Transport Technologies

Climate Change Working Paper No. 5

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Climate Change Project Working Paper Series

March 2006

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Transport Technologies

1. The Technologies

Introduction

The threat of increasingly unsustainable transportation systems in the large cities of the world comes from the interaction between growing demand for transportation services and the environmental impact of transportation. Demand tends to grow at a geometric rate, while the environmental capacity (at given technologies) to handle such growth is fixed. Technology offers enormous possibilities for change in the longer run, but unless harnessed to the goal of sustainability, may aggravate some problems (such as traffic congestion) while in the process of fixing others (reducing emissions per road vehicle kilometre).

A number of key influences are driving a process of accelerating technological change in land transportation. **Traffic congestion** is encouraging new technologies to be adopted in traffic management. Concerns about **traffic safety** are leading to a consideration of new technologies, particularly road design and automated vehicle control. The **availability and price of crude oil** is encouraging research and development on fuel economy, the use of alternative fuels, and the development of fuel cell-powered engines. **Air pollution** problems in urban areas are encouraging the development of technologies to reduce harmful emissions, and concerns about **global warming** are further adding to the search for low-emission transportation. These concerns are also reflected in the adoption of new **regulatory policies** by governments in such areas as fuel standards and fuel economy standards for new motor vehicles.

Significant reductions in greenhouse gas emissions can be achieved by increasing the energy efficiency of transportation equipment. However, increasing energy efficiency of the transportation system takes time, typically 15 years or more between efficiency gains in new equipment and comparable efficiency gains for the entire fleet of transportation vehicles.

Motor Vehicle Technology

The Automotive Industry

Substantial near-term improvements in the fuel economy of new light-duty vehicles can be achieved using available, cost-effective technologies. By 2015, new car fuel consumption can be reduced by up to 25% at low cost by fully exploiting available technologies. In some cases these have negative costs to consumers because the time –discounted vale of fuel savings is greater than the cost of the technologies. Technologies include direct injection systems, other engine and drive-train improvements, lightweight materials, and better aerodynamics. Although stock-turnover considerations mean that the full effect of these improvements would not be realised until 2020-2025, they could still reduce the average fuel use per kilometre for the entire stock of cars by 10-15% over the next ten years in IEA countries. This is a greater improvement than has occurred in some regions over the past 10 years (IEA 2005a).

The past 15 years have seen consumers increasingly choose larger, heavier, and more powerful vehicles. Vehicle efficiency improvements in many countries (notably the United States) have only just kept pace with this trend, resulting in flat or even slightly deteriorating average fuel economy over this period. Therefore, even a strong uptake of efficient technologies may not significantly reduce average vehicle fuel consumption per kilometre unless these trends turn around. The European voluntary agreements and the Japanese Top Runner programs are good examples of policies that encourage technical improvements, but neither has an explicit mechanism to discourage consumers from migrating to ever-larger, more powerful vehicles. Neither do the current U.S. and Canadian fuel economy regulatory systems discourage the purchase of larger vehicles except through a modest (sales-weighted) fuel economy floor that has remained relatively unchanged since 1985 (IEA 2005a).

The means for accelerated technological change in the automotive industry in the longer run will be advances in the application of information technologies, new materials technology, engineering breakthroughs in relation to advanced engine technologies, and the comprehensive utilisation of small scale technologies throughout the industry (note CSES 2003).

The scope of the changes ranges over every aspect of the car’s design, ranging from engines, motor parts, transmission, ignition systems, exhaust controls, vehicle bodies, suspensions, brakes, wheels, vibration dampeners, tyres, filters, coolants, external coatings, windscreens and windows, seats, dashboard and instrumentation, on-board diagnostics, enhanced electronics for driver comfort and entertainment, and automated vehicle control systems. At the same time, the design and manufacture of automobiles will be revolutionised by the application of advanced virtual reality design technologies.

Alternative Fuels

Introduction

One area of technological development of significance to sustainable transportation is that of alternative fuels. Transportation fuels that are alternative to refined petroleum products are: (i) natural gas-based fuels, and (ii) biofuels.

Alternative fuels do not necessarily emit less greenhouse gases than gasoline when used to power a vehicle. Most alternative fuels do contain less carbon per unit of energy than gasoline, but do not necessarily emit less total emissions *well to wheel* – including emissions from the extraction of the alternative fuel or feedstock, energy used in its production, distribution and storage, and its use in vehicles – in a life cycle analysis of fuel.

A few alternative fuels promise substantial reductions of greenhouse gases on a full fuel-cycle basis everywhere. These include ethanol and methanol under certain circumstances, namely when these alcohols are derived from cellulosic (woody) feedstock using advanced, low-energy production processes. However, current commercial alcohol production for transport in IEA countries does not use advanced processes and does not provide greenhouse gas reductions compared to gasoline.[1] Other low greenhouse gas fuels include highly efficient fuel-cell vehicles if produced from renewable or other low GHG feedstocks.

Short-term savings in well-to-wheel emissions can be gained through:

- the use of turbo-injection diesel engines running on low sulphur fuel (25%);
- the use of natural gas (LPG, CNG or LNG) as a fuel (around 20% for CNG);
- cellulosic alcohols (ethanol and methanol) and biodiesel promise larger reductions (50% or more); and
- hydrogen, although the net reduction of emissions depends on how the hydrogen is obtained – on current technologies it has substantially higher emissions, but it could be considerably lower with new, advanced technologies.

In the longer term, after 2010, improvements in vehicular efficiency should lead to improvements of 50% -55% in vehicular efficiency for all fuels used in three-litre combustion engines. Some fuels, such as cellulosic ethanol, promise even greater long-run reductions relative to gasoline, due to expected advances in upstream processes (OECD 2001).

Methanol and DME from Natural Gas and Coal

Alternative fuels currently subject o much interest are methanol and DiMethylEther (DME).[2] Both fuels could be produced from a wide range of feedstocks, including coal, natural gas and biomass. Methanol production from natural gas is an established technology. However, the bulk of this methanol is used for chemicals.

DME can be used as a fuel for power generation turbines, diesel engines, or as an LPG replacement in households. Current global DME production amounts to 0.15 Mt/yr. Its main use is as aerosol propellant for hair spray. Two coal-based DME plants are in operation in China, with a total capacity of 40 kt/yr. A rapid expansion of Chinese DME production is planned, to more than 1 Mt/yr in 2009. Further gas-based projects are planned and proposed in the Middle East.

Biofuels

In the future, ethanol and biogas have increased prospects for use in cars and trucks designed and built to be operable on different types of fuel. Piston engines in conventional motor vehicles can be adjusted to run on alternative fuels (such as ethanol and methanol) which reduce nitrogen-oxide emissions. A new technology known as the flexible-fuel vehicle has been developed which will detect which type of fuel its tank has been filled with and automatically adjust the engine; this would increase the flexibility of the vehicle for operational purposes.

[1] Ethanol produced from grains using conventional harvest and distillation techniques has relatively high emissions (median estimates above gasoline).
[2] DME is non-toxic, contrary to methanol.

Ethanol and biodiesel, as typically produced today in IEA countries, can reduce CO_2 emissions per litre of fuel by 20% to 50% compared with gasoline or diesel fuel, respectively, on a 'well-to-wheels' basis, but they are not near-zero-emissions fuels. Apart from fuel production facilities, the infrastructure investment required to support use of advanced liquid biofuels may be relatively small, since these fuels can be blended with conventional fuels and transported using today's fuel systems in the future. In the future, synthetic diesel fuel should be blendable in any proportions with petroleum diesel and used in conventional diesel vehicles (IEA 2005a).

In 2003, world fuel ethanol production amounted to 28 billion litres, equal to about 0.5% of global oil consumption. The production is mainly concentrated in Brazil and the United States. It is based on sugar cane (in the case of Brazil) and corn (in the case of the USA). The resource base is gradually widening to cellulosic crops and even wood.

Various countries and regions are planning a rapid expansion of ethanol production. Some scenarios suggest that a tenfold increase by 2020 (to 280 billon litres and 3.3% of the market for transportation fuels) would be feasible, based on sugar can ethanol alone (IEA 2005b).

The production of ethanol and methanol from advanced processes using cellulosic biomass (wood, grasses and wastes) is also being examined. These alcohol fuels offer potential for use in pure form, in mixtures with other fuels, in hybrid vehicles, or as a chemical fuel in fuel cell vehicles. The advantage of these fuels is that production of their feedstock is not as carbon-or land-intensive as grain crops. Because wood and grass resources are renewable and store vast amounts of carbon, most of the CO_2 emitted during the use of cellulosic biofuel could be offset by the additional CO_2 removed from the atmosphere by the renewable wood and grass used as feedstock. An important consideration in the development of biofuels is the environmental and agricultural effect of feedstock production (TRB 1997). Such feedstocks offer far greater potential for emissions savings than existing feedstocks such as sugar and grains. Their advantage comes from a broader range of potential feedstock, such as trees, grasses and forestry waste materials, and a more efficient chain of fuel production and use (OECD 2001; IEA 2004).

The Canadian firm Iogen opened a pilot plant for cellulosic ethanol a year ago. It now plans a full-scale plant. Another firm has begun studying a plant proposed for British Columbia using wood as a feedstock. In the longer run ethanol from switchgrass, a woody native American plant, could be the major source of biofuels.

Global Potential

The IEA has studied the question of global potential for biofuels production. Their studies yield a wide range of estimates, but all indicate that it may eventually be possible for biofuels to provide a high share of transport fuel, with 50% to 100% well within the range of several studies. Such estimates depend on assumptions covering many factors, including population growth, food demand, demand for alternative uses of biomass, and demand for transport fuel.

The higher the future fuel demand, the harder it will be for biofuels (or any energy source) to fully meet this demand. The IEA (2005b) projects that the range of biofuels production potentials could meet at least 20% of future transport fuel demand by 2050. Whether this can be done cost effectively is another matter. Other concerns include the effects of intensive biofuels production on ecosystems and the possible effects of developing genetically modified organisms. The latter might be important for improving productivity and lowering costs, but is controversial.

As liquid biofuels become a more important component of the transportation fuel supply, research collaboration has identified four key areas to address:

- bio-based ethanol processes such as pre-treatment and enzymatic hydrolysis of lignocellulosic feedstocks and end uses for lignin;
- potential volume and availability of liquid biofuels from the biomass industry;
- improved process economics (once feedstock availability and price are known); and
- standards and policies for improved deployment.

Engine Technologies

The most exciting area so far as potential for the increased energy efficiency of vehicles is concerned is engine technology. An increase of 25% or more in the fuel efficiency of the internal combustion engine is readily attainable through the gasoline direct injection petrol engine, the use of engines in a low-load mode, and advanced diesel engines (OECD 2004).

Among the new types of internal combustion engines likely to appear in the next decade or so is an advanced two-stroke engine accompanied by new electronically controlled fuel-injection techniques designed to both raise the efficiency of the combustion process and reduce emissions of unburnt fuel. Many of the two-wheeled vehicles which are prevalent in many developing countries are powered by two stroke engines. Two stroke motorcycles are a major source of white smoke and emissions of aromatic hydrocarbons and suspended particulate matter. Technological solutions to the smoke and unburned aromatic hydrocarbons associated with two stroke engines have now become available or are under development. They include catalytic exhaust conversion, direct cylinder electronic fuel injection and electronic computer control (Schwela and Zali 1999).

Hybrid Engines

Hybrid electric vehicles combine two power sources with at least one powering an electric motor. The range of alternative power sources includes batteries, flywheels, ultracapacitors, and heat engines. Hybrid systems come in a variety of configurations. One would use a small, constant speed internal combustion engine as a generator to power high-efficiency electric motors at the wheels, with a high-power-density battery or ultracapacitor used to provide a current boost to the motors for acceleration or hill climbing. The internal combustion engine in this case could be small, efficient and clean because it runs at one design speed. Alternative systems could rely exclusively on batteries for most trips, with the engine-generator for extended range only, or they could use both electric motors and a small internal combustion engine to drive the wheels, perhaps with the electric motors providing high power only when necessary.

Hybrid electric vehicles have three significant advantages over conventional vehicles: regeneration of energy during deceleration, automatic engine shutdown when the vehicle stops, and optimisation of engine drive to allow the electric motor to be used wherever possible. Their disadvantage is that they are heavier than conventional models because of the need to accommodate a relatively large battery pack, an electric motor and an inverter in addition to a conventional engine. This increases their manufacturing costs and reduces their potential efficiency in terms of emissions reduction (IEA 2004). Nevertheless, fuel-economy ratings suggest fuel economy for hybrids as being 25% or better than for conventional vehicles, although recent research conducted in the United States suggests smaller gains in fuel economy (The Economist 2006).

Some efficiency-improving technologies, such as hybrid-electric propulsion systems, are still fairly expensive. Hybrid cars on the market today cost several thousand US dollars more than their conventional-engine counterparts[3], although costs are falling and there is some indication that companies such as Toyota (with global sales of over 100,000 hybrid vehicles as of 2004 and 150,000 in 2005) are now at least breaking even on cost. In North America and Japan, consumers have shown enthusiasm for hybrids, although sales are low due to small production volumes and the availability of only a few models. In Europe, interest appears to be lower, perhaps because there are many diesel vehicles on the market that already fulfil the demand for high-efficiency vehicles to some extent. Although some governments (such as Japan and the United States) provide consumers with financial incentives to purchase hybrid vehicles (up to US$2000 in tax rebates in both countries), most do not (IEA 2005a).

The current high prices for petrol have triggered increased interest in hybrid vehicles. Toyota, the market leader, is aiming to increase hybrid production by 60% in 2006 and this could enable it to halve the price premium over conventional vehicles (Katz 2005). Toyota began offering hybrid versions of its Highlander and Lexus SUVs early this year, and will put a hybrid engine in one of its Lexus luxury sedans, and in its Camry. Toyota aims to sell 1m hybrid vehicles worldwide by 2010.

Honda has just launched a new hybrid version of its popular Civic in America and will put a hybrid engine into its luxury Acura. Producers in America, Europe and Korea have lagged behind Japan so far as hybrid technology is concerned. Ford has just announced it could increase its output of hybrid cars tenfold by 2010. Competitors, ranging from General Motors to BMW and DaimlerChrysler, are scrambling to roll out hybrids of their own. These three companies are cooperating on hybrid technology and will launch hybrid-equipped SUVS in 2007. Volkswagen is cooperating with Porsche (*The Economist* 2005c).

[3] This cost differential varies in different markets. An important additional cost of around $US7000 arises with the need to replace the battery pack (usually after ten years). This, in turn, is tending to depress resale values for these cars.

Fuel Cells

A fuel-cell-powered vehicle is essentially an electric car with the fuel cell and storage tank (for a hydrogen-carrying substance) substituting for the battery. If the fuel is a hydrogen carrier (methanol or natural gas), an on-board reformer is required to release the hydrogen from the carrier fuel. Fuel cells work by taking hydrogen and oxygen and putting them through a chemical reaction to produce electricity and water. Excess electricity from the fuel cell can be shunted to battery storage. The vehicle can then use a high-power-density battery (or other storage devices such as an ultracapacitor or flywheel) to provide the necessary power boost for acceleration, so that the fuel cell does not have to be sized for the vehicle's maximum power needs.

Fuel cells are particularly efficient energy converters, they generate no harmful emissions and they can be refuelled quickly, so that range constraints are less of a problem than with battery electric vehicles once sufficient refuelling infrastructure is put into place. Three types of fuel cells may be suitable for light-duty vehicles: proton-exchange membrane (PEM) fuel cells, alkaline fuel cells, and solid-oxide fuel cells. Of the three, the PEM fuel cells are closest to commercialisation. Substantial reductions in the manufacturing cost of the fuel-cell engine are required for them to become commercially viable.

A fuel cell system using hydrogen produces no carbon dioxide emissions during vehicle use. However, the use of hydrogen fuel means the hydrogen has to be either stored on-board or produced from other fuels such as natural gas or methanol by means of a reformer. In this case, the gains in emissions savings are reduced by the impact of reforming the fossil fuel source.

With hydrogen fuel, the engine technology is simple and emissions and energy efficiency are optimised. However, current on-board hydrogen storage options are either expensive or carry significant weight and space penalties[4]. The subject of hydrogen storage is covered more fully in the chapter on alternative energy.

In addition, the costs of developing a suitable fuel distribution network would be very large and there are difficulties associated with the potential for losses and leaks in the production process and during the filling of vehicle tanks (IEA 2004). The ultimates cost is uncertain because only limited operational experience is available. About 100 hydrogen refuelling stations have been built. These stations deliver either gaseous hydrogen (90% of the stations built in 2004 and 2005) or liquid hydrogen. They either produce the hydrogen on-site from electrolysis or steam reforming, or receive it from centralised plants. There are significant potential economies of scale operating in hydrogen distribution.

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[4] Hydrogen has a low energy content density so that it requires a comparatively large storage area compared with other fuels. For this reason, hydrogen is often stored as a compressed gas in pressure vessels or as a liquid in cryogenic tanks. Present on-bord gaseous storage is sufficient for buses, but the pressure is too low for passenger vehicles. On-board storage tanks are still too expensive and have short lifetimes, while the high energy needs for compression and liquefaction add considerably to the final cost of hydrogen. In the very long run solid storage has the potential to store hydrogen at a low volume of storage and low pressure and require fewer energy inputs (IEA 2005d). However, it is in the very early stages of development with more scientific research and a number of applier research problems needing to be solved.

The high cost of refuelling stations and the high initial cost of hydrogen for end-users due to the low level of demand and the low density of hydrogen infrastructure creates a problem. Little hydrogen supply infrastructure will be developed without significant hydrogen demand, but hydrogen demand depends on the existence of a large-scale hydrogen supply infrastructure that can deliver hydrogen at an attractive price. In order to achieve significant momentum in the transition phase, either a dedicated fleet of vehicles that operate in a small area (such as buses) or multi-fuel vehicles that can use hydrogen or gasoline (such as the forthcoming Mazda dual-fuelled RX8) will be required in order to encourage infrastructure growth (IEA 2005d).

Ballard Power Systems, the biggest maker of automotive fuel cells has formed a consortium with Daimler-Benz and Ford. A combined investment of $US1 billion is planned, and the new consortium hopes to produce an initial 10,000-50,000 cars a year powered by fuel cells. Ballard is seeking investment from China as it tries to increase sales in the world's third-largest vehicle market. Ballard has supplied the fuel cells for three DaimlerChrysler buses to be used in Beijing in a pilot project staring in November. The Chinese government plans to expand the test to Shanghai (Ohnsman 2005).

Ballard does not have the field to itself – about 30 companies are actively developing fuel cells for automotive applications, including Allied Signal and International Fuel Cells (part of the United Technologies Group) in the United States, De Nora in Italy, and Siemens in Germany. Among the vehicle manufacturers, General Motors, Honda and Toyota are also developing fuel cells (APEC Center for Technology Foresight 2000).

Most fuel cell use today is limited to vehicles owned by government agencies and universities. Hydrogen-powered fuel cell buses using methanol as a primary fuel are being trialled in Europe and Australia and General Motors, Ford Toyota, Honda and DaimlerChrysler are within a few years of selling fuel cell family cars. Mercedes has developed its latest fuel cell-powered A Class, the result of a six-year research program, that uses the space between its double floor to house its fuel cell (de Fraga 2005). However, the broad range of approaches being taken by vehicle producers suggests that there is no clear optimal strategy to get hydrogen and fuel cells to the market (IEA 2005d).

At present the cost of fuel cell vehicles is prohibitive. IEA (2005d) estimates it at $US167,000 currently, This decomposes into the cost of a conventional vehicle without engine ($US17,050), the cost of gaseous hydrogen storage ($US4,000), the fuel cell stock ($US144,000), and an electric engine ($US1,900). By 2010, the IEA expects the cost of the fuel cell stack could come down to $US40,000 and the overall vehicle to $US60,750. By 2030 the cost of such a vehicle might reduce to between $US22,000 (an optimistic projection) and $US27,000. The reduction in fuel stack costs to $US7,000 are achievable through mass-production and technology learning. To be competitive, the fuels stack costs need to be reduced below $US3,500, and that will require fundamental advances in materials, higher fuel cell power densities. Research is focusing on high-temperature membranes that are less prone to poisoning and enable on-board reforming. In addition to fuel cell stack cost reductions, hydrogen vehicles need improvements in their durability and reliability.[5] Other components, such as the cost of the balance of plant, electric drive and hydrogen storage systems, need more attention (IEA 2005d).

Other Fuel-Saving Technologies

Major improvements in the energy efficiency of motor vehicles can be achieved through a radical shift in technology and design. The basic features of an advanced automobile incorporating radical new technologies are outlined below.

Materials Technology

The materials used in an average vehicle – glass, steel, aluminium and plastics – are highly energy-intensive. Moreover, traditional materials technology in vehicles is well short of optimal for recurrent vehicle energy consumption. Reconciling safety with environmental sustainability offers a considerable challenge to materials technology. Light composite structures can be even stronger than steel, although the assessment of the robustness of composites to accidental impacts is more difficult than for traditional metals. The manufacturing technology for strong, lightweight composite materials is still accomplished largely by hand and costs are prohibitive.

Much research needs to be done on the feasibility of automated manufacturing processes for new materials. Nevertheless, materials technology and its application to transportation in terms of motor body construction and for components is a key area for research in both the United States and Japan. The utilisation of new vehicle body materials, such as carbon-fibre or other composite materials, and also lighter metal alloys should increase energy efficiency by reducing mass, and at the same time have a lower energy-content in their production. The extensive use of aluminium and other light-weight materials[6] in suspension and other components (such as brake fittings, sway bars, and wheels) can also improve energy efficiency.

The IEA is sponsoring research on the development of revolutionary materials (structural ceramics and ceramic matrix composites) for operation at higher temperatures and pressure. Hard, wear-resistant, durable and insulating ceramic coatings are an expanding technology for improving the durability, reliability, and efficiency of diesel and turbine engines for automotive and industrial power. A key feature of the research is to assess methods of quantifying thin ceramic coating adherence in order to establish test standards for evaluating new technologies.

Research is also being conducted in the area of surface engineering in order to improve the resistance to wear and contact damage. Friction loss is inherent in most mechanical systems. This research explores the possibility that surface texture designs could reduce friction using thin films and coatings under a broad range of contact conditions (IEA 2005c).

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[5] The addendum at the end of this chapter contains more observations on fuel cells for vehicles.

[6] Including high strength steels, magnesium, metal and polymer composites, titanium, and inter-metallic alloys.

Electronics

Integrated starter/alternator electrical systems allow engine shut down during idling or deceleration and instant restarting when needed. Regenerative braking is another energy saving technology. Improved engine efficiency operating under low-load conditions (e.g. shutting down cylinders) could increase engine energy efficiency by up to 25%. Improved drive-train efficiency and the introduction of more electric-drive-train components, such as ‘drive-by-wire’ (fully electric) steering can also improve energy efficiency.

Vehicle Maintenance

New technologies have an important role to play in enabling improvements in the maintenance of road vehicles. Better maintained vehicles will be able to operate close to their rated energy efficiency. On-board diagnostic systems monitor all the emission controls on a vehicle and warn the driver, through instrument panel displays, of any faults that may occur. These systems have become mandatory for new passenger motor vehicles in the United States. Even greater opportunities for detecting malfunctioning vehicles is provided by the use of transponders to allow roadside units to monitor the condition of vehicles as they drive by. Within 20 years, these systems could be installed in sufficient numbers to render inspection and maintenance programs unnecessary. The aerospace industry has been a leader in developing preventive maintenance strategies, and it continues to be an area of significant technological development. There are implications in all of this for maintenance of rail and marine transport equipment.

Other Technologies

Other specific examples of fuel-saving technologies are summarised below (Greene and Schafer 2003).

1. *Advanced transmissions* offer an improvement of several per cent in energy efficiency.
2. *Advanced aerodynamic styling.* Enhanced streamlining, using sophisticated body design and reduced frontal areas, aimed at reduce the vehicle’s drag coefficient, can offer improvements in energy efficiency of about 2%.
3. The introduction of high-pressure, low-rolling resistance *tyres* can reduce fuel consumption by 1.5%.
4. More efficient *accessory equipment* (such as air conditioners) can increase energy efficiency.

In-Use Vehicle Fuel Consumption

Light-duty vehicles (LDVs) on the roads in IEA countries typically use 20-25% more fuel per kilometre than indicated by their tested, rated fuel economy. Much of this gap is inevitable owing to traffic congestion. Integrated urban/transport planning and road traffic management therefore become important influences on fuel consumption (discussed in more detail in a later sub-section of this paper).

Other measures may help to reduce in-use vehicle fuel consumption. The IEA, in cooperation with the European Conference of Ministers of Transport (ECMT), recently completed a study of technologies and measures to improve ‘in-use’ or ‘on-the-road’ fuel economy of light-duty vehicles.

The IEA estimates that a 10% reduction in average fuel consumption per kilometre could be achieved for LDVs across IEA countries through a combination of the following measures:

- stronger inspection and maintenance programs that target fuel economy;
- on-board technologies that improve in-use fuel economy as well as driver awareness of efficiency, such as adaptive cruise control systems and fuel economy computers;
- better and more widespread driver training programs; and
- better enforcement and control of vehicle speeds.

Cost estimates for the CO_2 emissions reductions offered by in-use technologies and measures vary, but many technologies show low or negative cost per tonne of avoided emissions in some situations. The effects of technologies and measures on fuel consumption also vary, but a package can be developed that provides a 5-10% improvement in vehicle fuel economy on-the-road for a given tested fuel economy (IEA 2005a).

The self-driving car is undergoing developmental work. It can be the means of reducing in-fuel consumption through more efficient use of road space in urban areas. General Motors is the trialling a car that uses updated technology combined with several existing innovations and could be in production by 2008. The GM car is based on the Opel Vectra, a mid-sized family vehicle and is undergoing evaluation at General Motors’ subsidiary in Germany.

The advanced technologies incorporated in the self-driving car are:

1. Automatic cruise control (already available in many expensive cars) incorporating a new laser technology for use at shorter distances and lower speeds.
2. A system that corrects the car when it drifts out of its lane. Lane-departure warning systems have been introduced for a very few cars already, but the new technology uses cameras and laser beams linked to an electronic control unit attached to an electric power-steering unit.

The system is unlikely to have a smooth progression into production, however, despite achieving what General Motors says is a very high level of reliability during the development stage, and despite a modest estimated cost of US$1800 a vehicle. Several obstacles stand in the way. Self-steering cars are currently illegal in most European countries, and carmakers are concerned about issues of legal responsibility. In addition, most people would prefer to be active drivers solely in control of the vehicle. Moreover, the system is basically designed for heavy urban traffic or motorway conditions, and not the open road (*The Economist* 2005b).

Trucks and Buses

Trucks

Heavy-duty vehicle efficiency can be improved by about 25 per cent (in long-distance transport) to 50 per cent (in short distance stop-and-go transport). Heavy duty vehicles operate in both long-distance and local transport, with the total fuel use being roughly equally split. After driver compensation, fuel costs are typically the second largest expenditure item for heavy-duty vehicle operators. As a result, virtually every large new truck and bus in the United States is already equipped with a turbo-charged, direct-injection diesel engine, the most energy efficient internal combustion engine available. State-of-the-art turbo-charged diesel engines achieve 46 to 47 per cent peak thermal efficiency, versus only 25 per cent for spark-ignited gasoline engines. Thus, there is less potential for improving fuel efficiency in heavy-duty than light-duty vehicles (Greene and Schafer 2003).

A variety of new diesel engines are becoming available to freight trucks. *Turbocompound* engines are technically ready but have not been commercialised although high fuel prices may provide an incentive for commercial developments. *Low-heat-rejection diesels* are compression-ignition engines that run at very high temperature and do not use energy-draining cooling systems. *Gas turbines* harness fuel energy by using the burning fuel's kinetic energy to spin a turbine rather than drive a piston. Both engines types require the development of mass-producible materials with higher heat resistance than currently available (structural ceramics or heat-insulating composites). Estimated fuel savings for low-heat-rejection diesels are as high as one-third over modern diesels.

Electronic engine control systems can monitor and adjust fuel consumption, engine speed, idle time, road speed, and other factors. They can also provide extensive feedback data to drivers on energy use. They were developed largely to meet new emissions requirements, but they have energy-efficiency benefits as well. They are currently available on some long-haul heavy trucks (APEC Centre for Technology Foresight 2000; Office of Technology Assessment 1994).

Because they can recover braking energy and shut off the engine during idling, hybrid drive trains are a promising technology to heavy-duty vehicles that operate locally, in stop-go mode (Greene and Schafer 2003).

Electronic transmission controls measure vehicle and engine speed and other operating conditions, allowing the transmission to optimise gear selection and timing, thus keeping the engine closer to optimal conditions for either fuel economy or power than is possible with hydraulic controls. This technology offers about four per cent improvement in fuel economy.

Better power/load rations can be obtained through the increased use of B-double and B-triple combinations. However, there are ultimate mass limits to the extent these designs can be taken, as well as impacts on road wear and tear to be taken into account. In addition, allowable truck size are controlled by regulations in both the United States and Europe, which are not fully uniform in either region. The use of lighter materials in truck and trailer bodies, engines and components can also improve power/load ratios, but there is sometimes a trade-off with safety to be considered in implementing such technologies.

It should be noted that currently available technology does not allow automakers to improve light-truck fuel economy through advanced aerodynamics to the same extent that they improve passenger vehicles. Load carrying requirements impose structural and power needs that are more of a function of the payload weight than the body weight of the truck, yielding fewer flow-through benefits from weight reductions. Open cargo beds for pickups and large ground clearance limit potential for aerodynamic improvements. Additional safety and emission requirements would create penalties for fuel economy.

Nevertheless, modifying the shape of the truck and trailer can yield significant reductions in energy use by reducing air resistance. The primary aerodynamic improvement used on heavy trucks today is the cab-mounted air deflector, which began to be installed in the 1970s. Since then, a number of improved aerodynamic devices have been used, including various devices to seal the space between the truck and the trailer, front air dams, and improved rooftop fairings. The simpler devices can often be retrofit to existing trucks and, according to one analysis, offer rapid paybacks. Aerodynamic improvements to trailers include side skirts to minimise turbulence underneath the trailer and rear ‘boattails’ to smooth airflow behind the trailer. The energy savings of these devices are difficult to measure. Aerodynamic improvements to tractor-trailers are also limited by the need to connect quickly and simply to trailers of different designs and sizes, to tolerate road surface uncertainties, and to meet size regulations.

Radial tyres have largely replaced bias-ply tyres, except for special applications such as off-road use. This has resulted in reduced fuel use in miles per gallon. A more recent tyre innovation is ‘low-profile’ radial tyres, which weigh less than standard radials and thereby save energy. Also now commercially available are ‘low rolling resistance’ tyres, which use new compounds and designs to reduce rolling resistance. Finally, fuel savings can be achieved by tailoring tyres to specific types of service, powertrains, and roads, including the use of smaller-diameter tyres for low-density cargo, and of very wide single tyres to replace dual tyres. However, truck tyres, unlike automobile tyres, are often recapped when worn: low-profile and low rolling resistance technologies, which cannot be incorporated into recapped tyres, will largely be limited to sales of new tyres (APEC Centre for Technology Foresight 2000; Office of Technology Assessment 1994).

Buses

The use of *dimethyl ether* (DME) provides a way to put natural gas into a convenient liquid form as a motor fuel. A commercially viable process for DME production has recently been developed. Interest in DME is generated, in part, because it can be produced from a wide range of feedstocks, including natural gas, biomass, agricultural and urban waste and coal. Like natural gas and methanol, DME is also a potential fuel for future fuel-cell technologies. It can utilise LPG infrastructure to a large degree. It is some way of commercial application.

Biodiesel is an ester-based oxygenated diesel fuel made from vegetable oil or animal fats. It can be produced from oilseed plants such as soybeans and rapeseed, or from used vegetable oil. It has similar properties to petroleum-based diesel fuel and can be blended into petroleum-based diesel fuel at any ratio for use with conventional diesel engines. It significantly reduces greenhouse gas emissions. However, it is currently very expensive (an option is to produce it more cheaply for waste cooking oils, but supplies are limited) and there are concerns about its impact on NO_x emissions.

Several demonstrations for transit authorities of *hybrid-electric* vehicles have taken place. The total worldwide fleet could reach thousands within a few years. Fuel economy has been tested in the range 55-60 litres per 100km, compared with 70-73 litres per 100km for standard diesels. The efficiency advantage for the hybrid buses occurred despite the fact that they were heavier than conventional diesel buses. Much, although not all, of the additional energy used for accelerating this weight can be recovered via regenerative braking in the hybrid-electric vehicle. Vehicle weight is a concern for hybrids from the stand point of passenger-carrying capacity.

A life-cycle cost analysis of hybrid-electric vehicle technology is complicated by the fact that the technology is quite young and therefore a large body of real-world operating data does not yet exist. It is thought likely that capital acquisition costs, despite reducing sharply, will always be higher than for conventional buses since they include several additional components. Battery replacement costs are a second factor, while maintenance costs are as yet unknown. Against these higher costs, fuel costs and emission costs are very substantially lower. It is likely that these buses will require at least several more years of development, testing and cost reduction before they enjoy widespread commercial application.

While the understanding of the technology underlying *fuel-cell* stacks is approaching maturity, many surrounding vehicle and infrastructure issues remain in early development. In particular, costs, parallel development of electric-drive systems, on-board fuel storage and refuelling infrastructure challenges are likely to impede hydrogen fuel cells from becoming a competitive propulsion system in the near term and perhaps for another decade or more. Moreover, industry has no clear development path and seems to be moving in several different directions. Urban transit buses are serving as an important testing ground for fuel-cell buses.

When pure hydrogen is stored on board the vehicle and used directly, fuel-cell vehicles produce virtually no emissions except water. However, if emissions produced upstream, such as from the production of hydrogen, are included, the environmental impacts of fuel cells may be substantial, depending on the source of hydrogen and the method of reformulating hydrogen-rich fuels into hydrogen; production of hydrogen from natural gas produces a 30% savings, by electricity depends on the source of the electricity. The long-term vision is to produce hydrogen by electrolysis using renewable energy sources, which would yield zero GHG emissions. With on-board reforming of fuels shows that GHG emissions are only marginally lower than diesel buses.

One advantage to developing fuel cells for the transit bus sector is the central fuelling infrastructure. Since transit buses are typically centrally refuelled, new refuelling infrastructure would only be needed at bus depots. In addition, buses have more space than smaller vehicles to accommodate the fuel cell and the compressed-hydrogen tanks. However, scale economies for fuel cells will be largely driven by stationary applications, and the truck market will be of critical importance in developing transport-specific components of fuel-cell systems (IEA 2002).

Almost 80 fuel cell buses are in use world wide in several demonstration projects. IEA (2005d) estimates that the cost of hydrogen fuel cell bus engine systems is around $US1,000,000, compared with $US500,000 for conventional diesel engines. The IEA calculates that fuel cell buses will become competitive if their additional cost is around $US100,000. Buses are potentially the easiest market in which to introduce fuel cells in the transport sector because refuelling is concentrated at fleet depots. However, other potentially leading markets for fuel cell vehicles are delivery vans (which have been operating in Germany since 2001), electric wheelchairs and carts, and forklifts (IEA 2005d).

Other Vehicle Technology

Aerospace

The aerospace sector has always been considered as a high technology industry. The main impetus to innovation in aerospace technologies comes from four sources:

- increased competition in the airlines industry associated with deregulation, which is driving demand for cost-effective aircraft performance and enhanced passenger facilities;
- the medium-term trend towards increased air traffic volumes which necessitates increased focus on the safety of aircraft and aircraft operation;
- concerns about the environmental impacts on technology development in such areas as emissions reduction (not only in relation to air quality at airports, but also in relating to global warming emissions; in the long term, aerospace, because of the high rate of growth of air travel and the nature of upper atmosphere concentrations of gases, represents a major source of growth in global warming emissions) and reduced noise; and
- the resurgence in technological development in the defence industries.

From 1971 to 1998, a combination of technological and operational efficiency improvements achieved a 60 per cent reduction in the energy intensity of commercial air travel in the United States, an average rate of decrease of 3.3 per cent per year. Recent assessments foresee a slower rate of change of energy intensity.

Aircraft fuel efficiency depends on engine-specific fuel consumption, aerodynamic efficiency, structural efficiency (operating empty weight divided by maximum take-off weight), and operational factors, such as occupancy rates, the ratio of flying time to ground time, and the length of the actual route flown, including diversions, relative to the most direct route. Of the approximately 60 per cent reduction in energy use per passenger km achieved since 1970, 57 per cent can be attributed to improvements in the efficiency of aircraft engines, 22 per cent to aerodynamic improvements, 17 per cent to increased seat occupancy rates, and the remaining 4 per cent to a variety of factors, especially increased aircraft size (Greene and Shafer 2003).

The main areas of technological innovation in the aerospace sector are aerodynamics, materials, engines, avionics and electronics, design and manufacturing technologies, maintenance and repair, and safety. Opportunities for further improvements in fuel efficiency remain in all areas, with the largest contributions expected from improved engines and aerodynamics, although other significant sources of potential improvement include weight reduction associated with new materials technology, and low-friction surface coatings (Greene and Schafer 2003; CSES 2003).

In the near term, the fuel efficiency of new commercial aircraft can be improved by about 20 per cent; over the long term, fuel efficiency improvements of up to 50 per cent appear feasible. In the long run, aircraft powered by hydrogen may be possible. Prototype aircraft fuelled by hydrogen have been successfully demonstrated. Liquid hydrogen is used so as to minimise the volume and weight of the storage tanks. However, the volume occupied by liquid hydrogen is four times greater than that of kerosene. The hydrogen-fuelled engine would be as efficient as the kerosene engine, but the volume and weight of the hydrogen storage tanks would result in higher energy consumption of between 9% and 34%.[7] The payload of the hydrogen-fuelled aircraft would be 20-30% lower, and the passenger capacity would also be reduced, though only slightly.[8] As a result of these factors, hydrogen aircraft would be a very costly option for reducing CO emissions (IEA 2005d).

Marine Vessels

Aerospace is one of the most technology-intensive of all manufacturing industries. The technological linkages between aerospace and shipbuilding are becoming increasingly important with the developing complementarities between airframe and hull design and construction, and the extensive use of electronics. Several key technologies are expected to transform shipbuilding in the future – advanced materials, embedded information and communications technologies, advanced hydrodynamic design, engine technologies derived from the experience gained in the aerospace industry, and new technologies that assist maintenance and repair. Fuel savings can be achieved through improved engines, hydrodynamic innovations, improved propellers and the use of water jets as an alternative propulsion system, paint additives that make ship hulls more fuel efficient, the use of alternative fuels (including hydrogen in the long run), and computer controls for piloting ships (Greene and Schafer 2003; CSES 2003; *The Economist* 1999b).

Apart from replacing ageing fleet with larger modern vessels (primarily container ships), the main areas of marine innovation will be in the equipment supporting operations. In particular, short sea transport can be improved through the introduction of new technology (automated cargo handling, fast vessels, fully automated bridge design); and improvements in intermodal transport operation and design (efficient and flexible port handling facilities, multimodal transport management systems, EDI-

[7] Energy increases would be greatest for business jets and very large-long-range aircraft and much lower for regional and medium aircraft.
[8] An additional problem with the use of hydrogen as a source of energy for aircraft is that the emissions of water vapour associated with hydrogen use contributes to climate change at altitudes of 10 km or higher.

approaches for transfer of operational information). Pollution can be reduced through better monitoring and controlling progress of all ship operations, better training of shipboard personnel, and improved designs to reduce spillage in case of grounding (*The Economist* 1999b; Ulltveit-Moe 1993).

Rail

Railway Rolling Stock

The pace of technological change in railway rolling stock is fairly slow because railway rolling stock have long lives. Locomotives are typically rebuilt many times. The relatively slow turnover of both locomotives and freight cars has slowed the penetration of energy-efficient technologies into the railroad system. Nevertheless, the key aspects of technological change in railway equipment can be predicted. They involve suspension and drive, power and energy, communications and information, track, and track environment.

Current developments of both passenger and freight vehicles show that a major thrust of future development effort will be to make vehicles lighter and increase the usable volume. In addition to the obvious measures of exploiting new materials and manufacturing processes and intelligent use of the payload space, a major contribution can be made by the suspension and drive. The suspension and drive will be more compact and lighter, provide good ride quality with lighter car bodies, cope with larger variations of tare to laden mass, and maximise the use of structural clearance gauge.

Many railway diesel engines are special versions of marine or industrial engines and share some common development experience. This is particularly important as the railway engine market is very small. There is nevertheless continuing development – reductions in the number of cylinders required for given engine power, and improved fuel consumption. Further improvements can be expected as microprocessor control becomes more sophisticated and more refined models of engine behaviour are derived. More stringent emission standards have stimulated the use of alternative fuels. For example, the Burlington Northern railway has pioneered the use of liquefied natural gas. It is likely that developments in the application of heat engines to railways will follow those in the automotive field where the legislative stimulus and the market size is so much greater. This is equally true for energy storage devices like batteries and flywheels.

Electrification has obvious attractions for railways since the prime mover is not carried by the vehicle and a power/mass ratio better by a factor of up to 3 is obtained. Electric traction enables faster speeds and provides additional power for short periods more easily than the diesel engine. Of course, electrification requires intensive use to justify the higher infrastructure cost (Office of Technology Assessment 1994; Wickens 1993).

Control Technology

A new generation of control technology is already changing long established practices in railway operations. Combining electronic interlocking with advanced computerised control systems provides the basis for automation of traffic management on the railway. An extension of such technology facilitates multi-media communication of traffic information to customers. Ultimately, such systems would combine operational control including the monitoring and correction of real-time performance, such as energy use, and the allocation of resources in terms of vehicles, infrastructure and staff. These systems would embrace on-board signalling and train control with automatic vehicle identification and continuous track-to-train communication. The final logical step would be the automation of train driving and driverless trains as used in some forms of urban transit.

A major objective of research and development ought to be low cost tracks for guided systems. Little activity exists at present, although it is important to note that some people mover systems are marketed with a prefabricated modular steel overhead track. Another significant trend for the future is the continuing reduction of tunnelling costs in real terms with time.

There is a high degree of mechanisation of track maintenance and machines are becoming increasingly productive. On railways that are increasingly subjected to commercial pressures not only must track maintenance costs be minimised but their must be minimum disturbance to train services. An example of current technology is the Dynamic Track Stabiliser, which enables track renewal overnight with restitution of full speed operation the next morning (Office of Technology Assessment 1994; Wickens 1993).

People-Mover Systems

While inter-city trains have been the main focus of new technological development over the past thirty years, urban people-mover systems may also benefit from new designs. Guideway-based (driverless) systems are a form of ‘Advanced People Mover’ which has been under active development since the 1950s. These systems utilise various combinations of computer, communications and control systems technology. The basic technology of their operational systems has been available for more than 20 years, and some systems in actual operation were developed in the 1970s (APEC Center for Technology Foresight 2000). Vehicles may be ‘supported’ (run on guideways) or ‘suspended’ (hung from guideways). Support for the guideways may be via conventional wheels (rubber or steel) or magnetic suspension (‘maglev’). The Australian Austrans vehicle now in development uses a new type of wheel technology that enables vehicles to turn around tight corners, thereby enabling cheaper guideways to be built around winding streets (Roberts 1998).

Fuels

Owing to their high energy density in terms of both volume and weight, petroleum products are the ideal fuel for air transportation and also meet the requirements of railways and marine diesels.

Because of space and weight constraints, *aircraft* impose the most rigorous requirements on transportation fuels. Liquid hydrocarbons offer the highest energy content per unit weight and volume of any fuel. The only viable alternatives to jet fuel for air travel are liquid hydrogen and liquefied natural gas. The former offers a major challenge for technological development.

Railroad and *marine* two-stroke diesel engines are even more fuel-efficient than heavy-duty truck diesels. Given the current U.S. fuel mix for generating electricity, shifting rail locomotives from diesel to electricity could increase GHG emissions, unless the CO_2 associated with generating the electricity were captured or sequestered. Perhaps the most promising longer-term options for marine and rail transport are high-temperature fuel cells, with conversion efficiencies of 60 per cent and above. Of course, this would require an infrastructure for supplying hydrogen (Greene and Schafer 2003).

Pipelines

Although *pipelines* have been largely ignored in assessments of energy efficiency potential, there can be little doubt that greater efficiencies in pumps and motors are possible (Greene and Schafer 2003).

Transportation Systems

Passenger Transport Systems

Overview

Innovation in passenger transport systems are capable of improving the operational efficiency of such systems and hence fuel efficiency as well as assisting traffic demand management. Key innovations include:

- the use of global positioning satellites to facilitate the development of more complex electronic road pricing systems; and
- new approaches to transit network that improve the efficiency of systems and cater for dispersed travel demand and thereby displace emissions-intensive private passenger traffic.

Electronic Road Pricing

Road pricing represents an important technique for overcoming the economic and environmental costs associated with traffic congestion. Road pricing replaces a system that rations road use by queuing, which wastes people's time and consumes unnecessary amounts of fuel, with one which rations it according to the value different drivers place on their journeys. And as demand for road space varies, so can price: in cities at rush-hour process can be set high; at night and in the countryside they can be kept low (*The Economist* 2005a).

Road pricing is increasingly seen as a precise method of impacting on traffic demand. The latest automated tolling equipment, which deducts charges from electronically tagged vehicles, travelling at speeds of up to 100 miles per hour, is being installed in many countries around the world. Electronic road pricing had its origins as a means of implementing toll charges on major motorway projects. However, its application to time-sensitive roadway charges that discourage congestion have been adopted in Singapore and Noway. Vehicles diverting away from tolled routes on minor roads are a problem for existing electronic road pricing schemes. American plans using global positioning satellites, combined with in-car receivers and digital maps, will enable vehicles to be charged wherever they are within a specific geographic area and at rates that vary according to the time of day and degree of congestion (APEC Center for Technology Foresight 2000).

In political terms, the congestion charge levied in London provides an important demonstration of what can be achieved by road pricing. The congestion charge levied in 2003 has reduced traffic by 15% and increased speeds by 22% in central London without much damage to business. The scheme's success has given the British government the confidence to broach the idea of extending road pricing nationally (*The Economist* 2005a).

Technologies for Public Transit Systems

Many new technologies are under development that could lead to much improved public transit services and therefore more demand for them. For example, the use of Global Positioning Satellite technology to track buses allows bus operators to dispatch buses more efficiently and has led to the introduction of real-time information displays at bus stops that indicate the arrival time of the next bus. Similar displays can be used within buses to indicate upcoming stops.

Another intelligent system being introduced in many cities is traffic signal priority for buses, which increases the probability that a bus will have a green light when it arrives at an intersection, speeding trips (IEA 2005a).

Freight Systems

Introduction

Four approaches can be taken to securing more sustainable freight transportation: improvements in the engine technology and other aspects of truck design such as aerodynamics (dealt with above); utilising options such as load aggregation and electronic commerce to shift road freight to rail and sea or to new forms of intra-urban distribution; adaptations in land use planning; and improved transport logistics. The locations of major freight generating activities, such as transport terminals, distribution centres, factories and shopping centres, will have a major effect on the pattern of urban freight transport and its impact on the urban environment, particularly through reducing the number and length of freight trips.

Technologies that improve transport system efficiency, such as better logistics systems to combine shipments and make sure trucks use the most efficient routes, could also have a large effect on fuel use. The IEA estimates that, for most countries, adoption of an aggressive freight transport efficiency program could yield a 10% reduction in the fuel used for freight movement over the next ten years (IEA 2005a).

Trucking Operational and System Efficiency

The recent emergence of new information technologies has expanded the potential for improvements to freight operational efficiency (OECD 2001).

Driver Training, Vehicle Maintenance and Other In-Use Efficiency Measures

For heavy-duty trucks, *driving* style is generally acknowledged to be the single greatest influence on vehicle fuel performance. Various studies have estimated that regular training in fuel-efficient driving techniques can yield fuel savings up to 15%-20% per vkm. A British study found trained drivers were 6% more fuel-efficient than untrained drivers.

Relatively few drivers receive proper training on a regular basis. Constant reminders to drivers and regular feedback on performance are valuable tools for improving driver performance. Several emerging information technologies also may help drivers boost efficiency:

- advanced fuel-economy meters;
- advanced transmissions; and
- future navigation systems with optimal cruise control.

Overall, it appears that a combination of driver training and use of advanced technologies could improve fuel economy by 10%-15% for any given vehicle but by a lower amount averaged over an entire fleet.

Increasing Vehicle Load Factors and Improved Routing

Just-in-time delivery and increased outsourcing of production of component parts by many companies in the 1990s have probably contributed to increases in total freight kilometres of travel in many countries, since these trends often require more and longer delivery trips and therefore result in lower average truck loadings. However, recent studies point to opportunities for counteracting these trends through improvements in routing patterns and utilisation in general. As advanced logistics systems become more common, truck routing and utilisation is improving. Improvements in these areas could reduce truck travel by 10% or more.

Fuel economy might improve further if even more sophisticated systems are used to route vehicles, including global positioning systems and other real-time monitors of location that could enable rerouting while on the road. Such systems allow for complex routing systems, and may employ routing algorithms incorporating truck delivery experience in the algorithm to optimise it over time.

Truck load factors can be improved in various ways. They include capacity for loading each trip, and optimising the system of truck dispatching, routing, and loading. Potential improvements include:

- adoption of nominated day delivery systems;
- rolling billing to encourage smoothing of deliveries over the month;
- relaxing the requirement for dedicated delivery; and
- rescheduling trips to off-peak periods.

The Role of Logistics Centres

Logistics centres that coordinate the routing and delivery of goods for multiple firms become increasingly attractive as volumes increase. They facilitate the use of larger trucks, higher load factors, and fewer empty backhauls, using the hub and spoke system that has revolutionised passenger air travel.

Reductions in Empty Running

Unladen trucks produce emissions without any freight transport output. Greater coordination of pickups and deliveries can improve vehicle utilisation. Improved routing and scheduling of trucks, increased back-loading, driver communications and information systems and extended operating hours can all improve efficiency. The utilisation of advanced technologies for vehicle location monitoring, computer aided routing and dispatch, and data and voice communications can all yield benefits to freight efficiency. Extended warehouse operating hours enables trucks to make pickups and deliveries at times of low road congestion (APEC Center for Technology Foresight 2000).

Increased use of telematics has contributed to a decline in empty running in recent years and may continue to result in reductions, though no estimates of the potential for additional reductions in empty running are available. Telematics can contribute to reducing empty backhauls by:

- electronic load matching;
- electronic client validation;
- electronic monitoring of vehicle activity; and
- vehicle tracking.

Reductions in Truck Idling

Truck idling for extended periods (i.e. apart from in-traffic idling) has become a major source of fuel consumption for heavy-duty trucks in North America, but appears not to be a major issue in Europe. The reasons why truckers leave their trucks in idle mode for extended periods are:

- to keep the sleeper car heated or cooled;
- to mask out noises; and
- to keep the engine and/or fuel warm in the winter and/or to avoid a cold start.

It is estimated that long-haul trucks consume about 7500 litres of fuel per year while idling. There are a number of alternatives to idling which appear to offer quick pay-back. They are direct-fired heaters, auxiliary power units, thermal storage systems, and truck stop electrification.

Reductions in Freight Travel by Reducing Trip Distance

Reducing freight travel by relocating points of freight supply and demand closer together should be possible. This section discusses two possibilities: decentralising the inventory to put it closer to the customer and/or producer, and shifting the source of products and manufacturing inputs from more local suppliers.

Decentralisation of Inventory

Current arrangements of supply and distribution centres are usually designed to minimise cost, and to move toward greater decentralisation of warehousing and distribution would not be cost-effective for most goods unless fuel prices rose dramatically. However, even if reducing fuel costs is not significant, other benefits could be. Businesses are increasingly recognising the benefits of locating inventory near the customer or point of production, rather than at a large central location. These benefits can include increased responsiveness to customers, better timing of deliveries (including just-in-time deliveries), and reductions in required stock inventories.

Regionalisation of Sourcing

The cost of shipping itself is not a strong incentive for finding local suppliers. Factor cost differentials re usually much wider relative to road transport costs, making it economic to move products long distances for intermediate processing that may add only marginally to the product’s value. It appears only the most dramatic of increases in fuel costs would significantly encourage a trend towards regionalisation of sourcing.

Mode Switching: from Truck to Rail and Water

In terms of energy use per tkm, freight movement by rail is at least twice as energy efficient as by truck in virtually all IEA countries, and many times greater in some cases. There have been many studies of the potential, and many projects to assess and encourage greater intermodalism. Though some shifting has occurred in recent years, the potential for much more exists in many countries. On the other hand, rail and waterborne freight transport in many countries accounts for such a small share of total surface freight transport that even a major shift would not reduce truck travel or total energy use substantially.

Estimating how much mode switching is feasible or cost-effective is difficult, since the situation of each country in terms of infrastructure, average shipping distances, etc., varies greatly, as do assumptions regarding the responsiveness of industries to price signals and other measures that encourage mode shifting. The potential would also depend on the level of investment made in individual modes and internodal infrastructure.

While rail and boat are substantially less energy intensive than shipment by trucks, any new shifting to rail or water may save less energy than is suggested by looking at the average energy intensities of the different modes. To link road transport to rail or water transport, road feeder movements are often required at both ends of the haul, which may require a more circuitous routing of the shipment. Also, since much of the heaviest, densest freight is already moved by rail and water, additional shifts may involve freight of decreasing density, resulting in below-average hauling efficiency.

Logistics and Supply Chain Management[18]

Logistics is the management of the flow and storage of raw materials, goods-in-progress and final goods from point of origin to point of final consumption; it includes the recovery and disposal of waste products. Cost, quality of service and timeliness are the key parameters of the economic efficiency of logistics, while sustainable logistics also takes into account social factors (accessibility and safety) and environmental considerations.

Technological change has also offered new solutions to logistical problems. Improvements in information technology are one example of this trend, but the standardisation of container sizes and the development of group-age services is another.

The benefits of logistics management include savings in transport costs through improved routing and operations and the reduction of empty backhauls; reduced stock levels (facilitating savings in working capital); increased flexibility in the manufacturing process; the ability to customise the product close to the market; a reduction in the need for product tracking; and the smoother introduction, and phasing out, of product lines. In addition to these economic benefits, logistics management offers advantages with respect to the environmental and social aspects of transportation with its implications for the minimisation of transport movements and the potential for greater accessibility.

Logistics is only effective when there is an adequate supply of information about what is happening at each point in the supply chain, and when available alternatives are well known and understood. The improvements in information technology therefore make increasingly sophisticated logistics management possible. Technologies such as Automatic Equipment Identification (AEI), Global Positioning Systems (GPS) or selected components of Intelligent Transport Systems (ITS) are or will be useful.

The effectiveness of logistics can be enhanced if attention is given to removing certain obstacles and increasing awareness of the benefits among non-users. Among the obstacles identified in many areas are the absence of a bar-coding system suitable for tracking goods, a lack of policies on electronic commerce, and regulations against, or resistance to, night-time collection and delivery systems. With respect to raising awareness, support systems for electronic data interchange (EDI) have been identified as being important. Singapore, Hong Kong and Malaysia are leaders in this respect. High quality electronic logistics systems are increasingly being used by road freight operations in the advanced economies, as are rail freight operators.

The Internet is now beginning to be used to increase the efficiency of the road haulage industry. National Transportation Exchange (NTE) uses the Internet to connect shippers who have loads they want to move cheaply with fleet managers who have space to fill. NTE helps to create a spot market by setting daily prices based on information from several hundred fleet managers about the destinations of their vehicles and the amount of space available. It then works out the best deals. The

[18] APEC Center for Technology Foresight (2000), Demkes and Tavasszy (2000), De Witt and Clinger (2000), Euro-CASE (1996), Lundqvist (2000), Naito (2000), OECD (1997), and *The Economist* (1999a).

whole process takes only a few minutes. NTE collects commission based on the value of each deal, the fleet manager gets extra revenue that he would otherwise have missed out on, and the shipper gets a bargain price, at the cost of some loss of flexibility.

When NTE was first set up four years ago, it used a proprietary network, which was expensive and limited the number of buyers and sellers who could connect through it. By moving to the web, NTE has been able to extend its reach down to the level of individual truck drivers and provide a much wider range of services. Before long, drivers will be able to connect to the NTE website on the move, using wireless Internet access devices.

Urban Freight Systems[9]

For a vehicle operating in an evacuated tube, there is the possibility of propelling the vehicle by the action of atmospheric pressure, the tube in front of the vehicle being evacuated to a low pressure. By suitable valving, the vehicle could be brought to rest at a station by compressing the air in front of the vehicle, thus recovering some of the energy expended in accelerating it. If as well the track leaving the station is made to descend in a parabolic trajectory so that the acceleration experienced by passengers is minimised and on approaching a station is made to ascend then very high speeds are attainable with minimum energy use. Such deep tunnels together with their pumping equipment would be very expensive and moreover a total life cycle energy analysis would be necessary because of the high energy costs associated with tunnelling. Such a project is currently being advocated in Switzerland by Swissmetro, and by Subtrans in the United States.

Other new technologies for moving freight in inner city areas are:

- AGV Navigation System – a prototype from Israel that uses automated guideway vehicles for moving cargo at seaports;
- Combi-Road, a new concept from the Netherlands for the surface transport of containers;
- HighRail – an American system currently under development that uses a monobeam for two-way travel on one narrow guideway; and
- The Japanese Automated Freight System which proposes to use dual-mode trucks for inner-city and intercity freight movement.

Intelligent Vehicle Highway Systems

Intelligent infrastructure technologies can play an important role, not just for vehicles, but also for the manner in which transport systems are built and operated. Transport systems could eventually rely on external controls strong enough to take over the driving function (for example, on highways). In theory, this would improve, traffic flow, fuel economy and safety. At a much more basic level, the introduction into vehicles of real-time information and maps is already helping drivers avoid congested areas within cities, thus helping to reduce congestion itself. This not only improves

[9] APEC Center for Technology Foresight (2000) and Wickens (1993).

travel times but also reduces fuel consumption. Such systems can also be linked with congestion charging to provide real-time pricing that discourages less valuable trips, making way for more valuable ones (as reflected in willingness to pay the charge) (IEA 2005a).

Virtual Technologies

Technology may contribute to the extent to which non-transport alternatives can meet accessibility objectives. Examples of such alternatives include home entertainment systems, telecommuting for work, delivering services through the Internet, lean manufacturing and distribution systems that minimise transport movements, utilising transport logistics to the full, and improved urban design that minimises the need for environmentally damaging transport movements. Using advanced information technologies, a large range of travel movements could, perhaps, be displaced:

- journeys to work could be reduced by managerial and technological changes that greatly increase working from home;
- business travel (local and international) could be displaced by increased use of conferencing and other information technologies for communications;
- social and entertainment needs could be displaced to a significant extent by virtual reality, especially for the young; and
- on-line and distance education could displace journey-to-school or -campus (APEC Center for Technology Foresight 2000).

Recent experience suggests that further advances in telecommunications will continue to have effects that extend beyond the work environment and commuting patterns. Teleshopping, teleconferencing, and telebanking services are already being offered widely. The implications of the telecommunications revolution for transportation could be tremendous, yet they remain difficult to forecast.

Reducing Travel Growth

Efforts to stem the growth in vehicle travel are often related to goals other than saving energy or reducing CO_2 emissions, but they can of course also have important benefits in these areas. Technologies and measures are available that can reduce the demand for vehicle travel while improving the general efficiency of the transport system.

Reductions in road vehicle travel growth can be achieved through:

- improvements in transit systems (which switch traffic away from roadways or, in the case of buses, consolidate traffic);
- better routing systems;
- measures to reduce congestion; information systems that can help to reduce the need for travel; and
- road pricing programs.

The IEA believes that aggressive application of such measures could cut car travel on a national basis by at leat 10% over a ten-year period (IEA 2005a).

Timelines for Changes in Technology

Changes in transport technologies that facilitate reductions in GHG emissions can be considered with respect to three different time frames: near-term, medium-term, and long-term.

Technologies for the Near-Term

Transport technologies for emissions-savings in the near-term are those that are currently commercially available, but whose diffusion is limited. The principal examples are:

- advanced internal combustion engines;
- hybrid electric road vehicles;
- the use of light-weight materials in road vehicles;
- improved aerodynamic styling in road vehicles;
- advanced fuel-saving transmissions;
- the use of high-pressure, low-rolling resistance tyres;
- more efficient accessory equipment in road vehicles;
- the use of ethanol derived from sugar as a fuel for road vehicles;
- on-board diagnostics to monitor vehicle emissions;
- the wider use of adaptive cruise control systems and fuel economy computers;
- advanced truck and bus designs for fuel economy;
- advanced aerospace design for fuel economy including aero-engines, aerodynamics materials technology;
- advanced marine design and operational improvements;
- the increased use of electronic road pricing as a means of reducing traffic congestion;
- improvements in freight transport relating to trucking operation and system efficiency, reducing freight travel requirements, mode switching and advanced logistics and supply chain management; and
- the wider use of advanced information technologies to reduce transport requirements and facilitate virtual technologies.

The above list demonstrates that there are a huge range of newly available technologies that should provide individual incremental improvements in energy efficiency and, collectively, very substantial aggregate improvements. This would flow through to reduced GHG emissions on what would otherwise occur, given constant emissions-intensity of energy consumed in transportation. In addition, the wider use of biofuels would reduce the emissions-intensity of transport energy. The key issue for the immediate future is accelerating the diffusion of such technologies. This implies overcoming the barriers to the wider diffusion of these technologies.

Technologies for the Medium-Term

Transport technologies for the medium-term are technologies that may not be commercially available for some years but are likely to be in general use by 2050 at the latest. Examples include:

- advanced two-stroke engines for two-wheeled vehicles;
- fuel-cell-powered road vehicles;
- ultra light-weight road vehicles;
- integrated starter/alternator electrical systems for road vehicles;
- the use of ethanol derived from cellulosic biomass as a fuel for road vehicles;
- advanced vehicle maintenance systems focussing on fuel economy;
- the introduction of self-driving cars;
- further advances in truck and bus design;
- further advances in aerospace design, including aero-engines, materials technology and low-friction surface coatings;
- further improvements in the design of marine vessels and in the operational efficiency of marine transport;
- improvements in the design of railway rolling stock, including advanced engines, the use of lightweight materials and advanced suspension and drive;
- innovations in transit operating systems;
- advanced people-mover systems.

This list contains many examples of technologies that would further increase the energy efficiency of transport. It also contains examples of technologies that would facilitate the move towards zero-emission transport systems. These include advances in the efficiency of transit systems based on zero-emissions electricity and the commercialisation of fuel cell road vehicles based on ZET hydrogen. The latter would be accompanied by the initial development of a hydrogen fuel infrastructure to service road transport. The diffusion of ZET transport would most likely take a considerable amount of time.

Technologies for the Long Term

Transport technologies for the long term would not be commercially available before 2050. Examples of such technologies would be hydrogen-fuelled marine vessels, hydrogen-fuelled aircraft, and new types of urban freight systems.

Zero Emission Technologies for Transportation

The vision for the long term is to achieve a zero emissions technology (ZET) energy system. This ambitious goal is necessary if the world is to reduce anthropogenic GHG emissions to acceptable levels, given the difficulties in the way of containing such emissions form the non-energy parts of the global economy. Two possible routes are available to achieving ZET transportation: electrification, and hydrogen-fuelled transport.

Electrification provides a possible framework for a ZET transportation system. The essential requirement is that the electricity used in transportation is produced by zero emissions technology. In electrified transport systems, urban transport needs would be supplied by electrified rail, other electrified people-mover systems, and, possibly, novel urban freight systems. In order to provide the maximum scope for such urban transport systems, cities would need to evolve towards high density forms in which transport and urban planning were integrated. Advances in energy storage technologies could facilitate a major role for electrified cars, buses and delivery vehicles to cover the residual needs of urban transport. Inter-urban transported between heavily populated areas would be serviced by electrified rail. The transport gaps in an electrified system would be long-distance transportation in moderate to low population density areas, marine transport and air transport.

An alternative framework for a ZET transportation system would be based on hydrogen-fuelled vehicles. The key aspects of such a system would be hydrogen fuel derived by ZET and fuel cell-powered engines. Cars, trucks and buses would use fuel cell/hydrogen technology as would long-distance rail and marine engines. As such, the hydrogen-based transport would be capable of dealing with the transport problems of long-distance travel and freight needs as well as transport in low-density urban areas.

Aerospace provides the main challenge dor the introduction of a ZET transportation system. While research is being conducted on hydrogen-fuelled aircraft, they are most likely to be used in the niche area of unmanned aircraft. However, hydrogen storage poses problems in terms of space and weight. For most aircraft, the storage problems associated with the use of hydrogen as a fuel would probably preclude its adoption unless unforseen breakthroughs occur as a result of basic research on alternative methods of hydrogen storage.

A realistic long-term objective would be to cap the level of GHG emissions arising for air transport. The prospects for reduced emissions-intensities in air transport are quite good, building on the experience of recent decades. Innovation rates in aerospace are high, and continuing improvements in aero-engine and lightweight materials technologies should facilitate continuing reductions in emissions intensities. Against this, rates of growth in the demand for air travel are likely to be very high.

2. The Technology System in Transportation

Introduction

The technological system in transportation can be analysed in terms of four different transmission mechanisms that reflect four different time horizons.

The first transmission mechanism, of relevance to shorter-term trends in transportation technologies, is the diffusion of new, but commercially available, emissions-saving energy production technologies. Jaffe et al. (2003) provides a general reference on the diffusion process of environmentally-related technologies. The adoption of such technologies will generally bring with it the realisation of scale economies and economies related to learning-by-doing, thereby encouraging the further diffusion of the technology.

The second transmission mechanism is induced innovation in specific fields of transportation technology. Price incentives through such means as higher prices of fossil fuels or the introduction of carbon taxes would provide a swift incentive to such innovation although diminishing returns to R&D will set in after a while. For this reason, such induced innovation is a medium-term, rather than longer-term, influence on transportation technologies. The principal reference is, once again, Jaffe et al. (2003).

The third transmission mechanism is that of general purpose technologies (GPTs). The spread of GPTs can lead to complementary innovations in specific areas of technology. They also provide a stimulus to innovation in the management and organisation of businesses. GPTs provide a key means of overcoming diminishing returns in specific areas of innovation, and are therefore a longer-term influence on energy production technology. The main references for GPT analysis are Lipsey, Bekar and Carlaw (1998a, 1998b, 2005) and Carlaw and Lipsey (2001).

The fourth transmission mechanism is public research and development and its influence on commercial technology. The volume and quality of basic research in relevant scientific disciplines will shape the long term environment for technological development in transportation. Public research will, in turn, reflect the characteristics of the science and technology sector. Ruttan (2001), Weinberg (1964), David et al. (1992) and IEA (2000e) are the key references on the fourth transmission mechanism.

The Diffusion of Emission-Reducing Technologies

Positive Factors

The diffusion of new emissions-saving transportation technologies will be assisted by the following factors:

- the bank of new emissions-saving technologies already commercially available, the current cost competitiveness of these technologies, and the quality of such technologies;
- rises in the cost of high-emission transportation costs brought about by such influences as higher petrol prices or the introduction of carbon taxes; and
- high rates of learning-by-doing and/or conventional economies of scale that increase the cost competitiveness of new emissions-saving technologies as diffusion progresses.

The bank of new emissions-saving technologies is large. Examples include improvements in internal combustion engine systems, hybrid-electric vehicles, improved aerodynamics in road vehicles, alternative fuels for road vehicles, advanced transmissions and improved tyres, increased efficiency in new aircraft engines and improved aerodynamic design in new aircraft, and innovations in freight logistics systems.

Cost-competitiveness is an issue at present with many of these technologies, but diffusion will tend to narrow or eliminate this gap in most cases. Some improvements in road vehicle design, most changes in aircraft design and improvements in logistics are necessary to meet competitive pressures, but cost barriers are a constraint in other cases, such as hybrid engines, although not necessarily a permanent constraint, given the potential for cost reductions as scale increases.

Higher petrol prices are currently a significant stimulus to the adoption of fuel-saving technologies. They are encouraging a switch to more energy-efficient vehicles and encouraging the diffusion of such innovations as hybrid engines. In the longer run, the introduction carbon taxes and emissions trading regimes may be an important contributor to technology diffusion.

Negative Factors

The diffusion of new emissions-saving transportation technologies will be constrained by the following factors:

- consumer preferences for larger motor vehicles, particularly SUVs, and for energy-consuming auxiliary equipment;
- cost barriers to the adoption of new technologies; and
- the existence of a large pool of high-emitting vehicles of inefficient transport infrastructure (capital stock turnover rates).

As previously noted, the period since 1990 has seen consumers increasingly choosing larger, heavier and more powerful vehicles, particularly with the rise of the SUV. This trend has been offsetting and, in some markets even overturning, the benefits obtained from innovations that increase energy efficiency in road vehicles. However, there are signs that this trend may be weakening. Higher oil prices are a key influence, and the introduction of hybrid engines in SUVs another. It is therefore possible that if oil and petrol prices remain high (either through the operation of market forces or through the adoption of carbon taxes) the offsets to energy-efficient innovations could be reduced.

Capital stock turnover is another constraint on the pace, if not the direction, of diffusion. For road vehicles, 20 years is a rough approximation to overall capital stock turnover. It is much longer for aircraft, marine vessels and railway equipment, although retrofitting is common for aircraft and marine vessels. It is even longer for other aspects of transportation infrastructure that may impact on overall energy efficiency, such as roadways, airports, ports, and rail infrastructure.

Induced Innovation in Specific Fields

Inducements

Innovations in emissions-saving energy technologies can be induced by the following factors:

1. Increased non-renewable energy prices. Research indicates a significant short-to-medium-term impetus to innovation in specific areas of technology followed eventually by diminishing returns.

2. Growth in the demand for emissions-savings technologies (excluding supply-side factors and prices).
3. Reduction in the real after-tax cost of research and development.
4. Increases in opportunities for new technological developments (which would stem from factors analysed in the next two sub-sections of the paper).

The opportunities for new technological developments in such areas as cellulosic ethanol, fuel cells, materials technology, and marine vessels design and propulsion are considerable. If the current high oil prices persist for some time, it should give a powerful boost to innovations in specific fields of transport technology.

Constraints

Innovations in emissions-saving energy technologies can be constrained by the following factors:

1. Uncertainty about the future returns from R&D and technological innovation.
2. High transaction costs associated with innovation.
3. The difficulties of financing R&D.
4. Regulatory barriers to making the changes necessary to accompany innovations.
5. Low non-renewable energy prices (unlikely in the near future).
6. High after-tax costs of research and development.
7. Limited opportunities for new technological developments associated with diminishing returns to individual research areas.

Most of these factors are general constraints affecting most areas of innovation. They may slow the pace of innovation, but if there are strong positive encouragements, their influence is likely to be minor. Of greatest importance is the likelihood of diminishing returns to innovation in specific areas.

Taking all of these factors into account, there are strong inducements to specific transportation innovations operating at present. They should encourage the development of emissions saving technologies that will flow into the system over the next decade. However, in the longer run, continuing strength in emissions savings will depend on the third and fourth transmission mechanisms.

General Purpose Technologies and Complementary Innovations

General Purpose Technologies

The literature on general purpose technologies (GPTs) is framed in a macroeconomic context. In this report we are using the term in a sectoral context. A GPT is a technology that initially has much scope for improvement, possesses many technological complementarities, and is pervasive in the sense of having wide use inside, and frequently outside, the sector.

GPTs are capable of widening the scope for innovation in specific processes, thereby breaking the shackles that impede specific innovation in the long run. They also encourage co-investment in capital equipment, complementary investments in education and the development of labour skills. Finally, the long-term potential offered by many GPTs usually requires investments in the reorganisation of the production process (Lipsey, Bekar and Carlaw 1998b, 2005).

In the context of the transportation sector, five GPTs have been identified:

- aerodynamic/hydrodynamic styling;
- information and electronic technologies;
- materials technology;
- nanotechnology; and
- bioenergy/agriculture.

First, let us consider aerodynamic and hydrodynamic styling. By utilising these related technologies in the design process for transport equipment, equipment can be streamlined, thereby reducing the resistance to air or water pressure. This, in turn, enables increased energy efficiencies and fuel economy to be obtained. These styling technologies have specific applications in relation to road passenger vehicles, trucks and buses, railway equipment, aircraft and marine vessels. Synergies exist between the individual applications of such design technology. They arise with respect to certain commonalities in design processes, particularly modelling techniques and computerised simulation processes.

Second, information and communications technology and electronics have been the dominant GPT in the macroeconomy for some decades. In transportation it provides the means for further innovations in such areas as integrated starter and electrical systems, engine control systems, transmission control, operational control of transit systems and air control systems, and urban transport management. These technologies facilitate increased energy efficiency in transport equipment. In aerospace avionics incorporated in aircraft utilises ITC technologies to provide effective navigation and communication systems en route. Similar technologies are beginning to be utilised in road transport and marine transport. Advanced electronic display technologies are being utilised in new aircraft and road vehicles. These technologies facilitate improved transport management and safety.

Third, new materials technology offers the scope for increased energy efficiencies in transportation. The use of lightweight metal alloys and composite materials was pioneered by the aerospace industry and is now being taken up by motor vehicles and other transport equipment. Further development is occurring in lightweight metal alloys, while composites are undergoing development both in terms of materials design and in manufacturing technology. Other areas of technological development include structural ceramics, ceramic matrix composites, ceramic coatings, surface engineering to improve resistance to wear and contact damage, and protective coating systems. Synergies in materials technology can be obtained because of its use across such sectors as transport equipment, other manufactured equipment and structural engineering.

Fourth, nanotechnology has many applications across the whole economy. It is widely seen as having the potential to become a major macroeconomic GPT because of its development potential and many applications. It is relevant to improving the overall efficiency of transport equipment; enhanced energy efficiency may be a by-product of its utilisation. Almost every component in a motor vehicle is likely to use nanotechnology in the future,[10] with the use of nano-technologies in the storage of hydrogen being particularly important. Nanotechnology will likewise contribute to a long list of new technological developments in the aerospace sector,[11] and in other transport equipment.

Fifth, there are important synergies between the production of biofuels and agricultural systems. Innovation in core agricultural technologies and business processes can improve the competitiveness of feedstocks for biofuels. Technological progress in the processing of biomass into bioenergy (electricity and heat) and biofuels is required. The market that is offered by the development of biofuels as a transport fuel and other forms of bioenergy can, in turn, stimulate agricultural innovation as it impacts on feedstocks.

Inducements to Innovation

The main inducements to GPT-led innovation in low-emission transportation technologies are likely to be:

1. Increased non-renewable energy prices.
2. The pace at which the costs of GPTs are reducing.
3. Increased uses for the GPTs in energy production.
4. Reductions in the real after-tax cost of applied R&D to utilise GPTs in energy production.
5. The availability of appropriate skills among managers and employees.
6. The readiness of companies to adjust to change, innovate and comprehend appropriate organisational restructuring.

The process of complementary innovation based on the influence of GPTs follows longer time horizons than is the case for induced innovation in specific fields. This is because of the complexity of the two-way relationship between GPT development and complementary technologies in a diverse fields. Thus the stimulus to broader innovation associated with rising prices of crude oil will take longer to evolve and be

[10] Nanotechnology applications include materials technology (surface coatings, nanocomposite materials, layers in engine and transmission part), MEMS (microelectromechanical systems used for pressure indicators in materials and to reduce drag in truck bodies), engine technology (compact fuel cells, advanced energy storage systems and in solar cells providing an auxiliary source of energy), motor parts (ceramics incorporating nanotechnology), ignition (high power switches), catalysis (improving internal combustion exhaust control), vibration dampeners, filters, coolants, paint additives, plastics, high technology fabrics, glass, electronics, flat screen display technology, new technology tyres, advanced virtual reality design technologies, green manufacturing technologies, on-board diagnostics, environmental monitoring, and automated vehicle control.

[11] Materials technology, MEMS, energy technologies (compact fuel cells and new types of solar cells for auxiliary power, and aero-engine components), surface coatings, high technology fabrics, avionics, electronics, advanced virtual reality design technologies, on-board diagnostics, and safety technologies (smart alerting functions).

based on a longer run average of energy prices than is the case for induced innovation in specific fields. The implication is that a major reversal of current oil price trends could arrest the flow-on into encouraging broader emissions saving innovations.

The rate of development in many, if not most, of these GPTs is likely to be rapid. This, in turn, is likely to increase the opportunity for a diverse range of innovations in transportation technology in the coming decades.

Constraints on Innovation

The main constraints on GPT-led innovation in low-emission transportation technologies may be:

1. Low non-renewable energy prices.
2. High costs of purchasing GPTs, limited applications of these technologies, and high costs of applied R&D.
3. The level of adjustment costs and complementary investment costs in adopting these technologies.
4. The level of regulation in product markets and employment markets.
5. Uncertainty about the future outcomes of basic research on GPTs, uncertainty about future applications of GPTs and of the future social and economic trends that may influence GPT-led innovations.

The most important constraints on GPT-led innovation in some specific areas is likely to be cost barriers to complementary innovation and adjustment costs in adopting these technologies in production systems. But as with most prospective innovations, uncertainty is a powerful constraint.

Complementary Innovation in Business Processes

Lipsey, Bekar and Carlaw (1998b, 2005) suggest that a reorganisation of the production process is usually required before the potential of a new GPT can be realised. Specific channels of impact are summarised below.

1. Much of the initial impact of GPTs are typically on institutions and methods of coordination at all levels of the economy. These changes often require, or enable, subsequent changes in product and process technologies, which in turn are embodied in new capital goods.
2. Changes in materials typically require, or facilitate, the direct redesign of many product or process technologies. Eventually the effects spread through the entire economy, inducing changes in institutions and methods of organisation.
3. The use of new energy sources often requires the redesign of physical elements of the facilitating structure including specific capital goods embodying task-specific machinery, the layout and location of the factory, and many elements of the economy’s infrastructure including public institutions.

4. Organisational technologies typically enter the facilitating structure as changes in the layout of the factory floor, or changes in management procedures.
5. New technologies typically require new management structures to deal with new production and quality-control systems, the restructuring of work groups, the introduction of new management hierarchies and new performance, information and incentive schemes, and, perhaps, the development of new start-up companies, divestments, mergers, acquisitions and alliances.

Brynjolfsson and Hitt (2005) make the point in relation to ICTs that investing in such technology without organisational change or by only partially implementing some organisational changes can create significant productivity losses as any benefits of the introduction of new ICT are more than outweighed by negative interactions with existing organisational practices.

Challenges for the transportation sector lie in adapting business processes to GPTs such as aerodynamic/hydrodynamic styling, new materials technology and nanotechnology.

In some senses the aerospace industry provides leading example to other producers of transport equipment in the adaptation of a production systems to continuous innovation. The aerospace industry is always in the process of developing new aircraft models as well as revising designs for existing aircraft models and retrofitting old aircraft. The current production model has successfully absorbed major development sin aerodynamic styling, ICT, and new materials technology.

The production model that has proved to be successful in aerospace is one of specialisation in both production and design. The major aircraft producers – Boeing and Airbus – are basically integrators. They concentrate on design, marketing, the production of some strategic parts of the aircraft (particularly the nose cone) and the integration of aircraft components, fuselage etc. into the final aircraft. Aero-engines are designed and produced by separate companies. Primary contractors to the big aerospace producers are not only responsible for the major parts of the aircraft, they also have design responsibilities within broad parameters set by Boeing and Airbus.

The major limitation of the aerospace production model has been the actual methods of manufacturing and assembly which, while emphasising quality control, have tended to be less advanced than those employed in the motor vehicle industry. This is now changing as ways of adapting contemporary prose integration methods used in many other manufacturing industries to the aerospace industry.

The aerospace production model for managing continuous innovation may have some implications for the motor vehicle industry. GPTs that have considerable implications for business processes in the motor vehicle industry are aerodynamic styling (the modelling of aerodynamics in the design process), new materials technology (innovative least cost methods of manufacturing), and nanotechnology (manufacturing methods). Over the coming decades motor vehicles will embody completely new engine technologies, material technologies, and electrical/ignition systems. Optimal business processes have to be identified to accomplish this radical transformation. Process technologies, management procedures, product and quality control systems, and the organisation of work groups will all have to adapt. The relationship of motor vehicle producers with their suppliers could also be radically affected. Vehicle producers may choose to divest themselves of some parts of the production process. For example, specialist producers of fuel cell-powered engines may supply the industry.

Even greater changes in the structuring and organisation of business processes may occur in marine engineering and equipment associated with transit services. Innovation in business organisation will be of vital importance to the transportation sector as a means of ensuring that widespread technological change in products and components is managed without disrupting productivity and quality.

Finally, there is the question of innovation in business processes along the supply chain to transportation. A key issue arises in relation to the storage and distribution of fuel. Advances in the capacity of the fuel industry to deliver multi-fuel storage and distribution will have important impacts on the diffusion of innovations in transport equipment. Elsewhere in the broader chain of energy supplies, innovations in farming practices can improve the competitiveness of energy crops with links through the supply of biofuels through more innovative fuel distribution and impacts on the emissions intensity of transportation.

Public Research and Development

The impact of public research and development on commercial emissions-savings technologies in transportation appears to be determined by the following factors.

1. The volume and quality of public basic research in relevant scientific disciplines.
2. The development of collaborative research on new energy technologies involving cooperation between the public and private sectors.
3. Actions undertaken to promote the transfer of this research knowledge to the private sector.
4. The capacity of the private sector to introduce innovations that make use of the transferred knowledge.

The following areas of public basic research will be of great significance to the development of sustainable transportation systems over the coming decades.

1. Research on biofuels – the use of lignocellulosic feedstocks, the availability of liquid biofuels from agricultural sources, and improved process economics. There is also a need for research on land availability for biomass crops and the impact of developments in biomass agriculture on agricultural prices and the rural environment.
2. Fuel cells for transportation – advanced fuel cell systems, fuel infrastructure, and on-board fuel storage and processing. Paralleling these

developments is the need for major R&D in technologies for the production, storage and distribution of hydrogen.

3. Energy storage devices – new battery technologies drawing on basic electro-chemistry, ultracapacitors, hydraulics and flywheels.
4. Energy supply capacities – is the domestic and world-wide production capacity for clean and renewable energy carriers is sufficient to fulfil all world energy needs (of which transport is just part)? What are the priorities for allocating available clean energy?
5. New materials – the total materials life cycle must be addressed to make sure that the reduction in vehicular energy consumption is not offset by increases in other stages of the material life cycle; other important aspects of R&D are:
    - Development of revolutionary materials (structural ceramics and ceramic matrix composites) for operation at higher temperatures and pressure. Hard, wear-resistant, durable and insulating ceramic coatings are an expanding technology for improving the durability, reliability, and efficiency of diesel and turbine engines for automotive and industrial power. A key feature of the research is to assess methods of quantifying thin ceramic coating adherence in order to establish test standards for evaluating new technologies.
    - Surface engineering to improve the resistance to wear and contact damage. Friction loss is inherent in most mechanical systems. This research explores the possibility that surface texture designs could reduce friction using thin films and coatings under a broad range of contact conditions.
    - Development of durable coating systems for thermal, wear and environmental management. This relates to the effects of subsurface damage that results from component machining. Detailed reports on rolling contact fatigue will be produced.
    - Light weighting to improve fuel efficiency. Materials under consideration include aluminium, high strength steels, magnesium, metal and polymer composites, titanium.
6. Nanotechnologies – nanotechnology is a still expanding field for public R&D, but with respect to transportation, special attention needs to be given to the question of whether this technology can meet the energy density requirements that hold for vehicle applications of hydrogen use.
7. New types of urban freight systems.
8. Aerospace – the impacts on greenhouse gases of aircraft, with particular attention to the impact at high altitudes on ozone-depletion; the use of liquid hydrogen or biofuels as energy sources for aero-engines.
9. Transit systems – identifying areas of possible basic research with respect to new technologies for transit system infrastructure, and examining possibilities for novel types of urban transit systems.

10. Automated transport infrastructure – electronic/infra-red communication among vehicles and new technologies in satellite navigations systems.

A considerable volume of public basic research is being conducted in areas relevant to the future technological development of transportation. Research collaboration in the broadest sense is being encouraged at the international level by the IEA through a series of Implementing Agreements. These Agreements comprise Advanced Fuel Cells, Advanced Materials for Transportation Applications, Advanced Motor Fuels, and Hybrid and Electric Vehicles. In addition, Implementing Agreements on energy matters are relevant to many aspects of technological development in transportation. Agreements on Hydrogen and also on Greenhouse Gas R&D (the main focus of which is carbon dioxide capture and storage) fall into this category.

In addition to the international R&D cooperation and coordination being undertaken by the IEA, individual countries and regions are also working in this area.

An example of a comprehensive program is the FreedomCar program launched recently in the United States. It has new initiatives in the areas of: (1) batteries, electronics and motors, (2) fuel-cell vehicles operating on hydrogen, and (3) improved aerodynamics, reducing tyre rolling resistance, lighter-weight materials and better vehicle system optimisation. Other major RD&D activities in the United States include research activities under the 21st Century Truck program (engines, diesel emission controls, aerodynamics) and demonstrations of the viability of powering transit buses with fuel cells. Substantial activities are also underway aimed at helping cities deploy alternative fuel vehicles and associated fuelling infrastructure. The National Renewable Energy Laboratory leads a major effort to develop cellulosic ethanol conversion technologies and Oak Ridge National Laboratory leads the effort to develop feedstocks (and improve their production efficiency) for this program.

The European Union carries out a series of research framework programs. These include R&D on energy savings and efficiency, alternative motor fuels, fuel cells, hydrogen technologies, novel propulsion systems, the integration of clean energy systems into the energy system; traffic management efficiency projects.

3. Policies – Sustainable Transportation Strategies

Sustainable Transport as Concept

The issue of global warming is only one of many issues confronting the future development of the transportation sector. Improved services to customers in terms of speed, reliability, comfort and safety, cost-effectiveness, and more local environmental issues like air pollution are all important factors influencing the pattern of innovation and technological development in transportation.

Sustainability means capable of being continued. Sustainable transport means finding ways of meeting transportation needs that are environmentally sound, socially equitable, and economically viable in the long term.

To be economically sustainable, transport must be cost-effective and continuously responsive to changing demands. Cost-effective transportation is not easily secured because travellers are not directly confronted with many of the overall social costs associated with transportation. The combination of externalities and a lack of pricing of road space often gives rise to traffic congestion, a significant problem in many of the larger cities of the advanced economies (the net social costs of traffic congestion are estimated to be between two and three per cent of GDP in the advanced economies) (OECD 1997) and an acute problem in many third world megacities (notably Bangkok, where costs could be as high as 8 per cent of regional gross product, and Mexico City) (Khomnamool 1999; Pendakur 1995).

Socially, sustainable transportation systems should provide safe access and liveability for all sections of the community. Transportation is of vital importance for all groups in the community for accessing jobs, education and health services. Accessibility is attained through the provision of comprehensive and affordable transport services. Most major cities in the APEC region have failed to meet this objective (APEC Center for Technology Foresight 2000). Injury and death caused by road accidents is an important social cost associated with transportation, leading to losses estimated at between two and four per cent of GDP in the advanced economies (OECD 1997).

Environmentally sustainable transportation systems should: a) use energy resources and other natural resources at a rate not larger than rates of renewal of those resources; b) produce no more waste than can be accommodated by the planet's restorative ability; and c) make use of land in a way that has little or no impact on the integrity of ecosystems. At present, transportation systems in virtually all the major APEC cities fail to meet these criteria. Local air pollution, largely associated with the use of the motor vehicle, is one example of unsustainable transportation and could contribute as much as three per cent of GDP in terms of health costs in some cities in the advanced economies (ECMT 1996). The range of problems associated with transport emissions is greater in the cities of emerging economies because of the greater use of high-polluting vehicles and fuels. Air pollution generated by city traffic can also have an impact on substantial regional areas. Emissions of sulphur and nitrogen compounds from transportation can lead to acidic rainfall, and contribute to acid fog and snowfall (OECD 1996).

The Principles of a Sustainable Transport Policy

While technology offers the potential of major savings in transport-related emissions (both greenhouse gas emissions and emissions of local pollutants), the realisation of this potential will depend on the successful implementation of sustainable transport policies. The central economic issue is that the costs of transport-related emissions tend to be external to both transport users and transport providers. The internalisation of such costs requires policy intervention (for example, the introduction of carbon taxes). Moreover, the benefits associated with reducing transport-related greenhouse gas emissions are borne by the world as a whole, while the related costs are largely borne by transport users. Sustainable transportation strategies need to be employed to overcome this fundamental disjunction of benefits and costs, yet the political problems associated with the disjunction of costs and benefits will represent a barrier to the adoption of such policies.

It should be noted that there are potential synergies between policies that are aimed at reducing emissions of greenhouse gases, policies aimed at other environmental objectives, and policies aimed at improving the economic efficiency of transport systems. Many of the policy and technological measures advocated as parts of an overall sustainable transportation strategy will have spillover effects: reducing both greenhouse gas emissions and emissions that cause air pollution; reducing economic costs associated with traffic congestion and reducing the additional emissions associated with traffic congestion.

The underlying goals for transport sustainability relate to social, environmental and economic issues. A key challenge for policy is dealing with the conflicts that can exist between these goals. For example, environmental and social objectives may conflict when policies pursued for environmental purposes (such as the scrapping or retrofitting of leaded-petrol-consuming cars) lead to reduced accessibility for the poor (such as those without access to public transport that are reliant on older vehicles for transport). The pursuit of environmental goals may also conflict with narrowly-specified economic goals (for example, the costs of transport may need to be generally increased to deal with emission volumes). To some extent, these conflicts boil down to political problems associated with the fact that there are frequently gainers and losers when policies are changed. If a broad view is taken of economic development needing to be on a socially and environmentally sustainable basis, some of the apparent goal conflicts can be seen to be insubstantial on deeper analysis (for example, while environmental sustainability may appear to be in conflict with economic efficiency in the short run, it is a pre-condition for long-run economic efficiency).

That still leaves the equity issues associated with gainers and losers from policy change. Compensation mechanisms are important to maintain accessibility for disadvantaged groups. Broader notions of compensation on a wider basis are possible if transport reforms are pursued in a wide enough context. Examples of particular political problems associated with transport reforms include unwillingness to pay in a situation where external costs are priced, and the clash that often exists between individual and community interests (important with respect to urban land use, infrastructure development and, to some extent, safety).

The experience of recent decades shows that traffic demand has high income elasticities and low price elasticities, and the cross elasticity between public and private transport is very low. Under these circumstances, efficiency pricing would result in large price rises for particular transport movements and relatively small reductions in actual transport movements because of the low price elasticities of demand. A key objective for policy should be to influence technology and transport service development such that greater choice is available for consumers. This greater choice would be represented by increased alternatives within a given mode of transport, enhanced possibilities for intermodal substitution, and the development of non-transport means of enhancing accessibility requirements. In turn, such a strategy would facilitate greater responsiveness in traffic demand to changing prices, or to advanced traffic management systems that simulate market-type solutions to accessibility requirements.

The overall price elasticity of demand for high-emission transport movements, and the cross elasticity between public and private transport, could be significantly increased by increasing intermodal transport substitutability. Technological changes that increase the flexibility of urban transit services and system innovations that allow for increased customisation of such services are needed as would developments such as park-ride schemes which focus primarily on intermodality.

The growth in information technology, computing power and analytical techniques means that transport planners have increasing capabilities through the application of modelling and decision support technology. Modelling also provides a number of benefits, allowing transport planners and decision makers to:

- evaluate trade-offs in a structured and efficient way;
- identify better solutions to transport problems;
- undertake sophisticated what-if analysis;
- involve independent analysis, leading to more defensible decisions;
- facilitate the creative and strategic thinking needed to address the complexity of transport planning; and
- enable the introduction of advanced traffic management systems based on the use of simulation models to direct traffic and manage potential congestion problems.

Available Policy Instruments

A wide range of policy instruments are available for use in construction a sustainable transportation strategy.

1. Regulations

Regulations can cover a spectrum that ranges from outright bans to monitoring requirements and voluntary agreements. Standards can cover performance, environmental quality, design, behaviour and information. They have been used, inter alia, to specify mandatory fuel-efficiency. Conventional approaches to regulating the environment are often referred to as ‘command and control’ regulations. Indirectly, regulations in product and labour markets may inhibit innovation and are also therefore relevant to strategies designed to encourage the development of emissions-saving technologies.

2. Economic Instruments

Economic instruments make use of the price mechanism in order to provide incentives for the reduction of GHG emissions. Since GHG emissions are an external cost to agents concerned with the processes that give rise to such emissions, economic instruments used as part of a climate change policy involve interventions to modify and/or create relevant market processes through taxes, subsidies, the introduction of new or more complex pricing mechanisms and the encouragement of new types of market transactions. This approach has relevance to all sources of GHG emissions.

The most efficient tax-based instrument for use in climate change strategies would be a tax on the carbon-content of fuel in that it directly encourages the substitution of low-emitting fuels or energy sources for high-emitting forms of energy. However, with respect to transportation, road pricing is an important potential policy instrument.

3. Tradeable Emission Rights

Tradeable emission rights are a specific economic instrument that work best within a framework of agreed environmental standards, although they can be applied unilaterally in a more limited national context. Once overall limits on the total emission of a pollutant have been agreed, tradeable rights provide a mechanism for the allocation of rights to emit certain amounts of that pollutant. This creates a market that places a value on the right to emit, and an incentive is created for those who can most economically reduce emissions to do so, as they can sell the rights they no longer need at a profit.

4. Research and Development

Continuing research and development will be required to improve the attractiveness of options to reduce GHG emissions, and overcome technological uncertainty. Government can provide tax concessions, research grants, cooperative arrangements for public/private sector cooperation in R&D, and direct funding of public research institutions.[12] Public sector science and technology policies also have relevance to the development of commercial technologies.

5. The Development of Infrastructure

Transport infrastructure, in the form of roadways, transit-ways, airports and ports, plus the equipment associated with their efficient utilisation, is of major importance to economic efficiency, social access, and safety in the transportation system. New technologies can greatly assist in the efficient utilisation of this infrastructure and provide savings in the form of a deferred need for additional infrastructure. Greenhouse gas emissions can be saved by developments that minimise traffic congestion. The development of an infrastructure that supports the distribution of alternative fuels such as hydrogen is also of vital importance to the reduction of emissions.

Improvements in the competitiveness and flexibility of transit services[13] can make an important contribution to the environmental sustainability of transportation and, by increasing the degree of substitutability between transit and private vehicles as a means of transportation, enhance the effectiveness of demand management and pricing strategies to contribute to sustainability. Transit services can be enhanced by the harnessing of new technologies in the provision of such services; the extension of services coverage, capacity and frequency; improving operational flexibility; and increasing intermodality with different forms of transit and with private transport (APEC Center for Technology Foresight 2000).

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[12] Alic, Mowery and Rubin (2003) provide an outline of the R&D policy tools used in the United States (pp. 18-19).

[13] Transit services include the following categories: rapid rail or mass transit; commuter or interurban rail; streetcars or tramways; buses; and paratransit (vans, jitneys, shuttles, microbuses and minibuses).

6. The Integration of Urban and Transport Planning

The integration of urban land planning with transport planning is and important aspect of transport demand management. It is very relevant to social access and economic efficiency and can also provide additional benefits in relation to the overall energy efficiency of transport. Key aspects of the required policies are:

- encouraging higher urban density and mixed-use development in high income cities;
- improving the scope for walking and cycling to achieve mobility requirements;
- integrating land use planning with the development of transit infrastructure;
- managing parking supply; and
- providing for efficient distribution systems in urban planning (APEC Center for Technology Foresight 2000).

7. Education and Information

Education and information programs are important to overcome primary defects in emerging markets for reducing emissions-intensity. Markets can only be efficient if adequate information is available to all participants. Information programs are most effective when targeted at decision makers at various levels. Education and public awareness policies may shape attitudes in business and among consumers in such a way that they will ultimately influence the acceptance and pace of uptake of new environmentally sustainable technologies and of climate change policy initiatives. Education and training also has relevance to the capacity of firms to develop and utilise new emissions-saving technologies.

Education and information programs also have relevance to the advanced economies. The present level of public understanding of climate change and greenhouse gas issues is a serious barrier to progress in reducing GHG emissions from transportation. It appears that the public is generally not aware of the relationship between the transportation choices they make and their consequences for climate change. Better informing the public might not only change some behaviours (for example, by raising awareness of the value of fuel economy), but also make citizens more inclined to support public policies and measures to reduce GHG emissions (Greene and Schafer 2003). There are currently two principal main methods used to deliver information to consumers on the emissions and fuel consumption performance of motor vehicles: vehicle labelling, and information guides. Labelling schemes have been used with considerable effect so far as household appliances are concerned (as we shall see in the paper on energy consumption). Ranking vehicles according to environmental performance is helpful to consumers and an important prerequisite for encouraging shifts in purchasing patterns (OECD 2004).

8. Global Cooperation

Mitigating global climate change requires *global cooperation*. Cooperation is necessary to ensure the requisite volume of action to overcome the problems of climate change. However, the issues of defection and free riding need to be dealt with to ensure effective cooperation. Cooperation can take many forms:

- agreement on targets for emissions;
- coordinated carbon taxes;
- an agreement to promote fundamental emissions-savings technologies; and
- financing large-scale science that is relevant to the development of emissions-saving technologies.

Addressing the Barriers to Technology Development

To ensure that global warming considerations play an important role in shaping the future technological and investment agendas, appropriate incentives need to be offered. As well as shifting global warming up the scale of relevant factors affecting innovation, policies can also assist in reducing some of the costs and uncertainties associated with the innovation process.

Diffusion of Emissions-Saving Technologies

Beyond R&D, what is needed is more direct support for bringing technologies to a commercial state and introducing them into the marketplace. For example, substantial improvements in vehicle fuel economy can be achieved by applying incremental technology improvements to today's vehicles. This can be accomplished without much additional R&D – but steps will be needed to encourage full use of existing technologies, and to avoid having the benefits of these technologies offset by increases in vehicle size, weight and power.

Such steps will help promote commercialisation of technologies and encourage manufacturers to make the needed (but risky) investments. Support also must be geared to making sure that new fuels are widely available, that fuel systems and vehicles themselves are very safe, that they perform as well as or better than conventional vehicles, and that they are cost competitive. If consumers are confident that they will benefit from switching, and costs are not excessive, a mass-migration could occur quickly as manufacturers can develop and produce new models (IEA 2005a).

The barriers to the diffusion of emissions-saving technologies can be addressed in four different ways.

1. Cost barriers to diffusion can best be addressed through the use of economic instruments – for example, carbon taxes or feebates encourage the replacement of existing emission-intensive equipment, and subsidies on emissions-saving technologies are an alternative to taxes. Regulation, such as mandatory fuel economy standards, is a second best approach to cost barriers.
2. Consumer preferences for emissions-intensive transport options - such as the purchase of large SUVs and powerful automobiles, or the use of motor vehicles when good transit services are available – can be modified in two

different ways – education and information on the qualities of low-emissions alternatives, and the support of technologies that reduce emissions from large vehicles such as the speedy introduction of hybrid vehicles and, eventually, fuel cell vehicles.

3. Average emissions can also be reduced by increasing the rate of capital stock turnover. This can be accomplished by regulatory policies that encourage the retirement of old vehicles (e.g. mandatory maximum emission standards for classes of vehicles, or tough standards on the registration of old vehicles) and the replacement of old transport infrastructure, particularly in the area of transit services.
4. Investments in supporting infrastructure that facilitates the use of low-emission vehicles. Examples include the infrastructure for the distribution of alternative fuels.

Innovation

There are three aspects of strategies to reduce the barriers to commercial innovation in low-emission transport technologies, including innovation in supporting business process innovation.

Economic instruments (taxes/subsidies) or, where the former are politically infeasible, regulations can encourage such commercial innovation and overcome cost or other barriers. Such an approach can have a speedy impact in inducing innovation in specific areas and longer-run impacts on general purpose technologies and innovations complementary to GPTs.

Secondly, specific regulatory barriers to innovations in transport equipment and transport infrastructure need to be addressed. In some parts of the world, regulation of freight transport discourages innovative approaches to the design of new freight vehicles and/or infrastructure – Europe is an example. In the United States, on the other hand, innovation in transit services for passengers is inhibited by the failure to address the external diseconomies associated with passenger traffic in individual motor vehicles.

Thirdly, uncertainty may impede innovation in some areas of transport technology. This is particularly the case with respect to fuel cell vehicles. These uncertainties include the choice of materials for fuel cells, the nature of the on-board storage system, and the funding of a hydrogen production, distribution and refuelling infrastructure (IEA 2005d).

Fourthly, barriers to innovation may exist because of constraints on the adjustment of business organisation in the transport sector that would facilitate the successful take-up of innovative new equipment. Inappropriate product or labour market regulations can encourage inflexibility in business organisations. Complementary innovation in business organisations to accompany technological innovations may be inhibited by a lack of availability of necessary workforce skills which may, in turn, reflect inadequacies in the quantity or quality of education and training. Such inadequacies may also inhibit the capacity to undertake commercial innovation.

Public Research and Development

Many of the possible barriers to public research and development on low emissions technologies for the transport sector appear to have been addressed. There are a number of international and national research framework programs that are influencing the allocation of public resources to transport technologies and eliciting public/private sector cooperation. The interface between public and private sectors in relation to basic research and follow-on applied research has improved over recent decades.

However, two constraints on fundamental technological development need to be addressed. Firstly, the scale of imminent environmental problems necessitates an increased volume of basic R&D. Secondly, attention needs to be given to the capacity of the science and technology infrastructure to deliver the necessary resources to boost basic R&D on transport technologies in the future. The level and quality of training in science and technology is an important aspect of this issue.

The Use of Specific Policy Instruments

Economic Instruments

Introduction

Taxes have important roles to play in shaping transport demand and encouraging the adoption of sustainable technologies in transportation, as well as steering the structure of transport innovation towards emissions reduction and sustainability.

The principal limitations of taxes as a policy instrument is related to the possibility of low price elasticities of demand, including cross-elasticities, in transportation. Low price elasticities imply large tax increases are needed to secure small changes in quantitative outcomes. Securing a wide diversity of alternatives in transport choices is a means of increasing price elasticities and enabling taxes to become a more efficient policy instrument. Keys to securing such an outcome include widening transport choices through an increased range of transit services and overcoming non-price barriers to the widening of choice in low-emissions transport vehicles.

Choice of Instrument

The first choice for economic instruments in a sustainable transportation strategy are carbon taxes and road pricing. *Carbon taxes* are favoured over such taxes as fuel taxes because they tackle emissions-intensity as well as fuel-efficiency. They also have the advantage of fitting into a broader policy approach towards the energy sector as a whole (carbon taxes are effective in providing an incentive to reduce all forms of global warming emissions across all sectors of the economy).

Road pricing is the most effective means of addressing environmental and economic external diseconomies associated with road use. These externalities comprise traffic congestion (which wastes time, increases emissions, and damages health), road wear and tear (which increases future economic and climate change costs associated with road use and road reconstruction), and the environmental externalities associated with road construction and road use.

If the introduction of a carbon tax is politically infeasible in the short- to medium-term, *fuel taxes* are a second-best alternative. Fuel pricing sends a signal to consumers about both vehicle choice and the mode and level of travel. However, as previously noted, a tax on the carbon-content of fuel would be superior as a transport policy instrument because it discriminates between fuels of differing emissions-intensity. However, fuel taxes can be modified to reflect the GHG emissions-reduction potential of each fuel type, as is done in the United Kingdom (IEA 2005a).

A policy-pricing tool that could be used to emphasise fuel consumption differences among new vehicles is the *feebate*. The levels of fees and rebates are determined by specific attributes of each vehicle model, such as rated fuel consumption per 100 km. A feebate system based on rated fuel economy or emissions intensity can differentiate vehicle prices while leaving the average price of a new vehicle, and the overall tax burden on consumers, unchanged.

Pay-at-the pump fees are payments for driving-related services that are included in the cost of fuel, and are paid each time one fills up at the gas pump. They encourage both reductions in travel and increases in fuel economy. Revenues from pay-at-the-pump policies can complement current insurance systems to create revenue pools that cover the costs associated with uninsured motorists and to fund premium rebates to insured drivers. A number of other driving-related costs could be shifted, in all or part, to a variable cost at the time of refuelling. These include vehicle registration fees, and vehicle inspection and maintenance fees that could fund all inspections and required repairs. Even costs associated with providing emergency services to drivers (such as towing, policing and ambulances) could be shifted, at least in part, to the pump (OECD 2001).

Subsidies can be used to encouraging technology diffusion and stimulate commercial innovation. However, it is important to realise the disadvantages of such subsidy approaches when compared with tax-based approaches. First, unlike energy prices, (energy-efficiency) adoption subsidies do not provide incentives to reduce utilisation. Second, technology subsidies and tax credits can require large public expenditures per unit of effect, since consumers who would have purchased the product even in the absence of the subsidy still receive it. In the presence of fiscal constraints on public spending, this raises questions about the feasibility of subsidies that would be sizable enough to have desired effects (Jaffe et al. 2003).

Encouraging the Diffusion of Technology

Taxes reward consumers in choosing low emission transport options (including vehicles) and thus encourage diffusion. They also encourage the acquisition of learning-by-doing economies in newly commercialised technologies and the realisation of conventional economies of scale by stimulating the consumption of low-emission transport technologies.

Encouraging Innovation

The taxation of high-emitting transport technologies provides a strong short term impetus to innovation in specific areas of technology, and inducement to the adaptation of GPTs to transportation and the strengthening of the public/private R&D

interrelationship. Subsidies to new emissions-saving technologies would facilitate the decreased cost and/or improved quality of renewable technologies through inducements to innovation.

In contrast to command-and-control regulations, market-based instruments can provide powerful incentives for companies to adopt cheaper and better pollution-control technologies. This is because with market-based instruments, it pays firms to clean up a bit more if a sufficiently low-cost method of doing so can be identified and adopted (Jaffe et al. 2003). A similar analysis can be applied to low-emission transport technologies.

Goulder (2004) provides an analytical model to show that the efficiency of climate change policies can be significantly increased by the announcement of policies in advance.

Regulation

First Best Regulation

There are two first best arguments for regulation. The first is to increase capital stock turnover and thereby increase the pace of technology diffusion. This will be discussed in a later paragraph. The second justification for regulation is in relation to fuel distribution.

Emissions-saving technologies associated with the use of biofuels and, in particular, hydrogen are dependent on innovations in the fuel distribution before they can deliver widespread environmental benefits in transportation systems. Consumers must be satisfied that new fuels are not only widely available, but are also safe. Regulations in the form of standards regarding the transport, storage and fuelling of vehicles need to be adopted to support the adoption of new fuels.

Regulation as a Second or Third Policy Choice

Regulation is an alternative to taxes and subsidies where their adoption at appropriate levels is politically infeasible. The best-known emissions-saving transport regulatory approach is the adoption of minimum or average fuel efficiency standards for motor vehicles. This policy approach came into vogue after the 1970s oil crises, but the progressive tightening of standards has tended to lapse over the past decade or so. Regulation in this context is a third-best alternative to taxes and subsidies in that (i) it generally addresses minimum compliance rather than offering an incentive for ongoing improvement (although the progressive tightening of regulations can meet this objective to some extent), and (ii) it does not address fuel-efficiency and emissions-intensity associated with variable vehicle use. Speed restrictions address one aspect of in-use vehicle fuel consumption.

As an alternative to road pricing, which faces considerable problems in public acceptance in the current political climate in many parts of the world, parking taxes or restrictions on parking supply, may provide a simpler means of transport demand management. A further example of such an approach is the encouragement of mode-shifts that increase energy efficiency in transportation, such as reducing barriers to the competition of non-road modes of transport with road transport (APEC Center for Technology Foresight 2000; OECD 2001).

Encouraging the Diffusion of Technology

Although the empirical literature on the effects of policy instruments on technology diffusion by no means settles all of the issues that emerge from the related theoretical studies, a consistent theme that runs through both the pollution-abatement and energy-efficiency empirical analyses is that market-based instruments are decidedly more effective than regulatory (command-and-control) instruments in encouraging the cost-effective adoption and diffusion of relevant new technologies (Jaffe et al. 2003).

The reform of regulatory systems in the product markets and labour markets has been shown to reduce barriers to the diffusion of new technologies. A further instrument of policy for encouraging the diffusion of technology is government procurement. Alic et al (2003) notes that government procurement in the United States provided a major stimulus to the spread of technology in such areas as jet engines, semiconductors and computers. These authors suggest that government procurement policies could be used to provide markets for advanced energy-efficient and low-emissions equipment.

Encouraging Innovation

Conventional approaches to regulating the environment are often referred to as ‘command-and-control’ regulations, since they allow little flexibility in the means of achieving goals. Such regulations tend to force firms to take on similar shares of the pollution-control burden, regardless of the cost. Command-and-control regulations do this by setting uniform standards for firms, the most prevalent of which are performance- and technology-based standards. A performance standard sets a uniform control target for firms (emissions per unit of output, for example), while allowing some latitude in how this standard is met. Technology-based standards specify the method, and sometimes the actual equipment, that firms must use to comply with a particular regulation. While even technology-based standards provide an incentive for innovation that reduces the cost of using specific technologies, performance standards allow a wider range of innovation, as long as standards are met at the plant level. In contrast, market-based instruments allow even greater flexibility in innovation possibilities, including flexibility in plant-level emissions.

Holding all firms to the same target can be expensive and, in some circumstances, counterproductive. While standards may effectively limit emissions of pollutants, they typically exact relatively high costs in the process, by forcing some firms to resort to unduly expensive means of controlling pollution. Because the costs of controlling emissions may vary greatly among firms, and even among sources within the same firm, the appropriate technology in one situation may not be appropriate (cost-effective) in another.

All of these forms of intervention have the potential for inducing or forcing some amount of technological change, because by their very nature they induce or require firms to do things they would not otherwise do. Performance and technology standards can be explicitly designed to be ‘technology forcing’, mandating performance levels that are not currently viewed as technologically feasible or mandating technologies that are not fully developed. One problem with these approaches, however, is that while regulators can typically assume that some amount of improvement over existing technology will always be feasible, it is impossible to know how much. Standards must either be made unambitious, or else run the risk of being ultimately unachievable, leading to great political and economic disruption.

Technology standards are particularly problematic, since they tend to freeze the development of technologies that might otherwise result in greater levels of control. Under regulations that are targeted at technologies, as opposed to emissions levels, no financial incentive exists for businesses to exceed control targets, and the adoption of new technology is discouraged. Under a 'Best Available Control Technology' (BACT) standard, a business that adopts a new method of pollution abatement may be 'rewarded' by being held to a higher standard of performance and thereby not benefit financially from its investment, except to the extent that its competitors have even more difficulty reaching the new standard. On the other hand, if third parties can invent and patent better equipment, they can, in theory, have a ready market. Under such conditions, a BACT type of standard can provide a positive incentive for technology innovation. Unfortunately, there has been very little theoretical or empirical analysis of such technology-forcing regulations (Jaffe et al. 2003).

Dealing With Slow Capital Stock Turnover

The objective of policy is to increase fuel efficiency and reduce emissions intensity by speeding up the transition to state-of-the art transport vehicles, equipment and infrastructure. Transit equipment and infrastructure tends to have the longest lives and hence the slowest capital stock turnover. Aircraft and marine vessels also have quite long lives. Capital stock turnover in motor vehicles is around 20 years, but reductions in vehicle lives would be a significant influence on the effective diffusion of new technologies through the average vehicle fleet.

A number of policy approaches can be taken to speeding up capital stock turnover:

- fuel efficiency or emissions standards can be applied to existing vehicles in addition to new vehicles;
- roadworthiness (airworthiness, seaworthiness) can be applied with rigorous standards taking into account emissions ratings;
- standards for maximum emissions applied to all vehicles advanced microtechnology sensors to identify non-compliant vehicles; and
- public funding *or* public/private partnerships *or* private operator contract specification to encourage improvements in infrastructure quality and the replacement of old infrastructure.

Encouraging Commercial R&D

Should we encourage it?

The theoretical justifications for the encouragement of commercial R&D on low-emissions technologies are (1) the presence of negative externalities and (2) the spillover benefits that result from R&D investments. The empirical evidence suggests that positive externalities associated with knowledge spillovers lead to social rates of return to R&D in excess of private rates of return. In practice, virtually all industrialised countries engage in policies designed to encourage investment in innovation. It is difficult to determine how well these policies do in moving R&D toward optimal levels. There is some evidence that social rates of return remain well above private levels, but there is also evidence that R&D subsidies drive up the wages of scientists enough to prevent significant increases in real R&D. This implies that the supply of scientists and engineers is relatively inelastic; whether such inelasticity could hold in the long run remains unresolved (Jaffe et al. 2003). At the very least, strategy needs to consider the encouragement of commercial R&D and support for the science and technology as twin parts of an optimal policy approach.

Subsidising Private R&D

Reducing the real after-tax cost of R&D encourages induced innovation. Government policy affects the after-tax cost of R&D via tax incentives, direct subsidies and grants for research, and also via educational policies that affect the supply of scientists and engineers. Public policies can affect the market for new technologies via direct government purchase, subsidies for purchase or installation of products incorporating particular technologies, and also disincentives against the adoption of competing technologies (pollution fees, for example). Finally, policies can affect the extent to which firms can successfully appropriate the returns to their research, by establishing the institutional environment of patent systems, employment relations, and antitrust or other competition policies (Jaffe et al. 2003).

Science and Technology Policy

Public R&D

The volume and quality of basic R&D in relevant scientific disciplines can provide a stimulus to commercial technological development. Policy can try to increase social investment in R&D by engaging R&D in the public (and/or non-profit) sector, or by trying to reduce the after-tax cost of R&D for private firms. Public R&D may well play a particularly important role with respect to environment-related science and technology, since the external social benefits of environmentally benign technology are unlikely to be fully captured by private innovators (Ruttan 2001). Popp (2005) shows that public basic research has encouraged private sector innovation in energy technologies.

When discussing public research and development under the broader heading of the transportation technology system, a large range of public research topics was identified as being of significance to the development of less emissions-intensive transportation.

Allocation of Public Research Resources

Evaluation can occur at several levels and several stages. These range from the peer review of investigator-initiated project proposals at the time they are submitted to performance reviews of the program of a research institute or the research portfolio of a scientific agency. There is almost universal agreement within the science community that use of the peer review mechanism in the evaluation of project or program merit should be the primary method of determining priorities in the allocation of resources to research projects and programs.

There is much less consensus within both the scientific community and in the broader research community on how to evaluate research programs, institutes, or agencies. It is at this higher level that the issue of relevance to broader social objectives becomes increasingly important – is the research worth doing no matter how well it is done? It is clear that at this level reliance on peer-reviewed investigator-initiated proposals becomes a less adequate basis for making decisions about research resource allocation. In spite of the strictures about 'mindless application' of quantitative measures, rate of return analysis has, when applied with skill and insight, been exceedingly useful. There is also an appropriate role for methods such as citation and patent counts.

Each major mission-oriented public research organisation should have a small unit devoted to testing and refining the analytical methods research managers use in making research resource allocation decisions and in demonstrating the value of the contributions of the organisation's research program to agency administrators and congressional committees. A research institution that does not develop such a capacity will have great difficulty in responding to its critics or arming its defenders (Ruttan 2001).

Within the area of transportation technologies, the role of international and national coordination of basic R&D has already been noted. These methods of oversight provide a clear sense of direction for R&D on transport technology.

Other Aspects of Science and Technology Policy

There are benefits to *cooperative* approaches to R&D that involve the public and private sectors. These can embrace cooperative research programs and the transfer of relevant scientific knowledge from the public to the private sector. Cooperative research requires funding and effective consultative mechanisms. There is a considerable range of cooperative R&D being undertaken in transport technologies. Alic et al. (2003) discuss the lessons to be learned from cooperative R&D in the United States. Of specific interest is their analysis of the project Partnership for a New Generation of Vehicles (PNGV) which ran from 1992 to 2002. This program was replaced by FreedomCAR, which focussed on fuel cells.

The *education and training* of R&D personnel is another important facet of science and technology policy. IEA (2000c) indicate that a shortage of appropriately trained professional and technical labour was at that time a major bottleneck in regard to the demonstration and application of new energy technologies. There are global dimensions to this problem.

Infrastructure Development

Transport infrastructure development should have the following objectives:

- the development of an infrastructure for alternative fuels (notably hydrogen) and vehicles powered by alternative fuels;

- the availability of alternative fuels, their safety in storage and fuelling, and their compatibility with vehicle warranties comparable to conventional vehicles;
- the upgrade of existing infrastructure for transit systems and the development of new transit technologies; and[14]
- the construction of intelligent vehicle highways.

The policy approaches towards these objectives can embrace:

- public funding;
- a mix of public and private funding;
- imposing conditions of private sector licensing to provide transport services;
- setting and applying standards for transit infrastructure; and
- subsidies or tax breaks for the development of transit infrastructure.

Integration of Urban Planning with Transport Planning

The integration of urban planning with transport planning should be aimed at reconciling the multiple objectives for a fully sustainable transportation system:

- economic – reducing congestion, facilitating more efficient freight systems;
- social – access to all groups in the population;
- safety issues related to roadways and transit ways; and
- environment – reducing external diseconomies associated with infrastructure construction and use.

The integration orf urban and transport planning contributes to the realisation of the full range of objectives for a sustainable transport systems. While not primarily directed toward climate change issues, it does contribute to the reduction in emissions in a number of ways, including:

- reduced in-vehicle fuel use as a result of less traffic congestion;
- more efficient freight systems that reduce traffic and consequent emissions;
- fuel use declines because of traffic reductions through increased scope for walking and cycling; and
- Increasing the price elasticities in the transport system by facilitating wider transport choices to consumers and hence increasing the responsiveness of the transport systems to price signals.

The integration of urban and transport planning in a way that addresses the issues raised by sustainable transport as an objective requires two essential areas of

[14] The improvement in infrastructure should be aimed at increasing consumer transport choices through facilitating increased services coverage. Capacity, frequency and reliability, improving operational flexibility, and increasing intermodality.

competency. The first is effective governance systems for the region under question. The second is the provision of adequate information on current traffic flows and data relevant to constructing scenarios of future traffic flows so that planning models can be based on rigorous empirical analysis.

Education and Information

Information

Policies have a role to play in reducing uncertainty as to the viability of new technologies, and increasing the awareness of new technologies as a means of encouraging technology dissemination. The dissemination of information is directly aimed at overcoming information barriers to the diffusion of technologies. It appears, for example, that the public is not aware of the relationship between the transportation choices they make and their consequences for climate change. Better information to the public may change some behaviours (for example, by raising awareness of the value of fuel economy), but also make citizens more inclined to support public policies and measures that encourage the diffusion of emissions-reducing technologies (Greene and Schafer 2003).

There are several steps government can take to improve consumer awareness. For example, they can adopt more effective information campaigns to educate consumers about the fuel-economy implications of their choices. Because similarly-sized vehicles can have widely varying fuel economies, an important step is developing fuel-economy labelling systems that reflect this (as is being done in the Netherlands). Another promising approach to dampen shifts to heavier, more powerful vehicles is a system of fuel-economy-based vehicle fees or revenue-neutral fees-cum-rebates (so-called ‘feebates’) that encourages consumers to put greater emphasis on fuel economy in the vehicles they purchase (as has been successfully undertaken in Denmark and the Netherlands) (IEA 2005a).

The public sector can also engage in technology demonstration programs in order to reduce uncertainty about the diffusion of technologies and increase the rate of learning-by-doing in new technologies.

Education and Training

The training of managers and employees in new technologies would:

- increase the capacity of the private sector to make use of relevant basic research;
- increase the propensity to utilise GPTs;
- increase the propensity for induced innovation;
- facilitate changes in internal business operations and relationships with suppliers and customers that optimise the use made of new technologies; and
- remove bottlenecks to the capacity of science and technology systems to meet the emerging needs in basic research.

The main requirement for education and training systems that optimise opportunities for the realisation of sustainability in transportation is flexibility. Such flexibility is required in education, training and the management of employee skills in the workplace. A second requirement for education and training is to enable the capabilities of the science and technology systems to facilitate basic research in relevant transport technologies.

International Cooperation

Global cooperation is necessary to encourage the international spread of new sustainable transportation technologies. This cooperation should range from facilitating the diffusion of existing frontier technologies, encouraging international awareness of innovative research and cooperation in specific research where necessary, and identifying and attempting to resolve regulatory barriers to the commercialisation of such innovation.

In terms of basic research, there is a similar case for promoting awareness and cooperation. International cooperation will be particularly necessary in areas known as Big Science where the scale of the basic research required tends to exceed the capacities of purely national science and technology systems. The main examples of Big Science that is related to sustainable transportation is research relevant to the hydrogen economy, particularly relating to the distribution and storage of hydrogen.

4. Conclusions

The trend in GHG emissions from transport will be largely determined by the nature of the technologies employed in transport. Under the Reference Scenario of the International Energy Agency, slow but steady changes in transport technologies provide a source of emissions savings. These savings are mainly manifest in new technologies for such transport equipment as motor vehicles and aircraft. But despite these advances in technology, the trends in population and increased GDP per capita continue to contribute to a net increase in GHG emissions from transport, as indicated in Table 1.

The increase in emissions is particularly notable in the developing economies. Between 2002 and 2030 emissions of CO_2 from transport are projected to increase by 169.3%. This reflects particularly rapid growth in the two largest developing economies of China and India on top of the assumption that new emissions saving transport technologies are only adopted in the developing economies after a significant lag in time. It is little consolation that there is an anticipated marginal deceleration in the rate of growth of emissions over the period to 2030.

There is little cause for complacency about the situation in the OECD, where emissions of CO_2 from transport are assumed to increase by 43.5% between 2002 and 2030. Transport emissions are expected to comprise 54.6% of emissions from total final energy consumption in 2030, compared with 48.2% in 2002.

Table 1. Transport and the IEA Reference Scenario

CO_2 Emissions from Transport, Average Annual Rate of Growth	2002/2010	2010/2020	2020/2030	2002/2030*
OECD	1.7	1.5	1.3	43.5
Developing Economies	4.3	4.0	3.6	169.3
World	2.5	2.3	2.1	77.8
Transport Emissions as a % of Total Final Energy Consumption	**2002**	**2010**	**2020**	**2030**
OECD	48.2	50.2	52.7	54.6
Developing Economies	28.4	32.1	36.1	39.7
World	38.2	40.1	42.5	44.6
Oil Energy Consumed in Transport as a % of Total Final Energy Consumption of Oil	**2002**	**2010**	**2020**	**2030**
OECD	62.1	64.3	66.6	68.2
Developing Economies	47.5	49.7	52.7	55.4
World	57.1	58.7	60.6	62.1

Note: * percentage increase 2002 to 2030.
Source: Derived from IEA (2004, pp. 430-437, 478-483).

A more optimistic view of the future stresses the potential contribution of new technologies to emissions saving in transport. This chapter enumerates the range of technologies that could be developed over the next fifty years and the policy climate that would encourage such technological developments. The quantitative implications of advances in emissions-saving technologies for transport emissions are summarised in Table 2.

Table 2 sets out an Optimistic Scenario in which a combination of innovations in climate change policy trigger major advances in transport technologies on what otherwise might be the case. The Scenario applies only to the economically advanced economies. Progress in reducing the emissions-intensity of transport are likely to be slower in the developing countries, although the long run scope for change is still considerable.

Table 2a indicates that total GHG emissions (which include both carbon dioxide and other major greenhouse gases) could more than halve between now and 2050. Change could occur relatively speedily, with the growth in emissions easing significantly between now and 2010. In the following decade they would begin an absolute decline that would become quite rapid in the period 2020 to 2050.

Table 2b indicates the sources of emissions saving by 2050. The base of zero improvements in transport sustainability is much more pessimistic than the assumptions employed in the IEA Reference Scenario. In the base scenario of Table 2b, there are no transport demand savings, no net improvements in energy efficiency, and no changes in the sources of energy used by transport. The second column of the table indicates that improvements in technologies relating to these various aspects of transport convert a worst-case scenario of an increase in 123% in GHG emissions to a reduction of 52%.

Table 2. Optimistic Scenario for the Advanced Economies

2a. Average Annual Rate of Growth of GHG Emissions from Transport

2000/2010	0.4
2010/2020	-0.7
2020/2030	-2.3
2030/2040	-2.4
2040/2050	-2.2
2000/2050	-51.9

2b. Contributions to the Trends in GHG Emissions from Transport, 2050

	% change 2000-2030	Index
Zero Improvements in Transport Sustainability	122.9	100.0
Reduced Demand for Transport Movements	89.0	84.8
Increases in the Energy Efficiency of Transport	33.5	59.9
Shift in Energy Sources of Transport	-5.3	42.5
Optimistic Scenario	-51.9	25.4

Source: CSES (2004, p. 36).

The third column of Table 2b indicates the contribution of specific elements to GHG emissions compared with the base scenario. Thus savings in transport demand contribute a 15% reduction in emissions, increases in energy efficiency 40%, and a shift in the energy sources of transport 57.5%. Cumulatively, these savings partially cancel each other out (for example, a reduction in transport demand means other improvements now work on a smaller base that was previously assumed).

5. Addendum: The Hydrogen Economy for Vehicles[15]

Fuel Cell Vehicles

The cost of a proton-exchange membrane fuel cell (PEMFC) drive system can be split into the fuel stack, the balance of plant (BOP), the electric motors and hydrogen storage.

The Cost of the Fuel Stack

Overview

The cost of a PEMFC stack is the sum of the individual costs of the membrane, electrode, bipolar plates, platinum catalyst, peripheral materials and the cost of assembly. The total cost of US$1826/kW is dominated by the cost of bipolar plates ($826), and electrode ($712). The cost of the membrane ($250) platinum catalyst ($25), peripherals ($8) and assembly ($8) are of lesser importance. Both the major cost components are manually manufactured at the moment, but their future large-

[15] Based on IEA (2005d).

scale production should lead to a significant fall in their cost. In general, the switch from small-scale manufacturing to mass-production will be able to reduce the fuel cell cost significantly. Toyota claims that they can presently build fuel stacks at about US$500/kW. Ballard claims that their fuel stacks, if produced at a rate of 500,000 units a year, would cost US$103/kW and that they are aiming for US$30/kW by 2010.

Membranes

Current PEM fuel cells use membranes that were initially developed for electrolysers for industrial chlorine production. They have been in production for more than 30 years. The disadvantages of these membranes are: (1) they require humidification, and (2) they also require a platinum catalyst that is expensive and sensitive to CO poisoning. The choice of membrane material is a fundamental issue, as the whole fuel cell design may change depending on the membrane material used. Alternative materials that are not yet commercially available are being studied, and could result in significant cost reductions for membranes and opportunities for alternative designs in fuel cell stacks.

Electrode and Platinum Catalyst

In addition to tits technical disadvantages, platinum is a scarce commodity whose global production capacity is limited in the long run. Current PEMFC membranes use 1.4g/kW. The goal is to develop membranes that require only 0.2g/kW. His should be possible using a new technology known as Gas Diffusion Layer. Further down the track, new high-temperature membranes may eliminate the use of platinum entirely.

Bipolar Plates

Bipolar plates are currently made from milled graphite or gold-coated stainless steel. The cost of bipolar plates can be reduced if they are mass-produced. Carbon-polymer composites or low-cost steel alloys seem the best materials candidates for mass production. Ongoing R&D is concentrating on these materials.

The Overall Stack Cost

The principal changes that are needed to reduce the cost of PEM fuel cells from around US$1800/kW (US$144,000 per vehicle) to US$100/kW (US$8000 per vehicle) are:

1. The mass-production of membranes and the use of new materials in membranes.
2. The mass-production of electrodes based on the new Gas Diffusion Layer technology.
3. The mass production of either plastic or coated-steel bipolar plates.
4. Achieving a 50% increase in power density.
5. Achieving the production of 100,000 m^2 per year of fuel stacks, equivalent to 4000 vehicles per year for an 80 kW vehicle.

It is possible that the cost of the PEM fuel stack could be even lower than US$100/kW in the future. A projected cost of just US$50/kW (US$4000 per vehicle) might be possible assuming a doubling of the power density (from current levels) and the use of cheaper electrodes and bipolar plates. However, reducing costs to that level cannot be achieved with gradual improvements in existing technologies. It is based on new membrane technologies, a new electrode production technology and a different, unspecified, method to produce bipolar plates.

Fuel Cell Durability

Fuel cell durability is a critical element in the life-cycle cost of fuel cell application. In mobile applications a life of 3000-5000 hours for cars and up to 20,000 hours for buses is required. The average lifespan of PEM fuel cells for vehicles is currently about 2200 hours or 100,000km. However, this can vary from 1000 to 13,000 hours depending on the test conditions. Doubling the average life and reducing the variability in average life will be imperative to gain consumer acceptance. Given the significant advances in the durability of fuel cells achieved over recent years and the wide gap between average and best durability, further improvements should be feasible. Fundamental fuel cell design changes, such as different membrane materials and new high-temperature catalyst materials, may increase durability.

The Cost of the Balance of Plant

In addition to the stack cost, fuel cells require power electronics in the form of converters, inverters, electric motors, control electronics, as well as air and hydrogen humidification (depending on the fuel cell membrane type). The supply of air and hydrogen to the fuel cell must be within a fixed, very narrow, pressure range to prevent damage to the fuel cell. A cooling system is needed to cool the fuel cell and a voltage monitoring system is needed for performance and safety control.

The electric motors represent the most costly component, followed by the converter. A three-phase induction motor is the most likely choice for this component, as this is already widely used in electric and hybrid vehicle applications. The current cost of such a motor is US$2000. This estimated includes the converter. The nickel-metal hydride batteries used in current hybrid cars cost around US$2500 giving the total cost of the balance of plant of US$4500 a car. By 2030, an optimistic view is that the cost of the balance of plant could reduce to US$1350/car.

The Aggregate Costs of Fuel Cell Vehicles

Scenarios for the aggregate costs of fuel cell vehicles in relation to conventional vehicles are summarised in Table 3.

Table 3.Fuel Cell Vehicle Cost Reduction Scenarios

	2005	Target 2030	Alternate 2030
Fuel cell stack	144000	4000	4000
Balance of plant	4500	1350	1350
Gaseous hydrogen storage	4000	1000	1000
Conventional vehicle w/o engine	17050	17050	11750
Hydrogen fuel cell vehicle	169550	23400	18100
Conventional ICE vehicle	19450	19450	13400

Note: Costs are denominated in U.S. dollars and are for a representative vehicle. Columns two and three are sourced from IEA (2005d, p. 101), the final column is based on the hypothetical estimate of 1.5% annual productivity growth in conventional vehicle technologies.

In addition to the previously discussed cost of the fuel cell stack and the balance of plant (the motor and battery), fuel cell vehicles require a gaseous hydrogen storage tank, the cost of which is estimated to reduce from a current US$4000 to US$1000 eventually. The other components for the fuel cell vehicle are expected to be similar to that of conventional vehicles, a representative figure being US$17050. The example given in IEA (2005d) assumes these costs are unchanged over the next 25 years. The final column has an alternative view in which productivity increases at a steady rate for conventional vehicle technologies (in view of our earlier discussion of vehicle technologies, this appears to be a more realistic example. Nevertheless, fuel cell technologies increase in efficiency much more rapidly than conventional technologies.

An optimistic view of the development of fuel cell technologies suggest that the cost of the FCV could be lower in real terms by 2030 than is a conventional vehicle today (second-last line in the last column). Relative to a conventional vehicle, the FCV would decline from 8.7 today to 1.20 (not allowing for improvements in conventional vehicles) up to 1.35 (as in the last column of the table).

Hydrogen Storage

On-board Hydrogen Storage

The storage of hydrogen for transportation applications is the main focus for R&D. Hydrogen can be stored as a compressed gas in pressure vessels, as a liquid in cryogenic tanks and adsorbed or absorbed in solid materials. Cryogenic liquid storage and gaseous storage whereby the hydrogen is compressed to 700 bar requires the least volume of conventional storage options, but they are seven to nine times more voluminous than gasoline fuel tanks with an equivalent fuel content. Solid metal hydrides promise three to four times higher hydrogen density than gaseous storage. Solid storage, however, is not commercially proven and may result in significant weight penalties, depending on the specific hydride used as a storage material (IEA 2005d).

Gaseous Hydrogen

The most common method to store hydrogen in gaseous form is in steel tanks, although lightweight composite tanks designed to endure higher pressures are also becoming more and more common. Cryogas, gaseous hydrogen cooled to near cryogenic temperatures, is another alternative that can be used to increase the volumetric energy density of gaseous hydrogen. A more novel method to store hydrogen gas at high pressures is to use glass micro spheres.[16]

Composite Tanks

The main advantages of composite tanks are their low weight, commercially availability, quality of engineering and safety testing, and their possession of codes that are accepted in several countries for a range of pressures. Composite tanks require no internal heat exchange and may be usable for cryogas. The main disadvantages are the large physical volume required, their cylindrical shape makes it

[16] The reference for hydrogen storage is Riis and Sandrock (2005).

difficult to conform storage to available space, and the high cost, and energy penalties associated with compressing the gas to very high pressures. There are also some safety issues that still have not been resolved, such as the problem of rapid loss of hydrogen in the event of an accident. The long-term effect of hydrogen on the materials under cyclic or cold conditions is not fully understood either. Hence, there is still need for more R&D.

Glass Micro Spheres

Glass micro spheres can be used to store hydrogen gas onboard a vehicle in the following way. First, the hollow glass spheres are filled with hydrogen at high pressure and high temperature by permeation in a high pressure vessel. Next, the micro spheres are cooled down to room temperature and transferred to the low-pressure tank. Finally, the micro spheres are heated for controlled release to run the vehicle.

The main problem with glass micro spheres is the inherently low volumetric densities that can be achieved and the high pressures required for filling. The glass micro spheres slowly leak hydrogen at ambient temperatures. Another practical challenge is that there is too much breakage during cycling. The main operational challenge is the need to supply heat at temperatures higher than available from the PEM fuel cell. The high temperature required also makes rapid response control difficult.

Glass micro spheres do have some important advantages, however. They have the potential to be inherently safe as they store hydrogen at a relatively low pressure onboard and are also suitable for conformable tanks. This allows for low container cost.

R&D on glass micro spheres that leads to a reduction in the hydrogen liberation temperatures, currently about 300^0C and targeted less than 100^0C, needs to be performed. General studies on infrastructure and cost are also needed, along with the more specific R&D tasks of developing stronger glasses, developing specific low-temperature techniques, developing coating techniques for optimisation of hydrogen permeability, and developing techniques to control permeability by other than thermal methods (such as magnetic, electric, or microwave fields).

Liquid Hydrogen

The most common way to store hydrogen in a liquid from is to cool it down to cryogenic temperatures (-253^0C). Other options include storing hydrogen as a constituent in other liquids such as $NaBH_4$ solutions, rechargeable organic liquids, or anhydrous ammonia NH_3. This section discusses the three most promising methods: cryogenic hydrogen, $NaBH_4$ solutions, or anhydrous ammonia NH_3.

Cryogenic Liquid Hydrogen (LH_2)

Cryogenic hydrogen, usually referred to as liquid hydrogen (LH_2), has a much better energy density than the pressurised gas solutions mentioned above. However, it is important to note that about 30-40% of the energy is lost when LH_2 is produced. The other main disadvantage with LH_2 is the boil off losses during dormancy, and the fact that a super insulated cryogenic container is needed. The general public's perception of LH_2 as an unsafe and very high tech system should not be underestimated. The main advantage with LH_2 is the high storage density that can be reached at relatively low pressures. Liquid hydrogen has been demonstrated in commercial vehicles (particularly by BMW), and in the future it could also be co-utilised as aircraft fuel as it provides the best weight advantage of any hydrogen storage.

The main R&D tasks are to:

- develop more efficient liquefaction processes (such as hydride compressors, magnetic and acoustic cooling);
- lower costs and improve the insulated containers;
- develop systems that automatically capture the boil-off (such as via hybrids) and re-liquefy the fuel.

$NaBH_4$ Solutions

Borohydride ($NaBH_4$) solutions can be used as a liquid storage medium for hydrogen. The main advantage with using $NaBH_4$ solutions is that it allows for safe and controllable onboard generation of hydrogen. The main disadvantage is that the reaction product $NaBO_2$ must be regenerated back to $NaBH_4$ off board. The required cost reductions to make this technology commercially feasible are unlikely because of the unfavourable thermodynamics. However, $NaBH_4$ solutions may be useable in high-value portable and stationary applications.

Rechargeable Organic Liquids

Some organic liquids can also be used to indirectly store hydrogen in liquid form. The following three steps summarise the basic concept. First, an organic liquid is dehydrogenated (through a catalytic process) to produce hydrogen gas on-board. The next step is to transport the dehydrogenated product from the vehicle tank to a central processing plant, while simultaneously refilling the tank with fresh hydrogen-rich liquid. Finally, the hydrogen-depleted liquid needs to be re-hydrogenated and brought back to the staring compound and returned to the filling station. Research and development needs to focus on:

- detailed safety and toxicity studies of the relevant organic liquids;
- possible infrastructure scenarios and corresponding cost calculations;
- develop organic systems that can be dehydrogenated at low temperatures and produce useable hydrogen pressures;
- develop optimal metal dehydrogenation catalysts and onboard systems, and
- develop the re-hydrogenation process.

Conclusions

The handling and transport of liquid hydrogen, which may involve highly toxic chemical substances or extreme temperatures, requires a safe and well-organised industrial structure. The hydrogen-liquid production (or regeneration) infrastructure would have to be distributed in order to minimise the transport cost to the distributed refuelling stations. The build-up of such infrastructure could be quite costly and should be combined with non-vehicular applications, both stationary power production and aviation transport. Cryogenic liquid hydrogen could meet the demands for aviation, while the other two options (borohydride solutions and organic liquids) could be suitable for refuelling of motor vehicles.

Solid Hydrogen

Storage of hydrogen in solid materials has the potential to become a safe and efficient way to store energy, both for stationary and mobile applications. The four main groups of suitable materials are carbon and other high-surface area materials, H_2O-reactive chemical hydrides, thermal chemical hydrides, and rechargeable hydrides. Research on solid hydrogen is much least advanced than for other forms and much basic scientific work remains to be done in this area.

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