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Transport and climate change: a review

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Abstract

Transport accounts for 26% of global CO_2 emissions and is one of the few industrial sectors where emissions are still growing. Car use, road freight and aviation are the principal contributors to greenhouse gas emissions from the transport sector and this review focuses on approaches to reduce emissions from these three problem areas. An assessment of new technologies including alternative transport fuels to break the dependence on petroleum is presented, although it appears that technological innovation is unlikely to be the sole answer to the climate change problem. To achieve a stabilisation of greenhouse gas emissions from transport, behavioural change brought about by policy will also be required. Pressure is growing on policy makers to tackle the issue of climate change with a view to providing sustainable transport. Although, there is a tendency to focus on long-term technological solutions, short-term behavioural change is crucial if the benefits of new technology are to be fully realised.

Keywords: Transport; Climate change; Behavioral change; Technological change; Aviation; Freight; Car ownership; Alternative fuels

1. Introduction

Over the last century, the planet has metaphorically contracted as transport has developed to meet the demands of the populous. Global participation in this expansion has been disproportionate (WBCSD, 2001) as the driving force for transport demand is ultimately economic growth, which in itself results in an increased need for travel. Although this link is gradually weakening (DfT, 2004a), there are few signs of a full breakdown in the unsustainable relationship between increasing incomes and transport emissions (Schipper and Fulton, 2003). The reliance on transport appears to be causing long-term damage to the climate, and the ever-increasing consumption of fossil fuels means that peak production of petroleum is imminent (Duncan and Youngquist, 1999) and world resources will near exhaustion within 50 years (Oman, 2003). Rapid decisions now need to be made so that the impacts of transport on the environment can be minimised and fossil fuel resources conserved. This paper reviews the impact of various modes of transport with respect to climate change inducing greenhouse gas emissions and discusses ways in which society can adapt to reduce the impacts.

1.1. Climate change

Natural forces ensure that the Earth has experienced a changing climate since the beginning of time. However, during the last century, anthropogenic (human) activity has threatened significant climate change over a relatively short time period (Karl and Trenberth, 2003). The term 'global warming' is well documented and refers to the measured increase in the Earth's average temperature. This is caused by the build-up of key greenhouse gases in the atmosphere accumulated from continual combustion of fossil fuels and landuse changes over the 20th century (Weubles and Jain, 2001). The anthropogenic signal has now become increasingly evident in the climate record where the rate and magnitude of warming due to greenhouse gases is directly comparable to actual observed increases of temperature (Watson, 2001). Any change to the composition of the atmosphere requires a new equilibrium to be maintained;

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a balance ultimately achieved by changes to the global climate.

Radiative forcing, the change in the balance between incoming solar radiation and outgoing infrared radiation caused by changes in the composition of the atmosphere, is investigated by using global climate models (GCMs) that represent the interactions of the atmosphere, land-masses, oceans and ice-sheets. By predicting how the global climate will respond to various perturbations, projections can be made to determine how global climate will change under different conditions. Under the six illustrative emission scenarios used by the IPCC (Intergovernmental Panel on Climate Change), CO_2 levels are predicted to increase over the next century from 369 parts per million, to between 540 and 970 parts per million (Nakicenovic and Swart, 2000). This translates to an increase in globally averaged temperatures of between 1.4 and 5.8 °C (Watson, 2001), in turn leading to an increase in extreme weather events and a rise in sea levels. However, predictions made with GCMs need to be viewed with caution (Lindzens, 1990), as they are an oversimplification of what is a complicated and dynamic system. Indeed, the large number of emission scenarios considered underlines the uncertainty in making predictions so far into the future as it is unclear as to what extent technological and behavioural change will help the situation. Nevertheless, the growth in CO_2 emissions is unsustainable and will soon exceed the level required for stabilisation (currently estimated to be in the region of 400–450 parts per million; Bristow et al., 2004). Furthermore, the radiative forcing experienced from CO_2 today is a result of emissions during the last 100 years (Penner et al., 1999). It is this inertia that means that some impacts of anthropogenic climate change may yet remain undetected and will ensure that global warming will continue for decades after stabilisation.

1.2. The role of transport

Oil is the dominant fuel source for transportation (Fig. 1a) with road transport accounting for 81% of total energy use by the transport sector (Fig. 1b). This dependence on fossil fuels makes transport a major contributor of greenhouse gases and is one of the few industrial sectors where emissions are still growing (WBCSD, 2001). The impact of transport on the global climate is not limited to vehicle emissions as the production and distribution of fuel from oil, a 'wells to wheels' approach, produces significant amounts of greenhouse gas in itself (Weiss et al., 2000; Mizsey and Newson, 2001; Johannsson, 2003). For example, consideration of total CO_2 emissions from an average car showed that 76% were from fuel usage where as 9% was from manufacturing of the vehicle and a further 15% was from emissions and losses in the fuel supply system (Potter, 2003).

Transport was one of the key sectors highlighted to be tackled by the 1997 Kyoto protocol. The aim was to reduce worldwide greenhouse gas emissions by 5.2% of 1990 levels by 2012. Therefore, since 1997, transport has featured heavily in the political agendas of the 38 developed countries who signed the agreement. Fig. 2a shows that the transport sector accounts for 26% of global CO_2 emissions

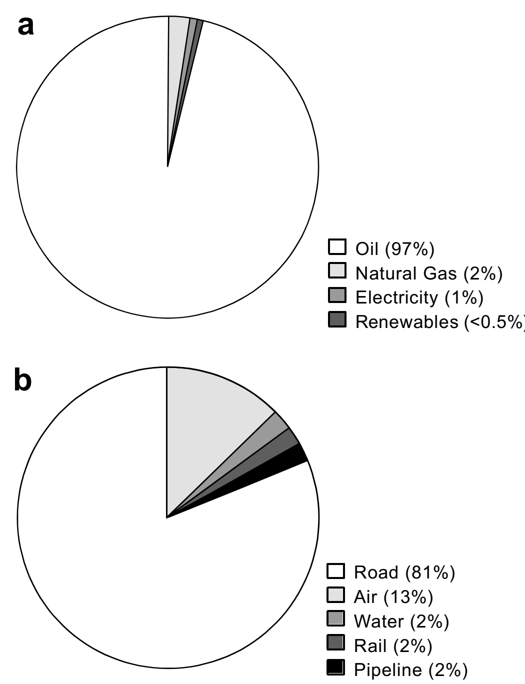

Fig. 1. (a) Fuel use in the transportation sector in OECD (Organisation for Economic Cooperation and Development) countries and (b) shares of transport modes in OECD countries. *Source:* IEA, 2002.

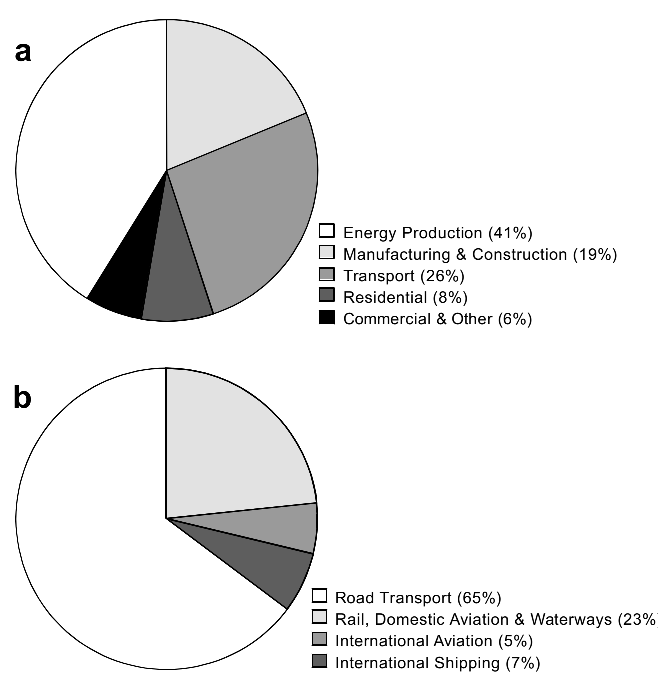

Fig. 2. (a) Carbon dioxide emissions per sector and (b) carbon dioxide emissions per transports sector. *Source:* IEA, 2000.

(IEA, 2000), of which roughly two-thirds originates in the wealthier 10% of countries (Lenzen et al., 2003). Road transport is the biggest producer of greenhouse gases in the transport sector, although the motor car is not solely responsible for all these emissions (Fig. 2b). Buses, taxis and inter-city coaches all play a significant role, but the major contributor is road freight which typically accounts for just under half of the road transport total. Away from road transport, the biggest contributor to climate change is aviation. Aviation is much more environmentally damaging than is indicated solely by CO_2 emission figures. This is due to other greenhouse gases being released directly into the upper atmosphere, where the localised effects can be more damaging then the effects of CO_2 alone (Cairns and

Table 1
Modal split of passenger transport energy consumption in OECD countries with projected annual growth rates in parentheses (*Source:* Lenzen et al., 2003)

Mode	North America	European OECD	Pacific OECD
Cars	57 (+1.4)	54 (+1.7)	57 (+1.2)
Railways	1 (+0.4)	1 (+1.0)	3 (+0.9)
Buses	1 (+1.5)	3 (+1.3)	1 (+0.8)
Aviation	8 (+2.3)	8 (+4.5)	5 (+3.3)

Table 2
Modal split of freight transport energy consumption in OECD countries with projected annual growth rates in parentheses (*Source:* Lenzen et al., 2003)

Mode	North America	European OECD	Pacific OECD
Trucks	24 (+2.0)	30 (+2.2)	25 (+1.9)
Railways	7 (+1.6)	3 (+0.1)	3 (+1.8)
Shipping	2 (−0.7)	1 (+0.1)	5 (+0.2)

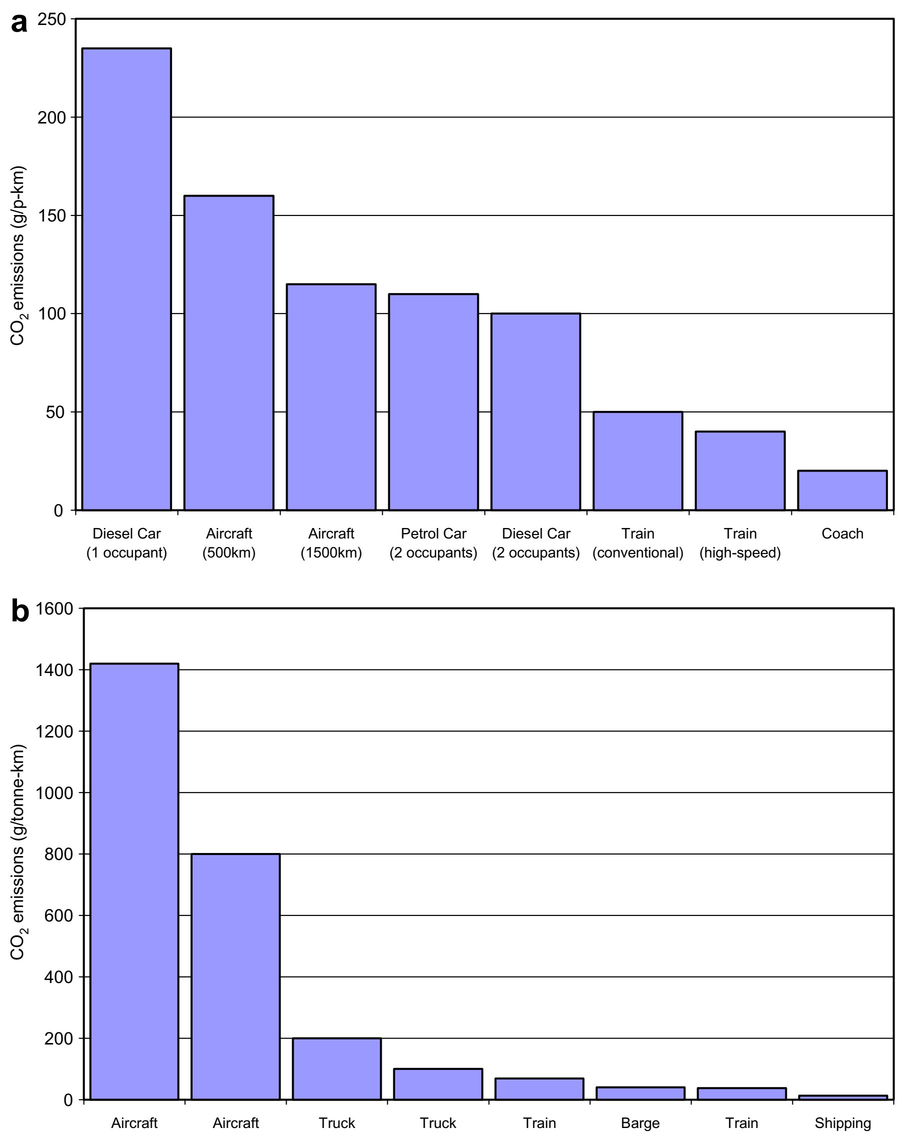

Fig. 3. Carbon dioxide emissions for long-distance travel per: (a) passenger kilometre (*Source:* Dings and Dijkstra, 1997 cited in Bonnafous and Raux, 2003) and (b) freight kilometre (*Source:* Roos et al., 1997 cited in Bonnafous and Raux, 2003).

Newson, 2006). Although, the actual energy consumption and CO_2 emissions from aviation appear relatively low when compared to the motor car (Fig. 2b, Table 1), it is the projected expansion in aviation which is the biggest concern. Air transport shows the highest growth amongst all transport modes (Lenzen et al., 2003) and is predicted to be as high as 5% per annum for the next decade (Somerville, 2003).

All transport sectors are experiencing expansion (Tables 1 and 2) and unfortunately there is a general trend that the modes which are experiencing the most growth, are also the most polluting. Fig. 3a shows a breakdown of CO_2 emissions per passenger kilometre. Aviation and motor cars are increasingly the favoured modes for passenger transport, but are also significantly the most damaging. A similar picture is shown for freight in Fig. 3b where again, aviation and road freight are both the sectors with the biggest growth and highest CO_2 emissions. Hence, there is a need to break the relationship between the current preferred movements of passengers and freight with the most polluting modes. Either the favoured modes need to be made less polluting through technological change or alternative modes need to be made more attractive via behavioural change driven by policy (DfT, 2005a). Clearly, the biggest challenges are car usage, the rapid expansion of aviation and the increase in road freight (Lenzen et al., 2003; DfT, 2004a). Hence, this review focuses on the impact of growth in car use, aviation and freight with respect to climate change inducing greenhouse gas emissions and discusses ways in which society can adapt to reduce the impacts.

2. Car ownership and use

2.1. Background

The developed world is obsessed with the motor car. As affordability increases, so does car ownership; a trend currently being seen in emerging economies such as India and China (Dargay and Gately, 1999). The motor car is the second biggest contributor to greenhouse gas emissions in the transport sector (behind road freight) and although advances in technology should eventually reduce fuel usage and emissions, these improvements will be offset in the near-term by increased ownership and use (WBCSD, 2001). Existing infrastructure cannot cope with large increases in the number of motor vehicles and congestion is becoming an increasing problem in many towns and cities across the world. Not only does this contribute to increased air pollution and CO_2 emissions, it also has significant economic consequences. However, changing attitudes regarding dependence on the motor-car will be a challenge. Using the UK as an example, where a quarter of all car trips made are actually under two miles in length (Mackett, 2000), 89% of motorists surveyed agreed with the statement "I would find it very difficult to adjust my lifestyle to being without a car." (Ryley, 2001). Goodwin (1995) estimated that just 20% of trips are not locked into car use. However, it is now thought that as many as 80% of journeys could be completed using an alternative mode of transport (Stradling, 2003). It is estimated that a viable alternative to the car already exists for 40% of journeys and with modest improvements to infrastructure, a further 40% of journeys could be completed without a car (Brög and John, 2001). Nevertheless, continual increases in car ownership and use confirm that these estimates are optimistic. Unless investment and policy force behavioural change, improvements in technology may be the only way to tackle the environmental damage currently being caused by the motor car.

2.2. Car mitigations

In order to reduce CO_2 emissions from road transport, a significant modal shift onto public transport is required (Waterson et al., 2003). Trains and buses provide the obvious solution, but additionally, 'zero-carbon' walking and cycling are real alternatives. Policies are required to encourage the shift to other transport modes, but will ultimately fail unless significant investment is used to make the alternatives viable and attractive. A commonly used tactic to encourage the use of public transport is to offset the affordability of car ownership with various forms of indirect taxation. This could be in the form of increased parking charges at destination or fuel tax levies (a 10% increase in fuel prices usually results in a 1–3% decline in travel; IEA, 2002; Anable and Boardman, 2005). Other options include road tolling or distance based charging based on Global Positioning System technology (Mitchell, 2005), where motorists are charged on vehicle use depending on the route taken and the time of day. Opponents to the scheme believe that such systems will be difficult and expensive to introduce and will offer no significant carbon reductions (Anable and Boardman, 2005). Instead, localised proposals are considered more appropriate in the short term. For example, congestion charging schemes in Singapore and London have resulted in a reduction in traffic congestion of 40% and 30%, respectively, offset by increased bus usage (WBCSD, 2001; Beevers and Carslaw, 2005). However, indirect taxation schemes are often unpopular and public acceptability can be low unless the revenue is reinvested appropriately (Lyons et al., 2004). Indeed, the social fairness of indirect taxation policies can also be questioned. For example, Ryley (2006) describes the dependence of young families on the motor car who would be disproportionately affected by indirect taxation. Ultimately, successful policies need to be sustainable both socially and environmentally (Button and Nijkamp, 1997).

Congestion is a cause of increased emissions and there is some logic in strategically increasing road capacity. A never-ending programme of road building is not the answer (Shrank and Lomax, 2001), but subtle junction improvements and active traffic management systems can significantly reduce congestion. However, the economic benefits of such measures are not guaranteed (SACTRA, 1999) and may not yield significant reductions in emissions (IEA, 2002). Ultimately, the number of vehicles on the road needs to be reduced. Behavioural change can be promoted by 'soft' transport policy measures which enhance the attractiveness of alternatives to car use (Cairns et al., 2004). For example, high occupancy vehicle lanes which encourage colleagues to carpool and share the trip to work via a common travel plan or car club is one solution (DfT,

Table 3
Summary of alternative fuels and vehicles

Description	Advantages	Disadvantages
Internal combustion engine vehicles can be modified to use *biofuels* which are liquid transport fuels produced from recycled vegetable oils or starch and sugar plants. Most vehicles can run on a blend of petroleum with 5% biodiesel or bioethanol (the petrol equivalent) with little or no engine modification or specialist infrastructure. In Brazil, substantial numbers of modified cars run on an 85% mixture where by law, all petrol needs to contain 22% ethanol, derived from subsidised domestic sugar cane	• A sustainable fuel. As the plants grow, they take up CO_2, which is then released back into the atmosphere when the fuel is burned (Maclean, 2004) • Political interest is growing (Jolly and Woods, 2004) and the sugar industry well placed to benefit from 'carbon finance' (Atkinson, 2004)	• Additional energy input is required to process the fuel • Energy yields vary with crop. Yields from rapeseed and wheat are an order of magnitude lower than sugar cane (Johannsson, 2003) • Increases in world population will place more demand on food production than biofuel from agricultural land (Black, 2001) • The cost of biofuels are more expensive than conventional fuels (Khare and Sharam, 2003)
Internal combustion engine vehicles can alternatively be modified to use *gaseous fuels* such as Autogas or Liquid Petroleum Gas (stored in compressed or liquefied form). These provide a 'clean-burning' alternative to traditional petroleum (Baert et al., 2004; Schulten, 2002) and can also be used in fuel cell vehicles to make hydrogen	• One of the most inexpensive fuels available • CO_2 emissions can be reduced by around 30% (Lave et al., 2000) • Potential to extract the gas from landfill or water/sewage treatment	• Most gaseous fuels are still derived from fossil fuels
Fuel cell electric vehicles make use of *hydrogen*, the most abundant element in the universe and has been used as a fuel for manned spaceflights (Oman, 2002). Although the long term vision is to produce hydrogen by the electrolysis of water, most hydrogen is presently formed from the stream reformation of methane; a process by which the hydrogen atoms are separated from the carbon atoms along with emissions of CO_2 (Davidson, 2003). Reformation can take place either on a vehicle using a portable reformer or could be installed as part of a hydrogen infrastructure allowing vehicles to refuel with pure hydrogen (Lovins, 2005). Once onboard the vehicle, the hydrogen is converted into electricity by reversing the electrolysis process using a stack of fuel cells	• A high quality energy carrier which can be readily converted into electricity (Lovins, 2005) • Hydrogen from electrolysis is a sustainable fuel where the only emission is pure water, addressing not only greenhouse gas emissions but also air and noise pollution (DfT, 2004a) • The greatest potential emission reductions of any alternative fuel (Khare and Sharam, 2003) • Proven popular with niche applications such as the urban bus market (Sperling, 2003)	• Does not occur naturally and needs to be liberated from chemical compounds • Additional energy is required for electrolysis • Electrolysis is currently not very efficient and just 51% of the energy is actually utilised after losses (Hammerschlag and Mazza, 2005). In the short term, hydrogen will have to be produced from natural gas and is thus still polluting • Hydrogen would be more expensive to produce then diesel (Lovins, 2005) • Although hydrogen is light, it is bulky making it expensive to transport, store and distribute • Will require a specialist infrastructure
Battery powered electric vehicles were first built in the 19th century and originally outnumbered gasoline vehicles. Electric vehicles also use fuel cells to converts chemical energy into electrical energy, where the electricity producing reactants are supplied from an external source (Khare and Sharam, 2003)	• Zero emissions at source • Electric motors increase efficiency by 20% by using a direct connection to the wheels and therefore use no power when the car is at rest or coasting (Khare and Sharam, 2003) • Additional energy production can be derived from regenerative breaking • 90% efficient compared to 25% of traditional internal combustion engines (Sperling, 2003) • Fuel cells are continually improving, e.g. low cost lithium ion batteries (e.g. Scrosati, 2005)	• The size of the fuel cells adds to the weight of the vehicle and constrains the performance of the vehicle in terms of maximum speeds and the distance vehicles can travel before requiring recharging (Lave et al., 2000) • No storage system is capable of providing driving ranges comparable to those of conventional vehicles (Johannsson, 2003) • The source of energy used for recharging is unlikely to be zero-carbon unless it is produced from renewables or nuclear
Hybrid electric vehicles provide an intermittent step between the internal combustion engine and the electric motor (Ortmeyer and Pillay, 2001). An energy management system is used to optimise the fuel economy of both engines because electric and combustion engines work better under different driving situations	• Provides the advantages of electric propulsion without the need for fuel cells (Lovins, 2005). Electricity is created with on-board generators or recovered from braking • A middling technology (Sperling, 1995) and can take on many forms	• Technology still reliant on the internal combustion engine • Expensive, although grants are often available to help with the purchase but these rarely cover the higher costs involved (Lave et al., 2000)

2004a). Additionally, an increase in the proliferation of communications technology such as the internet, email and video conferencing should mean that more people can now work at home instead of commuting. However, the numbers participating in teleworking are disappointingly low; just 3.4% of the UK workforce actually worked from home in 2001 (DfT, 2003). Teleworkers could also be tempted to make other journeys (e.g. school runs, shopping, etc.) and actually cover greater distances in the car than if they were in the workplace (Black, 2001). However, despite these drawbacks, both teleworking and carpooling remain valuable instruments with great potential to save oil (IEA, 2005).

Technological change will play an increasing role in the reduction of greenhouse gas emissions from transport. A car manufactured today emits less CO_2 and pollutants than a car manufactured a decade ago (DfT, 2004a). Cars are gradually being designed and manufactured differently with an emphasis on lightweight design and ultralow drag which can reduce power requirements by a third (excess weight increases inertia at low speeds and thus decreases fuel efficiency whereas at higher speeds, air resistance is more important: Lovins and Cramer, 2004). Ultimately, the biggest factor is the size of the engine. Smaller cars are far more efficient and use less fuel during travel and idling (EPA, 2006). Further energy can be saved by ecological driving which includes measures such as avoiding harsh acceleration and braking, using higher gears, observing speed limits and keeping the car regularly serviced with the correct tyre pressures (SDC, 2006). Further savings can be made by abandoning onboard air conditioning systems, removing roof racks and switching off the engine when idling. Ecological driving practices can be potentially automated using cruise control systems (IEA, 2002), or alternatively, skills could become part of a driving test or enforced by reduced speed limits complete with monitoring systems (DfT, 2006). However, perhaps the biggest scope for technological development lies in the diversification of transport fuel away from petroleum fuels which contribute to greenhouse gas emissions (Ogden et al., 2004). There is a myriad of options and alternatives such as biofuels, natural gas, hydrogen and electric motors (Sperling, 2003; Maclean, 2004) are all worth considering. A summary of the alternatives, along with their advantages and disadvantages is provided in Table 3. However, there is a need for governments to fund research and development of alternative fuels whilst using taxation policies to enable the switch to fuels with a low carbon content viable (DfT, 2006).

Overall, there is considerable progress in reducing emissions for new cars, but this progress is undermined by the increased use of cars, particularly old and inefficient models (Kim et al., 2003), accompanied by the trend to move to bigger cars such as sport utility vehicles (SMMT, 2006). Furthermore, in an analysis of the past 50 years, Moriaty and Honnery (2004) show that the adoption of new technology has been comparatively slow. Indeed, diesel engines continue to increase their market share worldwide (Sperling, 2003). Often this can be down to cost, but new technology is often expensive and sometimes unreliable. Indeed, when considering a 'wells to wheel' approach, many of the alternative fuels only offer minor CO_2 reductions (Schipper and Fulton, 2003). At the moment, the hydrogen car has the lowest potential purchase and running costs of new fuel solutions (Ogden et al., 2004; Castillo and Pitfield, 2002). However, it performs no better in terms of efficiency, cost and performance then electric vehicles (Hammerschlag and Mazza, 2005) which are perhaps a more sustainable option (Black, 2000). Indeed, hydrogen remains an immature technology requiring specialist infrastructure (Hart, 2003) and as such, biofuel mixtures are likely to provide the best short-term option as they can be adapted for use with existing infrastructure (Keith and Farrell, 2003). Ultimately, the take-up of alternative fuels is hampered by oil prices. Whilst oil remains affordable, alternative fuels are viewed as expensive and unnecessary, often requiring government subsidies (Black, 2000). For example, the economic cost of biofuel has been estimated to be around the region of double of traditional petroleum (Lave et al., 2000). Hence, the easiest solution is to promote the use of smaller, low emission vehicles by changing purchasing behaviour (Bristow et al., 2004). Manufacturers need to be encouraged to continually develop ultra-efficient engines such as those seen in small cars (DfT, 2006). For example, there is a voluntary agreement in the EU to improve fuel economy by 25% by 2008 compared to 1995 (Foley and Fergusson, 2003). However, there is a danger that any lower fuel consumption from new technologies may actually entice consumers to buy bigger vehicles (Schipper and Fulton, 2003). This could be overcome by tax incentives and awareness campaigns such as car labelling (DfT, 2006; Anable and Boardman, 2005). Owners of cars which are more polluting would then be left to pay for the environmental damage that they cause.

3. Road freight

3.1. Background

The growth of road freight is a continuing environmental burden. The movement of freight uses approximately 43% of all transportation energy and slow moving vehicles cause significant congestion on highways (WBCSD, 2001). Table 2 shows the energy consumption of freight for various modes and demonstrates that trucks are not only the dominant transportation mode, but also the fastest growing. Indeed, CO_2 emissions from freight relative to gross domestic product (GDP) are dominated by trucks, particularly in small countries where trucks are a more viable option than other modes (Schipper and Fulton, 2003). Policymakers had expected that dematerialisation (the reduction of material resources needed per unit of GDP) would cause the relationship between GDP and freight traffic to naturally decouple (McKinnon, 2000). Indeed, recent years has seen a trend of decreased material intensity (e.g. growth of the service sector, miniaturisation of products, changes of work materials to lighter materials, increased durability of products; Schleicher-Tappeser et al., 1998), but the total material consumption has actually increased due to overall economic growth. There are now mounting environmental pressures to reverse the growth of road freight to a more sustainable level.

3.2. Mitigations

Since 1980, fuel efficiency in the freight transport sector has been increased by 20% by increasing engine performance and improving vehicle design. A further improvement of 15–20% can be achieved by implementing initiatives to ensure vehicles are operated in a fuel efficient manor (McKinnon, 1999), for example increasing the proportion of deliveries made at night. New technology will play an increasing role in reducing the environmental cost of freight. For example, software based routing and scheduling can enable distance savings of the order of 10% (McKinnon, 1999). Eventually, the haulage industry will also benefit from new fuel technologies, as trucks are more able to cope with bulkier fuels such as hydrogen and heavy fuel cells (Table 3). However, technology will not stop the growth in road-freight and it is this expansion that needs to be targeted if a return to sustainable levels is to be achieved.

Increased dematerialisation can be encouraged by policy, for example the extension of manufacturer responsibilities to include the entire life-cycle of the product. The overall potential through targeted policies is estimated to be of the order of 15% until 2020 (Schleicher-Tappeser et al., 1998). However, this is not a solution to reducing freight to a sustainable level in itself and needs to be backed up by alternative approaches. Larger countries have a greater haulage per unit GDP then smaller countries as a larger proportion of freight is moved by ship or rail (Schipper and Fulton, 2003). Hence, a logical solution for long distance freight transport is a modal shift onto rail and sea. Moving a tonne of freight by rail produces just 20% of the CO_2 produced by moving it by road and as distances increase, rail becomes an increasingly attractive option (WBCSD, 2001). Unfortunately, rail freight can be expensive and requires investment to insure priority haulage routes and assured rights of access (DfT, 2004a). This could be partially subsidised by introducing lower vehicle taxes for environmentally friendly hauliers who use alternative modes wherever possible. However, in countries where road freight is the dominant transport mode covering relatively short distances, modal shift is unlikely to be the answer. Fig. 3b shows that the relative energy advantages of alternative modes are reduced when smaller less energy efficient trucks, still required for local journeys between nodes, are factored into the analysis (McKinnon, 1999). Even assuming large shifts to other modes, a reduction of CO_2 emissions by 25% seems impossible by modal shift alone (Schleicher-Tappeser et al., 1998). Hence, in many instances, larger trucks using improved logistics and sustainable distribution may yield greater environmental benefits (McKinnon, 2000).

Economic growth in developed countries is associated with globalisation characterised by global markets and global sourcing (Schleicher-Tappeser et al., 1998). As a result transport distances and demands increase. Hence, it is important to utilise a logistical decision making framework which affects the numbers, locations and capacities of facilities (McKinnon, 1999). Demand can then be reduced by the development of regional production clusters to reduce transportation costs (Schleicher-Tappeser et al., 1998). For example, *Just In Time* and *Material Resource Planning* systems are flexible and allow the rapid transportation of small loads whilst reducing the distances between suppliers. Regional consumer markets could be encouraged by taxation and by awareness campaigns. For example, lorry operators could pay distance related charges (Foley and Fergusson, 2003) and products could be regionally labelled to increase public awareness (DfT, 2006). In addition to regional and local sourcing, environmental benefits can be achieved by the improved utilisation of the vehicle fleet and, in particular, vehicle loading (McKinnon, 1999). There has been little research on the space utilisation of vehicles (McKinnon, 2000), but many vehicles are filled with low density products long before their maximum weight is reached. This could be improved by using more space efficient handling systems and packaging such as revised stacking heights and modular loads. Bigger vehicles could also be utilised to achieve greater load consolidation, although these are limited by bridge heights, road layouts, facilities at nodes and public opinion (McKinnon, 1999). There is also potential in combining loads with other operators to maximise vehicle capacity. New technologies could be used to implement this such as vehicle tracking and online freight exchanges (McKinnon, 2000). Such an approach could also be used in reducing empty running costs, where operators are unable to find a return load. Freight commonly travels in a single direction and hence there are significant economic and environmental savings to be made by tackling empty running (McKinnon, 1999). In summary, whilst technology, dematerialisation and modal shift will play a significant role in reducing road freight, improved logistics and efficient vehicle loading are probably the most viable solutions.

4. Aviation

4.1. Background

Aviation is a cause for environmental concern, not only because of the associated emissions of vast quantities of world climate changing pollutants, but also due to pollution at a local and regional level. Despite its relatively short history, commercial aviation has undergone tremendous growth. Since 1960, passenger traffic has grown at nearly 9% per year although this slowed to about 5% in 1997 as the industry began to mature (IPCC, 1999). Aviation is now an essential part of the world economic system (Somerville, 2003), but increasing numbers of aircraft will lead to delays in landing (reducing fuel efficiencies), increased greenhouse gas emissions and ultimately, an institutional failure leading to an unsustainable programme of airport expansion. There are many reasons for these increases. For example, cheaper and more abundant flights (often from more accessible regional airports) make travel easier. An increasing economy ensures more business trips and more money available for several holidays a year or even an overseas holiday home. Overall aviation emissions are difficult to quantify as domestic aviation varies greatly from country to country and there is limited agreement on the regulation of international aviation. However, using the UK as an example, aviation greenhouse gas emissions rose by 89% between 1990 and 2003 (ONS/DEFRA, 2005).

Aviation can be split into several sectors of which international travel has seen the most rapid growth, however short haul travel has recently seen large expansion courtesy of 'budget' airlines servicing short distances. Although these airlines appear to service leisure orientated routes, increasing numbers of business travellers are also using these highly polluting services (Mason, 2000). During a flight, the highest quantity of fuel is used during the ascent which means that short haul flights use disproportionately more fuel per km then longer flights (Fig. 3a). A problem compounded by the fact that these flights are more commonly serviced by an older, less fuel efficient fleet. An optimum distance actually exists for fuel efficiency. As the flight time increases, large quantities of fuel needs to be carried which increases the weight of the plane and thus burns more fuel. In addition to passenger aircraft, approximately 18% of aircraft are military where performance requirements ensure that they will produce significantly more emissions (RCEP, 2002). Finally, air freight is the fastest growing sector of aviation. Although, some freight is moved as 'belly' cargo in passenger airlines, there has been tremendous growth in dedicated express services which compete with surface transportation for shipments (WBCSD, 2001).

With respect to radiative forcing, aviation presents a unique problem as aircraft emit gases such as CO_2 and NOx (nitrous oxide) directly into the troposphere and lower stratosphere. Like CO_2, ozone is a greenhouse gas produced from the chemical reaction of sunlight with NOx. However, the reaction actually reduces methane concentrations in the atmosphere which has the opposite effect and promotes negative forcing. The impact of emissions will vary depending on where the aircraft is flying. CO_2 emissions are equally harmful wherever they are released as they become well mixed and have a long residence time (100 years or more) in the atmosphere. Other gases are less well mixed (e.g. ozone) and produce localised radiative forcing clustered around flight paths. Some gases have an increased effect at altitude. For example, NOx emissions in the upper troposphere produce more ozone for radiative forcing than the same quantity released at the surface (Penner et al., 1999). Similarly, water vapour released at low altitudes is removed from the atmosphere as precipitation. However, the small fractions which get into the lower stratosphere will remain there as a greenhouse gas (Penner et al., 1999).

Contrails provide another example of radiative forcing exclusive to aviation. Contrails form when high temperature air from aircraft engines mix with cold supersaturated air commonly found at the higher altitudes (Williams et al., 2003). Contrails are problematic as they can spread to form high level cirrus cloud, thus promoting global dimming (RCEP, 2002). Although there is a link between quantities of high level cirrus cloud and the growth of aviation (Marquart et al., 2003; Stordal et al., 2005), the present knowledge of contrail induced cirrus is not sufficient to provide a reliable estimate of associated radiative forcing (Sausen et al., 2005). For example, in the three days following the 911 attacks in the USA, when all US aircraft were grounded, there was a 1–2 °C increase in day-night temperature differences (Travis et al., 2002). This effect was directly attributed to a reduction in high-level cloud, thus providing some indication of the radiative forcing associated with contrail formation. However, as the US was subject to unusually clear weather in the period directly after the attacks, it was unclear whether the grounding of aircraft was actually the cause of the temperature differences (Kalkstein and Balling, 2004).

In summary, the complicated combination of emissions from aircraft means that the overall radiative forcing by aviation is estimated to be 2–4 times greater than just the impact of CO_2 alone (Lee, 2004). Aviation was largely overlooked in the Kyoto protocol partly due to the combination of gases which contribute to climate change (Somerville, 2003). No targets were set for either international aviation or greenhouse gas emissions other than CO_2 from domestic flights.

4.2. Aviation mitigations

With the exception of diesel motor cars, aviation is the most polluting mode of transport for the movement of both passengers and freight (Fig. 3). This, coupled with the forecasted growth for the sector, makes aviation the most unsustainable mode of transport currently available. Unless the impact of aviation per passenger kilometre can be substantially reduced, then environmental concerns will means that politicians will increasingly need to limit the current expansion of air travel (Cairns and Newson, 2006; Green, 2003). Although the general growth in aviation can be moderated through taxation, there is presently no tax levied on kerosene and any attempts have been unsuccessful due to difficulties in reaching international agreement (Somerville, 2003). Alternative policies could be introduced to optimise existing air capacity to counteract the current trend in airport expansion. By increasing the price of slots at airports, pressure is placed on airlines to maximise the income from each flight. However, the favoured approach to taxation is based on contraction and convergence. Here nations work together to reduce year on year emissions before converging over time towards equal per capita emissions (Bows et al., 2006). Central to this policy are emission permits which provide the buyer with the right to emit a certain quantity of greenhouse gas into the atmosphere. If the total value of all the permits is known and all countries participate, then a global target can be met. Additional mechanisms such as trading can then be used to help minimise the total cost of emission reduction activities worldwide (Troung, 2003; Somerville, 2003). However, there are potential problems in the way permits are distributed; what is an appropriate initial volume and should they be auctioned off or distributed in line with GNP? Ultimately, such schemes can only be successful if unilateral agreement between domestic and international schemes is achieved (Troung, 2003).

As with road transport, another obvious mitigation is to encourage a modal shift away from air travel. Many short haul flights could be replaced by inter-city rail travel where the impacts per passenger kilometre can be up to 20% lower (Fig. 3). However, for this to be attractive, railway infrastructure would need considerable investment and better integration with airports. Fares may also need to be subsidised to make this an affordable option. An equally important modal shift would be to stop the growth in air freight. This could be achieved by limiting air freight to essential perishable goods.

Other than policy change, aviation will also benefit from improvements in technology. The long term objective is to change the design of aircraft to reduce fuel usage and CO_2 emissions (Green, 2003). Although the industry is making advances with improved emissions technology, the sector is growing too fast for these benefits to be realised (RCEP, 2002). Alternative fuels may be an option. For example, the use of low concentration biodiesel could be introduced without significant modifications to aircraft or airport infrastructure and would enable passengers to choose to fly ‘green’ (Wardle, 2003), although there are concerns of the performance of biodiesel at the low temperatures found at altitude (Bows et al., 2006). Other fuels may also present new problems. For example, the use of liquid hydrogen as an aviation fuel will increase emissions of water vapour in the atmosphere. Ultimately, renewable fuels are not seen as a solution for aviation (Somerville, 2003) and instead, improving airframe and engine design to increase fuel efficiency remains a priority. There will be a change in design priority from reducing costs to reducing environmental impact (Green, 2005). Unfortunately, the refinement of conventional turbofan aircraft currently used by virtually all airlines (WBCSD, 2001) is unlikely to be solution, where as new aircraft configurations such as the blended wing-body aircraft and wing-in ground effect vehicles have enormous potential but are very much at the development stage (Bows et al., 2006). However, high speed propeller aircraft are an alternative and realistic proposition. Although the cruise speed is 25% lower than conventional turbofan, a 56% cut in CO_2 emissions per passenger kilometre can be realised (Akerman, 2005).

Changes to air traffic management could also improve fuel efficiency. Improvements in holding and addressing sub-optimal flight routings can reduce the quantity of fuel burned in the region of 6–12% (Somerville, 2003; AEA, 2001). However, there is some debate on whether changing the flight profiles can reduce the impact of aviation. For example, if aircraft cruise at decreased levels, the higher ambient temperatures will reduce contrail formation and the radiative impact from ozone at the expense of increasing both fuel usage and CO_2 emissions. Optimum altitude restrictions would need to be selected for a particular time period that provides the greatest reduction in contrail and ozone for the lowest increase in CO_2 emissions (Williams and Noland, 2005). In most cases, reductions of contrail formation will offset the increase in CO_2 emissions increases making this approach beneficial (Williams et al., 2003). However, a limited cruise altitude would severely reduce air space capacity and increase journey times (Williams et al., 2002). An alternative is to use weather forecasting techniques to identify and avoid areas of supersaturation in the upper troposphere.

5. Alternative transport modes

5.1. Shipping

Shipping is the dominant transport mode for overseas freight and is often recognised as a sustainable, energy efficient and relatively environmentally friendly form of transport (DfT, 2004a). However, shipping is still a considerable source of greenhouse gas emissions. Figures quoted range from 1.8% of total emissions in 1986 (IMO, 2000) to 7% in 2000 (IEA, 2000). The vast amount of sulphur emitted from ships also has a significant contribution to climate change. Sulphur particles can act as cloud condensation nuclei thus reducing the net-warming effect of greenhouse gases (Capaldo et al., 1999). Other environmental problems associated with shipping include vessel oil spills, ballast water disposal, air pollution, anti fouling pollution (tributylin), dredging, vessel scrapping and waste disposal at sea (Talley, 2003).

Currently, 90% of the worlds goods are moved at low cost by shipping with cargos proposed to treble by 2030, taking advantage from economies of scale. There have been large technological advances to improve fuel efficiency by developing better engines, slowing speeds and more efficient ship hulls, which can cut CO_2 emissions by as much as 50% (IMO, 2000). Furthermore, the use of cleaner fuels, such as gas, can reduce ship emissions by as much as 90%. Shipping could also be ideal for the use of fuel cells (possibly as a hybrid) as the bulk and size of these would be less relevant on a ship.

5.2. Rail

A modal shift onto rail is proposed as a mitigation to the environmental effects of both road transport and short-haul aviation (Shaw et al., 2003). Indeed, for many long distance journeys, rail is the only viable alternative. Wheel on rails is seen as an ecologically aware form of transportation, being four times more efficient than road transport for passengers and twice as efficient for freight (Bonnafous and Raux, 2003). However, to make rail an attractive and viable alternative to passengers, there is a need to ensure that strategic rail services are fully integrated with other transport modes such as buses and to ensure that complicated journeys, such as intercity travel, can be completed efficiently. However, Morellet (2002, cited in Bonnafous and Raux, 2003) demonstrated that it is not easy to attract passengers to trains and that a combination of methods is required to change behaviour. In a study in Paris, it was shown that subsidising fares by 50% would lead to a 34% increase in travel by train where as a 33% reduction in road speeds would lead to a 22% reduction in the number of people using their car. With respect to freight, more non-bulk volume on the railways needs to be encouraged as rail is traditionally seen as a transport for bulk markets (Woodburn, 2006).

Unfortunately, rail is not a perfect solution. Although short distance rail is priority for environmental policy, it remains a loss making market (Potter, 2003). Much of the rail system is run using diesel fuel (WBCSD, 2001) but other fuels could be utilised. For example, hydrogen may be more of a suitable fuel for trains than for cars as rail can easily utilise large fuel cells (DfT, 2004a). Electric trains are another alternative. Although these require a dedicated infrastructure, if the energy supplied to non-fossil fuel sources such as nuclear or renewables, production of CO_2 can be minimal (WBCSD, 2001). Increasing numbers of light rail schemes drawing power from overhead cables/third rails are being successfully implemented around the world. These are non-polluting at source and can offer a cost effective solution on routes with the highest traffic and passenger flows (DfT, 2004a).

5.3. Buses

The bus is extensively used as a mode of transport in low income areas (WBCSD, 2001) and is often the only alternative to using a car locally. Buses are flexible and can be deployed quickly in response to changing demand and do not need specialist infrastructure as is the case for trains (DfT, 2004a). A double-decker bus is a sustainable mode of transport and can replace up to 50 other motorised vehicles (IEA, 2002). Traffic and congestion are also reduced as a bus takes up a fraction of the roadspace. Whilst it is not a clean mode of transport, once bus occupancy exceeds three people, then the CO_2 emissions per passenger kilometre are far lower for buses than for cars (Stanley and Watkiss, 2003). Ever cleaner and more fuel efficient buses are being developed with hydrogen and LPG powered buses now in use in many world cities. These technological developments will further decrease emissions per passenger km (Stanley and Watkiss, 2003).

Policy makers need to encourage car users, where possible, to switch to buses (Romiley, 1999). The bus is the most viable form of urban transport and has a major role to play in the delivery of sustainable transport objectives (Bentley, 1998). Higher levels of priority are required to encourage this modal shift involving schemes such as roadspace reallocation (e.g. quality bus corridors, priority treatment at intersections and priority routes linked to park and ride schemes), more frequent services allowing for easier integration with other transport networks, subsidised flat fare schemes, real-time passenger information systems, pre-paid ticketing to speed up boarding and improved CCTV to ensure personal safety (DfT, 2004a; WBCSD, 2001). This could form part of a bigger sustainable development policy reallocating roadspace to public transport, cyclists and pedestrians, thus providing viable alternatives to the car. For example, an increase in bus capacity was seen as the driving force behind the success of the London congestion charging scheme (Santos and Shaffer, 2004).

5.4. Walking and cycling

Walking and cycling is the ultimate 'zero carbon' and environmentally friendly solution for personal transport. However, both walking and cycling have declined significantly over the last 20 years (DfT, 2004b). This decline strongly mirrors the growth and affordability of the motor car and a series of psychological and sociological factors influence this modal choice (Black et al., 2001), ranging from a general poor level of fitness to fear of crime to unfavourable weather. Behavioural change programmes are essential as reducing traffic from short journeys will not only reduce the environmental impacts, it will also make society healthier as a whole.

In order to make walking and cycling a real alternative for local trips, every local authority, business and school needs to consider 'soft' transport policy measures to encourage walking and cycling (Cairns et al., 2004). There are many relatively simple improvements that can be made. For example, 'walking buses' are proving a popular alternative to the traditional motorised 'school run'. Reallocation of space is crucial to increase the safety of zero carbon journeys, this would take the form of cycle lanes and pedestrian areas linked with improved road crossings and safer junctions; a sustainable street includes all modes (Marshall, 2003). Additional improvements can be made at schools and workplaces to incorporate racks, lockers and showers (DfT, 2004a). However, local measures are not the whole solution to make walking and cycling more viable. The main factor behind a decline in zero-carbon trips is that fewer destinations are within walking and cycling distance (Potter, 2003). Hence, the failings in modal choice are actually part of the wider challenge of sustainable development and needs to be viewed from a geographical perspective.

6. Sustainable development

All the mitigation strategies to stabilise greenhouse gases described in this review have the common underlying theme of sustainability. The World Commission on WCED (1987) states that "Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs." Hence, sustainability means no excessive degradation of the environment or consumption of non-renewable resources. It is easy to think that the sustainability of transport is just an environmental problem (Black, 2000), but it also means an avoidance of institutional failures, such as traffic jams which lead to non-sustainable policies of road building (Greene and Wegener, 1997). Sustainable development requires the collective consideration of economic development, environmental protection and social justice when formulating development strategies and policies (Mitchell, 2005).

Equity among generations, individuals and nations is also regarded as a key part of sustainability (Greene and Wegener, 1997). Often the people who cause an environmental problem are not the ones who suffer. Climate change is a classic example of this as one generation struggles against leaving an unwanted legacy for the next. On a smaller scale, air pollution in city centres is caused by commuters who live in the more affluent suburbs. Any move towards sustainable transport is likely to most effect low income groups. Affluent people can afford to buy more efficient vehicles, pay tolls and drive during less congested periods (Black, 2000). Similarly, developing countries face a struggle to grow their economies without facing international criticism about emissions. For example, the recent growth in car ownership in India and China is causing concern in the western world, yet climate change does not feature prominently within the agendas of developing countries. In reality, climate change is likely to have a greater impact here, with vulnerable populations often unable to adapt (Beg et al., 2002). The pressure is on the developed world to cut emissions, yet to police developing countries without hindering their development.

Although modern world economies have grown on transport, the oil upon which 97% of transport is based upon is finite. The advantages of car ownership and use have been outweighed by greenhouse gas emissions, air pollution, noise pollution and urban sprawl. North America has a predominance of highway infrastructure and people choose to drive everywhere due to both the cheap cost of fuel and because of the sprawl of urban centres in North America. Contrast this with the more densely populated Europe, where efficient public transport systems are easily supported (Greene and Wegener, 1997). However, the trend for planning is the continued separation of urban functions taking advantage of cheaper land on the outskirts of urban areas and increasing the dependency on the motor car (Foley and Fergusson, 2003; Herala, 2003). Other improvements to infrastructure such as long distance, high speed rail links further reinforces decentralisation (Potter, 2003). Suburbanisation has emptied the city centres as people have sought to escape pollution and congestion, but have ultimately spread these problems to the suburbs (WBCSD, 2001). Improved land use planning is needed to reverse this trend, creating high quality, sustainable communities in urban areas (Banister, 2000). However, the reality is likely to be the opposite. A growing population less tied to their jobs will encourage people to travel further in exchange for a better lifestyle (DfT, 2004a), but a balance is needed between the need to travel and the need to improve quality of life. Strategic urban planning and design is required which is focussed on reducing the need to travel by targeting car use in urban areas. Potential measures include reduction of space for vehicles, improved conditions for walking, cycling and public transport as well as the introduction of low speed and environmental zones (DfT, 2006). The aim is to make the space easier to get around by walking and cycling then it is by car (DfT, 2005b). Overall, landuse planning is a crucial component of sustainable development.

7. Conclusions

This review has investigated ways in which technological and behavioural change can reduce the combustion of fossil fuels, and thus greenhouse gas emissions in the transport sector. Although policy can respond quickly under pressure, in reality it is a slow process (Greene and Wegener, 1997) and there is a growing expectation on new technology to deliver the solution. Improvements in energy efficiency and research into new fuels will be part of the answer to meeting long-term CO_2 targets such as those laid down by the Kyoto protocol. Indeed, without new technologies, such emission reduction targets may be considered impossible to meet by policy alone, and therefore not adopted. (Sandan and Azar, 2005). Unfortunately, although technology could theoretically provide the required reduction in CO_2, this would be a difficult, expensive and long term solution. In the short term, policies to change behaviour and travel habits are more important than technological solutions (Anable and Boardman, 2005). Ultimately, policy needs to tackle the time management of people and lifestyles (Banister, 2000), yet technological solutions currently dominate policy for transport and climate change (Anable and Boardman, 2005). So called smart measures which encourage voluntary behaviour change do not have mainstream status, despite such policy change being essential to reap the benefits of future technology.

For the three problem sectors identified in this review, it would be simple to conclude that modal shift provides the answer to stabilisation of carbon emissions in the transport sector. In reality, modal shift may form part of the solution, but there are a combination other measures which would provide a quicker and easier solution over a shorter timescale.

- *Car ownership and use.* It is difficult to see how the large-scale behavioural change required to perform a modal shift could happen. Transport systems and urban layouts have great inertia and take years to change (Lenzen et al., 2003; Bristow et al., 2004). As a result, too many journeys remain tied into car usage and without large scale investment it would seem impossible to overcome the barriers. Instead, short term measures promoting behavioural change may provide the answer. By offering substantial tax incentives on smaller cars, manufacturers will make, and people will buy environmentally friendly cars. This can be further reinforced by targeted marketing and raising public awareness (e.g. car labelling). Other viable short term tools include promoting walking, cycling, ecological driving and soft measures (Anable and Boardman, 2005; Schipper and Fulton, 2003). Although seen as more of a long-term solution, landuse planning is perceived as a greater tool to sustainability then soft measures (Bristow et al., 2004) and simple adaptations such as reallocating roadspace and reducing parking are relatively quick and easy to implement. Finally, technology will play a role in the medium term, with an emphasis on improving engine and car design (e.g. hybrids and electric cars) perhaps providing the best way forward (Bristow et al., 2004).
- *Road freight.* Although a modal shift is desirable for road freight, in smaller countries this is simply not possible. Instead, there is a need to increase public awareness to encourage regional production over medium timescales. However, immediate sustainable transportation solutions can have an immediate impact in reducing freight kilometres. In particular, haulage companies need to work together using new technologies to achieve economies of scale by combining larger vehicles with efficient vehicle loading to reduce empty running.
- *Aviation.* The growth of aviation is a major concern, as any carbon savings from other modes could prove meaningless if these trends are allowed to continue (Anable and Boardman, 2005). Technological improvements in aviation are limited and will not address the problematic expansion currently being experienced. Although the policy of contraction and convergence with strict emission targets provides the medium to long term solution, immediate action needs to be taken to limit the growth of aviation. This can only be achieved by international agreement to impose a tax on aviation fuel. The recent expansion of the low cost airline industry is the most unsustainable transport sector and there is a pressing need to change behaviour by making long distance rail travel more financially attractive than short haul flights.

In summary, behavioural change is the key factor to enable transport to pull its weight in relation to other sectors, although technology will help to a certain extent (DfT, 2005b). By using a combination of taxes, regulations, better technology and demand restraint, CO_2 emissions could eventually stabilise, but the effect of these on transport and the wider economy is unknown (IEA, 2000; WBCSD, 2001); the results so far have not been impressive (Button and Nijkamp, 1997). Relying on new technology is not the answer in itself and increasing willingness of the populous to adapt to complement climate change mitigation by technology is crucial. Without an improvement in energy efficiency or a growth in zero-carbon technologies, the goal of CO_2 stabilisation is technically impossible (Schafer and Victor, 1999) as the transport policies in place will not significantly reduce CO_2 emissions in the short term (IEA, 2002). Ultimately, the overall issue of climate change and transport is in fact part of a much larger challenge of sustainable development.

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