine fuel consumed and acts as an appropriate index for the determination of energy efficiency levels. The International Maritime Organisation (IMO) study identified 1046 million tonnes of CO_2 emissions originating from ship exhausts, 240,000 tonnes of methane, 30,000 tonnes of NO_x and 400 tonnes of hydro-chloro-fluoro-carbons that where released during 2007[3]. Converting these emissions into CO_2 equivalents leads to a global GHG emissions of 1,067 million tonnes in CO_2 approximately 3% of the global total.

But what can be done to reduce these emissions? The IMO identified four fundamental categories for the reduction of emissions from shipping:

- i) Improved energy efficiency
- ii) Use of renewable energy sources
- iii) Using low emission energy sources
- iv) Use of emission reducing technologies

4.1 Energy Efficiency

The initial area identified and the one with most scope for development is improvement to the energy efficiency of vessels. In order to improve energy efficiency, *i.e.* increasing the amount of work done per unit of energy, in shipping fall into one of two categories, design and operation. Design changes can usually only be applied to new build ships although retrofitting may be possible in some circumstances. Operational improvements can be applied fleet-wide with little or no alteration to the vessels. With respect to design changes, these can be divided into three areas: i) concept design and capability, ii) hull and superstructure and iii) power and propulsion systems. These design changes take advantage of the development of Energy Efficient Design Index (EEDI) by MEPC. The EEDI expresses the emissions of CO_2 from a ship under specified conditions in relation to a nominal transport work rate[4]. The energy efficiency of a ship is closely linked to the specification of the original design. Key parameters such as speed, size, beam, draught and length have significant influence on the potential energy efficiency of the design. Restrictions on these parameters due to infrastructural constraints (*i.e.* Panamax) can have a significant effect on energy efficiency. Vessels with extra capabilities such as ice hulls and geared ships (with cranes to unload cargo) also suffer from lower energy efficiency due to the redundant systems[5]. With a lifetime of 30 years or more, it is exceedingly difficult to design a vessel that will be optimal for its entire working life. For example whilst a larger vessel will be more efficient per tonne kilometre at full load, a smaller, more flexible vessel may have higher utilisation levels and thus be more energy efficient[6]. The emission reduction potential at the design stage should therefore not be under estimated. With regard to the optimisation of the hull and superstructure, similar levels of care at the design stage are required. Careful shaping of the underwater hull, focusing on reduced resistance and improved propulsive efficiency can lead to significant gains in efficiency with studies indicating a 5%-20% saving for hulls optimised in still water[7]. However optimisation of the hull in waves must also be considered. Reducing the wetted area (the area of the hull in contact with water), achieved by reducing the weight of the vessel, lowers the drag and consequently improves the energy efficiency. Unlike aviation, reduced weight would be achieved by using higher quality steels rather than lightweight material is due to design constraints. The superstructures of hulls represent a small fraction of the total resistance, but by introducing slant bows and square cut corners improvements can be made. Similarly to aviation, significant gains can be made with developments in the power and propulsion methods of vessels. The majority of vessels involved in maritime trade utilise low or medium speed diesel engines and the efficiency of these units can be improved in a number of ways, such as replacement with newer technology, energy recovery through two-stage turbo charging and by use of exhaust heat to drive secondary engine systems. These secondary systems can be used to provide power for electricity generation or to assist main engine functions. Recovery can amount to approximately 10% of total power[8]. Other more specialised power systems such as diesel-electric should be considered in special cases, but it should be noted that the secondary conversion adds additional transmission losses. On the whole, ship-borne propulsion is provided by propellers. High propeller efficiency is obtained by a large propeller rotating at a relatively low speed with the minimum

number of blades to reduce blade area and frictional resistance[5]. Another method of improving propeller efficiency is to employ devices to either recover rotational (tangential) energy from the flow or to provide some pre-rotation to the flow. Such devices include co-axial contra-rotating propellers, free rotating vane wheels, ducted propellers and pre and post swirl devices. Gains of up to 20% in efficiency have been reported though more typically 5% to 10% is achievable.

Operational improvements can be defined into one of three areas: i) fleet management, logistics and incentive, ii) voyage optimisation and iii) energy management. Similarly to the design criteria the IMO has defined an Energy Efficient Operational Indicator or EEOI that expresses the ratio between CO_2 emission and the benefit produced. It considers the fuel consumption, carbon content of the fuel, the mass of cargo and the distance its transported[9]. There is also a draft proposal for a Ship Efficiency Management Plan (SEMP) which provides a possible mechanism for monitoring ship and fleet efficiency performance over time and some of the options to be considered when seeking to optimise the performance of the ship[10]. There are various efficiencies that can be applied through fleet management, logistics and incentives. These included using the appropriate vessel in the transport system, reductions in scheduled speed and improvement in port management, such as changing from first come first served to an on demand system. These improvements can offer savings of up to 50% in CO_2 emissions, but for the upper level of savings, significant speed reductions are required with the knock on effect of lower amounts of cargo carried per annum have large impacts on the economics of shipping[11]. Voyage optimisation offers gains through weather routing, just-in-time arrivals, ballast optimisation and trim optimisation offering up to a possible 10% saving. Energy management offers similar level of savings through a number of measures centred around conscious and optimal operation of ship systems.

4.2 Renewable Energy

The next fundamental area identified for improvement is the use of renewable energy sources. Wind was traditionally utilised as an energy source for trade ships and is again gaining interest as an assistant power source. There are a number of different ways wind can be exploited such as traditional sails, solid or wing sails, kites and Flettner type rotors, offering savings of approximately 5% to 20%[12]. Other renewable energy sources such as solar, wave and shore based renewable energy suffer from issues with cost effectiveness and technology, making them unsuitable for maritime use.

4.3 Low Carbon Fuels

As with land transport and aviation, significant hope is placed on replacing conventional fossil diesel with low carbon fuels, such as biofuels and liquefied natural gas (LNG). With respect to biofuels, technical issues with their use are minimal although there are difficulties with using either first or second generation biofuels in marine engines: cost, lack of availability globally and other issues such as land use (see section 2.2)[13]. The use of LNG as an alternative fuel in the shipping industry has also been explored as it has a lower CO_2 per kg emission than diesel, no sulphur content and allows the reduction of NO_x due to reduced peak temperatures within the engine. However, as with aviation the volume required to store LNG onboard is an issue, as with high pressure requirements the use of LNG reduces a ship's range to a third of that if fuelled with diesel and hence rules this fuel out for many use patterns[14].

Table 6.1 Assessment of potential reductions in CO_2 emissions from shipping [3]

Design (new vessels)	% Saving of CO_2	Combined	Combined
Concept, speed & capability	2% to 50%		
Hull & superstructure	2% to 20%		
Power and propulsion systems	5% to 15%		
Low Carbon Fuels (LNG)	5% to 15%	10% to 50%	
Renewable energy	1% to 10%		
Exhaust gas CO_2 reduction	0%		25% to 75%
Operational developments			
Fleet management, logistics & incentives	5% to 50%		
Voyage optimisation	1% to 10%	10% to 50%	
Energy management	1% to 10%		

4.4 Emissions Reduction

The final area of interest is in the use of emission reducing technologies. Whilst it is technically possible to remove CO_2 emissions from exhaust gasses by chemical conversion to $CaHCO_3$ for sequestration in the water, it is currently not considered feasible in an onboard ship environment. Nevertheless, drastic reduction in NO_X, SO_X, PM, CH_4 and VOC emissions are possible by using established technologies such as fuel desulphurisation, combustion optimisation and exhaust-gas treatment. This would allow a considerable reduction in non-CO_2 emissions but compared to the amounts of CO_2 released the overall impact would be small.

4.5 Conclusion

There are a number of technological and operational improvements available to the shipping industry; the most significant however are restricted to new ships and are detailed in table 4.1. With the long life span of vessels (30+ years) the time for these developments to make an impact on global CO_2 emission from shipping is similarly long term. But the efficiency of vessels as bulk cargo carriers, with an average 19 g of CO_2 emitted per tonne kilometre of cargo carried compares impressively with other modes of transport.

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"Unless profound changes are made to lower oil consumption, we now believe that early in the 1980s the world will be demanding more oil that it can produce.World oil production can probably keep going up for another six or eight years. But some time in the 1980s it can't go up much more. Demand will overtake production. We have no choice about that."

Former U.S. President Jimmy Carter

5 COMMODITIES

Current transport technology relies heavily on a number of commodities to provide the necessary energy source and catalyst. The most important of these is crude oil, which almost universally provides the energy source for human mobility. In recent years, concerns have grown over conventional oil production and its capacity to meet growing demand. Unconventional reserves are abundant and may meet supply deficits, although the capacity for substitution is contingent upon the effective mitigation of environmental, social and technical challenges associated with the production of unconventional resources[1-3]. Furthermore, the technology previously discussed (sections 2 to 4) which will meet the input and output challenges of transportation in the 21st century, rely heavily on a number of other commodities, such as precious metals, rare earths and biomass. The majority of these materials are mined in a few locations around the world. As the demand for these materials is growing, the concentrated nature of the deposits is leading to a number of potential threats. Monopolistic behaviour, output uncertainty, geopolitical relations and environmental considerations are threatening the availability of precious metals and the unhindered expansion of mining and exploration[4,5]. Amplifying the rarity effect is the dwindling supply. Scientists claim that several precious metals on which the global economy relies, are likely to run out within the next 10-40 years[4,5]. Commodities which are not constrained by natural formation, such as biomass, the feedstock for biofuels, are also restricted. The growth of biofuels could have far reaching impacts due to food security, land use, water use and the environmental effects of mass production.

5.1 Fossil Fuels

As global conventional oil resources are going into decline, the era of 'cheap oil' is slowly coming to an end[1-3, 6-8]. However, public data is often contradictory in nature, and figures available on current reserves should be interpreted with caution. Conventional P50 oil reserves, those reasonably probable of being produced, should have their estimates revised downwards from 1150 giga barrels (Gb) to 1350 Gb, to between 800 Gb and 900 Gb[9]. Conventional crude oil has an extremely limited capacity to meet additional demand, and production rates are likely to start declining between 2010 and 2018. Resources that provide the entire liquid fuel today, will likely service a mere 50% of demand in 2020. The capacity to meet the demand for liquid fuels is therefore contingent upon the rapid diversification of the liquid fuels mix. Almost all additional demand will have to be serviced by unconventional resources such as fuels derived from tar sands or coal and alternative fuels such as biofuels. A condition of meeting higher demand is higher fuel prices, and it is overwhelmingly likely that fuel prices will increase significantly.

5.2 Precious Metals

Another method for meeting the demand for fuels in transport is in the use of electricity. These can be broadly described as either hybrid systems or pure electric drivetrains (section 2). However both these technologies rely on a number of precious and rare materials, the shortage of which is imminent. For example, the platinum group metals (PGM) which are required for some fuel cell and catalyst technologies have been identified by Andersson and Råde as nearing exhaustion[10]. If the current extraction rate of 159 Giga grams (Gg) per annum (*p.a.)* of primary platinum is maintained deposits of PGM are expected to be fully depleted by 2060. Given the distinctive characteristics of platinum deposits, geologists consider it to be highly unlikely that any significant additional volumes will be found within the short to medium-term future[11]. Estimates show that re-equipping of 500m cars globally with fuel cells would consume all currently accessible platinum sources within the next 15 years [11,12]. Assuming the growth vehicles continues, the current platinum reserves will be completely depleted by 2053. Additionally, in order to satisfy the precious metal consumption of a global fuel cell fleet industry, the annual rate extraction will have to increase by a factor of 20[10].

Similarly for battery electric vehicles (BEVs), essential materials are restricted. The current volume of economically recoverable lithium is sufficient to meet the global demand for passenger vehicle production of 2.1 billion (bn) vehicles within the next 50 years[11,13]. However, to power all global passenger vehicles with $LiC_6/LixNiO_2$ batteries, the current extraction level of 10,000 metric tonnes of lithium *p.a.* will have to rise by a factor of 13[13]. Other battery technology also has limitations due to the availability and extraction rates of materials. Nickel-cadmium (NiCd), lithium-ion (Li-ion (CO)) and lead-acid (PbA) batteries have the most limited fleet-size potential with 20m-50m, 200m-500m and 500m-800m producible vehicles respectively[14]. Li-ion (Mn), Sodium Nickel Chloride **(**NaNiCl**)** and Li-ion (Ni) batteries are the most available types, with respective potential production volumes of 3bn-8bn, 3bn-5bn and 2bn-4bn vehicles[14]. Other materials such as lanthanoids and actinoids are also in limited supply. Gordon *et al.*[7], highlighted the alarmingly high exploitation rates for zinc and copper, both important in BEV production, with 19% and 26% respectivly of recoverable resources in the lithosphere already in use or lost as unrecoverable waste.

These restrictions have led to an increase in the recycling and reuse of secondary metals in recent years due to the rising metal prices and lowering exploration volumes. Environmental benefits are also considerable and include the conservation of energy, biodiversity, natural resources and the reduction of toxic and non-toxic waste streams[6]. According to industry reports by Johnson Matthey [5], in 2008 the weight of recovered platinum loadings from spent catalytic converters rose to 28.63 million grams (Mg) as the recycling industry was encouraged to process stocks it had previously hoarded. The increased recovery of platinum volumes, was mainly due to the accelerated collection of average metal loadings from the catalyst industry and total platinum demand figures of 180.01 Mg in 2008 which drove prices to a record of US$81 per g[5].

5.3 Biomass

In the case of biofuels there are a number of restrictions on the production of the necessary feedstock. While it remains likely that liquid biofuels will only provide a niche market, sustainable production practises must be adhered to[15]. Evidence is provided through statements by the FAO, which state '…for the foreseeable future liquid biofuels would still be able to supply only a small portion of global transport energy and an even smaller portion of total global energy' [16]. There is only a future for sustainable biofuels if their production is not in direct or indirect competition with arable land used for the cultivation of food crops[17]. It remains crucial for policies that ensure that biofuel related agricultural expansion is directed towards marginal or idle land are enacted. In the case of combined food-fuel forming policies, it has to be assured that only wastes and residues which are not crucial for the farming process are used as biofuel feedstock. Given the accelerating land-use change effect, the reduced biodiversity and increased food prices, the detrimental consequences will be first and foremost directly felt by the undernourished and poorest. Furthermore, in the last few years biofuel production impacted the increase in crop prices and weakened global food security. This negative price relationship will get considerably worse in absence of good governance. However, the magnitude of impacts is expected to fall in the future when markets adjust more rapidly. The use of mandates and subsidies to spur the production of biofuels is likely to be a more expensive method of curbing greenhouse gases and will outsource the production of feedstock to the developing world.

5.4 Conclusions

We support the contention held by many independent institutions that conventional oil production may soon go into decline[3-5,12,13,18], and it is likely that the 'era of plentiful, low cost petroleum is coming to an end'[14]. Almost all additional demand will have to be serviced by alternative resources such as unconventional oil supplies derived from tar sands or coal and non-fossil fuels such as biofuels. While alternative fuel resources are abundant, a condition of developing such resources is a tacit increase in fuel price, which will be paid for by the consumer.

It remains likely that liquid biofuels will only provide a niche market and will neither eliminate nor significantly reduce the global dependence on fossil fuel sources or replace a considerable percentage[16]. Given the current level of agricultural production, process technology, crude oil and soft commodity prices the competitiveness of biofuels will continue to vary considerably according to production and feedstock location. They should not be seen as the 'silver bullet' solution to replace fossil fuels or deal with total transport emissions[16,19]. Increased biofuel production will effect the undernourished and poorest segments of society first, as the accelerating land use change will increase food prices. Widespread growth of biomass for fuel production will also reduce biodiversity.

A shift towards an increased electric vehicle production will be limited by the volume of available and extractable precious and rare earth metals. Estimates show that the re-equipping of 500m cars globally with fuel cells would consume all currently accessible platinum sources within the next 15 years[7,9]. To satisfy the precious metal consumption of an expanding global fuel cell fleet industry, the annual rate of mining and metal extraction will have to increase by a factor of 20[20].

Given the scientific prediction on the volume of available precious and rare earth metals, BEVs have the lowest level of commodity-restrictions. If global lithium reserves are taken into account, a maximum of 2.9m BEV's could be manufactured annually if the battery technology remains at the current level. This compares to over 70 million ICE vehicles produced in 2008[21]. Other materials are much less constrained, such as Li-ion (Mn) which could produce 3-8 bn vehicles[11].

The capacity to meet liquid fuel demand is therefore contingent upon the rapid diversification of the liquid fuels mix. The successful transition to a multi-fuel economy will depend on economic conditions that are conducive to investment in alternatives, the abatement of environmental issues, demand and the capacity for substitution of petrochemical based products.

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"A very Faustian choice is upon us: whether to accept our corrosive and risky behavior as the unavoidable price of population and economic growth, or to take stock of ourselves and search for a new environmental ethic."

E. O. Wilson

Two-time winner of the Pulitzer Prize

6 BEHAVIOURAL CHANGE

A number of policy levers have been discussed, both in the previous sections and in a companion report, *Road Transport Externalities and Economic Policies: A Survey*. Many policies designed to move towards a model of sustainable transport do this by trying to change peoples behaviour. Economic policies, such as taxes and subsidies, do this by making people pay the social cost resulting from their transport choices. In this section we consider how such behavioural changes can be brought about by some of the soft, or as the UK government refers to them, 'smart' policies. These policiespolicies are the provision of information and education to the user, as well as the promotion of sustainable transport. We aim at unveiling some of the cultural, social and psychological factors that influence travel behaviour and mode choice, and which can therefore also have an impact on behavioural change. Crucial to this section is the understanding that underlying all policy design is a picture of human nature, the expectation of how people will react to certain policies when they are implemented. In designing economic policies a very simple picture tends to be sufficient: in order to make people reduce a particular behaviour, they must simply be made to pay a higher price for it. This tends to work very well in general, but there are some puzzles: for instance, people appear to have preferences for 'green products' and the Stern Review[1] concludes that there is 'clear evidence of shift towards environmentally and socially responsible consumption and production'. Crucially, this implies that information, advertising, and education policies can affect the choices people make.

6.1 Information and Education

Cairns *et al.*[2] estimate scenarios for the potential impact of 'smart policies' in the UK. 'Smart policies' are defined by Cairns *et al.*[2] as policies including personalised travel planning, travel awareness campaigns, public transport information and marketing, as well as policies considered in previous sections such as car clubs, sharing schemes or teleworking. Projecting from 2004, they argue that under a 'high-intensity scheme' of such policies together with supporting conventional economic policies it would be possible to achieve a nationwide traffic reduction of about 11% by 2020. A 'low-intensity scheme' could achieve 2 to 3%[2]. Although as stated in Section 2 of the report, those projections were initially used for transport policy planning by the government, the UK Department for Transport (DfT) has recently changed their view and decided to make 'more realistic but cautious assumptions'[3]. They now assume 'smart policies' would reduce car-trips and car-km by 7% and 3.7% respectively by 2020[3].

In his review, Stern[1] argues that policies addressing barriers to behavioural change constitute a critical element of a climate change strategy, as cost-effective mitigation options may not be taken up due to reasons such as a lack of information and the complexity of available choices as well as upfront costs. He thus notes that 'a shared understanding of the nature of climate change and its consequences should be fostered through evidence, education, persuasion and discussion'[1]. Information policies, if well-designed, can then be used to:

- Inform people about the economic and environmental consequences of their actions and prompt them to act in a sustainable way.
- Stimulate innovation and competition in greener goods and services and facilitate environmentally friendly investment.

Beyond this, information policies can also address social norms and private attitudes. Stern notes that 'shared social and institutional norms are important determinants of behaviour'[1]. This is analysed using concepts of 'evolutionary' or 'procedural' rationality. Unlike the narrower concepts of rationality conventionally used in economics, evolutionary rationality can account for the fact that people's behaviour is shaped by their habits and the customs and expectations of their society. For policy, this implies an obstacle in bringing about behavioural change. For example, people will not adjust their behaviour instantaneously in response to economic incentives. However, norms can change over time, which allows for a role for policy. Therefore governments and the media can play a role in the development of a shared concept of responsible behaviour.

Travel Behaviour Under Risk and Uncertainty

In order to better understand people's travel choices it is important to understand the concept of rationality and decision making. People's choices regarding their travel behaviour often have a prior unknown consequences, and it is thus unsurprising that there has been 'increased academic interest in questions of how travellers handle uncertainty and unreliability in transportation networks'[4]. For several decades the standard model of Expected Utility Theory[5] was dominant in decision making under risk and uncertainty, defining rational choice as choosing the alternative with the greatest expected utility. However, 'a substantial body of evidence shows that decision makers systematically violate its basic tenets'[6] including, for instance, influential papers by Allais[7], Ellsberg[8], and Kahneman and Tversky[9]. Tversky and Kahneman[6] thus list five major violations of the standard model:

i) Framing effects: there is evidence that, contrary to the rational theory of choice, preferences differ depending on how the options are framed (i.e. in terms of gains or losses).

ii) Nonlinear preferences: the expectation principle, according to which the utility of a risky prospect is linear in the outcome probabilities, was famously challenged by Allais[7], who showed that the impact on preferences resulting from a difference in probabilities of 0.99 and 1.00 was greater than from a difference between 0.10 and 0.11.

iii) Source dependence: the source of uncertainty, not just the degree, matters for people's willingness to bet on uncertain events.

iv) Risk seeking: while people are generally assumed to be risk averse, in certain settings risk-seeking choices are observed.

v) Loss aversion: in choices both under risk and under uncertainty, 'losses loom larger than gains'[6, 9].

Prospect Theory, and its successor Cumulative Prospect Theory[6] accommodate these violations of Expected Utility theory and are starting to be applied in transport research. Schwanen and Ettema [4], for instance, use cumulative prospect theory in order to analyse how employed parents deal with unreliable transport networks when collecting their children from nursery[4]. Their study indicates violations of the axioms of Expected Utility Theory, and the authors thus conclude that 'if travel behaviour researchers wish to better understand how travellers cope with travel time variability, then they should develop alternatives to expected utility theory (EUT) as the analytical framework on which empirical work is based'[4]. Examples include Avineri and Prashker[10, 11], Fuji and Kitamura[12], Senbil and Kitamura[13], Jou *et al.*[14], De Palma and Picard[15], Schwanen and Ettema[4] .

Information, Attitudes, and Behaviour

Most economic policies, relying on 'carrot and stick' measures and modelling individuals as having a set of fixed preferences and valuations, are central to policy-making. However, they ignore the fact that 'much of public policy is actually about changing attitudes'[1] with respect to climate change and this involves both changing people's notions of responsible behaviour as well as promoting their willingness to co-operate. Regarding transport policy, in particular, policy could play a role in changing people's attitudes. Dargay[16] notes that economic incentives, such as taxes and subsidies, appear to have to be very large in order to bring about effects on people's fuel consumption and travel mode choice. Car travel is thus relatively insensitive to changes in costs, indicating that people perceive car use to be a necessity, even if this is objectively not the case. Dargay[16] concludes that information campaigns raising people's awareness of travel alternatives and the negative environmental impact of car use could change people's attitudes and improve their awareness of alternative transport options. She cautions, however, that the question whether this will in fact lead to change in behaviour is debatable.

Regarding this issue, the evidence seems mixed. Parkany *et al.*[17], for instance, conclude that their study, in line with many others in the transport literature, shows that 'attitudinal data is an important component in the travel behaviour decision process', recommending that attitudes should be studied to gain an understanding of the processes and factors that affect people's choices. On the other hand, however, Jacometti[18] shows that knowledge does not always change attitude, and attitude does not always change behaviour. In other words, she argues, raising awareness and providing information are unlikely to result in behavioural changes. Although she concludes that local programs may have an important role to play, she also admits that they are more resource intensive. In the area of transport, where the required change is so large and at so many levels (technological, cultural, psychological and ultimately, behavioural), local programs may result in higher costs than benefits. However, considering attitudes can be important in policy design. Cao *et al.* [19] note that in analysing the impact of land use policy measures it is important to control for potential self selection on the basis of attitudes, which can play a role in the relationship between the built environment and travel behaviour in a number of different ways. Attitudes may be antecedent, intervening or irrelevant in this relationship. If attitudes are 'antecedent', they may be the cause for both people walking more, as well as them choosing to live in a walkable neighbourhood. Attitudes may be 'intervening' in two directions: if walking more establishes or strengthens a walking preference, which, in turn causes people to live in a walkable neighbourhood, or, if living in a walkable neighbourhood establishes a walking preference, which then induces people to walk more. In these potential relationships there is no direct causal link between the built environment and travel behaviour. A direct causal link exists only if attitudes are secondary or 'irrelevant', i.e. if choosing to live in a walkable neighbourhood directly causes people to walk more, and attitudes towards walking have no causal role. Understanding the precise nature of the relationship between the built environment and travel behaviour is crucial for policy making: when assessing the potential impact of land use measures it is important to determine the extent of the causal effect of the policy measure, which implies making sure that the measured impact is in fact due to the policy, and not caused by people's attitudes.

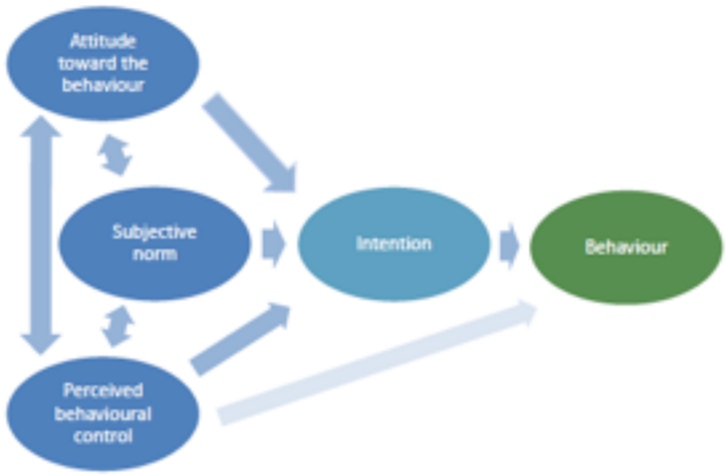
Personalised Information and Marketing

When trying to bring about change in travel behaviour through information and marketing, there is evidence indicating that personalised communication measures are more effective in changing people's travel behaviour, especially in breaking habitual car use, than non-personalised mass communications[20]. It is thus unsurprising that policymakers have increasingly become interested in using personalised information and marketing strategies, techniques adopted from commercial marketing[2]. Thus, individuals or households are engaged in one-on-one dialogue and provided with targeted information to enable them to choose a more sustainable pattern of transport choices. Personal Travel Planning (PTP) thus aims to overcome people's habitual use of the car and their psychological barriers to using sustainable transport [21]. Personal transport planning has been employed in many different locations and on many different scales. Cairns *et al.*[2] review the evidence on different programs' success. The first large-scale PTP project was undertaken in 2000 in the Australian suburb of South Perth. Amongst the sample of 35,000 people, the policy was estimated to have brought about a 14% reduction in car driver trips[2]. Regarding the UK, Cairns *et al.*[2] report individualised marketing projects to have reduced driver car trips by five and 10% respectively in different areas of Bristol, and find that a pilot project in London 'reduced car driver trips by 11%, with another potentially reducing them by 16%'[2]. These results are found to be comparable with those reported from similar projects in Germany. Fujii and Taniguchi[22] find evidence that such 'soft' transport measures relying on personalised communication are also effective in changing travel behaviour in Japan - indicating that the effectiveness of these policies extends beyond 'Western' cultures. The UK DfT also reviews the cost-effectiveness of PTP, noting that cost-benefit analyses typically report cost-benefit ratios around 1:30 over a 10-year period. PTP programs tend to cost between £20 and £38 per household and become increasingly cost-effective as the scale of the program increases. Thus, for large-scale UK PTP projects value for money estimates in the first year of implementation are reported as being between £0.02 and £0.13 per vehicle kilometre saved[21].

Impacts from Information and Education

What can we then conclude as being the role for information and education in bringing about behavioural change with respect to transport choices? The review by Anable *et al.*[23] addresses the infamous attitude-behaviour gap: the question why people's knowledge and attitudes towards environmental issues or climate change so often fail to induce people to make changes in their travel behaviour in order to mitigate its effects. They note that this gap can be considered 'one of the greatest challenges facing the public climate change agenda'[23] a key issue in bringing about behavioural change. Their review suggests an emerging consensus on the view that information is necessary but not sufficient for behavioural change. Thus, measures addressing attitudes and intentions are not likely to be very effective on their own, but classical economic policies 'without a targeted strategy of information and attitude campaigning are also set to be less effective and possibly even counterproductive'[23]. The optimum solution thus involves successfully combining both types of

Figure 6.1: The Theory of Planned Behaviour[26]



policies. Researchers studying transport behaviour have also made use of the psychological 'Theory of Planned Behaviour', an extension of the theory of reasoned action[24, 25], to behaviour over which agents have incomplete volitional control. A behaviour is under incomplete volitional control if a person cannot simply decide at will to perform this behaviour, but also requires some non-motivational factors, such as opportunities or resources, for example, time, skills, money, co-operation[26]. According to the Theory of Planned Behaviour, it is possible to accurately predict intentions for different kinds of behaviour from 'attitudes toward the behaviour, subjective norms, and perceived behavioural control'[26]. An agent's perception of his perceived behavioural control together with his intentions then 'account for considerable variance in actual behaviour'[26]. Gardner notes that the Theory of Planned Behaviour is the most widely used model to analyse the cognitive determinants of car use[27]. Studying behaviour of car and bicycle commuters, Gardner finds that commuters' mode choice is stable over time and, in line with the Theory of Planned Behaviour, commuting could be modelled as reasoned action. However, his studies also show that the effect of intention on behaviour is moderated by habits, such that 'intention predicted behaviour where habit was weak, but where self-reported habit was strong, behaviour was determined solely by habit, and not by intention'[27].

6.2 Advertising and Marketing

One of the key tasks in advertising and marketing is market research: knowing the market, how it is composed, knowing what drives consumers' decisions therein. Thus, policy-makers aiming to bring about behavioural change in people's transport decisions can similarly benefit from an understanding of what drives behaviour. A key concern in bringing about behavioural change is to encourage people to reduce their car use. In order to address this problem effectively, an understanding of why people use cars will be necessary. Steg[28] conducted studies in the Netherlands examining people's reasons for using cars. Her results reveal that car use, in addition to fulfilling instrumental functions, also fulfils important symbolic and affective functions. Furthermore, she finds that commuters' car use was 'most strongly related to symbolic and affective motives, and not to instrumental motives'[28] and differences between individuals were also greatest in their evaluation of symbolic and affective motives. Regarding policy-making, Steg[28] notes that her results suggest that in designing effective policies, policy-makers should consider the multitude of people's social and affective motives that are driving car use in addition to their instrumental motives. Golob and Henscher [29] suggest, for instance, that 'the car as a status symbol can be countered by public transport as an environmental symbol'[29]. In addition to marketing public transport as an alternative to the private car, Wright and Egan[30] propose that targeted propaganda could also de-market the car as a status symbol. Unlike most public information campaigns this would focus not on people's sense of public duty, but rather on their self-image. They note that peer group pressure could play an important role in changing attitudes amongst potential car users in young people. The campaigns should be delivered by non-government agencies in order to lend them credibility: 'to avoid the appearance of a sermon, a campaign of this kind must employ subtlety and wit. A celebrity or public figure can deliver the message and lend credibility to the exercise'[30]. Kahn[31] considers differences in consumption patterns between environmentalists and non-environmentalists in California, using as a proxy a community's share of registered Green Party voters. The study finds that environmentalists are more likely to use public transport, purchase hybrid-vehicles and consume less fuel than non-environmentalists. Notably, however, there is a huge 'Prius' effect: the Toyota Prius is preferred by consumers relative to other similarly green vehicles. This suggests that the Prius is an environmental status symbol as it is widely recognised as the 'Green car' due to extensive marketing and celebrity endorsements. The 'social interactions effect', the benefit that people derive from being seen to behave in an environmentally friendly way, may thus be more important than the private utility they receive from their choice[31]. In evaluating a policy measure it is also crucial to consider its costs. Regarding marketing costs for city-wide bus services, Cairns *et al.*[2] find that public sector costs for such measures in the UK are about 2 pence per car kilometre saved. If bus companies' investment is also taken into account, which may more than pay for itself in terms of generating additional revenue, this reduces the overall cost per car kilometre saved. However, they conclude that 'even without this effect, it appears that once a public transport service exists, additional money spent upon its promotion represents excellent value per car kilometre reduced'[2].

Crucially, successful marketing policies will address the right people. Anable[32] argues that marketing campaigns to encourage people to use alternatives to the car should be focused on and tailored towards those segments in the population 'with the greatest potential to increase their frequency of use'[32]. In order to do this she proposes a segmentation approach similar to that used in conventional marketing: people should be divided into categories not only on the basis of socio-demographic factors, but also on the basis of a 'combination of instrumental, situational and psychological factors affecting travel choices'[32], since these will differ distinctly for different groups of people. She thus determines different categories of people along these dimensions. 'Malcontented Motorists' and 'Complacent Car Addicts', for instance, exhibit similar current travel behaviour, but have very different environmental attitudes. Using a more sophisticated measure of market segmentation allows Anable to overcome to some extent the attitude-behaviour gap, finding that 'environmental concern combined with a sense of moral obligation has helped to account for some of the variance in attitudes, intentions and behaviour'[32].

6.3 Family Life Changes

Goodwin[33] uses panel data in order to investigate the effect of important transitions in people's lives on their transport choices, considering changes in people's life cycle, employment status, income, and car ownership. The results from the panel data study give a very different picture of transport behaviour compared to other studies. Goodwin[33] also undertakes a cross-section analysis, which comes to similar conclusions as other studies do, finding that higher incomes seem to lead to increased car ownership, leaving the public transport market increasingly to consist of those dependent on it, *i.e.* the young, the elderly, and the low income group. Cross-section data, however, can only capture statistics: it can only reveal the current situation. Panel data, on the other hand, can reveal how behaviour changes over time amongst different groups of people. Goodwin[33] thus finds that when people join the 'dependent' group they do not necessarily fully adopt that group's transport behaviour. For instance, when people become unemployed they do not necessarily use public transport to the extent that the average unemployed person does. On the other hand, changes in income appear to have little effect on car ownership, at least in the first two years after the change occurs. The panel data study thus leads to very different conclusions, contradicting two well-established policy expectations:

- The expectation that increasing incomes will rapidly lead to increases in car ownership, such that the market for public transport will collapse
- The expectation that public transport can safely rely on its group of dependent customers

Goodwin sums up the results on family life changes very succinctly: *'People whose lives are more stable and uneventful tend to respond less to changes in the relative attractiveness of the current travel choice, whether that change affects their current choice getting worse or an alternative getting better. People whose lives are being changed by some important event or development, tend to respond more to whatever changes in relative attractiveness there have been.'*[34].

This has important implications for transport marketing campaigns, indicating that campaigns are most effectively aimed at people in the process of important transitions in their life, as this is when they are most likely to respond with behavioural change. For example, campaigns should not target 'the retired', but rather those 'in the process of retiring'.

6.4 Conclusions

Information, education, and advertising campaigns can bring about change in people's travel behaviour. Information and advertising policies are most effective when carefully targeted, on an individual basis, towards those most likely to change their behaviour. Bringing about behavioural change through these policy measures thus requires a better understanding of people's transport choices, and we therefore consider how economic and psychological theories such as Prospect Theory and the Theory of Planned Behaviour can contribute to transport research. Well-designed information and advertising campaigns can then be very cost-effective measures for bringing about behavioural change.

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7 SUMMARY

Global greenhouse gas (GHG) emissions have to be reduced drastically in order to meet the targets set out in the Kyoto Protocol; this emissions reduction is inextricably linked to a decarbonisation of transport, the second most emissions intensive sector. As transport is intrinsically tied to societal welfare and economic growth, there are a variety of challenges and opportunities associated with the transformation of our transport systems. According to our research there is ample opportunity to reduce emissions in the short-term, (within the next decade) optimising the current vehicle technology combined with modal shifts to less carbon-intensive public transport, which could be supported using a combination of policy levers. We will summarise these options for each sector.

7.1 Land

Road transport is the land mode with the highest emissions; neither novel fuels nor drivetrains can significantly contribute to overall emission reduction goals in the short-term. There are three main reasons for this; i) the impact of vehicle technologies is delayed by a fleet lifetime of 12 to 15 years, ii) most alternative low carbon drivetrains still have significant hurdles to overcome and ii) the large scale production of low carbon fuels bears significant problems, *vide infra*.

Vehicles with a purely electric drivetrain will remain a niche market up to the medium-term. Both fuel cell and battery technology require significant breakthroughs before achieving mass market penetration. In the case of fuel cells, platinum-based polymer electrolyte membrane (PEM) fuel cells offer the best prospect for use in automotive applications. These fuel cells have to be improved before they can become commercially viable. Most importantly, the amount of platinum metal required for the fuel cell catalyst has to be reduced. Current technology requires considerable amounts of platinum. Were mass production to occur, the increased demand would drive up platinum prices making fuel cell vehicles economically non-competitive. In the case of the distribution and storage of hydrogen, massive infrastructural investments would be required, as the current system is not suitable for gaseous or liquefied hydrogen.

Battery electric vehicles (BEVs) are indeed efficient, low emissions cars. The additional electricity required for an increasing BEV fleet could be serviced by the base-load of the electricity grid, because these vehicles will mainly be recharged overnight when cheap, excess electricity is available. However, these cars are not zero-emissions vehicles as in most regions of the world the electricity generation relies upon fossil fuels and hence these vehicles cause indirect emissions (see section 2.1). Due to the higher efficiency of electric engines, these indirect emissions are lower than the direct emissions of a comparable internal combustion engine (ICE) vehicle. Decarbonisation of electricity production should go hand-in-hand with the introduction of BEVs in order to reduce indirect emissions. The success of BEVs is contingent upon the performance of battery technologies. At present no battery technology satisfies the range requirements for an average car user. The current batteries merely cater for cars that are used for short ranges only (see section 2.1). Hence, we conclude that these technologies might have an impact on the medium to long-term if their development is supported by incentives, but will clearly stay marginal in the short-term.

In the short-term, improved ICE drivetrains such as hybrid electric vehicles (HEV) and a simple down-scaling could significantly reduce emissions. This is provided that the appropriate vehicle set-up for a certain use pattern is chosen: HEVs only unfold their full potential when they are operated in the environment they were designed for, routes with dense traffic such as an urban area. The stop-and-go nature of urban driving means that the electric drivetrain is frequently recharged, making full use of the secondary drivetrain. If they are mainly used on a motorway, the additional weight of the electric drivetrain and increased carbon debt incurred during manufacture might outweigh the benefits of the back-up drivetrain. Hence HEVs are the choice for vehicles primarily or frequently driven in dense traffic, as in the case of taxis. When the main use pattern is long distance travel in areas with light traffic, these cars are at a disadvantage. Here, the set-up of choice is efficient turbo-charged gasoline or diesel drivetrains in down-sized vehicles. These vehicles are considerably cheaper than HEV and their manufacturing is less emission intensive. Emissions from modern mini or compact ICE vehicles are competitive with compact sized HEVs. A mini car with four seats and a diesel engine emits merely 10% more than a compact car with a hybrid drivetrain. Ricardo plc estimates that from a journey length of 70 miles or more, efficient ICE vehicles are less emissions intensive than HEVs (see section 2.1).

In the medium-term, plug-in hybrid electric vehicles (PHEV) could have a significant impact upon emissions from transportation. These vehicles are equipped with a larger battery than HEV that can be recharged from the grid. For short journeys they use the purely electric drivetrain. For longer journeys electric power is used at the start and a HEV approach at further distance. This is beneficial when the use pattern is mixed, *i.e.* long and short distances have to be covered. For frequent long distance travel however, the heavy battery in a PHEV is a disadvantage. A discrete problem with HEVs and PHEVs is that the electric engines used in these depend on magnets based on rare earth metals. Supplies of these materials are scarce and hence could limit the manufacture of hybrid drivetrains (see section 5.1). Nevertheless, there are electric engines based on nickel magnets, which would ease the strain on rare earth metals.

We conclude that road transport will continue to rely on the internal combustion engine, in an optimised, classic or hybrid set-up. Electric vehicles will remain a small percentage of the overall fleet composition up to the medium to long-term. When combined with a drastic downscale of both vehicle size and weight, a significant reduction of emissions from road transport could be achieved, especially in combination with low carbon fuels.

Emissions from ICEs can furthermore be reduced by using alternative low carbon fuels. These are fuels that emit less CO_2 per unit of energy retrieved than conventional fuels or only marginally more than consumed in their synthesis. Some biomass derived fuels, so-called biofuels, are potentially low carbon. The exact carbon footprint, however, depends on various parameters such as the feedstock, the land it is grown on (see section 2.2) and the carbonisation grade of the electricity used for their synthesis (see section 2.1). Biofuels are currently roughly divided into first and second generation. First generation biofuels are derived from edible biomass such as corn, sugar cane or vegetable oils. Hence the synthesis of these fuels competes with food production, potentially having a negative effect on food security in the developing world (see section 5.3). Moreover, not all of these fuels offer GHG emissions savings. Many of them have other adverse effects on the environment, especially when produced on a large scale. Corn ethanol produced in the United States for instance does not offer emissions savings and additionally has dire impacts on the environment (see section 2.2). A notable first generation biofuel is sugar cane ethanol in Brazil. This fuel can be a local solution, as not every country has such huge areas of arable land available. Second generation biofuels, fuels synthesised from inedible cellulosic biomass, such as agricultural residues, municipal solid waste or dedicated energy crops, have the potential to be true low carbon fuels. Their effect on food security is minimal and they can be used in a variety of applications, such as cars and aircraft. However*, even second generation biofuels do not have the capability of replacing the current liquid fuel demand. The main reason for this is the limited availability of land.* Another set of advanced biofuels is derived from algal oils by hydrotreating or transesterification. Algae are farmed in plastic bags or ponds filled with degraded water, minimising land-use change as well as freshwater issues and they can yield large amounts of oil per unit area. Farming them in a controlled way remains a hurdle and hence a breakthrough in mass production techniques for algal farming could completely alter the current biofuel picture.

Fuels derived from unconventional oil such as tar sands, coal *etc.* could provide us with fuel security by mitigating potential shortages, though at an even worse environmental cost because of the significantly higher carbon footprints of these fuels (see section 2.2). Combined with an increasing demand in transport fuels, these high-carbon fuels would drastically increase emissions from road transport (see section 2).

Electrified rail transport has distinct advantages over road transport, most importantly very low operating emissions and competitive travel times. Suburban commuter trains can significantly reduce emissions provided good occupancy rates are achieved, with the additional benefits of reduced inner-city congestion and improved urban air quality. High-speed intercity trains have journey times competitive with domestic air travel combined with higher carrying capacities and reduced operational emissions. Germany, Japan and France have shown that efficient high-speed train networks significantly reduce the number of domestic flights, thereby reducing emissions from domestic transport. Reducing domestic flights would ease constraints on air traffic control and potentially reduce circling, further reducing emissions.

Despite the benefits of electric rail, in many areas of the world slow diesel trains still dominate. For instance, in Great Britain only 33% of the railway network is electrified, the United States even less. So, when talking about emissions reduction through electrification, we should first consider extensive electrification of major railroads. When compared to other modes of transport, electrified heavy rail has a significant benefit for operational emissions. To illustrate this we have calculated the emissions produced for two domestic journeys within the United Kingdom, using a selection of different modes of transport.

Apart from land transport technologies, this report pays special attention to transport externalities and policy instruments for sustainable road transport. An efficient mobility model for the future must take into account the true costs of transport and its required regulatory framework. This must create incentives to encourage sustainable transport choices. Command-and-control policies, such as government regulations and/or incentive based policies like taxes or charges and tradable permits, can be used in combination with other complementary policies to achieve this. Complementary policies broadly fall into three categories: physical, soft, and knowledge policies. All three aim to change consumers' and producers' behaviour. Physical policies have some infrastructure element: public transport, land use, walking and cycling, road construction and freight transport. Soft policies inform consumers and producers about the consequences of their transport choices, and potentially persuade them to change their behaviour (through advertising, for instance). These measures include car sharing and car pooling, teleworking and teleshopping, eco-driving, as well as general information and advertising campaigns. Finally, knowledge policies emphasise the important role of investment in research and development.

Regulations and standards are not efficient from an economic perspective. They are excellent instruments if the level of an activity needs to be drastically reduced or altogether eliminated; or when the constraints faced by the regulator, such as public and political acceptability of incentive based measures, are severe; or as complements to incentive based policies. We do not recommend widespread and blind adoption of incentive based policies as although efficient from an economic point of view, in reality, they do not always fulfil their cost minimisation potential. Taxes, charges and permits are excellent instrument, when the revenue generated from such methods is used to reduce distortionary taxes in the economy or returned to the road transport sector. This can occur in the form of investment in public transport or research and development of cleaner technologies; and as a driver to change economic agents' behaviour, such as driving less or increasing the use of public transport. Combining all these policy levers in an integrated framework will reduce negative externalities from road transport in general, and CO_2 emissions in particular.

7.2 Air

The second biggest contributor to emissions from the transport sector is aviation. While aviation is only responsible for 2–3% of global fuel consumption, the IPCC has estimated that aviation's total climate impact is approximately 2-4 times that of its GHG emissions alone. This is because of indirect effects such as contrails alter the atmosphere's radiation budget. The emissions from aviation can be reduced by (i) technological developments which increase the efficiency of the airplane, (ii) applying low carbon fuels, analogous to the road transport sector and by (iii) improving operational efficiency. Aircraft efficiency can be achieved via reducing the weight of the aircraft, increasing the efficiency of the propulsion system and improving the aerodynamic efficiency of the airplane itself with improved design. Up to now, weight reduction achieved by application of novel materials has been offset by increases in entertainment systems and aerodynamic changes. Evolution of current engine architecture could lead to a 20-30% decrease in specific fuel consumption by the time the pinnacle of design is reached in 25-30 years. Efforts to reduce drag include winglets (up to 5% fuel saving) and silicon paints (1-2%), as well as smoother more integrated designs with improved aerodynamic efficiency. Over the next few decades these endeavours are estimated to result in a further 10-15% reduction in fuel consumption. With the current aircraft architecture the possible overall reduction in fuel burn is limited to an estimated 30-50%, the majority of which is provided by developments in propulsion efficiency. Manufacturers and consumers have to move away from traditional 'tube-and-wing' designs and embrace novel aircraft architectures in order to reduce fuel consumption and emissions further. An example of such is the Blended Wing Body, which offers the possibility to reduce fuel burn by 32% with a load of 500+ passengers. Consumer acceptance will be crucial here as these novel designs bear a significant financial risk to aircraft manufacturers. Impact from these novel technologies will be delayed due to long development times for new aircraft and fleet lifetimes of up to 30 years.

The range of low carbon aviation fuels is considerably smaller when compared to those available to road transport. This is due to the harsh conditions under which aviation fuels are required to combust. The best option for a low carbon fuel for aviation is Hydrotreated Renewable Jet (HRJ) fuel made from vegetable oils. While HRJ fuels derived from jatropha oils are a likely regional solution, globally these fuels will only have a significant impact if algal oils are used as feedstock. It is unlikely, in the case of aviation, that alternatives to highly energy dense hydrocarbon fuels, such as kerosene or HRJs, will penetrate the market. Nuclear powered aircraft are highly unlikely due to a lack of customer acceptance even though the technology is still propagated by some.

The IPCC estimates that improved air traffic management could reduce emissions by another 12%. Hence, the overall impact of aviation on GHG emissions could be substantially reduced if new technologies, fuels and operational improvements are embraced. Since fuel prices are the determining cost factor in aviation and this sector is to be included in the EU-ETS. The assumption is that consumers and airlines will demand low carbon fuels and efficient aircraft, and consequently manufacturers will invest in these technologies. Of these technologies we see improvements in air traffic control as the 'low hanging fruit', allowing fleet-wide improvements in a relatively short time scale, when compared with technology that requires new airframes, such as propulsion improvements. However, such changes are neither cheap nor straight forward and require significant work to develop and implement successfully.

7.3 Sea

Maritime transport accounts for only 3.3% of global emissions and is the least significant contributor to GHG emissions in the transportation sector. However, globally more than 70% of all cargo (by volume) is transported using ships, making shipping an efficient means of transport with the lowest GHG emissions per tonne kilometre. The up-scaling of naval vessels, for instance the spread of supertankers, improved this efficiency even further. In the case of maritime navigation, local pollutant emissions are more of a concern than GHG emissions. Low-sulphur fuel standards could reduce the environmental impact even further. Maritime transportations main disadvantage is the slow transportation speed and is not suitable for every kind of cargo, *e.g.* forfeitable goods. The International Maritime Organisation estimates that operational and technical improvements could reduce the GHG emissions by up to 75% and more than 80% in the case of pollutant emissions. We conclude that shipping will remain the major means for cargo transportation with technical improvements reducing adverse environmental impacts to near zero levels in the medium to long-term.

7.4 Behavioural Change

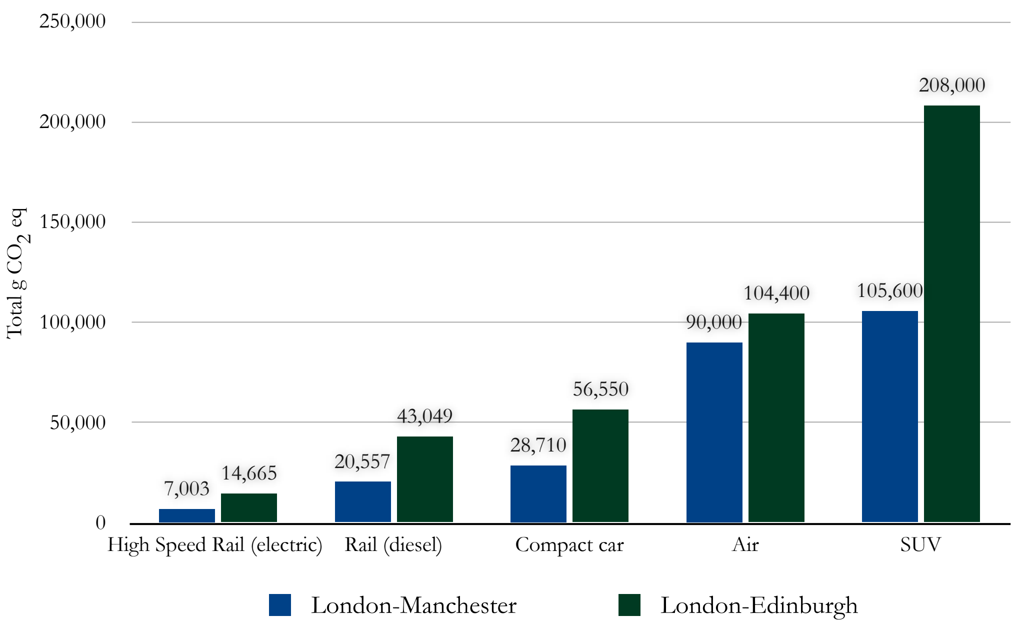
Information, education, and advertising campaigns can bring about change in people's travel behaviour. These soft policies are most effective when carefully targeted towards those most likely to change their behaviour. Bringing about behavioural change through these policy measures requires a better understanding of people's transport choices. We therefore consider how economic and psychological theories such as Prospect Theory and the Theory of Planned Behaviour can contribute to transport research. Well designed information and advertising campaigns can be very cost-effective measures for bringing about behavioural change.

Our research strongly suggests that no true low carbon technology will penetrate the mass market in the short-term and transport will continue to rely on fossil fuels. *There is ample opportunity though, for emissions reductions by further improvements of currently available technology* combined with a change in user habits.

7.5 Modal Changes

To illustrate how these short-term recommendations could affect emissions from the transport sector *using currently available technology*, the emissions caused by a hypothetical journey was calculated. The journey from London to Edinburgh *via* Manchester using i) a hypothetical high-speed train operated with the carbon-intense electricity available in the UK, ii) a domestic flight iii) a sports utility vehicle (SUV) and iv) Gordon Murray's T25 were calculated. Our calculations show that using the hypothetical high-speed rail route between London

Figure 7.1: GHG emissions from a domestic journey using different modes of transportation



and Edinburgh, the journey would emit nearly 15 kg of CO_2 per passenger, while the same trip would cause 104 kg per passenger when flying. Driving there in an SUV causes more than twice the GHG emissions of air travel and more than four times the emissions compared to the low emission T.25. It is clear from this comparison (figure 7.1) that shifting domestic flights to high-speed rail and down-scaling our car fleet could provide us with drastic emissions savings while easing our dependence on crude oil.

At the local scale, car use could be minimised by shifting to human-powered transport (HPT) and mass-transit systems (MTS) (see section 6). In rural and isolated areas where MTS is not suited, novel public transport systems such as demand responsive transport (DRT) could reduce car usage. Nevertheless, the car will remain an important means of transport at the local level, especially for families with children. Short to medium distance journeys could be covered with rail and, when combined with MTS or car sharing on arrival, this approach would reduce emissions while continuing to allow human mobility.

Aviation will remain important, as the mode of choice for medium to long distance travel. Many European countries have already shown that the number of domestic flights can be reduced by providing an efficient, high-speed rail network. Hence, infrastructure investments are crucial to emissions reduction. Most crucially, behavioural change has to be induced using a bottom-up approach, in order to stimulate a rethinking of modal choices.

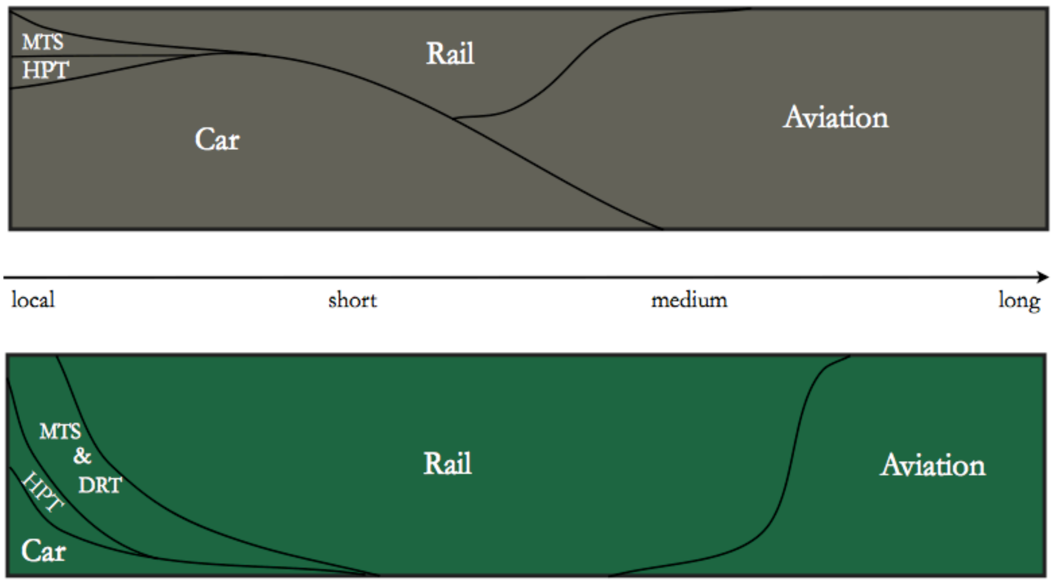
If these measures are successful, a shift from a high-carbon scenario, which is the *status quo* (figure 7.2. grey), to a scenario with considerably lower carbon emissions (figure 7.2. green) would be possible using available technology.

We conclude that a combination of physical, soft and knowledge policies has to be applied in an integrated framework. This would direct consumers to low carbon transport modes and create a low-emissions transport scenario. Leaving emissions reduction to 'silver bullet' technologies that might be available in the future, is not enough. Action has to be taken now in order to make an impact. This is due to the long fleet lifetimes and a consequently delayed impact of technology. Many technological options are already available and in combination with infrastructure investments only support the economy, reduce GHG emissions and also provide other long-term benefits such as increased mobility, reduced air pollution and easing congestion.

Research and development incentives should be given for the promotion of scientific and engineering research on low carbon technologies. This could make advanced, low carbon fuels and drivetrains available in the medium-term providing environmental and societal benefits.

How certain policy measures will influence our transport system and travel behaviour will be assessed in a comprehensive foresight study by the Smith School of Enterprise and the Environment, utilising scenario building and transport modelling that will follow this initial horizon scanning project.

Figure 7.2: Status Quo (grey) and possible low-emission (green) scenario
(Visualisation, y axis represent 100% of journeys, x axis represents journey distance)



MTS = Mass Transit System (urban)
DRT = Demand Response Transport (rural)
HPT = Human Powered Transport

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