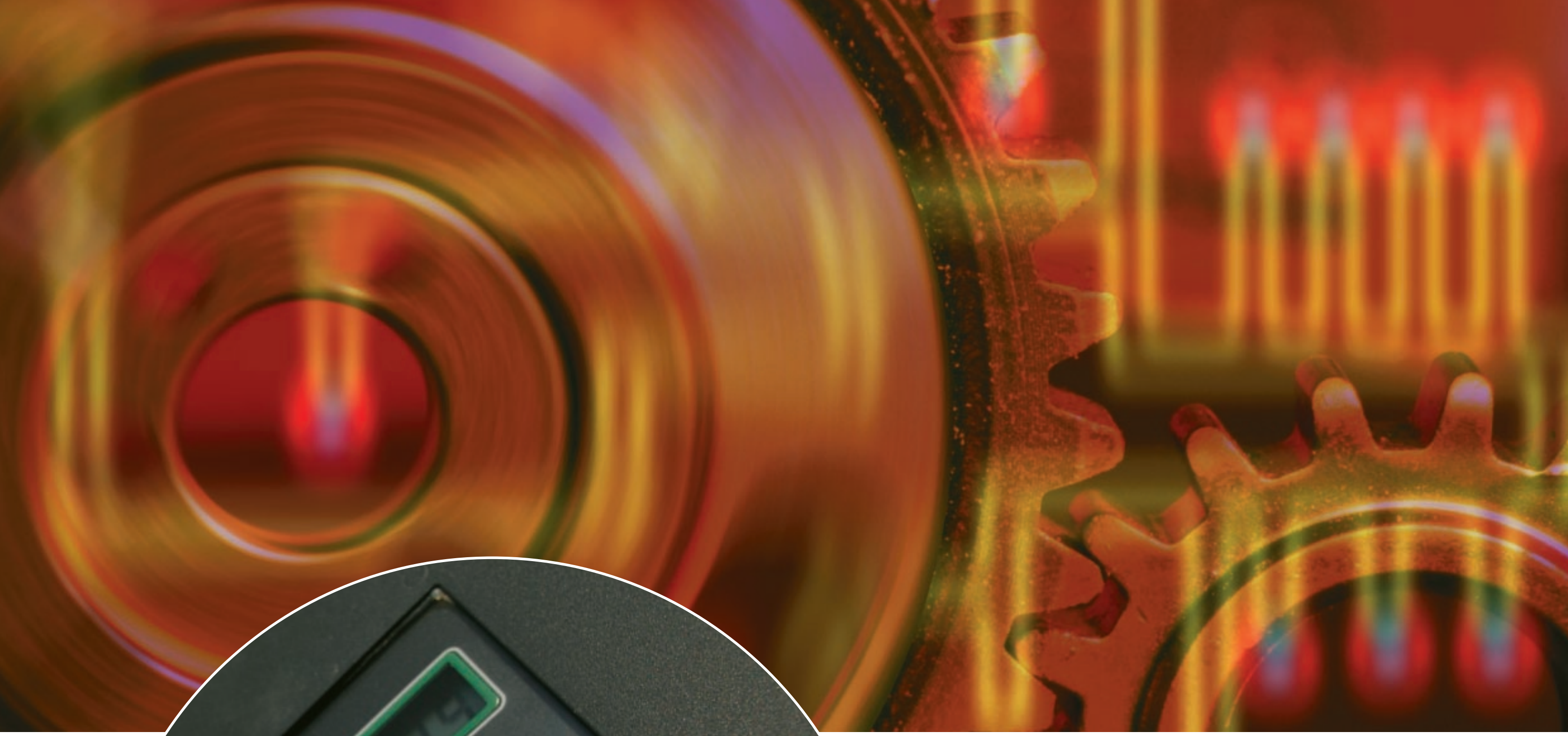



Chapter 3

The potential of vehicle technologies and transport fuels to be major "building blocks" of sustainable mobility



In this chapter, the SMP assesses the potential of a range of vehicle technologies and transport fuels to serve as "building blocks" of sustainable mobility. The word "potential" is crucial in interpreting the information in this chapter. In Chapter 4 we will explore the factors that will determine the extent to which this potential might actually be realized.

I.

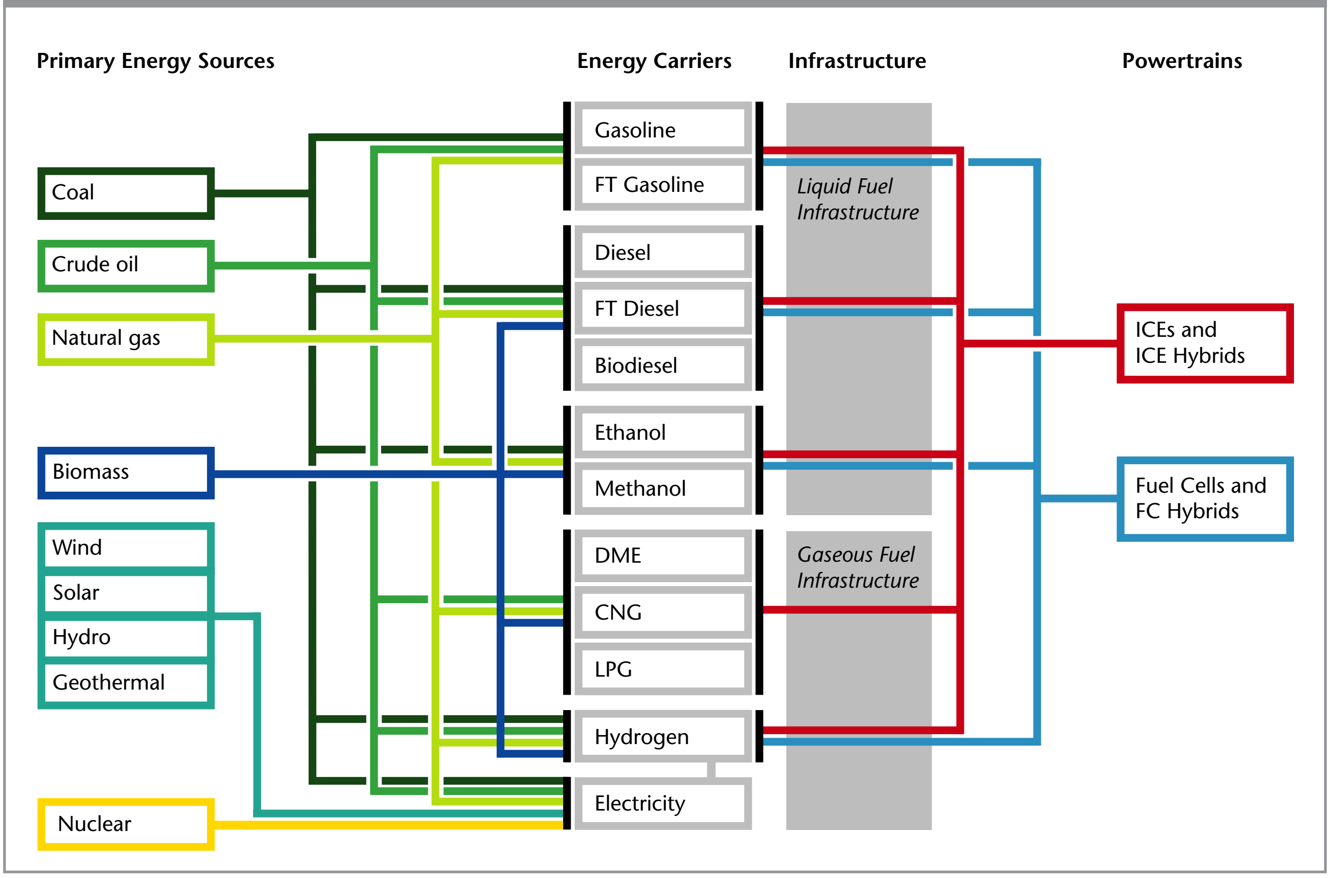
Propulsion systems and fuels

Today's motorized road transportation system has been built up over the last 100 years following the late 19th century invention of the internal combustion engine and the realization of the transport fuels potential of light petroleum products (such as gasoline and diesel fuel) produced by the distillation of crude oil. From these early beginnings vast multibillion dollar industries have developed worldwide distributing and servicing every transport need. But with a few minor exceptions, these industries are still rooted in the same basic technologies – the internal combustion engine (ICE) and petroleum-based fuels. These technologies are beginning to be viewed as barriers to sustainability, and alternative fuel and power technologies believed to be more sustainable are now being explored.

The organization of the fuels and propulsion system sections of this chapter is reflected in Figure 3.1.

The first column identifies various sources of primary energy, sometimes referred to as "feedstocks," available to propel transport vehicles. In most cases these primary energy sources are not used directly as transport fuels, coal and natural gas being major exceptions. Rather, society uses energy carriers produced from the primary energy sources. The second column shows energy carriers in use at present or proposed for use in the future as transport fuels. The lines connecting

Figure 3.1 **Possible transport fuel pathways**



Source: Sustainable Mobility Project.

Box 3.1 Is the world about to run out of oil?

Ever since the first oil well was drilled in Titusville, Pennsylvania in 1859, people have been asserting that the world was about to "run out of oil." Projections of substantially increased oil demand, such as those in our reference case, are prompting this question to be raised again. In a recent article in the *New York Times*, Daniel Yergin, Chairman of Cambridge Energy Research Associates and author of "The Prize: The Epic Quest for Oil, Money and Power," addressed these concerns. An excerpt follows:

Adherents of the "peak oil" theory warn of a permanent oil shortage. In the next five or 10 years, they maintain, the world's capacity to produce oil will reach its geological limit and fall behind growing demand. They trace their arguments back to the geophysicist M. King Hubbert, who in 1956 accurately predicted that American oil production would reach its apex around 1970. In a recent book, "Hubbert's Peak," Kenneth S. Defeyes, an emeritus professor of geology at Princeton, wrote "Global oil production will probably reach a peak sometime during this decade." Current prices, he adds, "may be the preamble to a major crisis." In "Out of Gas," David Goodstein, a professor at the California Institute of Technology, also argues that world oil output will peak "most probably within this decade" and thereafter "will decline forever."

... Are the peakists right?

Yes, oil is a finite resource, and fear of running out has always haunted the petroleum industry. In the 1880s, John Archbold, who would succeed John D. Rockefeller as head of the Standard Oil Trust, began to sell his shares in the company because engineers told him that America's days as an oil producer were numbered. . . .

The oil crises of the 1970s - the 1973 Arab oil embargo and the 1979-80 Iranian revolution - were also seen as the harbingers of the "end of oil." In 1972, an international research group called the Club of Rome predicted the world would soon run short of natural resources. Spiraling oil prices in the following years - from $3 a barrel to $34 a barrel - seemed like a confirmation.

Historically, ... dire oil predictions have been undone by two factors. One is the opening (or reopening) of territories to exploration by companies faced with a constant demand to replace declining reserves. The second is the tremendous impact of new technology. After World War I, seismic technology, used for locating enemy artillery, was adapted to oil field exploration. And in the 1990s, it became feasible to drill into deep offshore fields, which was inconceivable during those crisis years of the 1970s.

Better technology and management have increased Russian output by 45 percent since 1998, making Russia the world's second-largest oil producer. And if United States sanctions are lifted on Libya, new investment there could push up production. In the meantime, advanced information technologies and sophisticated remote sensing techniques are making exploration and production much more efficient, which could make an additional 125 billion barrels available over the next decade, an amount greater than the current proved reserves of Iraq.

Those who don't believe a shortage is imminent do not deny that a peak will eventually be reached. They just believe that it is much farther off into the future.

"You can certainly make a good case that sometime before the year 2050 conventional oil production will have peaked," said the head of exploration for a major oil company. He and others believe, however that oil production will simply plateau, and then farther into the future begin to decline.

They also argue that the proponents of peak oil consistently underestimate the reserves of regions in Russia, the Caspian Sea, the Middle East, and the deepwater Gulf of Mexico. Also, they say, the industry will continue to increase the percentage of oil that can be recovered from a given field.

A major question concerns the real size of the Persian Gulf reserves. The world's proven reserves, in total, currently stand at 1.2 trillion barrels (almost double the level of the early 1970s). Of that, nearly 60 percent is in the Persian Gulf. But many worried about near-term oil shortages believe that the gulf reserves have been overstated for political purposes by Persian Gulf countries. Others believe that with so much still to be explored, the reserves will prove to be much larger. Both views may be right.

Meanwhile, technology is expanding the definition of oil. In the decades ahead, more and more of our gasoline, heating oil, and jet fuel will be made of so-called unconventional oils. These include petroleum mined from Canada's oil sands, once prohibitively expensive to extract, and liquids derived from natural gas. Conversion of large, remote deposits of natural gas into usable liquids appears to be on the edge of commercial viability.

The world will need all these sources of supply, since even with increased energy conservation, economic growth, led by China and India, could well mean that the world will use 20 percent more oil a decade hence.

Yet it looks as if supplies will meet that demand. If there is an obstacle, it won't be the predicted peak in production, at least in the next few decades. Rather, it will be the politics and policies of oil-producing countries and swings in global economic growth. And the extent of these difficulties, whatever they turn out to be, will register in the ups and downs at the gasoline pump.

Source: **Yergin 2004.**

the first and second columns show some of the many possible ways that different primary energy sources can be transformed into energy carriers.

For an energy carrier to be used widely as a transport fuel, there must be an infrastructure capable of distributing it. The third column identifies two major categories of transport energy distribution systems – ones that transport liquid fuels and ones that transport gaseous fuels. The lines connecting the second and third columns show which energy carriers are capable of being distributed by each category of energy infrastructure. The fourth column of Figure 3.1 shows the two major categories of propulsion systems either presently being used or likely to be used in road, rail, and waterborne vehicles. These are ICEs (including ICE hybrids) and fuel cells (including fuel cell hybrids).[1]

A. Primary energy sources

All transportation fuels are produced from one of the primary energy feed-stocks shown in Figure 3.1. It is outside the scope of this report to undertake a detailed discussion of society's energy options, but the following summary explains the technology trends in the production and transport of primary energies as a background to the energy needs of transportation.

Most *coal* consumed today is used to produce electricity. Coal can also be gasified or liquefied to produce a range of gaseous and liquid synthetic fuels. Abundant coal reserves exist in many parts of the world, with North America, Russia, and China having the largest estimated reserves. Making use of these abundant reserves in a sustainable manner is likely to require the successful development and application of a group of technologies known as "carbon sequestration."

Crude oil is the primary feedstock used today for transport fuels, accounting for well over 95% of transport energy. Though crude oil is produced in many parts of the world, production through 2030 is expected to be concentrated in the OPEC member states. Some are predicting that OPEC oil production might peak during the 2020s. Oil demand has been growing rapidly, especially in some developing world countries. Indeed, as already noted in Chapter 2, China has now displaced Japan as the world's second largest consumer of oil. Factors such as these have raised concerns about the long-run adequacy of oil supply. While we can understand why there might be such anxiety, we believe that there is little empirical basis for it. *(Maugeri 2004)* (See Box 3.1 – Is the World About to Run Out of Oil?)

Historically, oil demand has shown a tendency to increase faster than the discovery of new oil fields. Oil production outside OPEC often takes place under more severe conditions – either at deep-sea offshore sites or at remote locations on land. But improvements in drilling technology have increased oil recovery rates and reduced the production cost for existing fields, so helping to offset the impact of tougher conditions.

Natural gas resources are abundant but as much as one-third of the world's known reserves are "stranded" – that is, the costs of producing them and getting them to market are too high at current prices to make it profitable to exploit them. "Stranded gas" must either be liquefied for transport by cryogenic tanker or converted to fuels that are liquid at normal temperatures and can be moved along pipelines. For those reserves already moved by pipeline, improvements in natural gas production will mainly result from sub-sea installation and improved seismic techniques. Transport applications of natural gas will compete with use by the chemical industry as a highly valued feedstock for plastics and pharmaceuticals.

Renewable energy resources, such as wind, solar, and water, have been estimated as adequate (regardless of affordability) to meet the energy needs of 10 billion people (Figure 3.2). For the transport sector, there are two broad options for obtaining propulsion energy

Figure 3.2 Estimated renewable energy resources

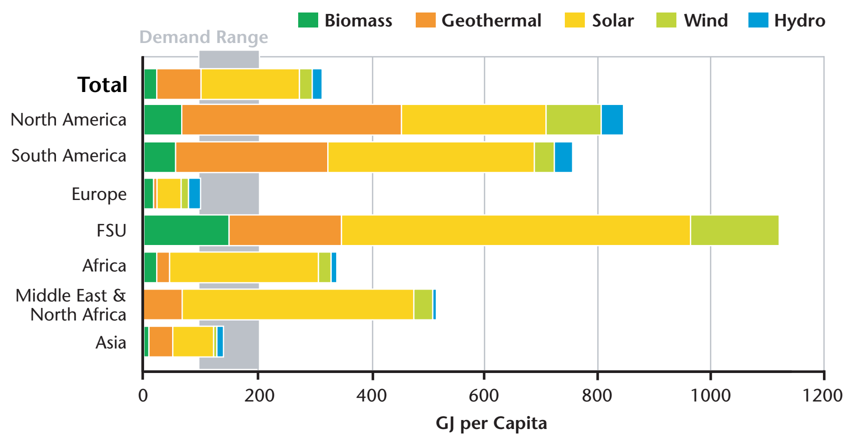


Figure based on 10 billion people.

Source: **Shell International, Ltd.**

from renewable energy sources: fuels produced from biomass and fuels produced using "renewable" electricity. Each is discussed in more detail later.

Nuclear energy produces electric power with low GHG emissions. Environmental and economic concerns, together with social acceptance issues, have prevented growth of this energy pathway in many countries. At present the IEA is projecting a decrease in nuclear energy's role in electric power generation in coming decades as some countries phase out nuclear generation in favor of cheaper, more publicly acceptable alternatives such as natural gas. Nevertheless, new developments in nuclear reactor technology, including "intrinsically safe" designs, may make nuclear power a viable alternative or supplement to fossil fuels, especially if large-scale carbon sequestration turns out to be impractical or unduly expensive.

B. Propulsion systems and associated fuel developments

In this section, a range of engine/fuel combinations, summarized in Table 3.1, is examined. These are presented in the following sections together with their potential impacts on energy use and emissions.

1. INTERNAL COMBUSTION ENGINES

Over the next 30 years ICE technology will continue to improve, given the availability of suitable and appropriate cleaner enabling fuels. For gasoline technology, downsized ***spark ignition engines*** are expected to take a much greater share of the gasoline engine market in the near future. Static downsizing with redesigned engines can reduce engine displacement by up to 30%, which in turn leads to significant reductions in fuel consumption and CO_2.[2,3]

Table 3.1 Matrix of possible fuel/propulsion system combinations

	Spark Ignition	Compression Ignition	Fuel Cell	Reformer + Fuel Cell	Electric Motor
Gasoline	●			●	
Diesel		●		●	
CNG	●			●	
LPG	●				
Hydrogen	●		●		
Methanol	●	●	●	●	
Ethanol	●	●		●	
Biodiesel		●			
DME		●		●	
Electricity					●
F - T Diesel		●		●	

Source: **Frost & Sullivan 2002, Figure 2.2**

Gasoline direct injection (DI) engines are likely to be more important than conventional port fuel injection engines by 2020. Such engines could cost 10-15% more than conventional spark ignition engines because they use advanced injection technology and additional nitrogen oxide after-treatment necessitated by lean burning. Beyond 2010, DI engines will provide the option for engine shut-off at idle without hybridization. Spark ignition engines with variable and electro-mechanical valve trains and other reduced friction technologies, displacement-on-demand, turbocharging and multispeed transmissions will enable improved energy utilization with additional costs of about 20%. The most advanced technology discussed for gasoline engines is controlled auto ignition (CAI). It represents a future alternative to DI combustion systems requiring sophisticated De-NOx after treatment and might be commercially available by 2030.

By 2010 the dominant ***diesel*** engine technology will be direct injection with high turbo-charging, inter-cooling and downsizing. These engines will use injection systems with increased injection pressure (up to 2500 bar) and fully variable injection characteristics (pilot, post and split injection, and injection rate shaping). Injection nozzles with optimized injection-hole size and exhaust gas turbochargers with variable turbine geometry will be part of the standard design. Electrically assisted exhaust gas turbochargers and variable valve train technologies will be available by 2020. Engines with these features may cost 20% more than today's diesel engines.

Although diesel engines already have a very high efficiency, there is still a technical potential for reduced fuel consumption of diesel vehicles. Much depends on the need for active emissions controls (particulate filters, NOx traps). The most promising future diesel engine technology is the homogenous charge compression ignition combustion process (HCCI). This advanced combustion process reduces the complexity of exhaust gas after treatment systems and could become available after 2010. Partly homogenous combustion processes are expected earlier.

The development of lean burn gasoline engines, especially with direct fuel injection, reduces the fuel consumption advantage of diesel compared to gasoline engines. Engine downsizing, which has a larger potential for gasoline than for diesel engines, will further reduce the gap. In principle, very stringent exhaust regulations will increase fuel consumption for all engines, but the extent of this reduction varies with engine type. The trade-off between very stringent exhaust emissions and GHG emissions is least critical for port-injection gasoline engines and most severe for DI diesel engines. Lean burn (DI) gasoline engines range in between. The same order is valid for the additional cost necessary to achieve extremely low emissions levels.

With the development of the CAI gasoline engine and the HCCI diesel engine, both engine types would come much closer to each other and share features like direct injection, homogeneous mixture and self-ignition. At some time in the future, both developments might merge into one engine type, combining low fuel consumption with very low engine-out emissions, especially for nitrogen oxides and particulates. In some regions, this might make active exhaust after-treatment unnecessary.

The large number of influencing factors including different technical features, cost targets and exhaust standards, make a precise quantitative forecast of how diesel and gasoline engines' consumption figures develop impossible. It can be anticipated that until 2010 the fuel consumption of gasoline engines will decline more than that of diesel engines. Later, when homogeneous diesels are successfully developed, this trend will reverse.

Vehicle fuel consumption, and with it GHG emissions, are determined not only by engine efficiency but also by vehicle parameters. Forecasts give a potential for specific fuel consumption reduction for vehicles with direct drive until 2030 of around 20%, compared to current diesel vehicles as today's best practice. This assumes that all technical means of engine, transmission and vehicle technologies (such as aerodynamics, lightweighting, tires and efficient accessories) are taken together.

2. HYBRID ELECTRIC PROPULSION SYSTEMS

Another way in which the efficiency of the ICE can be enhanced and conventional and GHG emissions reduced is through the use of hybrid electric propulsion systems. The term "hybrid electric propulsion system" covers a wide range of possible power-train arrangements. All combine an ICE engine or fuel cell with a generator, battery, and one or more electric motors. But these components can be arranged in a variety of ways. And the electric motor(s) can bear a larger or smaller share of the load in propelling the vehicle. Generally speaking, a vehicle is only classified as a "full hybrid" if it can be propelled at least some of the time solely by the electric motor(s).

Hybrid systems achieve lower fuel consumption in a number of ways:

1) The ICE engine can be turned off completely whenever the vehicle is stopped. Hybrids use their battery both to restart the ICE engine and to power the electric motor(s) that "launches" the vehicle when the operator wishes to resume moving.

2) The vehicle can switch to Electric Vehicle (EV) mode at low speeds; the efficiency of the ICE engine is low at low speeds.

3) Engine operation can be optimized as a result of using a continuously variable transmission (CVT) in combination with the electric motor.

4) A high efficiency engine designed to achieve optimal efficiency during hybrid operation can be utilized. This can be a small displacement, high expansion ratio engine using lean-burn technology. The battery can deliver extra power when required, e.g., during acceleration when the vehicle is already traveling at high speed.

5) The electric motor can function as a generator to regenerate electricity. This energy can be reused as drive energy in 2) and 4) above.

Regeneration efficiency can also be improved during braking through use of a coordinated regenerative braking system. This reduces brake pressure in response to regenerative braking force, through a motor layout which reduces energy transfer loss, and through reduction in engine revolution loss through mechanisms to stop the engine cylinders and the engine itself during deceleration via a double clutch or planetary gear mechanism.

The level of fuel consumption achieved by a hybrid system depends on its operating mode; effects will be limited if the vehicle is run at high speed with infrequent acceleration/deceleration and infrequent stopping. However, reduced fuel consumption can be achieved through operation at optimal engine operation [(3) above] and in conjunction with high-efficiency engines [(4) above]. Efficiency in metropolitan and suburban environments will also vary greatly depending on the system design and its specifications, with a minor reduction in efficiency in hybrid systems that stop their engines when the vehicle is stationary and that employ only limited regenerative braking.

The benefits of engine performance optimization in diesel engines are limited, achieving smaller reductions in fuel consumption when compared with gasoline engines. For this reason, diesel hybrid engines will be best suited to urban buses and trucks.

Although ICE and ICE hybrids will never be "zero emission" vehicles, their potential for CO_2 reduction per mile/km driven is substantial, especially if based on a future downsized clean gasoline- or diesel-powered ICE. Some current hybrid electric powertrains incorporating the basic hybrid functions of engine stop and go while the vehicle is not moving and simple energy regeneration systems achieve very significant reductions in fuel consumption compared with a conventional gasoline powertrain. Combined with advanced aerodynamics, reduction of rolling resistance (including low rolling resistance tires) and with a high efficiency engine (such as one using lean burn technology and having a high expansion cycle) able to operate optimally, a hybrid system may show even lower values of fuel consumption.

We foresee the continuous evolution of technologies in each area of hybrid components including electric motor controllers, batteries, and optimized engine tuning for hybrid system. Advanced clean ICEs, advanced aerodynamics, vehicle weight reduction and reduction of rolling resistance will additionally reduce the overall fuel consumption of hybrids (as well as of conventional vehicles.) Therefore, in the foreseeable future, hybrid vehicles incorporating all of these latest technologies will show extreme reductions in fuel consumption over current conventional ICE and ICE hybrid vehicles with comparable interior space. (Well-to-Wheel comparisons are shown below in Figure 3.3).

3. FUELS FOR INTERNAL COMBUSTION ENGINES AND ICE HYBRID VEHICLES

Although there are a wide variety of alternative energy carriers, ICE fuels have been synonymous with gasoline and diesel refined from crude oil. Over the last 30 years, reduction of vehicle emissions, both by reducing emissions produced by the engine and by using exhaust catalysts and ancillary systems, has driven improvements in these fuels. Further change will be motivated by the more fuel efficient future engine technologies described in this chapter, by reduction of the fossil carbon intensity of ICE fuels, and by considerations of feedstock diversity and energy security. Fuel infrastructure will also play a key role – either the existing ones or new, separate networks for new fuels.

a) ICE fuels that can be distributed through existing fuel infrastructures

Gasoline and diesel are likely to remain the major road transport fuels for the ICE and its derivatives to 2030, tailored to enable the most efficient engine technology and vehicle emission control systems to function effectively. Global economies have developed around these fuels, with significant investment in production processes and extensive existing supply infrastructures. Investment in new production is incremental and relatively low risk versus other fuel options, given demand from existing vehicle fleets and the widespread availability of a distribution infrastructure.

For spark ignition engines (including hybrids), unleaded gasoline will remain the primary fuel. By 2010, unleaded gasoline will be available across the globe so permitting the use of catalytic exhaust after treatment systems. Low sulphur gasoline and diesel fuel (often less than 10 ppm) will be the norm in the developed world after 2010 and by 2030 in most developing countries.

Ultra-low sulphur fuels are not only necessary for vehicles with extremely low emissions, but also for concepts that combine very low emissions with sharply reduced fuel consumption – lean burn gasoline engines with NOx storage catalysts, and ultra clean diesel engines are equipped with a NOx storage catalyst, a particulate trap, or both.

Although the technology for refining crude oil to produce gasoline and diesel is well established, new processes have been needed to produce the ultra-low sulphur fuels required to enable effective operation of current and future vehicle exhaust clean-up technologies and to reduce deterioration of catalysts on older vehicles. This deep desulphurization is energy intensive, mainly because of the high hydrogen consumption of the process, so improvements in local emissions have a cost in refinery CO_2 emissions. Therefore it makes sense to coordinate the introduction of ultra-low sulphur fuels with vehicles that have catalytic converters for emissions cleanup and can exploit the fuel properties to achieve improved local emissions and reduced fuel consumption.

To attain optimum performance, developing engine technologies (such as homogeneous charge compression ignition) may require changes to the specification of gasoline and diesel fuels. As a general trend, reduction of fuel carbon intensity – lowering the carbon to hydrogen ratio of fuels as far as possible (eventually to zero in the case of hydrogen) – and diversification of energy supply will require modified energy carriers.

In the short to medium term, it is likely that gasoline and diesel, in addition to being more severely refined by hydrogenation processes in upgraded refinery plants, will increasingly contain (and may in certain circumstances be replaced by) blend components that are derived from primary sources other than crude oil. Such components will always be selected because they offer sustainability benefits either from reduced local and/or global emissions, greater energy security and/or reduced dependence on oil. Fuels modified in this way will be able to use the existing supply infrastructure without major modification.

Several alternative fuels or components offer reduced engine-out emissions over conventional fuels of current specifications. They include:

FT diesel.
This product is a highly desirable component or fuel for diesel engines because it has a very high cetane number, and is free of sulphur and aromatics, enabling diesel concepts with very favorable emissions characteristics and reduced fuel consumption. Derived from natural gas, it is produced by the Fischer-Tropsch process (FT gasoline or naphtha is also possible).

There are drawbacks. The FT process is energy intensive with correspondingly higher CO_2 refinery emissions. The capital costs are high (currently around $2 billion per project), although they may become competitive with conventional low sulphur diesel before long. Perhaps more importantly, its economic success in the current market situation, where comparatively cheap crude oil is still abundantly available, depends very much on very low cost natural gas. This is only realistic for "stranded" gas reserves far removed from natural gas markets. As noted earlier in this chapter, there is an abundance of such natural gas. But the complications and costs of moving it, or of locating FT plants at suitable sites for their markets, may limit the development of FT diesel as a major global fuel component.

Although FT diesel produced from natural gas will not become a mainstream fuel, the potential exists to extend its availability through the use of other feedstock such as coal and biomass. In the case of coal this would need to utilize CO_2 sequestration to make it acceptable in terms of GHG emissions.

Conventional Biofuels.
Alcohol fuels, methanol and ethanol generated from natural gas or biomass or other renewable sources, are candidates as gasoline components. For compression ignition (diesel) engines, biodiesel, containing biomass-derived fatty acid methyl esters, or FAME, (such as rapeseed methyl ester, RME) is an option.

In theory, biomass-derived energy, which itself takes advantage of natural processes that remove CO_2 from the atmosphere as the biomass grows, has the potential to provide 100% of the world's transport energy requirement. This assumes that all biomass residues are collected and processed. In reality a much smaller percentage is feasible taking into account commercial and social considerations. Nevertheless, biofuels are realistic contenders as a major low carbon fuel source for the future – one that could reduce reliance on fossil fuels and offer independence from sources of imported energy.

The ultimate potential of biofuels is harder to estimate. This reflects several factors:

- The extent to which fuel cropland use will compete with food and other domestic or commercial crop demand use. In some parts of the world biofuels derived from energy crops may be limited by land and water resource availability.

- The difficulty of assessing accurately true greenhouse gas reduction potential when all counterbalancing emissions from crop collection (using diesel tractors etc.) and fertilizer use (which releases nitrogenous GHGs to atmosphere) are considered.

- Lack of information about the real costs of the variety of biofuel production routes. Economies of scale are unlikely to parallel those of the oil industry because of the logistics of biofuel production. These favor a larger number of smaller plants rather than fewer large ones. For the foreseeable future actual costs will need to be offset by favorable fiscal support mechanisms for many, if not all, biofuel routes.

Biomass should not be seen as separate fuel entities in their own right, but could be part of an evolving distribution system for gasoline and diesel fuels that becomes commonplace worldwide. An important challenge will be to develop and maintain suitable standards to ensure a consistent high quality supply.

Advanced Biofuels.
New methods of producing "advanced" biofuels are being sought that increase the yield of biofuels or decouple their production from that of food. Two examples are the conversion of lignocellulosic material to fuel components by enzymes and biomass gasification followed by a Fischer-Tropsch process (known as "biomass to liquid" – BTL).

All such processes have the potential to use a range of biomass feedstocks, including agricultural or municipal waste. Successful commercialization of these technologies has the potential to lower the cost of biofuels to levels that are closer to being competitive with conventional gasoline and diesel. However, the rate at which progress can be made is highly uncertain at present. Neither BTL (predominantly diesel) nor lignocellulosic gasoline component (ethanol) manufacture has yet been proven on a commercial scale.

Another relevant factor is feedstock logistics, which require biomass feed-stock production on a very large scale to be fully optimised. A world scale BTL plant (one capable of producing 1.5 million tonnes per year) would require woody biomass collected over an area half the size of Belgium. Alternatively, a world scale lignocellulosic fermentation plant (0.2 million tonnes per year) would consume surplus straw from a planted area of wheat approximately one tenth the size of Belgium.

b) ICE fuels that require a separate fuel infrastructure

Alternative fuels that cannot be used as blend components – liquefied petroleum gas (LPG), compressed natural gas (CNG), di-methyl ether (DME), and hydrogen – require a significant level of investment in delivery infrastructure. This investment presents an economic barrier to their widespread use.

Infrastructure costs increase significantly as one move from liquids stored under low pressure, such as LPG or DME, to gaseous fuels requiring high pressure storage, such as CNG or gaseous hydrogen. LPG, derived from crude oil or gas condensate, requires only a pressurized "bottle" or "tank" in the infrastructure, with distribution primarily by truck or railcar. CNG and hydrogen require a much more sophisticated safe distribution and storage network. Hydrogen additionally requires a manufacturing capability.

CNG and LPG fuels can be considered on their merits for local emission control or for fleet use in (mainly) urban areas where investment can be localized and justified on the basis of local emission reductions compared with the current mixed vehicle fleet. ICEs and hybrids running on gaseous fuels require expert conversion. Almost all operate with spark assistance. To gain optimum performance, gaseous fuels should be used in dedicated vehicles rather than bi- or dual-fuelled systems, where the compromises associated with bi-fuel operation mean that the vehicle operates under less than optimum conditions on both fuels. Still, bi-fuel vehicles offer the possibility that consumers who are not willing to purchase vehicles dedicated to a specific alternative fuel may instead purchase bi-fuel vehicles and utilize alternative fuels when that choice is attractive.

The attraction of gaseous fuels as regards reduced criteria pollutants is decreasing as the ICE itself and exhaust after-treatment technology, as well as associated gasoline and diesel fuels, improve. The longer-term benefit of these fuels is therefore limited.

CNG offers potential for reduced dependence on petroleum and compares well with diesel in particulate emissions in older vehicles. But the use of advanced exhaust treatment has removed most of the advantage CNG held over modern diesel-powered vehicles. It is not as widely available as a transport fuel as gasoline or diesel, and infrastructure development has been slow. Nonetheless, it is favored over oil by many governments as resources are more evenly spread throughout the world, and its use may reduce reliance on oil imports.

While CNG faces the obstacles inherent in all gaseous fuels today, CNG engines are able to achieve relatively low emissions without the advanced exhaust treatment required for diesel engines. By 2030

CNG is likely to gain in significance if current trends and government incentives continue. Potentially, it could meet a large proportion of the total demand for road transport, being already extracted in huge volumes for stationary power generation. The fuel's low energy density (compared with liquid fuels), and hence reduced vehicle driving range and specific power, remain consumer issues. Operation of bi-fuel vehicles are likely to continue for an interim period as the gaseous infrastructure grows.

The cost of infrastructure investment will remain a central issue. In some places the existence of networks set up to utilize domestic supply has promoted CNG uses as a viable alternative fuel. While natural gas is not a "sustainable fuel," its infrastructure has been used in Sweden to distribute biomethane refined from biogas. So just as CNG-engines can operate on hydrogen, development of a CNG infrastructure can provide the experience needed to establish a new infrastructure to support hydrogen-based mobility.

LPG shows improvements over gasoline for some, if not all, criteria (urban) pollutants. It is derived from crude oil and natural gas condensate. Its refueling infrastructure is better established than natural gas and it has gained some acceptance as an alternative to diesel and gasoline, particularly in fleet vehicles. As a liquid fuel, consumer perception of safety is reasonable, and it is relatively affordable in comparison to other alternative fuels. By 2030, it is thought that LPG refueling infrastructure will have expanded as new refueling points are inexpensive to install. LPG is likely to remain a niche fuel in most markets though it may be more widely used in selected national markets.

Hydrogen used as an ICE fuel offers vehicle tailpipe emissions with zero CO_2. But completely CO_2-free mobility – zero CO_2 from both the vehicle and the manufacture of the fuel – can only be achieved if hydrogen is produced from renewable sources or in conjunction with carbon sequestration. Hydrogen used as an ICE fuel also offers extremely low local urban pollutant levels.

c) Propulsion systems not utilizing ICEs – Fuel cells

Fuel cell systems – especially fuel cell systems using hydrogen – are attracting growing attention. If run on hydrogen derived from carbon-neutral sources, fuel-cell vehicles (FCV) would offer the highest overall propulsion system energy efficiency (more than 40%) and the lowest GHG and conventional emissions. As with ICEs, their performance might be further enhanced in designs where batteries provide supplementary electrical power. Although the additional benefits of battery power are less than in the case of ICE hybrids (because the fuel cell itself is so efficient), some of the same advantages such as regenerative braking still apply. Such concepts are now under development.

It is the fuel cell's high efficiency and contribution to low (maybe zero) GHGs, along with the potential widespread availability of hydrogen from a range of sources, which constitutes the primary attraction of fuel cells. The assurance that vehicle emissions remain zero even when the vehicle ages and is not maintained by the owner is another attractive feature.

Regardless of ultimate promise, substantial obstacles must be overcome before the fuel cell can be considered to be a realistic commercial alternative to conventional propulsion systems. The most promising technology applied at present is the proton exchange membrane (PEM) fuel cell operating on hydrogen, with on-board hydrogen storage. Storing hydrogen is a challenge as compressed hydrogen tanks, cryogenic tanks and metal hydride tanks are not yet suitable for mass production vehicles. Other major problems to be resolved include reducing the level of high-cost precious metals required for the fuel cell stacks, better cell membrane technology, and overall packaging of the fuel cell system into a vehicle that is proven and perceived to be safe, reliable, attractive and affordable by the consumer or operator.

d) Fuels for fuel cells – hydrogen produced centrally, at a refueling point or on board a vehicle

Fuel cell concepts conceived for vehicular use almost certainly will be developed to operate on hydrogen as the fuel since hydrogen is critical to the function of the fuel cell itself (the combination of hydrogen and oxygen creates electrical power and water). Hydrogen fuel cell vehicles produce "zero" tailpipe emissions (other than water). The GHG impact of hydrogen and fuel cells depends on the availability of hydrogen from processes or other sources that are themselves low in greenhouse gas production. If hydrogen is derived from water by electrolysis using electricity which has been produced using renewable energy (solar/hydro/wind/geothermal), the entire system from fuel production to end use in the vehicle has the potential to be a truly "zero emissions" – one that produces no emissions of either greenhouse gases or local pollutants.

The same is almost true of hydrogen derived from fossil sources where the CO_2 produced during hydrogen manufacture is captured by sequestration. The only difference is the local urban emission of pollutants during hydrogen manufacture in this case. Crucially, both offer "near-zero greenhouse gas" mobility options.[4]

Technologies for manufacturing hydrogen from coal, natural gas or water electrolysis are well known, and applied commercially – particularly in the oil industry where hydrogen increasingly is required for the production of low sulphur gasoline and diesel fuel. Almost 90% of the high-purity hydrogen produced today is derived from steam methane reforming of natural gas, and this is expected to remain the dominant and most economic route for the foreseeable future. Technology advances in hydrogen production and distribution will be required to drive down the cost and increase the energy efficiency of these processes.

The transition to a fully developed hydrogen infrastructure that allow a vehicle market to develop would be a massive undertaking, especially as regards making the product available safely to a mass consumer market. In any transition phase, it is unlikely there would be sufficient hydrogen demand to justify investment in large-scale production and distribution except in some advantaged locations.

Fuel cells using liquid fuels would greatly reduce (or even eliminate) this problem, since they might use fuels that are, or could be, made available within the current fueling infrastructure. At present only fuel cells equipped with an on-board reformer can use liquid fuels in this way. Developments in reforming technology might serve as a bridge to a longer-term future based on centrally produced hydrogen, although these concepts appear too complex for market application in a private car. If less complex reformer systems are developed (possibly by 2010), they are likely to require methanol or sulphur-free, highly paraffinic fuels, perhaps resembling GTL (natural gas to liquid) fuels. Rather than being deployed on board vehicles, such systems would be available in retail refueling stations.

These very specialized fuels would not necessarily be compatible with the existing ICE fuel infrastructure. They might well require separate systems or significant infrastructure modifications, segregations and extensions to ensure delivery of precisely the correct, uncontaminated, fuel. Perhaps most importantly, onboard reformers offer no advantage in feedstock diversity and little or no advantage in GHG emissions or energy efficiency over advanced ICE systems – although the application of reformer-driven fuel cell auxiliary power units in heavy-duty vehicles could be an attractive method of electrical power generation.

C. The evolution and potential impacts of different vehicle propulsion systems and fuel combinations

The propulsion system and fuel combinations so far highlighted are in very different stages of development. Some are in commercial use today. Others are in their early stages of development. Given these differences, any estimates of the future performance or cost characteristics of possible propulsion system/ fuel combinations when in full-scale commercial production are highly speculative. But such estimates are important if only to illustrate the nature of the challenges to be overcome in order to make these technologies commercially viable.

It is also important to focus on the transition phase that is inevitable between current vehicle propulsion system/fuel combinations and future systems. It is easy to conceive a situation in the middle of this century where large numbers of vehicles with a new propulsion system are operated on renewable energy fuels. But getting from the present situation to this point will be challenging as will moving beyond it. Intermediate steps that bring vehicle technologies, vehicle numbers and required fuel qualities and quantities in harmony and assure adequate compatibility with technologies already in the market are bound to be necessary.

1. GHG EMISSIONS CHARACTERISTICS

To estimate the potential impact of various new propulsion system/fuel combinations on greenhouse gas emissions, it is necessary to use a methodology known as "Well-to-Wheel (WTW) analysis." This approach considers not only the GHGs produced when a fuel is used in the vehicle ("Tank-to-Wheel" – TTW), but also the GHGs emitted in the fuel's production and distribution ("Well-to-Tank" – WTT). Focusing on the GHG emissions produced by fuel consumed by a vehicle can give a misleading impression of the true GHG impact of the propulsion system/fuel combination. This is because reductions due to improvements in the vehicle can be counterbalanced – or exceeded – by increases resulting from the production and distribution of the fuel.

Figure 3.3 shows the project's estimate of WTW emissions for various fuel/ powertrain combinations some 10-20 years (or more) in the future, with each combination being separated into its WTT and TTW components. As Figure 3.3 shows, all combinations using ICE engines and any fuel other than hydrogen have relatively high TTW emissions. The CO_2 savings from biomass- derived fuels occurs in the WTT part of the product chain as plants absorb CO_2 from the atmosphere during growth. Only a holistic view of CO_2 emissions in a WTW analysis can show the benefits/ disadvantages of different fuel and powertrain technologies for reducing greenhouse gas emissions.

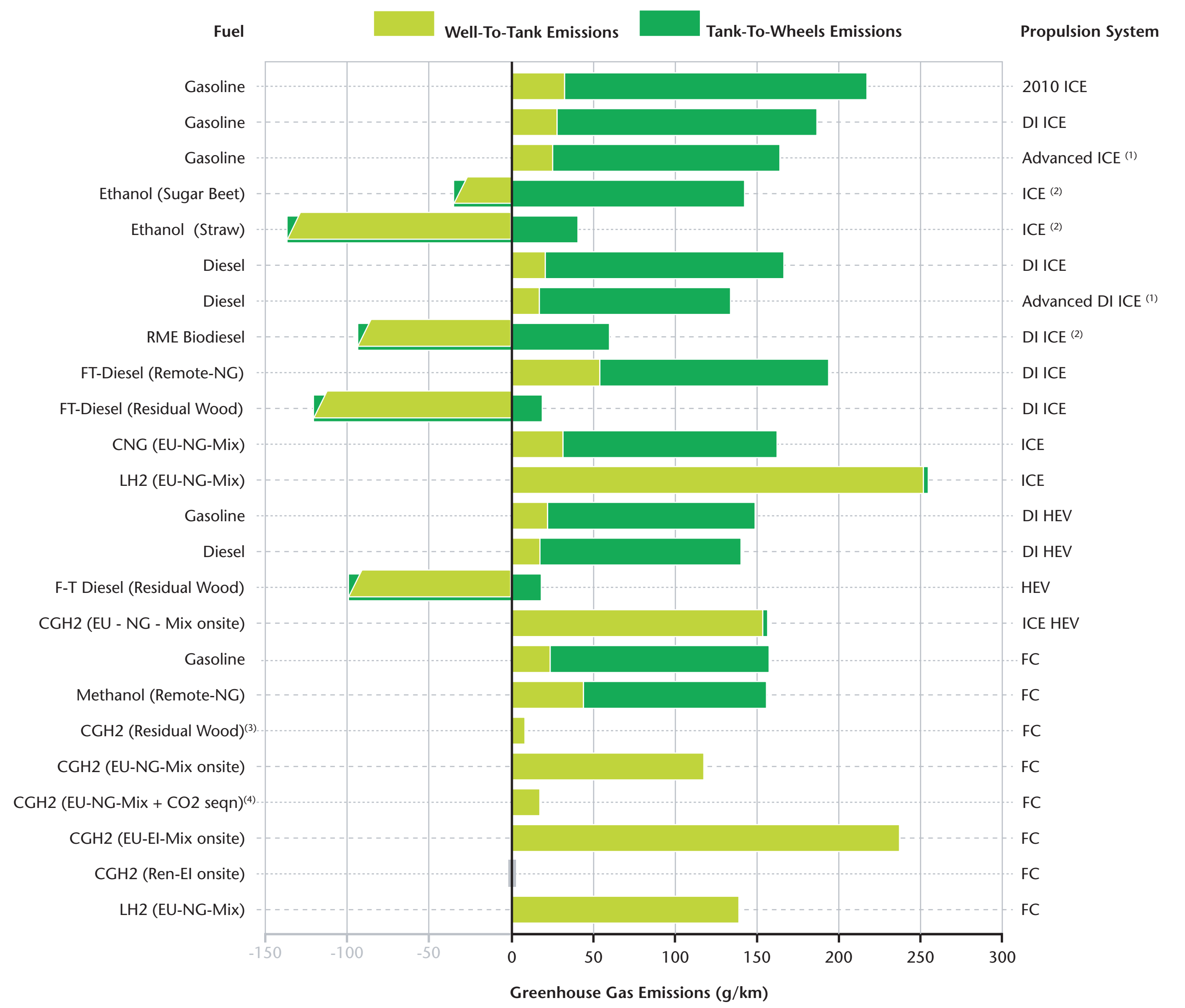
Figure 3.3 also demonstrates that the total WTW GHG emissions of vehicles powered by hydrogen depends almost entirely on the process used to produce and distribute the hydrogen. This varies widely. Indeed, some hydrogen production methods have such high WTT emissions that the WTW emissions exceed those of current gasoline ICE systems.

Also apparent is that biofuels/ICEs sometimes have very low WTW emissions. This is because CO_2 emissions produced by fuel production and distribution (WTT emissions) are negative, reflecting the fact that plants from which the biofuels are produced are net absorbers of carbon. All WTT studies consulted by the SMP emphasize the difficulty of accounting accurately for GHG emissions generated through biofuels production. They also stress the difficulty of determining the appropriate carbon sequestration credits to allocate to the growing of the biomass that is subsequently converted into biofuels.

2. VEHICLE OWNERSHIP AND OPERATING COSTS AND THE COST-EFFECTIVENESS OF VARIOUS POWERTRAIN/FUEL COMBINATIONS IN REDUCING GHG EMISSIONS

Estimating the possible cost of vehicles and fuels that may not be available for many decades is an extremely challenging exercise. Moreover, the

Figure 3.3 **Well-To-Wheel (Well-To-Tank + Tank-To-Wheel) greenhouse gas emissions for various fuel and propulsion system combinations**



(1) Estimated by VKA (2) Estimated by BP, from GM data (3) Net output from energy use in conversion process (4) Based on Hydro figures
Source: Sustainable Mobility Project calculations.

results of such an exercise are easy to misinterpret. Assumptions must be stated carefully, and the limitations of the analysis need to be understood.

At the same time that the SMP was examining vehicle powertrain and fuels issues, the European Council for Automotive R&D (EUCAR), Conservation of Clean Air and Water in Europe (CONCAWE), and the Joint Research Center of the EU Commission (JRC) were jointly engaged in an effort to provide just such information. The objectives of this joint study effort were to establish, in a transparent and objective manner, a consensual well-to-wheels energy use and GHG emissions assessment of a range of automotive fuels and power-trains relevant to Europe in 2010 and beyond; to consider the viability of each fuel pathway and estimate the associated macro-economic costs; and to have the outcome accepted as a reference by all relevant stakeholders. Several reports detailing and documenting this initiative were released in late 2003 and early 2004. *(EUWTW 2003, 2003a, and 2004)* Rather than duplicate this effort, we decided to use its results in our project.

The different fuel/powertrain pathways described above involve quite different levels of investment in vehicles and fuels. To compare the costs of these different pathways, it was necessary for the EUWTW project to define a scenario in which the level of transport services performed by each pathway was common. This determined the number of vehicles that must be produced and sold and the volume of fuel that must be delivered.

The scenario developed in EUWTW was intended to reflect travel conditions in a 25-state European Union as of 2010. The vehicles characterized by each powertrain/fuel combination were assumed to account for 5% of automotive travel projected for the EU-25 during 2010 – 225 billion vehicle kilometers. At an assumed utilization rate of 12,000 km per vehicle per year, this requires approximately 14 million vehicles. For those powertrain/fuel combinations requiring a different fuel infrastructure, it was assumed that 20% of the refueling stations in the EU-25 (about 20,000 refueling stations) would need to offer the fuel. *(EUWTW 2004, pp. 20-22)*

As the authors of the analysis were careful to point out, this scenario is an analytical exercise – not a judgment on anyone's part that such a level of penetration actually would be technologically possible or economically practical by 2010:

"Purely in terms of availability of the energy resource, the alternatives considered all have, in principle, the potential to reach the 5% substitution level. This does not imply practical feasibility, particularly within the timeframe of the study. Indeed, in a number of cases, practical and technical limitations make this level of penetration unlikely within the timeframe of the study." (EUWTW 2004, p. 22)

Estimating the possible increase in retail price for vehicles using each of nearly 50 powertrain/fuel combinations proved to be a particularly difficult challenge. To do this, the study authors chose a common "virtual" vehicle, reflecting the characteristics of a typical European compact size five-seater sedan, comparable to a VW Golf. To obtain an estimate of retail price, the study authors first subtracted the price of the original internal combustion engine for the reference vehicle (a 1.6 liter PISI engine) as well as other components that would not be needed (e.g., certain emissions controls). They then added the price (as estimated by others) of

Table 3.2 **Technology impact on vehicle retail price**

Technology/Component	Cost
ICEs	
Engine + transmission	30 €/kW
DICI	1500 €/kW
DISI	500 €/kW
Turbo	180 €/kW
Stop & go system SI	200 €/kW
Stop & go system CI	300 €/kW
Double injection system for CNG Bi-fuel	700 €/kW
EURO IV gasoline	300 €/kW
EURO IV Diesel	700 €/kW
Credit for 3-way catalyst	430 €/kW
Fuel Tanks	
CNG tank	1838 €/kW
Gasoline tank	125 €/kW
DME tank	1500 €/kW
Liquid hydrogen 2002	1150 €/kg of H_2
Comp. Hydrogen 2010 @35 MPa (350 bars)	635 €/kg of H_2
Comp. Hydrogen 2010 @70 MPa (700 bars)	575 €/kg of H_2
Liquid hydrogen 2010	575 €/kg of H_2
Fuel Cells	
Electric Motor	8 €/kW
Motor Controller	19 €/kW
Electric Motor + Motor Controller	27 €/kW
Li-ion battery	250 €/kWh
FC + reformer	251 €/kWnet
FC	105 €/kWnet

Note: The European WTW Analysis assumes a net tank capacity of 4.7 kg of compressed hydrogen for its hydrogen fuel cell vehicle. At fuel tank costs shown in the table above (expressed in terms of €/kg of hydrogen stored), the fuel tank for a vehicle designed to carry 4.7 kg of compressed hydrogen would cost between €2700 and €2900, depending upon the storage pressure assumed.

Source: **EUWTW 2004, p. 17.**

the new powertrain components that the "virtual" vehicle would require. Table 3.2 shows the prices assumed for these various components.

The estimates of the additional retail price due solely to this powertrain substitution are shown in Figure 3.4 below.

The authors considered the estimates of the additional costs of vehicles powered by fuel cells to be highly uncertain. Today the cost of fuel cells is much too high for fuel cells to be used commercially. Over the next several years, vehicle manufacturers around the world will be working to determine if technical issues surrounding the use of fuel cells as a method of vehicle propulsion can be solved and the cost of fuel cells can be brought down substantially.

A high degree of uncertainty also exists concerning the cost of producing and distributing hydrogen for powering vehicle fuel cells. A very wide range of estimates exists concerning what these costs might be, especially for hydrogen produced using processes that do not themselves result in the emission of significant volumes of CO_2.

Table 3.3 summarizes the results of the EUWTW 5% substitution scenario. The first and second columns identify the fuel and powertrain being analyzed. Where significant, the first column shows the process by which the fuel is assumed to be produced. The third column shows the total amount of fuel that this vehicle/powertrain combination would require (expressed in PJ/annum) in order to provide 225 million vehicle kilometers of transport capacity.

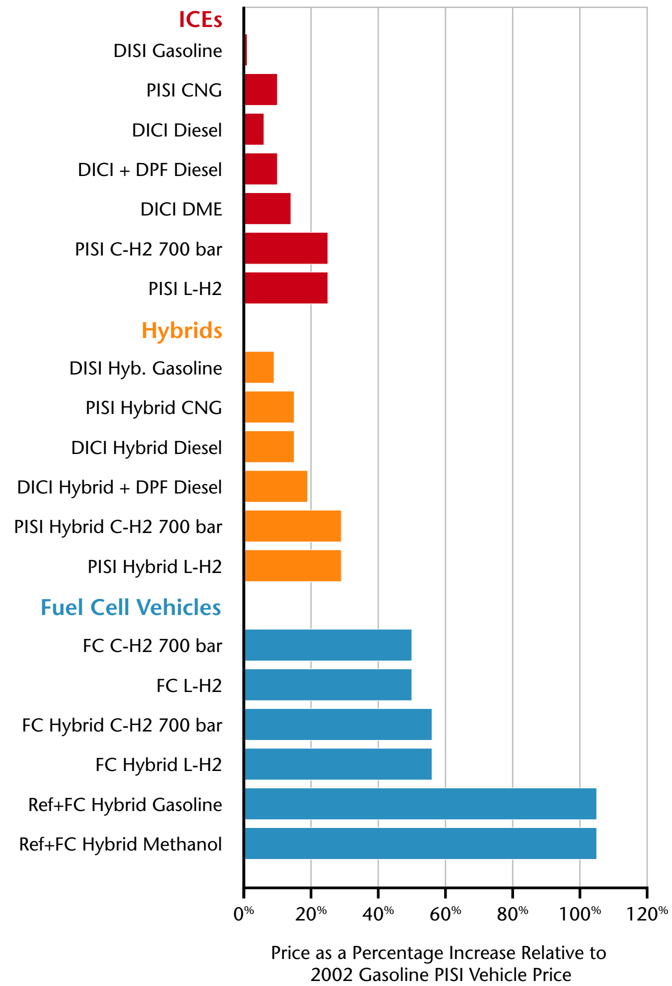
Column four shows changes in WTW energy use (expressed in PJ/annum), while column five shows changes in WTW GHG emissions (expressed in Mt CO_2 equiv/year), both with respect to the reference vehicle. Where a number in either column four or five is negative, the powertrain/fuel combination requires either more energy than the reference vehicle or generates more WTW GHG emissions than the reference vehicle.

Columns six, seven, and eight show the incremental WTT cost, vehicle cost, and total cost, respectively, for the powertrain/fuel combination, expressed in billions of euro per year. Column nine, the final column, shows the cost per tonne of CO_2 avoided (in € per tonne of CO_2 equivalent) for each powertrain/fuel combination where such a figure is meaningful.[6]

The additional total cost per year relative to the reference case ranges from less than €1 billion (for FT-diesel from NG used in a vehicle with a CIDI+DPF[7] powertrain) to over €30 billion (for indirect hydrogen generated by an on-board reformer using methanol produced from wood in a vehicle using a hybrid fuel cell powertrain.) The cost per tonne of CO_2 equivalent avoided exhibits an equally broad range – from about €200 to over €6500.[8]

The EUWTW study helps put into perspective the relative potential of various powertrain/fuel combinations to reduce transport-related GHG emissions and the relative cost of doing so. In the final chapter of this report, we will return to the results of EUWTW study as we examine approaches for reducing transport-related GHGs in ways that society might find acceptable and affordable.

Figure 3.4 **Estimated incremental vehicle retail price relative to 2002 gasoline PISI vehicle**



Source: **EUWTW 2004, p. 17.**

Table 3.3 European WTW analysis, 5% passenger car transport distance substitution scenario for various alternative fuels and powertrains

1	2	3	4	5	6	7	8	9
Fuel	Powertrain	Fuel Demand	WTW Savings[1]		Incremental Cost over Reference Scenario[2] *Millions of Euro per Annum*			Cost per Tonne CO_2 Avoided[2]
		P J/a	*P J/a*	*$MtCO_{2equiv}$*	WTT	TTW	WTW	*Euro/tonne*
Conventional	Hybrids	357	73	6	-0.4	2.4	2.0	364
CNG	PISI	434	-50	5	0.3	1.9	2.2	480
	Hybrid	331	76	12	-0.1	3.3	3.1	256
Syn diesel fuels								
FT - diesel ex NG	CIDI + DPF	405	-508	-5	0.7	0.0	0.7	
FT - diesel ex wood	CIDI + DPF	404	-748	32	9.5	0.0	9.5	300
DME ex NG	CIDI	404	-214	1	1.1	1.1	2.2	2039
DME ex wood	CIDI	388	-576	33	6.3	1.1	7.5	227
Ethanol	PISI	428						
Sugar beet								
Pulp to fodder			-724	14	6.0	0.0	6.0	418
Pulp to EtOH			-591	12	6.5	0.0	6.5	563
Pulp to heat			-499	24	6.1	0.0	6.1	254
Ex wheat			-760	5	8.2	0.0	8.2	1812
Ex wood			-714	29	9.9	0.0	9.9	346
FAME	CIDI + DPF	405						
RME								
Glycerine as chemical			-378	16	4.6	0.0	4.6	278
Glycerine as heat			-399	14	5.0	0.0	5.0	345
SME								
Glycerine as chemical			-288	22	4.8	0.0	4.8	217
Glycerine as heat			-309	20	5.2	0.0	5.2	260
Hydrogen *(thermal processes)*								
Ex NG reforming	ICE PISI	377	-273	-7	7.6	5.8	13.5	
	ICE hybrid	335	-187	-2	7.1	7.0	14.1	
	FC	212	58	12	5.7	12.7	18.4	1539
	FC hybrid	189	105	15	5.4	14.3	19.8	1351
Ex coal gasification	ICE PISI		-424	-41	8.7	5.8	14.6	
	ICE hybrid		-321	-32	7.8	7.0	14.7	
	FC		-26	-7	5.1	12.7	17.8	
	FC hybrid		30	-2	4.6	14.3	18.9	
Ex wood gasification	ICE PISI		-361	32	11.8	5.8	17.6	
	ICE hybrid		-265	33	10.9	7.0	17.9	
	FC		9	34	8.3	12.7	21.0	615
	FC hybrid		61	34	7.9	14.3	22.2	645
Hydrogen *(electrolysis)*								
Electricity ex NG	ICE PISI		-891	-45	13.5	5.8	19.3	
	ICE hybrid		-735	-35	12.1	7.0	19.1	
	FC		-288	-9	8.3	12.7	20.9	
	FC hybrid		-204	-4	7.6	14.3	21.9	
Electricity ex Coal	ICE PISI		-1169	-129	13.7	5.8	19.6	
	ICE hybrid		-981	-110	12.4	7.0	19.3	
	FC		-444	-56	8.4	12.7	21.1	
	FC hybrid		-343	-46	7.7	14.3	22.0	
Electricity ex Wind	ICE PISI		-192	33	18.9	5.8	24.8	746
	ICE hybrid		-116	34	17.2	7.0	24.1	718
	FC		104	35	12.1	12.7	24.8	714
	FC hybrid		145	35	11.2	14.3	25.5	730
Electricity ex Nuclear	ICE PISI		-1868	33	22.6	5.8	28.4	857
	ICE hybrid		1601	34	20.7	7.0	27.7	825
	FC		-837	35	15.4	12.7	28.0	808
	FC hybrid		-692	35	14.4	14.3	28.7	822
Indirect hydrogen	Ref + FC hybrid							
Gasoline			65	5.0	-0.4	27.5	27.2	5487
Naptha		366	76	6.5	-0.4	27.5	27.2	4215
Diesel		366	58	4.1	-0.4	27.5	27.2	6656
Methanol ex NG		366	-55	4.0	-0.3	27.5	27.2	6828
Methanol ex wood		333	-208	32.8	4.1	27.5	31.6	964
		333						

(1) a negative denotes an increase

(2) relative to the "business-as-usual" gasoline PISI + diesel CIDI scenario

Source: **EUWTW 2004, p. 22.**

II.

Vehicle technologies other than propulsion systems

The potential for improving the sustainability of a transport system is determined in part by the propulsion system/fuel combination it employs. But the materials used in construction, safety technologies employed, enhanced electronic systems made available, characteristics of the vehicle's tires, and other design features can also impact the SMP indicators of sustainable mobility.

A. Changes in materials use

On average, light-duty vehicle weight in Europe has increased about 30% over the last 30 years. During the same period, average light-duty vehicle weight in the US, which was (and still is) significantly higher than in Europe, declined 21% (from 1845 kg in 1975 to 1455 kg in 1981/82) before rising again. By 2003 it had returned to its 1975 level, gaining 24% since 1981/82.

(USEPA 2004, Table 2, p.9)

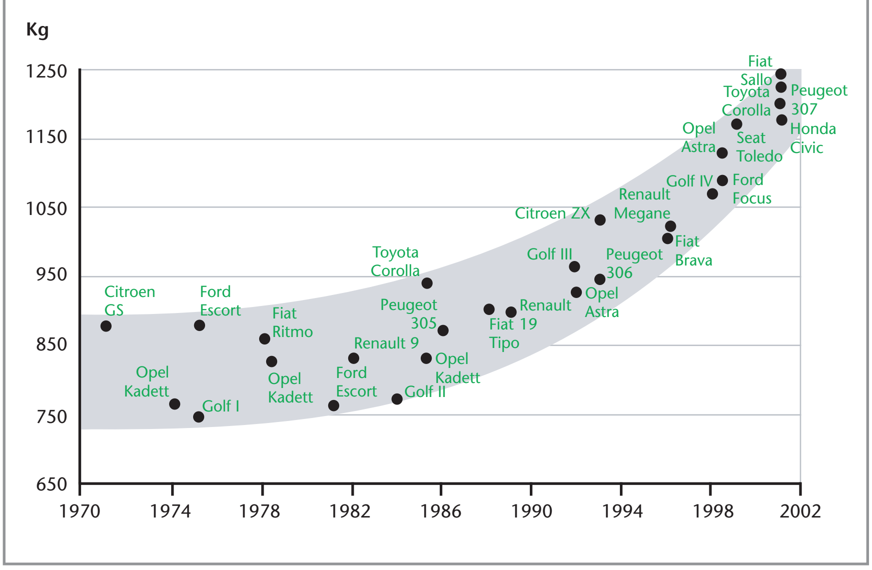
Increases in average vehicle weight in both the US and Europe reflect the combined impact of two trends – the growth in the average weight of vehicles within individual vehicle classes (see Figure 3.5), and increases in the proportion of total vehicle sales represented by larger vehicle classes.

What explains the within-class weight increase? As vehicles have evolved, they have added more and more features – add-ons that increase safety, improve driving characteristics, reduce noise, reduce emissions, and increase comfort. This has required adding new components to the vehicle interior, body and chassis. Increasingly, these components have been structural. They also have been electrical or electronic – for example, the capacity of electrical systems has had to be increased to handle the additional electric power demands. Heavier cars also require additional equipment to maintain driving performance.

The weight of some components has been reduced through design changes and materials substitution. But these reductions have been more than offset by the growth in weight due to the increase in vehicle functionality.

There are two main ways by which within-class vehicle weight can be reduced: 1) by design changes related to the vehicle appearance as well as by changes made possible by the geometry available for each part and (2) by direct substitution of lighter materials (aluminum, high-strength steel, magnesium, plastics). Often these are done at the same time and are

Figure 3.5 **Weight of European compact cars at date of model introduction**



Source: **FKA 2002**

interdependent. Moreover, weight reduction creates the potential for further weight reduction – for instance through the use of smaller (and lighter) engines while maintaining performance.

In most cases, a lightweight solution will be more expensive than ordinary mild steel designs. Consequently, these solutions will not be competitive unless the customer is prepared to accept some premium for reduced weight or unless they simplify production and/or increase safety. Different materials will provide different potential for weight reduction, and also different impact on the component cost.

A rule of thumb is that a 10% reduction in vehicle weight can produce a 5-7% fuel saving (in mpg terms) provided the vehicle's powertrain or km/l is also downsized. *(IPAI 2000)* If the vehicle's weight is reduced but no change is made in the powertrain, the fuel savings will be less – generally about 3-4%. Actual savings depend on the vehicle in question and the driving cycle. Adopting the midpoint of this range and translating percentages into absolute numbers yields projected savings of 0.46 liter of gasoline saved per 100 km driven for each 100 kilograms of mass reduced.[9] Over the life of a vehicle this produces savings in CO_2 emissions of 25.3 kilograms for each kilogram of reduced weight.[10]

Total energy impact of materials use.
The net energy savings, and consequently total GHG reduction, of different materials used also depends on the energy consumed in the production of the materials. This, in turn, can be quite sensitive to the ratio of secondary versus primary material used. In particular, primary aluminum requires a great deal of energy to produce. Only a fraction of this energy is required when recycled aluminum is used. If only primary aluminum is used to accomplish weight reduction, 45% of the potential energy saving from the use-phase of the life of the vehicle is "lost". However, recycled aluminum is likely to constitute a significant share of aluminum used in the construction of vehicles in the future. Indeed, the researchers who conducted the SMP materials analysis project that 42% of total vehicle-related aluminum demand in 2030 will be met by secondary aluminum. Applying this percentage to the estimated cited above reduces the "loss" in use-phase fuel savings potential from 45% to between 10-30%.

Weight (mass) and occupant safety.
Occupant safety is a function of vehicle weight (mass), structural geometry, and "crush" distance. The nature of this relationship is complex and tradeoffs are involved.[11] It has been well established for over three decades that when traffic crashes occur, occupants in heavier/larger vehicles are at lower risk than occupants in lighter/smaller vehicles. However, in two-vehicle crashes, an increase in mass of one vehicle exposes the occupants of the other vehicle to increased risk. The increased size of a vehicle also protects its occupants, but without any adverse impact on occupants of vehicles into which it crashes.

A vehicle's mass and size are strongly correlated, which has made it difficult to determine the separate causative roles of mass and size on risk. Recently, Evans has demonstrated one way of doing so analytically. He has developed an equation that expresses the fatality risk to a driver in a two-car crash as a function of the mass and size (length) of the driver's car and the mass and size (length) of the other involved car. (The qualitative risk results in his analysis all relate exclusively to two-car crashes. However, Evans asserts that it is plausible to interpret them as reflecting principles that are transferable to crashes in general.) He then used this equation to explore what size (length) increases would be required to reduce risks to the occupants of vehicles andto the occupants of other vehicles into which they crash. *(Evans 2004)* In short, Evans' analysis shows how vehicles can be made both lighter and safer.

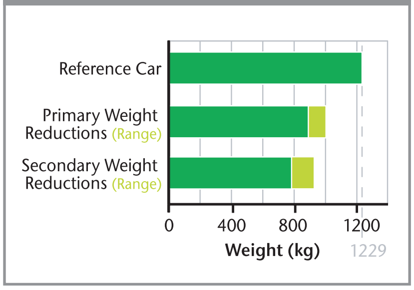
Evans notes that his study did not address such important design considerations as structural stiffness or geometric details. It was generic and did not offer specific design methods to increase vehicle length while reducing mass. Material substitution sufficient to make a longer vehicle lighter than the original vehicle would be required. This likely would require increased use of lightweight materials, which tend to cost more than steel.

Evans also did not explore whether the mass/size (weight/length) tradeoff he derives might be reduced. Some companies in the SMP strongly believe that through the use of appropriate structural design and materials, vehicles can be made not only lighter and safer, but also smaller.

Weight and ride & handling.
Reducing vehicle weight may improve ride and handling and reduce braking distance. Lower weight solutions may provide increased stiffness and so improve handling. Reduced weight solutions for selected components can also be used for improved vehicle weight distribution.

Strategies for weight reduction.
As noted above there are two main ways in which vehicle weight can be reduced. One is by design changes

Figure 3.6
Primary and secondary weight reduction opportunities



Source: **FKA 2002, p.8**

related to the vehicle appearance as well as changes possible due to the geometry available for each part. Another is by direct substitution of lighter for heavier materials.

A recent study sponsored by the European Aluminium Association and conducted by the German research institute FKA illustrates the potential for cumulative weight reduction. *(FKA 2002)* The reference car used in this study is a composite developed using average values for five different European compact class cars. A methodology was developed to break down the car into a useable set of components. Then, a steel reference car was built using average weights for steel parts. The weight of this conventional car was then compared to the weight of the car using aluminum solutions.

The study's results are illustrated in Figure 3.6. The top bar in Figure 3.6 shows the weight of the steel reference vehicle – 1229 kg. Using a variety of aluminum parts, it was found possible to reduce the weight of the vehicle by between 226-301 kg, yielding a vehicle weight of between 928 kg and 1003 kg (middle bar). Following this "primary weight reduction," it became possible to reduce more weight without sacrificing vehicle performance. One reason was that the vehicle could use a smaller engine. This "secondary weight reduction," shaved an additional 116-143 kg, producing a final vehicle weighing between 785 kg and 887 kg (bottom bar). Total weight saving therefore ranged between 342-444 kg or between 28-36%.

Potential weight saving for individual components.

Different studies have identified ranges in the potential for weight saving for individual parts. The variation in weight saving potential depends in part on judgments concerning the possible improvements in the geometry of the replacement parts. The more a component can be optimised with respect to the function and geometry it is to fill, the more its weight can be reduced.

Lightweight materials are commonly seen as being aluminum, magnesium, high-strength steel, and various plastics. Applications made of these materials are widely available and are already integrated in many vehicles. Intense innovation and design development is now taking place, which increases the chances that the potential of materials to improve sustainability can be utilized.

Requirements for successful substitution of lighter materials.

When reducing vehicle weight by introducing lightweight materials such as aluminum and magnesium, the material price per kilogram is significantly higher than for mild steel. Although the vehicle manufacturer may accept a somewhat higher price for a lower weight product, this material cost represents a major marketing issue. Several remedial strategies exist:

- ***Weight reduction.***
  Minimizing the weight of a component can reduce the effect of higher material price significantly. In addition to the specific weight of the material itself, alternative materials may permit more optimized geometry and further reduce weight.

- ***Reduced manufacturing cost.***
  Different materials may allow the use of alternative manufacturing processes, thereby reducing manufacturing cost. Processes such as extrusion of aluminum alloys and casting of magnesium are often utilized to provide solutions not possible with steel. In some cases use of lightweight materials can lead to increased manufacturing cost. An example is the welding of aluminum, which is generally more costly than mild steel welding.

- ***Optimized design.***
  To provide competitive solutions based on lightweight materials, design has to be adapted to the material used. Opportunities for weight optimization, integration of functions and reduced number of components and joints must be fully exploited. Often this requires adaptation of "defined boundary" conditions such as packaging space or attachment solution. Fully optimized solutions are more likely to be found when lightweight solutions are considered early in development projects.

B. Intelligent transport systems (ITS) technologies

Intelligent Transport Systems technologies have the potential to enable individuals, vehicle operators, and governments make better-informed and safer transport decisions. ITS technologies include a range of wireless and wired communications-based technologies, most of which were originally created for the telecommunications, information technology and defense sectors prior to being applied to traffic and transport.

Among the critical ITS enabling technologies are microelectronics, satellite navigation, mobile communication, and sensors. When integrated into vehicles and the transportation system infrastructure, these technologies can help to monitor and manage traffic flow, reduce congestion, provide alternate routes to travelers and save lives.

The ITS applications in widest use are traffic management systems, traveler information systems and automated toll collection. These applications focus primarily on improving the "intelligence" of the infrastructure.[12] However, ITS technologies are now being integrated into the vehicle itself. The trend for future developments of in-car ITS technologies (also known as Advanced Driver Assistance Systems, or ADAS) is towards integration of different functionalities and technologies (sensors, communication). This may contribute to safer traffic and smoother traffic flow and lead to more efficient use of the infrastructure.

Two vehicle technology developments have been critical in spreading the use of ITS systems. The first is "x by wire" – the use of electronic or electro-mechanical connections to control various vehicle functions. Braking, throttling, and motor management are already being controlled in this manner. Now work is progressing to permit "x by wire" solutions to be applied to other vehicle functions such as steering. The second is the planned conversion of vehicle electrical systems from 12V to 42V. Twelve-volt electrical systems are reaching their limits due to the increasing number of electrical and electronic components in today's vehicles. Higher voltage electrical systems will permit these limits to be overcome. Together, these developments open up new possibilities to support the driver in the driving task, potentially contributing to enhanced safety and smoother traffic flow.

One hurdle to be overcome is the level of market penetration required to make some of the technologies useable. The impact of more advanced technologies relying on vehicle-vehicle/vehicle-infrastructure communication will be severely limited if too few cars are equipped with the necessary electronic systems. The minimum penetration for significant efficiency is about 20%. One option is to introduce onboard units with communication and localization capability that is combined with other systems such as automatic emergency signaling.

1. EXAMPLES OF VEHICLE-BASED ITS TECHNOLOGIES

The first step in a vehicle becoming more intelligent is the addition of intelligent sensor systems to support the driver in the observation of the vehicle's surroundings. An important next step is the addition of vehicle-vehicle and vehicle-infrastructure communication systems that inform drivers at an early stage about what is happening on the road before them.

The European project Advanced Driver Assistance Systems in Europe (ADASE) recently produced an inventory of commercially available systems or systems that are under research and development worldwide. *(ADASE 2004)* In it, ADA systems were defined as systems that support or take over the driver's task. ADASE ranked these systems in terms of their potential to improve safety and their complexity:

- ***Speed alert.*** Examples are curve speed prediction, traffic sign recognition, speed advice, road status, intersection support, and vehicle infrastructure communication. These systems help to keep the driver informed about recommended speed relative to the road and environment or when approaching curves, congestion, or adverse road conditions. By doing so, they have a potential to increase safety and improve traffic flow. Inappropriate speed is intimately related to the risk and severity of a crash.

- ***Lane support.*** Examples are lane keeping, blind spot warning, and lane change assistant. These systems decrease the risk of unintentional lane departure, which can result in side-impact collisions with other vehicles or in single-vehicle collisions with roadside obstacles. Preventing steering errors in heavy traffic could also help to avoid the unpredictable congestion that affects travel reliability.

- ***Safe following.*** Examples are collision warning, collision avoidance, "Stop & Go," vehicle-vehicle communication and active cruise control (ACC). These systems maintain distance automatically and adopt speed optionally. Most of the proposed systems require a controlled traffic situation, such as found on motorways. Very large estimates of the safety potential of such systems have been claimed, but there are difficulties in many of the concepts, both in technical and in behavioral terms. Other potential effects are smoother speeds, safer distances between vehicles and smoother traffic flow.

- ***Pedestrian protection.*** An example is vulnerable road user and pedestrian awareness. These systems warn when there is a high risk of a crash with a pedestrian or a vulnerable road user (cyclist, motorcyclist).

- ***Enhanced vision.*** An example is night vision. These systems help the driver to improve perception of the environment, especially in tricky conditions such as night driving and bad weather.

- ***Driver monitoring.*** An example is driver drowsiness detection and warning. These systems monitor the driver and notice when attention declines. The effect of drowsiness on accidents is still inadequately understood but up to a quarter of all fatal motorway accidents have been ascribed to sleepiness. The share is smaller in rural and urban road accidents.

- ***Intersection safety.*** An example is intersection collision avoidance. In addition to the conventional vehicle-related collision warning systems, there are also systems in development (particularly in Japan and the US) that monitor dangerous intersections and warn drivers of vehicles entering or approaching a hazard zone. Such systems employ detection functions and roadside-to-vehicle or even vehicle-to-vehicle communication. Due to the complexity of such situations, there is a high requirement for reliability and accuracy.

- ***Vehicle diagnostics and dynamics.*** Examples are rollover warning systems, roll stability control and road surface monitoring (loss of traction alarms). Such systems combine vehicle dynamics and speed assistance with support in vehicle management when, for example, reducing braking distance or preventing a car from skidding or toppling. These systems are particularly attractive to heavy road users including freight transport.

- ***Human/Machine Interface.*** Driver support systems and services are intended to support driving tasks. They require interaction with the driver by auditory, haptic or visual feedback, or by taking over some driving tasks. The human/ machine interface is therefore a vital element in all driver support systems and services. Driver status monitoring is an additional in-vehicle system that can help to detect fatigue or driver impairment. Some of these systems are based on video image processing technology.

Though not specifically mentioned in the ADASE roadmap, tires also can incorporate ITS technologies:

- ***"Smart" tires.*** As the only contact between vehicle and road, the tire plays a key role in improving safety. Within a few years tires will be fitted with pressure sensors preventing the risk of a burst, consequence of leakage, or underinflation. "Smart" tires capable of providing information on adherence to the road (by sensors embedded in the tire) are under development. In this case data provided could be processed instantaneously allowing ESP or ABS to prevent adherence loss.

2. THE POTENTIAL OF ITS TECHNOLOGIES TO FACILITATE THE DEVELOPMENT OF INNOVATIVE MOBILITY SYSTEMS

ITS technologies can facilitate the development of more sophisticated versions of existing transport systems as well as enabling entirely new transport systems. In the short term, the most promising developments are those in the fields of telecommunication and information services. These technologies can make existing systems more flexible and efficient by permitting them to "cooperate" with each other. This can be accomplished with relatively small investments. Much depends on the manner in which systems are tuned to connect to each other and also on how the relevant information is presented to users.

At present bus systems are the focus of attention in both the developed and developing world. The main reason is that buses do not need any special infrastructure. In the developed world, one of the main problems bus operators face in attracting passengers is the perceived low status and attractiveness of bus transport. ITS technologies are beginning to be used to offset this problem. The CIVIS and Phileas bus systems are examples. Both support the driver in such a way that smaller lanes, narrower bus stop distances and comfortable vehicle behavior are possible. Fully automated driving is possible, but legal and liability issues are an issue. A rigorous extension of these products is the Intelligent Multimode Transit System (IMTS) being developed in Japan. Here buses drive on a strictly separated infrastructure, automatically guided without drivers.

Tram systems are popular in many European cities because of their good service and their contribution to the quality of life. Dynamic travel information available at tram stops is becoming an important positive feature of some networks. Germany is experimenting with trams that start in the city centre and continue on regular train tracks into regional areas to deliver passengers without the need for buses. Such systems are also under development in the Alsace region in France.

ITS technologies are also used to guarantee traffic safety in mixed traffic situations with heavy rail vehicles. In the metro sector ITS innovations enabled the world's first fully automated rail systems (VAL), introduced in France in the 1980s at Orly Airport and Lille. This is a compact metro system that uses a relatively small tunnel-tube and drives on rubber tires to improve acceleration. The driverless vehicles are in continuous contact with a control room. Since the introduction of the VAL, other and bigger automatic metro's and urban trains have been introduced in France, Great Britain, and Canada. These advanced systems deliver a cost-efficient and punctual high-frequency service. They have proven to be very safe because of screens and doors between the platform and the train and the integral safety regime.

Mobility systems such as "people movers" and "personal rapid transit" can operate autonomously but require dedicated guideways. Vehicles capable of "driving themselves" while operating on conventional roads already have been demonstrated in several countries. Obstacle detection techniques, using sensor technology and image recognition, are required to enable vehicles to "see" their surroundings and react appropriately to events occurring in their drive path. Positioning systems and visual recognition techniques offer new ways of dealing with navigational issues.

Dual-mode systems aim to combine the best features of cars and public transport. Dual-mode systems can be used on the conventional road infrastructure and offer considerable advantages when used on a dedicated infrastructure. Interesting examples of dual-mode concepts are RUF and Autoshuttle from Europe and Megarail from the US. In this system specially designed cars can be operated on the road by a normal driver, but can also be guided mechanically on a special rail system with short following distances.

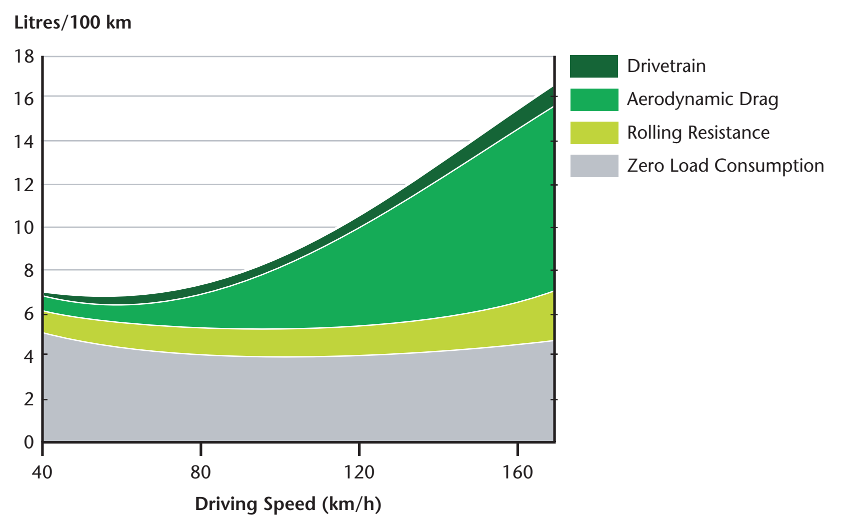
Dual mode is also used to refer to manually steered/automatically guided vehicles operating on a special infrastructure. Because of developments in in-car ITS technologies, and the limited adjustments to infrastructure needed for electronic guidance, this type of dual mode system has potential. The IMTS system described above is a dual mode system that allows both automatic operation on dedicated roads and manual operation on open roads. Automatic vehicle guidance enables electrical power pick-up from the infrastructure for vehicles equipped with an electric powertrain.

C. Reducing aerodynamic drag

Aerodynamic drag is the result of pressure and friction forces that are transmitted to a vehicle as it moves through the air. The vehicle's size and exterior shape and the function it is designed to perform are all major influencing factors. Functional requirements (the number of occupants a vehicle is designed to carry, luggage space, pickup box, trailer towing, off-road capability, and performance) are important parameters in determining overall aerodynamic resistance. The shape of the vehicle's rear end has an important influence on the pressure distribution on the vehicle's base – the lower the pressure and larger the area, the greater the resistance. Additionally, air pressure differences between a vehicle's top and bottom can produce cross-flows that form two large longitudinal swirls. These will interact with the wake and increase drag.

Air resistance depends on the size of a vehicle (which determines the frontal area) and on the aerodynamic efficiency factor (which represents the shape and function of a vehicle). For a given vehicle speed, air resistance is proportional to the product of these two factors. All else being equal, increases in driving speed cause air resistance to increase in a

Figure 3.7 **The effect of air resistance on fuel consumption for passenger cars at different speeds**



Source: **RAND Europe, RWT, and DLR 2003, p. 323** more than linear fashion. Figure 3.7 shows the relationship of air resistance to fuel consumption depending on the speed of the vehicle.

For a given vehicle size and functional requirement, minimizing air resistance mainly depends on improving shape of the vehicle. This can be done in a number of ways.

At the front of the vehicle there are numerous possibilities for reducing aerodynamic drag but many lead to design conflicts. Reducing the vehicle's size and frontal area conflicts with customers' desires for comfort and with safety demands. Lowering the engine hood, for example, is inconsistent with the size requirements of the engine compartment, better forward visibility, and the ease with which the driver can see the front end of the vehicle.

Designers can also introduce changes in the vehicle's rear end. Slightly raising the rear end as well as pulling in the sides and underbody can reduce aerodynamic drag. Compromises have to be sought between demand for a low rear end to improve rearward visibility and for more trunk space. For pickup trucks and SUVs, these will significantly compromise the function of the vehicle.

Smoothing the underbody and covering the engine compartment can also achieve improvements in aerodynamic drag. However, the vehicle must be designed to ensure sufficient airflow into the engine area and around the exhaust system for removal of waste heat. Excessive temperature buildup is detrimental to product reliability and safety. Reducing the distance between the vehicle body and the ground can also reduce aerodynamic drag but conflicts with customers' demands for easy-entry and off-road capability.

A moving vehicle is not only exposed to external airflows, but also to internal airflows – that is, airflows used to cool the engine, brakes, underhood components and ventilate the passenger compartment. When air flows across or through the radiator, engine compartment, wheelhouses and passenger compartment, losses arise from friction as well as turbulence and separation in the vehicle's interior. The resulting internal resistance contributes to overall aerodynamic drag.

Many of the most obvious opportunities for drag reduction in LDVs have been incorporated into vehicles. Today LDV aerodynamic efficiency factors are at historically high levels. Further improvements are likely to be achieved incrementally in the short term rather than by major design breakthroughs.

Advanced technology does offer some potential. Wood, who estimates that 16% of total energy consumed in the US is used to overcome transport vehicle drag, provides a useful overview of the role of advanced aerodynamic technology on potential vehicle fuel consumption. *(Wood 2004)* But, realistically, given customer preference for the many utilitarian and functional aspects of today's LDVs and the economic pressures in the marketplace, designers' will probably only achieve minor additional reductions in aerodynamic drag in the next several years. There may be more opportunities for reducing aerodynamic drag for trucks and buses.

D. Reducing rolling resistence

Rolling resistance is defined as the energy dissipated by a tire per unit of distance covered. Rolling resistance can only be overcome by expending energy. In the case of a motor vehicle, the energy is supplied by fuel. Rolling resistance thus affects fuel consumption.

For a given vehicle, the percentage of fuel consumption accounted for by rolling resistance depends on the speed and acceleration at each moment of the driving cycle in question, the vehicle's characteristics (mass, streamlining, internal friction, transmission), and the tires' rolling resistance coefficient. The consumption caused by rolling resistance (in litres per 100 km) also depends on the engine's efficiency at each moment in a cycle. From one type of driving cycle to another, a tire with a rolling resistance coefficient of 12 kg/t accounts for between 20% (motorway cycle) and 30% (urban cycle) of fuel consumption. Expressed as an absolute value, the tire's contribution varies between 1.4 litres per 100 kilometres (motorway cycle) and 2.6 litres per 100 kilometres (urban cycle) for a small size passenger car (Renault Clio type, 51 kW).

To minimize fuel consumption, tires must be properly inflated. Field studies on French roads have revealed that more than half of cars are driven with tires inflated 0.3 bars below the prescribed pressure or even lower. This results in a significant increase in rolling resistance: + 6 % when 0.3 bars below the recommended pressure, and +30 % when 1 bar below. A 30% increase in rolling resistance increases fuel consumption by between 3-5%. Seriously under-inflated tires are also prone to irreversible damage. Hence the interest in technologies that enable drivers to know while driving if their vehicle's tires are inflated properly.

The primary purpose of a vehicle's tires is to enable safe operation in all types of weather and under all road conditions. Any reduction in rolling resistance compromising tire safety performance. Tire characteristics also have a significant impact on a vehicle's ride and handling performance – an attribute that is important to vehicle purchasers.

E. New technologies for controlling temperatures within vehicles

A non-trivial share of the energy consumed by road vehicles is used to keep vehicles' interiors comfortable. Two types of technologies could reduce this energy requirement. The first type focuses on improving the efficiency of vehicle climate control systems. The second type focuses on reducing the task that these systems perform.

Improving the efficiency of climate control systems.

Over the last eight years, the environmental performance of current vehicle climate control systems, including both the amount of energy required to drive the compressor and the greenhouse gas characteristics of the refrigerant HFC-134a, has been receiving increased attention. Industry has started to develop improvements by focusing on improved system tightness against leaks, reduced refrigerant charge size, increased energy efficiency, and improved recovery and recycling practices during vehicle service and disposal. More recently, systems using alternative refrigerants with lower global warming potentials are under development, although none have yet been commercialised and introduced on new vehicles.

Some of the new possibilities include alternative HFC gases such as HFC-152, supercritical CO_2 and hydrocarbons. The CO_2 system is compatible with new generation direct injection diesel or other engine concepts that give off little or no surplus heat for heating the passenger compartment since it is suited for configuration as a heat pump to provide additional interior heat in winter as well as cooling in summer. It is expected that total direct (refrigerant) and indirect (fuel use) emissions from new automotive climate control systems can be substantially reduced by 2020.

Reducing the size of the task that climate control systems are called upon to perform.

The heating or cooling load determines the required capacity of a vehicle's climate control system. Reducing this heating or cooling load enables the capacity of the vehicle's climate control system to be reduced without compromising vehicle occupant comfort. Work has been done to develop low energy loss vehicle interior environmental control systems. These systems require less heating in winter and less cooling in summer.

III.

Applicability of the vehicle technology and transport fuels "building blocks" to road vehicles other than LDVs

Light-duty vehicles – passenger cars, light trucks, and variants of both – are the world's most numerous motorized transport vehicles. They consume the largest share of transport fuel, and are responsible for the largest share of the world's transport-related greenhouse gas and "conventional" emissions. So far our review of vehicle technology and fuels has focused largely on these vehicles. But the technologies and fuels that we have been describing also have relevance for other categories of road vehicles.

A. "Heavy" road vehicles – medium and heavy duty trucks as well as transit and "over the road" buses

Trucks are the principal carriers of freight over land. Buses are the workhorses of many local and regional public transport systems. They also carry a significant number of intercity passengers, especially in the developing world. Both trucks and buses are powered by ICEs and utilize many components that are similar in design and construction (though not necessarily in size) to those found in light-duty vehicles.

"Heavy" road vehicles account for a significant share of transport-related energy use, GHGs[13] and "conventional" emissions (especially NOx and particulates) as outlined in Chapter 2. Increasing attention is being devoted to improving the energy efficiency of the powertrains used in these vehicles – overwhelmingly diesels – and also to reducing their "conventional" emissions.

Engines powered by natural gas, methanol and ethanol are already being used in selected truck and bus applications around the world. Efforts are underway to apply new propulsion system technologies such as hybrids and fuel cells to selected truck and bus types. These efforts are less well known than those associated with light-duty vehicles. But they deserve wider recognition. Fuel and emissions savings from applying a hybrid system to a single city bus can reduce CO_2 emissions by as much as applying this technology to more than 20 light-duty passenger vehicles. *(Reynolds 2003)*

In December 2000, the US Department of Energy published a "technology roadmap" identifying what it considered to be promising technologies for heavy trucks (Class 8s),[14] transit buses, medium trucks (enclosed, single-axle delivery trucks), small trucks ("working" pickups with a manufacturers gross vehicle weight exceeding 8500 pounds – approximately 3900 kg.), and military vehicles. The technology roadmap also discussed "crosscutting technologies" such as alternative fuels, internal combustion engine technologies, exhaust after-treatment technologies, hybrid electric propulsion technologies, mechanical hybrid truck technologies, fuel cells, auxiliary power, thermal management, materials, more-efficient and/or lower-emissions engine systems, vehicle intelligence, and other innovative high-payoff technologies. *(US DOE 2002)*

The inclusion of Class 8 trucks in the Partnership scope was especially significant. Although these vehicles represent only about two million of the 45 million commercial trucks in use in the US, they consume 68% of all commercial truck fuel used. Indeed, long-haul Class 8 commercial trucks (those whose typical trip exceeds 100 miles) alone account for almost 50% of all commercial truck fuel used in the US.

A report prepared by the International Energy Agency, *Bus Systems for the Future*, includes information about innovations occurring worldwide relating

Table 3.4 **Bus technology cost estimates**		
Category	**Bus Purchase Cost** *(Thousands US$)*	**Other Costs**
Small, new or second-hand bus seating 20-40, often with truck chassis	10 - 40	
Large, modern-style diesel bus that can carry up to 100 passengers, produced by indigenous companies or low-cost import	40 - 75	
Diesel bus meeting Euro II, produced for (or in) developing countries by international bus companies	100 - 150	Some retraining and possibly higher spare parts and equipment costs
Standard OECD Euro II diesel bus sold in Europe or US [(1)]	175 - 350	
Diesel with advanced emissions controls meeting Euro III or better	5 - 10 *more* than comparable diesel bus	If low sulphur diesel, up to $0.05 per litre higher fuel cost (for small or imported batches)
CNG, LPG buses	25 - 50 *more* than comparable diesel bus (less in developing countries)	Refuelling infrastructure costs could be up to several million dollars per city
Hybrid-electric buses (on a limited production basis)	75 - 150 *more* than comparable diesel bus	Potentially significant costs for retraining, maintenance and spare parts
Fuel-cell buses (on a limited production basis)	Up to one million dollars more than comparable diesel buses, even in LDCs at this time	Possibly millions of dollars per city for hydrogen refuelling infrastructure and other support-system costs

[(1)] Note that this range of prices includes transit buses in both Europe and North America. Buses in Europe are generally less expensive than in North America, with the prices in Europe for non-articulated buses generally below $275,000.

Source: **IEA 2002, p.120.**

to transit bus systems. *(IEA 2002)* Much of this report is devoted to a description of advanced bus propulsion system technologies and fuels. Advanced propulsion system technologies covered include diesels, hybrid-electrics, and fuel cells. Fuels include water-in-oil emulsions, biodiesel and blends, compressed natural gas, liquefied petroleum gas and dimethyl ether (DME). The report also outlines research underway and identifies demonstration projects being undertaken. Table 3.4, from the IEA report, summarizes the report's findings concerning the cost and performance characteristics of various transit bus technologies.

1. PROTOTYPE, DEMONSTRATION, AND FLEET-SCALE TEST HEAVY VEHICLE PROGRAMS USING ADVANCED POWERPLANTS AND FUELS

A significant number of prototype, demonstration and fleet-scale test HDV programs are underway in various places around the world.[15] Hybrid-powered buses are being tested in several urban areas including in Brazil *(Ribiero 2003)* and the US. In October 2003, the city of Seattle ordered nearly 250 hybrid electric buses. *(King County Department of Transportation 2003)* Three Japanese truck manufacturers have developed hybrid-powered medium trucks. Each is reported to cost about 25% more than a diesel truck having comparable capacity. One of these trucks is estimated to achieve fuel consumption of approximately 23-25 mpg (9.4 – 10.2 l/100km). In the US, one firm has developed a hybrid propulsion system for medium trucks, aided by a grant from the US Department of Energy. The vehicles are intended to reduce particulate emissions by 90%, "smog-causing" emissions by 75%, and increase fuel efficiency by 50%. FedEx Express, a subsidiary of FedEx Corp., has agreed to utilize 20 of these vehicles as a test fleet. FedEx Express states that if the tests go as planned, it might replace its entire fleet of 30,000 W-700 step van delivery vehicles with hybrids over the next 10 years. *(Eaton 2003)* UPS has also agreed to test a prototype fuel cell powered commercial delivery vehicle. *(UPS 2003)*

B. Powered two- and three-wheelers

In some countries in South and East Asia, powered two- and three-wheelers constitute a majority of road vehicles. They are inexpensive and they provide mobility for millions of families. On a per vehicle basis they also use less fuel than an automobile or light truck. But they contribute disproportionately to "conventional" pollution. Efforts are now underway to lessen their emissions.

One of the most important initiatives is to shift from two-cycle to four-cycle engines. Two-cycle engines are high polluters since oil must be added to the fuel. Some countries have now enacted emissions standards that effectively ban the sale of new two- and three-wheelers powered by two-cycle engines. This will produce a significant improvement in emissions performance. But additional steps will be needed if real progress is to be achieved given the large numbers of two-cycle engines still in use.

Several solutions seem technologically feasible. For example, one major manufacturer announced recently that it had developed the worlds' first electronically controlled fuel injection system for use in 4-stroke, 50 cc engines. *(Honda 2003)*[17] The system, known as PGM-FI, is expected to be available in Japan on a new-model scooter sometime in 2004. All of this manufacturer's scooters for sale in Japan are scheduled for conversion to PGM-FI by 2007, and a majority of its models for sale worldwide will be so equipped by 2010.

The addition of a three-way catalyst will bring two- and three-wheeler emissions down to a level with passenger cars. As is the case for automobiles and light-duty trucks, catalytic converter equipped two- and three-wheelers will require unleaded fuel (which is becoming widely available) and, eventually, fuel that also is lower in sulfur. These innovations raise an issue of affordability as well as increasing the need for proper fuel use and proper vehicle maintenance.

C. Transport vehicles other than road vehicles

1. RAILROAD ENGINES

Most railroad engines use electricity generated externally or diesel fuel carried on board as their primary energy source.[18] For the world as a whole, 27% of energy used by railroads is externally generated electricity, 59% is diesel, and 12% is coal (virtually all in China). Countries vary widely in the extent to which their railroads rely on electric power. Railroads in Canada and the US are almost totally diesel powered. In Japan, 78% of the rail energy used is electrical, in Europe 61%. *(IEA 2003)*[19]

In recent years, there have been major improvements in the efficiency of electric locomotives brought about by the use of AC power. In the case of diesel-powered locomotives, propulsion system developments have focused primarily on improving the power, reliability and efficiency of the diesel engines used to generate on-board electric energy, as well as the efficiency of the electric traction engines that deliver this energy to the driving wheels. In addition, diesel locomotives have become subject to emissions standards and, in some places, to noise standards.

Diesel-electric locomotives range in size from 1500 horsepower (hp) shunting (switching) engines to 6000+ hp over-the-road locomotives. Diesel-electric locomotives are now being built with alternating current (AC) traction motors rather than the traditional direct current (DC) motors. AC locomotives have proved more reliable, require less maintenance and produce more horse-power than DC technology locomotives.

Locomotive manufacturers have also experimented with alternative fuels. In 1994, one manufacturer produced four switch engines (powered by spark ignition engines) that operated on 100% natural gas. Other companies have experimented with "dual fuel" engines – compression ignition engines that use up to 10% diesel fuel to initiate combustion. These experiments have not led so far to volume production of either type of locomotive. *(Railway Age 2000)*

A Canadian company recently produced and tested (and is now marketing) a hybrid-electric diesel switcher offering comparable levels of traction power to conventional diesel-powered switcher engines. This hybrid-electric switcher uses a much smaller diesel engine – one generating no more than 100 to 200 hp – to drive a mini-generator. The power produced by this mini-generator is fed into specially designed batteries. The batteries power the electric traction motors. This switcher is claimed to cost half that of a new switcher,[20] to use half the fuel when compared to a late model conventional yard switching locomotive of comparable power, and reduce NOx and particulates by 90%.

Meantime interest is growing in using fuel cells to provide auxiliary power for locomotives. This would permit the main diesel engine to be shut down when the locomotive is not in use but still has power needs. Idle time constitutes a surprisingly large share of the total time the diesel engine is in operation. A recent study of locomotive duty cycles on Canadian railroads found that engines were idling between 54% and 83% of the time. Using either fuel cells as auxiliary power units or the "hybrid" approach described above would permit engines to reduce the amount of idle time substantially. Though fuel use and emissions are much greater when a locomotive is operating at full power than when it is idling, the potential fuel use and emission improvements are non-trivial.

An effort to determine whether fuel cells might be used as the prime motive power for over-the-road locomotive engines is underway in the US. In a $12 million, five-year project, a US Army diesel-electric EMD GP10 locomotive is being disassembled and rebuilt with PEM fuel cells and metal-hydride storage equivalent to 400 kg of hydrogen. Other types of fuel cells and fuel storage systems are being analyzed for possible use in this demonstration project. *(Railway Age 2003)*

2. OCEAN SHIPPING, COASTAL SHIPPING AND INLAND WATERWAY TRANSPORT

Almost all commercial vessels are powered by diesel engines. The engines used in large ocean-going ships are the largest ever built. These giant diesels can have up to 14 cylinders, each with a bore of 980 mm and a stroke of 2660 mm, giving the engine a displacement of nearly 1000 liters.[23] Most of these very large engines are classified as "slow speed." That is, they operate at about 100 rpm, and are coupled directly to the ship's propeller, eliminating the need for reduction gears.

The diesel engines powering towboats or self-propelled barges on inland waterways are much smaller – about the size of a large diesel-electric locomotive, though there may be more than one such engine. Large towboats on US inland waterways are rated at over 10,500 horsepower. Fuels used by waterborne transport vehicles are "heavy" grades of diesel fuel and an even "heavier" petroleum product known as "residual fuel oil." Typically, these fuels are higher in sulphur than other transport fuels (see below).

A report to the International Maritime Organization published in March 2000, details the energy use and emissions characteristics of ocean-going vessels as of 1996. *(IMO 2000)* Table 3.5 shows the emissions estimated to result from the 138 million tonnes of distillate and residual fuel consumed during that year by these ships.

The same report identified and evaluated the impact of a range of technical and operational measures that could be applied to new and existing ships to reduce energy use and CO_2 emissions. Table 3.6 summarizes the report's findings concerning technical measures that might be applied and their estimated impact.

3. AIR TRANSPORT

The SMP projects that air transport will continue to be the most rapidly growing form of personal transport between 2000 and 2050 (Chapter 2). It already accounts for nearly 12% of transport energy use worldwide. In the SMP reference case, air transport's energy share is forecast to grow to more than 18% by 2050.

Since the 1960s, turbine engines fueled by a "light" petroleum product known as "jet fuel" have powered virtually all new commercial aircraft. While the combustion process of these turbine engines is quite efficient, the energy required to lift an aircraft and its payload off the ground and propel it long distances at high speeds is formidable. In fact, a large share of the "payload" transported by any aircraft is its own fuel. Not surprisingly, fuel usage and fuel costs are therefore an extremely important component of the total operating cost of an air transport system, comparable in magnitude to crew costs and ownership and investment costs.[24]

In a review of historical and projected future trends in aircraft energy use, Lee, Lukachko, Waitz, and Schafer *(Lee, et. al. 2001)* analyze the relative contribution of different technological improvements and operational factors in reducing the energy intensity of commercial aircraft over the period 1971-1998. As measured by megajoules per revenue passenger kilometer (MJ/RPK), this energy intensity has declined by more than 60%– an average decline of about 3.3% a year. (See Figure 3.8.)

Three technological factors – reduced specific fuel consumption, an increased engine efficiency reflected in aerodynamic efficiency, and improvement in structural efficiency – have been responsible for much of this decline. Engine efficiency improved by about 40% between 1959-1995, with most of the improvement achieved before 1970 with the introduction of high-bypass engines. Other factors include higher peak temperatures within the

Table 3.5 Marine emissions, 1996

Gas Component		Range *(Mton)*
CO		0.7 - 1.1
NMVOC		-
CH_4		-
N_2O		-
CO_2		436 - 438
SO_2	*Residual*	5 - 7
	Distillate	0.2 - 0.8
	Total	5.2 - 7.8
NOx		10.1 - 11.4

Source: **IMO 2000, p.11.**

engine, increasing pressure ratios and improving engine component efficiencies.

Aerodynamic efficiency has increased by approximately 15% historically, driven by better wing design and improved propulsion/airframe integration. Improvements in structural efficiency have contributed less despite some improvements in the materials used to construct aircraft. As has also been true for motor vehicles, reductions in aircraft weight produced by these improved materials have largely been traded off for other technological improvements and passenger comfort.

Lee, Lukachko, Waitz, and Schafer project that over the next several decades, commercial aircraft energy intensity will still decline, but at a slower rate – 1.2% to 2.2% per year compared to the 3.3% average annual decline experienced over the past several decades.

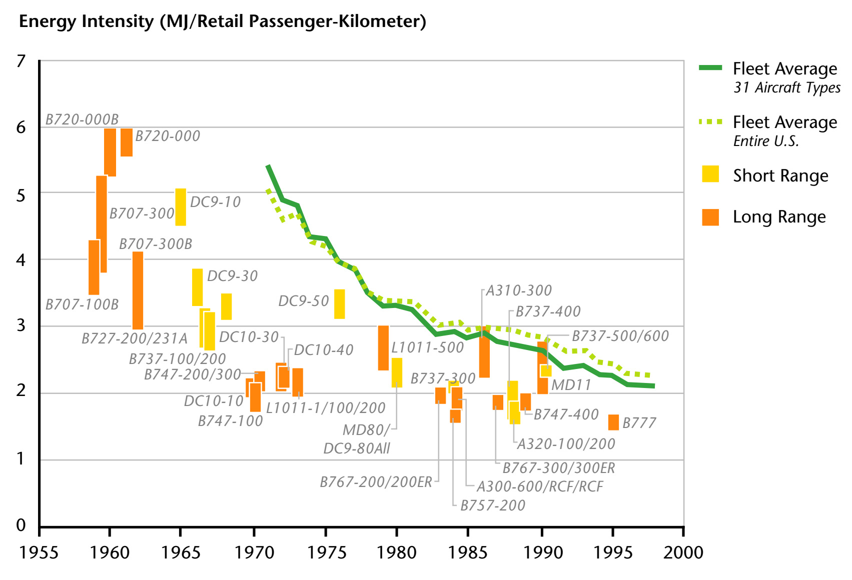
Table 3.6 Marine CO_2 reductions by technical measures

Measures	Fuel/CO_2 savings potential	Subtotal (1)	Total (1)
New Ships			
Optimised hull shape	5 - 20%		
Choice of propeller	5 - 10%	5 - 30%	
Efficiency optimised	10 - 12% (2)		
	2 - 5% (3)	14 - 17% (2)	5 - 30%
Fuel (HFO to MDO)	4 - 5%	6 - 10% (3)	
Plant concepts	4 - 6%		
Fuel (HFO to MDO)	4 - 5%	8 - 11%	
Machinery monitoring	0.5 - 1%	0.5 - 1%	
Existing Ships			
Optimal hull maintenance	3 - 5%		
Propeller maintenance	1 - 3%	4 - 8%	
Fuel injection	1 - 2%		
Fuel (HFO to MDO)	4 - 5%	5 - 7%	4 - 20%
Efficiency rating	3 - 5%		
Fuel (HFO to MDO)	4 - 5%	7 - 10%	
Eff. rating + TC upgrade	5 - 7%		
(HFO to MDO)	4 - 5%	9 - 12%	

(1) Where potential for reduction from individual measures are well documented by different sources, potential for combination of measures is based on estimates only
(2) State of art technique in new medium speed engines running on HFO
(3) Slow speedengines when trade-off with NOx is accepted

Source: **IMO 2000, p.14.**

Figure 3.8 Historical trends in the energy intensity of new aircraft by year of introduction and the fleet average over time in the US



Source: **Lee, et al., 2001, p.184.**

IV.

Differential impacts of improvements in vehicle technologies and fuels on developed and developing regions

The way in which technologies will become incorporated into transport systems globally will depend mostly on prevailing social and economic influences in the various regions. Different scenarios can be envisaged for different regions.

In the developed world, the key drivers are expected to be the desire to reduce both conventional and GHG emissions and secure energy supplies whilst maintaining and improving reliability, comfort, local urban pollution, performance, utility, convenience, cost, and safety. Not everything will be possible or affordable, but it is in the developed world that most possibilities are likely to be explored to the fullest degree. Most areas will experience increasing use of cleaner fuels containing non-conventional and more sustainable components, probably biofuels. Gaseous fuels (CNG and LPG) will continue to be favored for inner city fleet use to combat local pollution. These developments will facilitate improved performance in vehicles that incorporate many of the technology enhancements outlined including, increasingly, hybrids. The use of hydrogen as a fuel is also likely to appear first in areas of the developed world, probably as a fuel for controlled fleets of vehicles (fuel cells and ICEs), with more wide-spread distribution later.

Existing systems for enhancing vehicle safety in developed countries already achieve a high standard of safety. Increasing use of electronics is likely to result in even safer vehicles. Safety system technologies designed to produce active safety systems like "X-by-wire" and "driver assistance" systems will become increasingly important. The same is true for of brake-by-wire and steer-by-wire systems, while active suspension systems will enhance vehicle safety and improve driving comfort. Legislative and regulatory initiatives will drive the adoption of pedestrian protection measures and improved driver behavior. They also will encourage societies' abilities to utilize technologies that give more – or less – driver autonomy.

In many ***developing countries***, especially those enjoying rapid economic growth, road transport is increasing much more rapidly than in the developed world. This growth has often been accompanied by increasing congestion, noise, pollution, and road accidents. Many developing countries have not yet been able to introduce beneficial technologies and practices that are already in place in developed countries.

Changes in access to advanced technologies, regulations, trade policies, and taxation will progressively narrow the average performance gap between vehicles in developing and developed countries. As a result, different factors will prevail in the developing world, with different consequences. In particular, the priorities will reflect the local situation. Energy supply security, affordable transport, use of the existing infrastructure, and resources may all be given higher priority than in developed countries. Another possibility is that there will be greater focus on reducing and controlling local emissions as opposed to reducing GHGs.

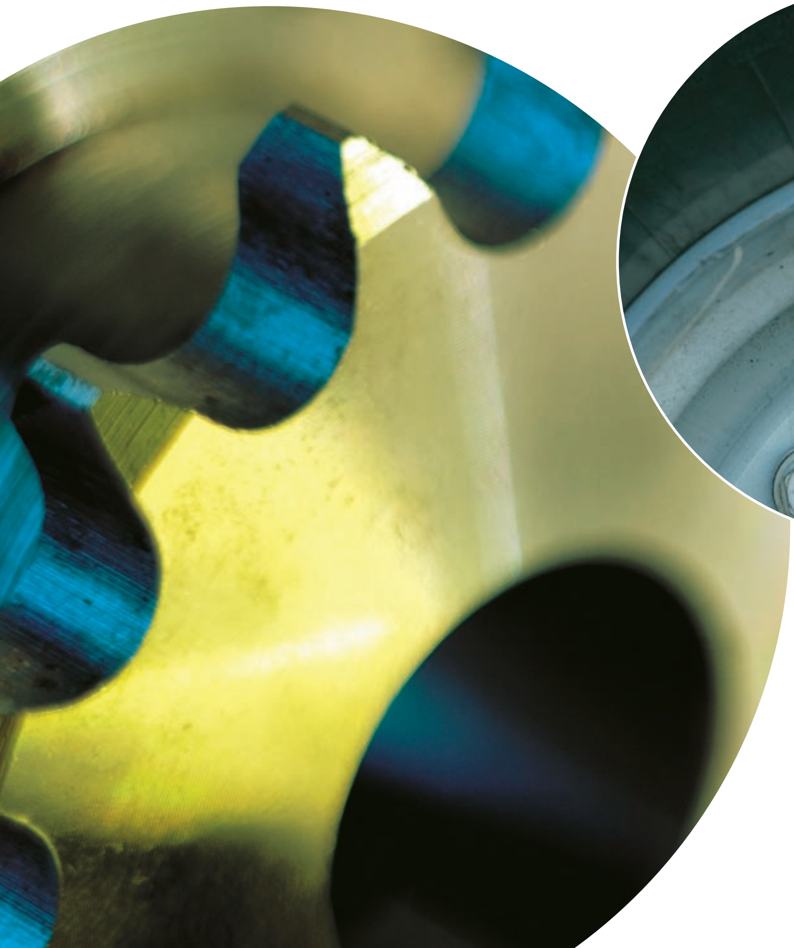
One of the most significant sustainability trends in developing societies will be the adoption of vehicle emission control technologies. Global car manufacturers are already responding to developing country markets by designing vehicles that fit the budgets of local consumers. Improvements associated primarily with developments in ICEs and after treatment, along with non-drive-train and materials changes, increasingly will become commonplace in the developing world. Over time the result will be improvements to the existing liquid fuels base (gasoline and diesel) and associated infrastructure.

In particular, there will be a strong movement in developing countries towards unleaded gasoline and lower sulfur levels – and probably towards locally sourced biomass-derived fuel components – in order to permit vehicles with modern emission control equipment to become more widely available. CNG and LPG will also find increasing application for local pollution control in rapidly expanding cities, especially where they replace “old” high-emitting vehicle technology. Two-stroke engines, widely used for two- and three-wheelers, are likely to disappear over the course of the next decade, to be replaced by more efficient, cleaner four-stroke engines.

It is also possible that some countries with abundant natural fossil resources (such as coal in China) will seek to use them to derive fuel products like FT-diesel, gasoline or possibly even hydrogen. This will depend on the development of cost and energy-effective conversion technology and also CO_2 sequestration methodology. It is unlikely that the fuel cell will make a major contribution to transportation in developing regions in the time span covered by this report due to the cost, infrastructure and vehicle technology factors described earlier. This could change if developments in affordable technology for CO_2 sequestration made it viable to convert the vast coal reserves of a country such as China to hydrogen and so create a hydrogen network that leapfrogs the existing conventional fuels infrastructure.

Existing trends should result in dramatic improvements in safety in developing countries but much of this improvement will result from the more widespread use of currently available technologies. In general, city governments in developing countries are more likely to emphasize regulatory approaches rather than technological approaches to reduce congestion and improve traffic management.

Whilst these developments may not have the potential to deliver the same overall benefits as some of the more advanced approaches, the improvements they deliver – particularly in the context of the anticipated growth in these regions – will be a very important factor in the overall drive for sustainable mobility. Today developed countries account for 75% of the global stock of motor vehicles. But motor vehicle ownership in developing countries has risen rapidly over the last decade, and during the next 30 years developing countries will account for most of the net increase in the world motor vehicle fleet. So achieving greater sustainable mobility in these countries inevitably will become a central element in achieving global sustainable mobility.



[1] There is a third type of propulsion system – the external combustion engine. Reciprocating steam engines, steam turbines, and gas turbine engines are examples of this type. At present, only the latter is used extensively in transportation, and its use is confined almost totally to air transportation. It is discussed later in this chapter.

[2] Over at least the past decade, the worldwide trend for engine displacement has been in the opposite direction due to the market pull for larger vehicles with greater performance and more features.

[3] Technical changes would need to be made to the engine in order to avoid deterioration in performance or function.

[4] This also applies to the case of hydrogen used to power an internal combustion engine.

[5] These cost figures are for individual technologies and do not include the vehicle integration costs which in many cases can exceed the base technology cost.

[6] Where the combination generates increased WTW GHG emissions relative to the reference vehicle, no number is shown in column nine, since it would not be meaningful.

[7] DPF = diesel particulate filter.

[8] Where no figure appears for cost per tonne avoided, the WTW GHG emissions are actually larger than in the base case.

[9] This value applies to a midsized North American vehicle with a curb weight of 1532 kilograms.

[10] Vehicle lifetime is estimated at 193,000 km.

[11] For example, the addition of certain safety features (e.g., air bags) can also add to vehicle weight.

[12] Traffic management systems optimize traffic flow on the basis of monitoring and simulation based predictions by, for example, dynamic speed signs, ramp metering and flexible lane allocation. Incident management aimed at removing accidents as quickly as possible often is an integral part of traffic management. Traveler/driver information systems provide transport users with information to enable them to make better transport choices. Information can be supplied by dynamic route information panels, radio broadcasts, the internet and information that is processed in the car navigation system leading to an adjusted route proposal. Electronic toll collection was introduced to speed up the process of collecting toll on specific infrastructure sections. It is in use in several countries including France, Italy, Spain, Australia, Japan, Canada, and the US.

[13] In 2000, trucks and buses combined accounted for almost thirty percent of all transport-related GHG emissions. This is about two-thirds of the volume of GHG emissions from LDVs.

[14] Class 8 trucks are trucks defined as having a manufacturers gross vehicle weight of 33,001 pounds (15,000 kg) or greater.

[15] The US Department of Energy's Advanced Vehicle Testing Activity maintains a website identifying heavy-duty hybrid vehicle projects around the world. As of mid-November 2003, the website listed over 60 projects in the US and Canada and over 50 in Europe, Asia, and elsewhere. US DOT 2003a.

[16] Isuzu's truck is reported to cost US$9000 more than a diesel truck of comparable capability. (The current price of a diesel truck of this size ranges from US$27,000 to US$36,000.) Nissan Diesel's truck is reported to cost US$8200 more than a standard diesel truck of comparable size. Automotive News, January 12, 2004, p. 28L.

[17] Honda 2003. Fuel injection has been offered on larger motorcycles (from 1800 cc down to 125 cc models), but this is the first time that such technology is being applied to the very smallest scooters. 50 cc-class scooters are the largest sales category in Japan.

[18] Indeed, virtually all "diesel" locomotives are, in fact, electrically powered. The diesel engine drives an electric generator, and the traction motors are electric.

[19] In this case, "Europe" stands for European countries belonging to IEA.

[20] Most shunter engines in North America are 30 to 40 years old, and some are older road locomotives that have "migrated" into switching service. Thus, for many railroads, the relevant cost comparison is to the variable operating costs of these switchers.

[21] The 83% figure applied to switcher engines.

[22] For post-1990 freight duty cycle Canadian EMD 645 E3 locomotives, eliminating idling reduced fuel consumption by 5% to 8%; reduced NOx emissions by 6% to 9%; CO emissions, by 18% to 21%; and HC emissions, by 27% to 29%.

[23] In contrast, a four-cylinder passenger car will have a displacement of 2.0 to 3.0 liters. MAN/B&W website 2003

[23] Lee, et. al. 2001, p. 182.

Chapter 4

Achieving sustainable mobility

I. Introduction

Up to this point in our Final Report we have identified a set of indicators of sustainable mobility and projected the course of their evolution to 2050. Based upon these projections, we concluded that mobility is not sustainable today and is not likely to become so if present trends continue. We proposed a set of goals that, if achieved, should substantially enhance the sustainability of mobility. Finally, we described the potential contribution that various transport vehicle technologies and fuels might be able to make in enabling achievement of these goals.

In this final chapter we turn our attention to how the goals might actually be achieved. We distinguish between achievements that in principle appear possible by 2030 and achievements that only appear possible over a longer period of time.

II.

Ensure that the emissions of transport-related conventional pollutants do not constitute a significant public health concern anywhere in the world

In the developed world, the time is approaching when conventional transport-related pollutants will no longer represent a significant public health concern. We believe that this goal is achievable by 2020. In the developing world full achievement will take longer, but substantial progress can be made prior to 2030.

Progress so far mostly has been achieved as a result of a four-part strategy:

First, governments have established increasingly stringent, health-based emissions limits that, in turn, have required manufacturers to install increasingly effective pollution control technology on new vehicles. Second, governments have required manufacturers to certify that these devices are capable of meeting the limits to which they have been certified throughout a vehicle's "useful life." Governments also have introduced inspection and maintenance regulations to assure that these devices are operating properly. Third, governments have mandated that the fuels required to permit these devices to operate properly will be made available. Fourth, additional costs of the pollution control technologies and fuels have been borne in the first instance by vehicle and fuel producers and then passed through to vehicle purchasers and operators.

To complete the process of eliminating transport-related conventional emissions as a significant public health concern, a fifth element may be necessary – the identification and control of individual "high emitter" vehicles.

A. Completing the task of controlling conventional emissions from road and transport vehicles in the developed world

The SMP reference case projections have shown that emissions limits already in place (or scheduled to be introduced) in OECD member states should permit transport-related conventional emissions in these countries to fall rapidly and significantly over the next few decades. This decline will not only include light-duty road vehicles but also heavy-duty road vehicles (trucks and buses), railroad locomotives, waterborne vessels, and aircraft.

For the developed world to achieve the SMP goal, however, another challenge will have to be addressed. As emissions reduction devices become standard on the developed world transport vehicle fleet, a higher share of remaining emissions are likely to be produced by vehicles not in compliance with their required limits. Roadside monitoring and random testing in the US and elsewhere has demonstrated that a relatively small number of "high emitter" vehicles are responsible for a disproportionate share of actual emissions.[1]

Table 4.1 shows data collected by the University of Denver (Colorado) at the same Denver site over four years (1999, 2000, 2001, and 2003) plus two earlier years of data (1996 and 1997) collected as part of a separate study. *(Burgard, et. al. p. 7)*. Mean CO, HC, and NOx levels decline over time, reflecting the introduction of newer vintages of emissions control technologies plus the retirement of older vehicles. But the percentage of total CO, HC and NOx from the dirtiest 10% of the fleet remains relatively stable (CO and HC) or rises (NOx). Table 4.2 shows SMP calculations using the USEPA Mobile 6 model of the "high emitter" fraction of total US LDV emissions in 1999.

In principal, detecting "high emitter" vehicles should not be a great challenge. In most countries the extremely stringent emissions limits imposed on new vehicles are accompanied by requirements that the vehicles using them be equipped with devices that permit an electronic "readout" of emissions system performance and alert drivers to the possibility that their emissions control systems are malfunctioning. However, experience so far with inspection and maintenance programs has been decidedly mixed. Even when vehicles are determined to have malfunctioning emissions control systems, authorities sometimes are reluctant to force owners to bring these systems into compliance. Failure to deal effectively with "high emitter" vehicles will not totally negate any emissions reductions that improved emissions systems generate. But it will lessen the magnitude of these reductions.

As onboard and roadside monitoring systems become more sophisticated and less expensive, the challenge of detecting and dealing with high emitter vehicles will become less a technological and more a political and cultural matter. Before long, vehicles will be able to "self-report" their actual emissions to their operators and to government authorities. As already noted, different societies are more or less willing to accept different levels of "governmental intrusiveness." Having one's own vehicle "self-report" that it is not meeting emissions limits, or having a vehicle's excess emissions spotted by a roadside detection device that automatically sends the vehicle owner a notice to have his or her vehicle repaired and automatically fines the owner if her or she does not do so, will be technologically feasible. But it may not be widely acceptable. *(Automotive News, September 22, 2003)*

Another challenge will be to cushion the impact of enforcement on lower-income families and individuals. Car-owning lower income households tend to possess older vehicles, in a worse state of repair, than households with higher incomes. As a result, drivers from lower-income families are likely to be disproportionately represented among the targeted "high emitters." This is especially true where public transport systems do not provide a viable substitute for private LDVs.

Table 4.2 "High Emitter" share of total US LDV emissions

	CO	NMHC	NOx
Share of Emissions	65%	54%	47%
Share of Vehicles	11%	13%	23%
Share of VMT	11%	12%	22%

Note: Data is for 1999

Source: Sustainable Mobility Project calculations

Table 4.1 Remote sensing results from Denver, Colorado site, 1996-2003

	1996	1997	1999	2000	2001	2003
CO from Dirtiest 10% of Fleet (% of Total)	63.8	67	66.3	65.3	73.2	68.9
Mean CO (ppm)	*0.53*	*0.51*	*0.45*	*0.43*	*0.34*	*0.35*
HC from Dirtiest 10% of Fleet (% of Total)	77.5	72.5	66	77.6	77.2	74.8
Mean HC (ppm)	*180*	*160*	*125*	*115*	*112*	*88*
NOx from Dirtiest 10% of Fleet (% of Total)	38.1	43.6	44.6	48.4	51.7	53.5
Mean NOx (ppm)	*860*	*620*	*600*	*511*	*483*	*456*
Mean Model Year (year.month)	1989.2	1990.3	1992.4	1993.4	1994.6	1996.4

Source: **Burgard et. al. 2003, p.7.**

B. Controlling conventional emissions from road vehicles in developing world regions

The technologies that are being used to control conventional emissions from road vehicles in developed countries and to detect "high emitters" are available for application to vehicles in developing countries. But achieving comparable results in developing world countries presents several distinct challenges.[2]

1. THE AFFORDABILITY CHALLENGE – VEHICLES

Average per capita incomes are far lower in developing than developed countries, so the initial cost of emissions control equipment represents a greater financial burden on a prospective vehicle purchaser in these countries than it does in developed countries. This increases public resistance to advanced emissions control equipment, especially when fitted to smaller, less expensive vehicles such as small passenger cars, small trucks, and two- and three-wheelers. This resistance is likely to be aggravated if the requirement for stringent controls disadvantages (or appears to disadvantage) indigenous manufacturers.

Lower incomes also mean that vehicles, once purchased, tend to stay in service longer. As a result, the rate at which any particular emissions control technology spreads across a country's vehicle population will be slower in the developing than the developed world.

2. THE AFFORDABILITY CHALLENGE – FUELS

Assuring that the latest low-pollutant fuels are available and used is also more difficult in the developing world. Such fuels tend to be more expensive than conventional fuels. The same affordability factors that slow the spread of advanced emissions control equipment also slow the introduction of more expensive fuels. When more expensive vehicles and more expensive fuels are introduced together, as is often the case, this becomes even truer. In addition, in many developing countries the refining and sale of transport fuel is a government monopoly. Innovations that involve expensive refinery upgrades, improved fuel-distribution systems or refurbished filling stations often face strong political resistance.

3. THE AFFORDABILITY CHALLENGE – MAINTENANCE

Making sure that vehicles possessing advanced emissions control equipment are properly maintained and appropriately fueled is another major challenge for developing countries. Cost is certainly a reason. But perhaps more important are cultural factors. Even in wealthier countries it has proved difficult to persuade officials to devote adequate resources to enforce compliance. It has also proved difficult to convince the public to support measures to get older, higher-polluting vehicles off the roads – far more success has been achieved by putting the burden of assurance that emissions control equipment is working efficiently on vehicle manufacturers.[3] Moreover, in many parts of the developing world, vehicle maintenance and repair is performed "unofficially." Inspection and maintenance programs are either totally lacking or not conducted rigorously. And officials have few resources and little motivation to make sure such work is performed properly.

4. THE CHALLENGE OF CONTROLLING CONVENTIONAL EMISSIONS FROM MOTORIZED TWO- AND THREE-WHEELED VEHICLES

Motorized two- and three-wheelers are relatively energy efficient. But, due to their large numbers and their two-cycle engines, they are responsible for a disproportionate share of transport-related conventional emissions. As mentioned in Chapter 3, steps are beginning to be taken to control emissions from these vehicles. The most important of these steps is to require that such vehicles be equipped with four-cycle rather than two-cycle engines.

This action alone will not be sufficient. Technologies to permit sharply reduced emissions from four-cycle two and three wheelers are becoming available. These include electronically controlled fuel injection and three-way catalysts. If implemented, these developments have the potential to reduce two- and three-wheeler emissions levels comparable to those being achieved by the latest passenger cars. But as is the case for automobiles and light-duty trucks, catalytic converter-equipped motorized two- and three-wheelers will require unleaded fuel and (eventually) low sulfur fuel, raising issues of affordability and correct fuel use and vehicle maintenance. In the developed world these challenges seem surmountable. The prognosis is much more uncertain in developing countries.

5. THE IMPACT OF IMPLEMENTATION LAGS OF DIFFERENT LENGTH ON EMISSIONS IN COUNTRIES AND REGIONS OF THE DEVELOPING WORLD

In producing the emissions projections for developing countries detailed in Chapter 2 the SMP made an assumption that they lag developed countries in the control of emissions of conventional pollutions from road vehicles by ten years. In this context, "controlling emissions" involves more than passing laws or regulations mandating that new vehicles to be equipped with advanced emissions controls and requiring the introduction of fuels to permit these controls to perform as designed. It also means assuring that these advanced controls are deployed throughout the vehicle fleet and that they operate as intended over vehicles' entire working lives. In the circumstances, a ten-year lag time seems reasonable given the intention of some developing countries to adopt European Union vehicle emissions limits and the actual adoption of these limits by many other developing countries in recent years.

The length of this implementation lag has a significant impact on emissions. This is shown in Figures 4.1-4.4 in which emissions resulting from lags of varying length are shown for various substances.

Figures 4.1.to 4.4 show that by 2050, there is no difference in total emissions regardless of the length of the lag. This is because OECD countries are assumed not to further tighten their emissions limits beyond 2010 levels. Under this assumption, by 2050 non-OECD countries will have "caught up" with OECD countries regardless of the lag. Still, during much of the 2000-2050 period the level of emissions differs, sometimes quite dramatically, depending on the lag. For example, in 2020, CO and PM-10 emissions each vary by a factor of almost four, NOx emissions vary by a factor of almost two. For emissions of each pollutant, the length of the lag determines whether emissions decline significantly, decline slightly or increase by 2010.

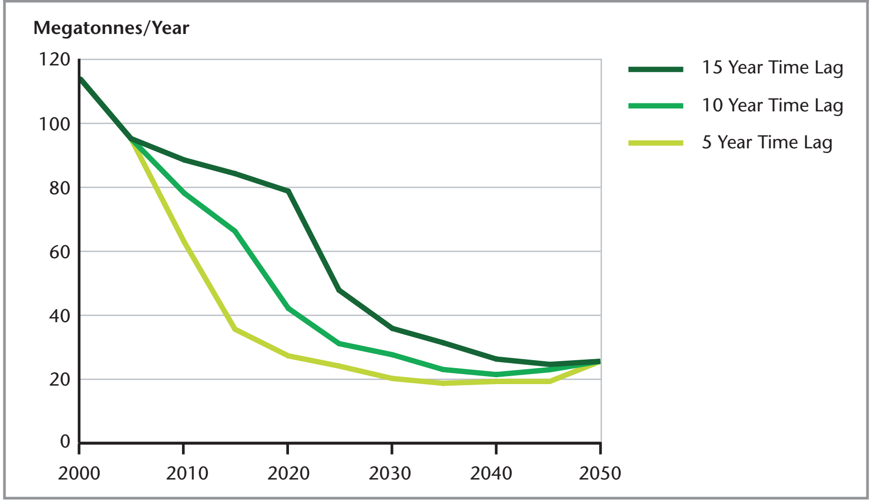
Members of the SMP can do little to help developing countries address the political and cultural issues mentioned above. But we may be able to help to reduce other elements of the time lag. For example, the development costs of advanced emissions control technologies now being introduced in OECD countries are likely to have been recouped by the time that they are introduced into "mainstream" vehicles sold in the developing world. Pricing such technology at its incremental production cost might improve its affordability and accelerate its use in the developing world. On the fuels side, efforts could be made to convince government-owned petroleum companies to accelerate the rate at which refineries are upgraded to produce higher quality fuels.

Careful coordination of the introduction of advanced emissions control technology and the fuels needed to allow them to operate effectively will be necessary all over the world. Otherwise, efforts to speed up emissions reduction will not only be ineffective but actually counterproductive.[4]

C. Summary assessment

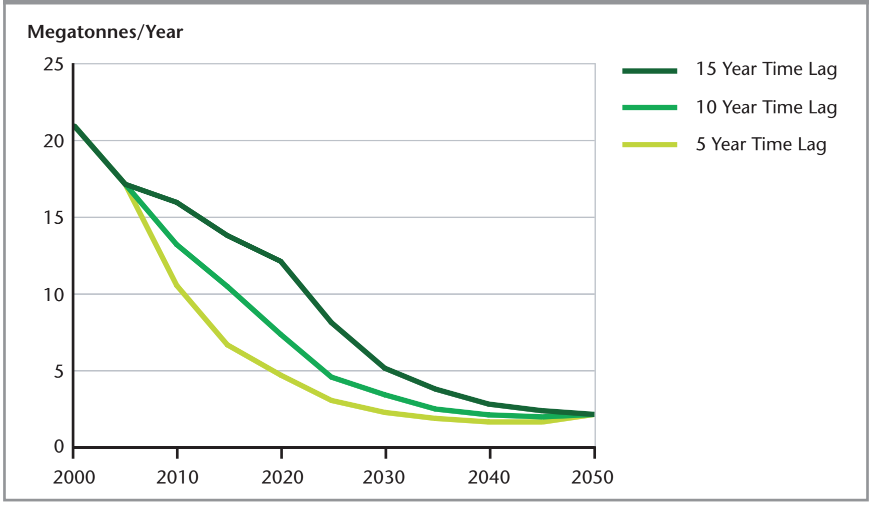
In the developed world, transport-related conventional emissions are on a track to decline sharply during the next few decades. The principal remaining challenge to the total achievement of the goal we have stated is to detect and control emissions

Figure 4.1 Non-OECD regions: Carbon Monoxide (CO) emissions by year depending on the time lag in implementing developed world emissions standards



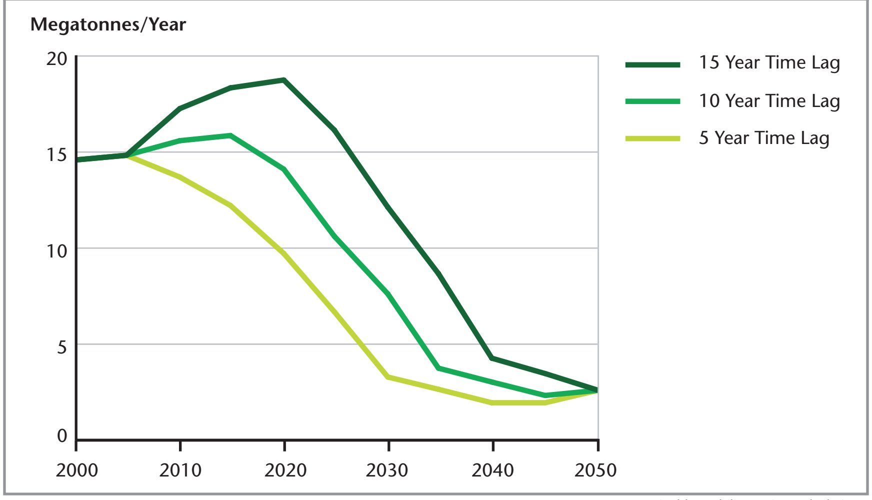
Source: Sustainable Mobility Project calculations.

Figure 4.2 Non-OECD regions: Volatile Organic Compound (VOC) emissions by year depending on the time lag in implementing developed world emissions standards



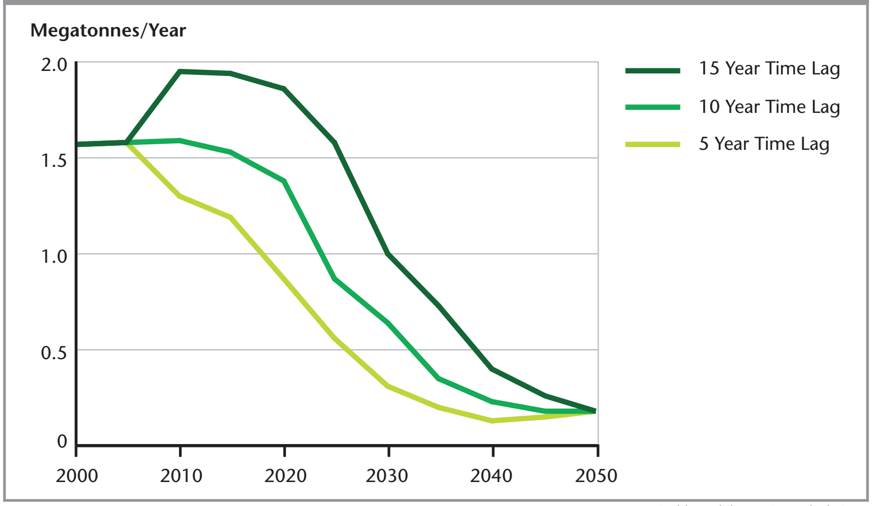
Source: Sustainable Mobility Project calculations.

Figure 4.3 **Non-OECD regions: Nitrogen Oxide (NOx) emissions by year depending on the time lag in implementing developed world emissions standards**



Source: Sustainable Mobility Project calculations.

Figure 4.4 **Non-OECD regions: Particulate Matter (PM-10) emissions by year depending on the time lag in implementing developed world emissions standards**



Source: Sustainable Mobility Project calculations.

from “high emitting” vehicles. The technologies to do this exist, but societies are likely to differ in how – or even whether – to make use of these technologies.

Developing countries have the potential to match the achievements of developed countries in controlling transport-related conventional pollutants. But the affordability of the necessary technologies and fuels is a key concern. It will also be a major challenge to implement developed world emissions limits although many developing countries seem prepared to do so. If the cost of emissions control equipment and “cleaner” fuels can be reduced significantly, the chances of achieving this goal worldwide will be enhanced greatly.

III.

Limit worldwide transport-related GHG emissions to sustainable levels

While it may not be possible to define precisely what a "sustainable" level of transport-related GHG emissions might eventually be, clearly it is below current levels. In contrast, the SMP reference case shows transport-related GHG emissions more than doubling by 2050. This is clearly unsustainable. How might this outlook be changed significantly?

A. Four factors that determine total transport-related GHG emissions

As noted in Chapter 2, the total volume of transport-related GHG emissions is the result of four factors:

> *Factor 1 – The amount of energy required by the average vehicle used by each transport mode to perform a given amount of transport activity.* This depends on the energy consumption characteristics of the mode or conveyance and the conditions under which it operates.
>
> *Factor 2 – The WTW greenhouse gas emissions generated by the production, distribution, and use of a unit of transport fuel.* This is related directly to the carbon content of the fuel used and the way in which the fuel is produced and distributed.
>
> *Factor 3 – The total volume of transport activity.* This depends on the number of transport vehicles operated and their use, and is a function of consumer demand.
>
> *Factor 4 – The modal mix of the total volume of transport activity.* This depends on consumer choice, vehicle or mode pricing and prevailing legislative or fiscal measures that influence mode selection.

The SMP discussion of approaches to reducing transport-related GHG emissions is organized around these four factors. We begin by discussing actions impacting factor 1 and/or factor 2. Taken together, these factors determine the GHG emissions characteristics of any individual transport vehicle. Then we discuss actions impacting factor 3 and/or factor 4. These factors determine how much each vehicle is utilized and the pattern of utilization across the transport fleet.

B. Reducing GHG emissions per unit of transport activity

To reduce GHG emissions per unit of transport activity, it is necessary to reduce the amount of energy required to produce that unit of transport activity (factor 1) or to reduce GHG emissions (measured on a WTW basis) generated by the production and use of each unit of that energy (factor 2). Doing the first requires that the transport fleet become more energy-efficient. Doing the second requires the production, distribution, and use of lower-carbon transport fuels.

1. STIMULATING DEMAND FOR "LOWER CARBON-EMITTING" TRANSPORT SYSTEMS

Technologies having the potential to reduce the fuel consumption when used in different types of transport vehicles and to curb the average carbon emissions produced by the manufacture and use of different types of transport fuel were described in Chapter 3. But for this potential to be translated into actual reductions in transport-related GHG emissions, these technologies must find widespread use. In addition, the size of any reductions will be influenced significantly by how vehicles incorporating these technologies and fuels are used in day-to-day service.

At present there is no guarantee that many of these technologies and fuels will be used widely. In general, both the vehicles incorporating them and the fuels that they must use if GHG emissions are to be reduced are more expensive than the vehicles and fuels they would replace. Moreover, the benefits of GHG emissions reduction accrue to society at large rather than to any individual transport user. So the incentive for individuals to incur significant extra costs voluntarily to acquire and operate vehicles that emit significantly fewer GHGs is likely to be quite limited.[5] Incentives will probably be needed, and only governments have the resources and authority to create them.

In considering the incentives that might be required, what their impact on GHG emissions might be and the time period over which this impact might be felt, it is important to separate the vehicle technologies and fuels discussed in Chapter 3 into two categories. One category includes vehicle technologies and fuels for which there is, or soon will be, some degree of commercial experience somewhere. Light-duty vehicles using advanced ICE gasoline, advanced ICE diesel and ICE hybrid-electric power-trains are already on the market or are close to being so. The application of these technologies in medium- and heavy-duty road vehicles lags but the costs involved are reasonably well defined, as are the likely performance characteristics that such vehicles would exhibit. "Conventional" biofuels are also in commercial use in several countries.

The fact that there is (or soon will be) some commercial experience with these vehicles and fuels in some parts of the world does not mean that all technical issues relating to them have been solved or that their cost and performance in all situations is known. But in the case of these vehicles and fuels, it makes sense to discuss in general terms what incentives might be required to enable large-scale implementation.

The second category of vehicle technologies and fuels includes more advanced vehicle technologies such as fuel cells and fuels such as carbon-neutral hydrogen and advanced biofuels. Their potential to cut transport-related GHGs is beginning to be understood but they are not nearly as close to large- scale commercialization. Important questions of technical feasibility must still be answered. The cost of such vehicles and fuels when produced in high volume is also highly speculative, as is the day-to-day performance of the vehicles under normal operating conditions. All these uncertainties mean that it is not practical at this stage to define what incentives might eventually be needed to enable their widespread use. However, it is possible to describe what governments can do over the next several years to help industry reduce these uncertainties to the point where a meaningful discussion regarding implementation can be held.

a) Vehicle technologies and fuels for which we have (or may soon have) commercial experience

The SMP reference case projections in Chapter 2 did not suggest that the fleet penetration rates of vehicles employing advanced diesel or hybrid-electric powertrains will reach significant levels (on a worldwide basis) by 2030 – or even by 2050. The same is true of penetrations rates of "conventional" biofuels. As indicated earlier, this is because the cost of vehicles incorporating these powertrains and the cost of the fuels almost certainly exceed the cost of today's vehicles and fuels. For higher penetration rates to be achieved, demand will need to be stimulated.

Many ways of increasing demand for "lower carbon-emitting" vehicles and fuels have been suggested. All are variations of two basic approaches:

- The value that users attach to any given reduction in fuel consumption increases. This is because fuel prices are rising (and are expected to rise even more in the future) consumers' basic preferences change in a manner that increases their willingness to pay for improved fuel economy and/or reduced GHG emissions.

- Governments create incentives making the purchase and use of these vehicles and fuels more attractive. There are two basic ways that governments can this:

  Using their powers to raise and spend public revenue, governments can use taxes, subsidies, and other fiscal measures to change the cost/benefit tradeoff facing consumers and businesses in their vehicle purchase and fuel purchase decisions. This may include altering the level and structure of fuel taxes to encourage the purchase and use of such vehicles and fuels by subsidizing the purchase of such vehicles and fuels. Or it may include imposing heavier taxes on the purchase of less fuel-efficient vehicles and fuels with higher fossil carbon content.

  Using their regulatory powers, governments can enact laws or adopt regulations requiring vehicle manufacturers to produce – and successfully market – vehicles offering reduced fuel consumption. A similar approach can be used with fuel producers. Alternatively, governments can enter into voluntary agreements with vehicle manufacturers and fuel producers having the same aim.

Several nations have experience with respect to the use and effectiveness of each of these pathways.

Increasing the inherent value that users attach to reductions in fuel consumption.

The global climate is the prototypical "public good." All are affected by changes that human activities might generate, but no single individual can gain any measurable benefit from any conceivable action that they might undertake unilaterally. Altruism aside, the only benefit that an individual can ever expect to see from purchasing a vehicle that reduces GHG emissions by reducing fuel consumption is a reduction in his or her outlay for fuel.

Factors that impact this outlay, or that are expected to impact it in the future, can change vehicle purchase behavior. The most important is the current and expected future price of transport fuel. The evidence is overwhelming that vehicle purchasers respond to higher actual and expected fuel prices by demanding vehicles that offer reduced fuel consumption. They also respond by changing their volume and modal mix of transport activity.[6]

Even if energy prices do not increase and are not expected to increase, vehicle purchasers could decide to place a higher value on expected future energy cost savings – they might increase the importance they place on "fuel economy" performance when deciding to purchase a vehicle. Or they might decide to favor fuels with lower carbon content. Today vehicle purchasers are assumed to value "fuel economy" in economic terms and to make the sort of tradeoff between it and other vehicle attributes that one would expect a "rational consumer" to make. That is, they estimate the annual energy cost savings they believe they will obtain and discount these savings back to the present. Purchasers today also place no weight on a fuel's carbon content.

But vehicle purchase decisions are not always totally "rational" and purchasers sometimes attach a heavy weight to certain vehicle attributes. Fuel purchasers can do the same thing. Under circumstances such as envisioned in the "Global Citizen" scenario, increased fuel economy, or lower carbon content for fuel, might become factors with strong appeal to the buying public.

Fiscal incentives (subsidies and/or taxes).

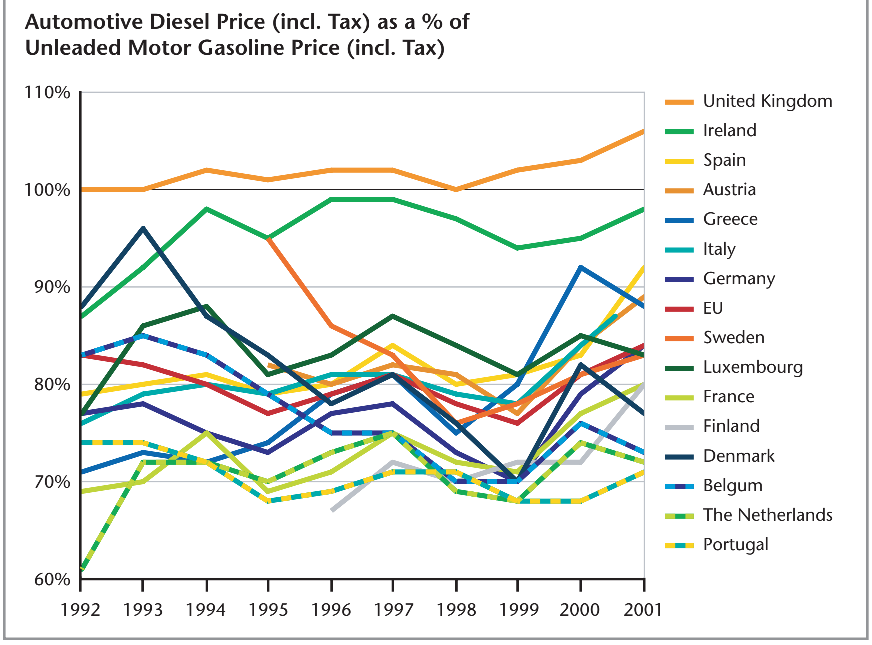
If the inherent value that vehicle purchasers place on reduced fuel consumption does not change, or if this change is too small to increase the demand for more fuel-efficient vehicles to the extent felt necessary, governments must step in to influence demand for vehicles that emit fewer GHGs.

Governments have a range of fiscal measures at their disposal. To mention only a few, they can raise taxes on transport fuel and also apply different tax rates to different fuels. They can subsidize the purchase of propulsion systems and/or fuels emitting fewer GHGs. Or they can levy different registration fees based on a vehicle's GHG emitting characteristics.

Experience has shown that fiscal measures can have a significant long-term impact on the demand for vehicles offering reduced fuel consumption. In some European countries sales of more expensive diesel-powered light-duty vehicles[7] have been supported by a variety of fiscal measures. Among them are lower fuel taxes on diesel fuel relative to gasoline.[8] (See Figure 4.5) The share of new cars in Europe that is diesel -- less than 15% in 1990 – is expected to reach 45.9% in 2004. *(Automotive News Europe, October 20, 2003)* Diesel cars already outsell gasoline cars in France, Spain, Austria, Belgium, and Luxembourg. In September 2003, Italy became the sixth European country where this is true.

Although diesel-powered light duty vehicles have always been more common

Figure 4.5 **Diesel price relative to the price of unleaded gasoline (RON 95) -Europe**



Source: **European Union Energy and Transport in Figures 2002**.

in Europe than North America or Japan, there is nothing inherently unique to Europe to explain this situation. What is different is the higher cost of transport fuel in Europe (due to higher fuel taxes) and the differential incentives that some governments have provided to encourage dieselization. Emissions limits applicable to diesels also have been more stringent in North America and Japan. A recent study by J.D. Power-LMC stresses that the local regulatory and fiscal environment will continue to be a major influence in determining diesel penetration rates across countries.[9] According to this report, global diesel light-vehicle sales could rise from 12.5 million units annually in 2003 to 27 million by 2015, with 60% of this growth occurring outside Europe.

Some governments have also encouraged the purchase of conventional biofuels and, indirectly, the purchase of vehicles capable of utilizing them. A good example is the penetration rate for ethanol-fueled vehicles achieved by Brazil during the mid-1980s.[10] In 1985, sales of new cars and light trucks capable of operating on pure ethanol accounted for 96% of Brazilian new light-vehicle sales. Brazil's cumulative subsidy for ethanol production between 1978-1988 is reported to have amounted to $1 billion. *(Nakicenovic 2001)* Although the gap between the cost of ethanol and the cost of petroleum narrowed over time, as of the mid-1990s ethanol still cost considerably more to produce than gasoline. To lower the cost to the government, gasoline was "taxed" at a level that effectively doubled its price, with the resulting revenues being used to support alcohol production.[11] Meantime the efficiency of Brazilian ethanol production continued to improve, and by 2003 Brazilian ethanol was priced about the same as gasoline on a volumetric basis and the subsidy was long gone. As ethanol subsidies were cut, and as government policy shifted from promoting alcohol fuels to promoting the sale of inexpensive vehicles (known as "popular cars"), sales of vehicles capable of operating on pure ethanol fell almost to zero.[12] By 2000, all Brazilian motor fuel had to contain 22% ethanol. Light-duty vehicles can use this 22% ethanol blend without special engines. "Flex fuel" vehicles (vehicles capable of utilizing up to an 85% ethanol blend) will soon be introduced in Brazil.

Regulations, legislation, and/or voluntary agreements.

Governments, however, may consider it too expensive to use fiscal measures to boost the demand for propulsion systems and/or low GHG fuels, particularly if such measures have to be retained for many years. Instead they may employ a different set of powers – their powers to regulate – to minimize budgetary outlays to boost the demand for low-carbon vehicles and fuels. The United States Federal government, the European Union, and the Japanese government have each used such powers to encourage (or, in some cases, to require) motor vehicle manufacturers to develop and market light-duty vehicles offering fuel consumption lower than the unaided market will support. Now China is reported to be considering similar actions. *(The New York Times, November 18, 2003.)*

It is important to understand that regulations, legislation and voluntary agreements do not by themselves increase purchasers' willingness to pay higher prices for low carbon-fuels or for vehicles offering reduced fuel consumption. Rather, it is the economic incentives and/or penalties that accompany these regulations, legislation and voluntary agreements that actually cause the changes in vehicle and fuel-buying behavior. Unlike the subsidies provided directly by governments and the taxes levied directly by the governments, these incentives and/or penalties are felt in the first instance by vehicle and fuel manufacturers before being passed on to customers.

Sometimes these incentives or penalties are overt. At other times they are subtler. The US Corporate Average Fuel Economy (CAFE) regulations provide perhaps the best example of an overt set of incentives and penalties. Vehicle manufacturers that fail to meet the fuel-economy goals established under the US CAFE program must pay a penalty on each vehicle sold equal to US$5.50 for each 0.1 mpg that they fall below the standard.[13] Manufacturers facing a possible shortfall may pay this fine, add technologies, alter features of the vehicle regardless of customer requirements or "cross subsidize" their more fuel-efficient vehicles by lowering the prices they charge for these vehicles while raising the prices they charge for less fuel-efficient vehicles. In any event the customer pays higher prices or settles for fewer features.[14]

The higher cost gets passed on to vehicle purchasers in the form of overall higher vehicle prices. This reduces vehicle demand and drives down the manufacturer's profits. But because vehicle manufacturers cannot print money or borrow it in unlimited amounts at favorable interest rates, their capacity to absorb losses due to the demand impact resulting from the cross subsidization of vehicles is not nearly as great as that possessed by governments. Ultimately, a regulatory approach designed to encourage fuel-efficient vehicle fleets has less impact than that produced by the direct subsidy/tax approach.

Table 4.3 **European WTW analysis "5% Passenger car Transport Distance Substitution" Scenario for various alternative fuels and powertrains**

Fuel	Powertrain	GHG Savings			Additional Cost	
		Mt CO_2 equiv	Change from Reference Case	Cost per tonne CO_2 Equiv Avoided per annum (Euros)	Per vehicle using alternative fuel and/or powertrain (Euros per annum)	Per 100 km per vehicle using alt fuel or pt (Euros per annum)
Conventional	Hybrids	6	-16%	364	141.8	0.89
CNG	PISI	5	-14%	460	156.0	0.98
	Hybrid	12	-32%	256	219.9	1.38
Syn diesel fuels						
FT-diesel ex NG	CIDI+DPF	-5	14%	n.m.*	49.6	0.31
DME ex NG	CIDI	1	-3%	2,039	156.0	0.98
Ethanol	PISI					
Sugar beet						
Pulp to fodder		14	-38%	418	425.5	2.67
Pulp to EtOH		12	-32%	563	461.0	2.89
Pulp to heat		24	-65%	254	432.6	2.71
Ex wheat		5	-14%	1,812	581.6	3.64
FAME	CIDI+DPF					
RME						
Glycerine as chemical		16	-43%	278	326.2	2.04
Glycerine as heat		14	-38%	345	354.6	2.22
SME						
Glycerine as chemical		22	-59%	217	340.4	2.13
Glycerine as heat		20	-54%	260	368.8	2.31

*n.m. = not meaningful

Source: **EUWTW 2004, p.22**, with additional calculations by the Sustainable Mobility Project.

The potential impact of these" levers."

The examples above suggest that changes in fuel prices, taxes, subsidies, regulations, "voluntary agreements," and legislation, as well as changes in consumer tastes – can shift vehicle technology purchase and use patterns in ways that reduce GHG emissions from levels that they otherwise would reach. Whether these "levers" are strong enough to "bend" the curve of transport-related GHG emissions significantly depends on (1) the magnitude of any cost penalties that must be overcome and (2) the willingness of governments to commit the necessary resources (taxes and subsidies) over the long term.

To obtain a sense of the possible magnitude of the cost penalties associated with different powertrain/fuel combinations and the GHG reduction potential of each, it is necessary to reexamine the results of the European WTW Analysis first discussed in Chapter 3.

Table 4.3 uses data from Table 3.3 and includes additional calculations made by the SMP. Table 4.3 includes only those fuel and powertrain combinations about which we have (or will soon have) some commercial experience. This means that all powertrain/fuel combinations using hydrogen, advanced biofuels, and/or fuel cells are omitted. (They are discussed separately below.)

Except for CNG, the fuels included in Table 4.3 are liquid fuels that can be distributed through existing fuel-distribution systems with little or no modification. The vehicles are powered by gasoline or diesel engines or are ICE hybrids. For the powertrain/fuel combinations included, Columns (1), (2), (3), and (5) contain data that is identical to the corresponding power-train/fuel combinations in Table 3.3. Column (4) has been added to show the percentage change in GHG emissions from the EUWTW reference vehicle. Columns (6) and (7) show the additional cost per annum calculated on a per-vehicle and per-100 km basis.

For those powertrain/fuel combinations that reduce GHG emissions, reductions range from3% to 65%. They do so at a cost per year per tonne of GHG emissions avoided of between €217-2000. The increase in cost per year per vehicle replaced is between €142-582. Looked at another way, each 100 km traveled using a vehicle equipped with a powertrain/fuel combination shown in Table 4.3 costs between €0.89-3.65 more than traveling the same distance using the reference vehicle and fuel.[15] Such figures give a sense of the magnitude of incentive required to induce the purchase and use of these vehicles in Europe.

The results shown in Table 4.3 should be viewed as "order of magnitude" estimates. The additional vehicle costs are based on simple powertrain substitutions. The additional fuel cost estimates reflect both the additional cost (if any) of manufacturing the fuel plus, where appropriate, extra costs involved in distributing fuel to the customer.[16] Moreover, the calculations reflect European experience only.

b) Advanced vehicle propulsion technologies such as fuel cells, "carbon neutral" hydrogen, and "advanced" biofuels

To change the basic trajectory of transport-related GHG emissions worldwide, it is clear from simulations undertaken by SMP and others that the world eventually will have to move beyond current technologies to advanced vehicle-propulsion technologies such as fuel cells and to advanced fuels such as "carbon neutral" hydrogen and "advanced" biofuels.

Although the European WTW analysis referred to in Chapter 3 included estimates of the cost of introducing limited numbers of fuel cell vehicles powered by hydrogen derived from various sources and the use of limited quantities of advanced biofuels in vehicles using various powertrains, both the cost estimates and the time scale over which such technologies and fuels might be introduced were highly speculative.

The SMP assessment is that the most accurate judgment that can be made at present about these advanced vehicles and fuels is that their current costs are much too high for them to compete in the marketplace with today's vehicles and fuels. At these cost levels, the incentives required to bring about their introduction in significant numbers almost certainly is beyond governments' ability to sustain financially. So the most important challenge over the next decade or so will be to determine whether the high costs of these vehicles and fuels can be reduced to the point where it is meaningful to consider them as serious candidates for adoption on a worldwide basis.

In this report we will limit ourselves to sketching possible pathways for the introduction of each of these technologies.

(1) Possible pathway for the introduction of fuel cells for road vehicles

Fuel-cell vehicles are now being introduced in very limited numbers in a few markets as technology demonstrators. Current costs for test and prototype fuel cell vehicles are high, often by a factor of 50 compared with current ICE vehicles, and important technical questions concerning fuel-cell reliability and durability, as well as on- vehicle fuel storage, remain to be resolved.

As the technical and cost challenges are overcome, the number of such vehicles in operation should increase. But the first commercial introduction might well be in certain types of vehicles that can be refueled from central locations such as depots, so reducing the need for extensive new fuels networks. These commercial vehicles might also be less constrained by the space requirements of current (early) fuel-cell systems and compressed hydrogen gas storage. If costs can be further reduced, public acceptance verified, and reliability and durability demonstrated, larger scale fleet applications – for example in city buses or selected urban delivery fleets – might develop the market further. Compressed hydrogen is the most probable major fuel for such field trials and for buses and other fleet uses after 2010.

Under this scenario, the initial market launch of fuel-cell passenger cars likely would occur no earlier than about 2015, with significant high volume production not occurring until about 2020.

(2) Possible pathways for the introduction of hydrogen as a transport fuel

Fuel-cell vehicles will require hydrogen. Through about 2020, most of the hydrogen produced would probably be derived from natural gas reforming or conventional grid electricity with their associated emissions of CO_2.[17] As demand grows for hydrogen, it could be made increasingly from natural gas in large-scale steam reformers, with capture and storage of CO_2. Such a scheme would create both an economically viable and carbon-neutral pathway for hydrogen supply – that is, one that does not result in CO_2 emissions to atmosphere at any stage – and a bridge to a future renewable based hydrogen.

The significant cost, technical, and political/social/environmental challenges of carbon sequestration would have to be addressed hand-in-hand with this process. Carbon capture technologies could be adopted for coal gasification routes to hydrogen generation. This might be an attractive option for countries with large coal reserves or where the availability of natural gas is limited.

In contrast to the transport sector, natural gas rather than hydrogen is seen as the fuel of choice for fuel cells in electricity generation and combined heat and power applications although there may be a role for hydrogen in stationary applications like distributed generation systems. One issue is the limited supply of natural gas. Its extensive use as a feedstock for hydrogen production is likely to strain supply and lead to concerns about availability and energy security paralleling those of oil, especially as natural gas is now being used increasingly as a substitute for coal and nuclear energy in power generation.

The phase-in of centralized hydrogen production could be facilitated to a limited degree by the introduction of some hydrogen into the natural gas pipeline system with subsequent membrane extraction of the hydrogen. (This process has yet to be proven technically.) It is likely that specific high-pressure, hydrogen main pipeline systems would be needed, with final distribution in cryogenic liquid form. In more remote or less populated areas, electrolysis or liquid hydrocarbon reforming could also find applications.

Beyond 2030, biomass gasification and water electrolysis are likely to be key technologies, assuming that sufficient supplies of electricity can be provided affordably to make electrolysis practicable and competitive. Water electrolysis is particularly suited to on-site production at refueling stations, home fuelling or as part of an energy storage system to control the fluctuation in production and demand in a renewable based energy system. Other carbon-neutral sources of hydrogen (coal gasification with carbon-sequestration, and nuclear) might contribute in regions with these energy sources.

In the long term a hydrogen pipeline system developed in the previous period could operate as both an energy-storage and fuel-supply system. Other more futuristic alternatives such as direct hydrogen from renewable sources – for example, biological production or advanced photovoltaic technology – are forecast to make some contribution to innovative hydrogen solutions.

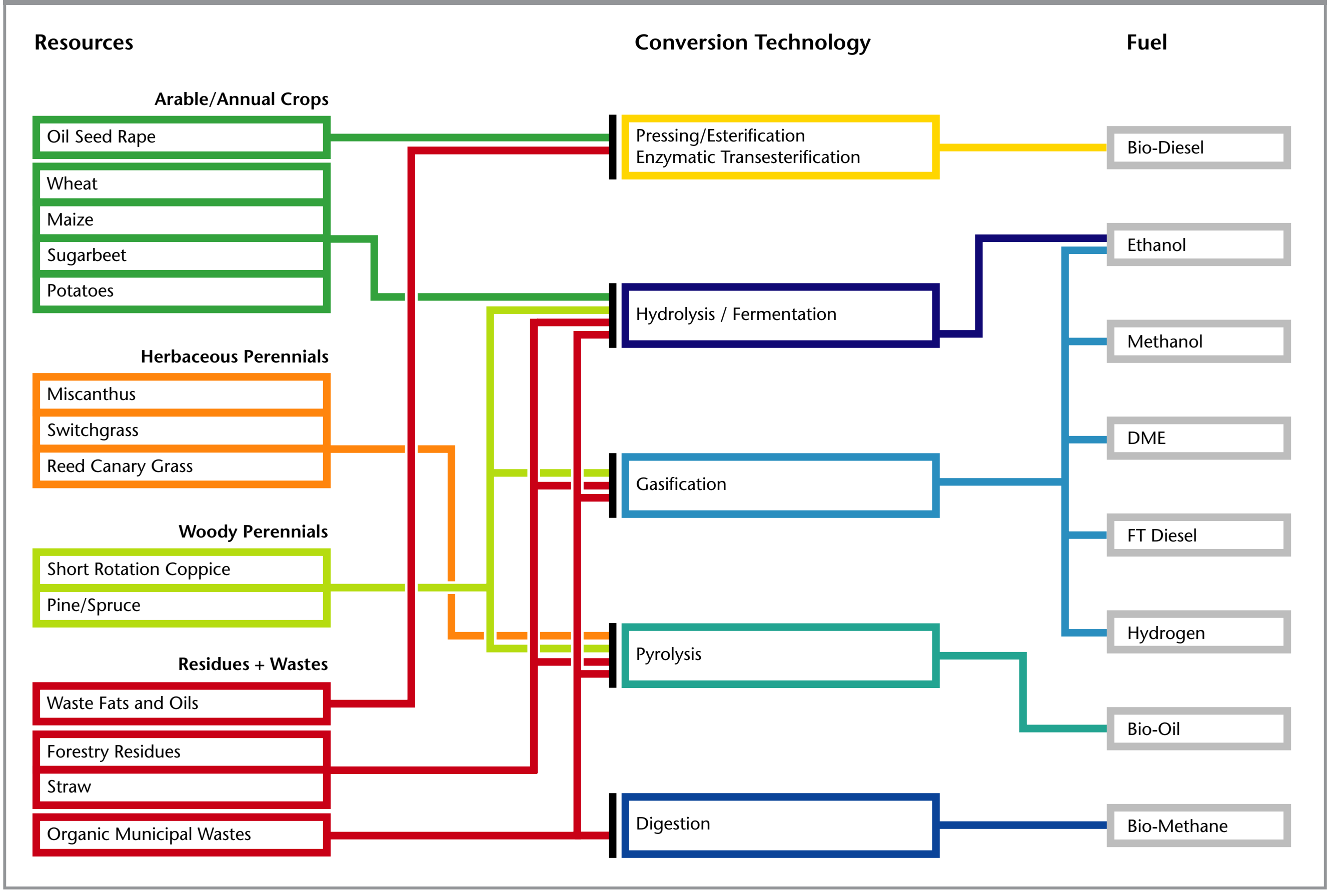
(3) Possible pathways for the introduction of advanced biofuels

The starting point for any description of possible pathways for the introduction of advanced biofuels is recognition that "conventional" biofuels are already in use in a few countries (notably Brazil and the US) and that certain regions (most notably, the EU) have announced their intention to increase significantly the use of these fuels. Figure 4.6 is intended to illustrate "conventional" and "advanced" biofuel resource materials, conversion technologies, and fuels.

At present bio-diesel and ethanol are produced from arable/annual crops (such as those listed in the top section of the "resources" column of Figure 4.6) and in very limited amounts from waste fats and oils (the first item in the "residues & wastes" section of the same column.)[18] The conversion technologies being used to process these resources are pressing/esterification and hydrolysis/ fermentation.

Transitioning from "conventional" to "advanced" biofuels requires expanding the range of feedstocks to include herbaceous perennials, woody perennials, and residues and wastes. In addition it will be necessary to expand conversion technologies to include both advanced versions of currently used technologies

Figure 4.6 **Possible advanced biofuel pathways**



Source: Adapted from **E4tech 2003**

(e.g., enzymatic transesterification) and three new technologies – pyrolysis, gasification, and digestion. Raising, collecting and processing these other sources of biomass in the quantities needed requires solving formidable logistical and processing challenges, some of which are identical to those necessary to produce "carbon neutral" hydrogen. As emphasized in Chapter 3, the new conversion technologies for utilizing these resources have yet to be proved at commercial scale.

Another difference between the two principal sets of pathways is the amount of fuel that must be produced and distributed to enable vehicles to provide the transport services that society historically requires. It is in this area that fuel cells offer significant advantages. They are extremely efficient energy conversion devices. A current gasoline vehicle with automatic transmission can have a WTW efficiency of less than 15 percent. A fuel-cell vehicle can have a WTW efficiency that is double and, eventually perhaps, nearly triple this level. *(Muta, Yamazaki, and Tokieda, 2004)* This means that the fuel-cell vehicle requires less fuel to be produced in order to provide the same transportation services.

(4) What governments can do today to advance these technologies

While it is premature to detail the "levers" that might be required to enable widespread commercial introduction of the advanced vehicle technologies and fuels just described, there are some things that governments can usefully do now to help advance these technologies to the point where such discussions become relevant.

Support basic and pre-competitive applied research. "Basic research" is research for which there is not yet a clear commercial application. Although private companies do undertake (and fund) basic research, in general the incentives are insufficient to conduct (or fund) adequate levels of basic research from the viewpoint of society as a whole. Various governments do provide tax deductions for research and development. They have also supported the formation of research consortia to work on such problems and provided partial (or, in some cases, complete) funding for the work of these consortia.

"Pre-competitive applied research" is research for which a commercial application has been identified, but the ability of an individual company to capture enough of the benefits in a saleable product to make the research profitable has not.

Support prototyping and limited volume production activities. The next stages of development of a commercial technology are prototyping and limited-volume production – in this case of both vehicles and fuels. The first of these stages is designed to show that the technology can be made to work in a practical application. The second is designed to help determine just what the cost of commercial-scale production of a product utilizing the technology might be.

When technologies reach these stages, the rationale for direct government funding of them declines. Government can still play an important role, but political pressures make it increasingly difficult to carry out this role and there begins to be a danger that official involvement retards rather than advances the goal of determining whether the technology is commercially viable. One useful role that government can play at these stages is to declare its readiness to purchase a limited (but significant) number of vehicles embodying low- or zero-carbon propulsion technologies and fueled with the low- or zero-carbon fuels. The price at which these vehicles are purchased needs to be sufficient to render their production profitable (or nearly so) but higher than the price at which the product would expect to be sold when (if) full-scale production began.

Will this be enough? The magnitude of the changes required to transform today's transport systems is daunting. Systems built up over a century or more will have to be reshaped fundamentally. One mandatory and unique aspect to any transition to fuel cell vehicles and a hydrogen infrastructure is the requirement that it occur simultaneously. Both the new hydrogen production systems and the devices to convert that hydrogen into transport services must be developed in parallel. Neither serves any purpose without the other.

All this creates special requirements for, and special challenges to, the role that governments will be expected to play to enable such transitions to occur. A recent report by the US National Research Council focused on the implications of a hydrogen transition merely for the US. It summarized the challenges as follows:

> *"In no prior case has the [US] government attempted to promote the replacement of an entire, mature, networked energy infrastructure before market forces did the job. The magnitude of change required if a meaningful fraction of the US energy system is to shift to hydrogen exceeds by a wide margin that of the previous transitions in which the government have intervened. This raises the question of whether research, development, and demonstration programs will be sufficient or whether additional policy measures might be required."* (NRC 2004, p. 2.4)

Governments of other developed countries have a different history of promoting the adoption of technologies. They also have different powers that they can use. So what applies to the US will not necessarily apply to them. But facilitating a successful transition to the advanced powertrains and fuels outlined here is going to be a challenge to any government, regardless of its powers and experience. To eliminate transport as a significant source of GHG emissions, it will be necessary to carry out the sort of transition described earlier not merely in a single developed or developing country but throughout the entire world.

C. Reduce GHG emissions by influencing the volume of personal and goods transport activity and/or the mix of transport modes used to move people and goods

Until now the focus of this chapter has been on the role that might be played by advanced vehicles and fuels – factor 1 and factor 2. But in the SMP reference case, it is the growth in the volume and mix of transport activity – factor 3 and factor 4 – that is primarily responsible for the large projected increases in transport-related GHG emissions over the coming decades.[19] In view of this, and in view of the cost and time required to implement approaches based upon new vehicle and fuels technologies, it is not surprising that some have suggested trying to slow (or even reverse) this growth in transport activity.

a) Political and social considerations

It is the SMP view that there is a role to be played by "demand channeling" measures in reducing transport-related GHG emissions. Such measures also have the potential to mitigate congestion, reduce noise, and enhance safety. But determining just what their role in GHG reduction could be, designing effective and efficient policies and gaining political acceptance for them would be complex indeed. Individuals' decisions regarding where they live and work, how they allocate their time, and how they spend their money are extremely sensitive. Yet these are the very factors that would need to be changed in significant ways by demand channeling if these measures are to yield significant GHG emissions reductions.

b) Economic considerations

Demand channeling of the scale necessary would also be expensive. The out-of-pocket costs they would impose on transport users could be quite large. But the cost they might impose on society as a whole could be much greater. As emphasized in Chapter 1, transport activity is an important enabler of economic growth. Restraining the growth of transport poses a direct threat to the sector's ability to fulfill this vital role.

c) Speed of impact

Demand channeling of the scale necessary to produce major reductions in GHG emissions would not, however, produce "quick" results. While each individual makes decisions relating to transport use every day, most of these decisions are constrained by decisions that have been taken decades or even centuries ago. Some of these decisions can be altered relatively quickly – in a matter of days or months. But many require a much longer period to take effect if unacceptable disruption is to be avoided.

Over short periods of one or two years, most of the technological and physical characteristics of transport systems, most of the demand-related location and transport use characteristics and many of the behavioral response patterns of transport users are largely fixed. As a result, many demand channeling measures at best can have only a very limited impact on personal travel choices and goods transport arrangements over such periods. Most studies of the impact of changes in the price of transport fuel, the imposition of road tolls or altering the relative price of shipping freight by road versus rail, for example, have found that the impact of these measures on total transport activity or on the modal mix of transport activity over periods of one or two years is likely to be relatively small.[20] Studies of the responsiveness of personal transportation demand generally find that a 1% increase in the cost of transport reduces transport demand by about one-tenth of one percent. *(VTPI 2003)* This is a significant response. But it is not large enough to produce a major change in the trajectory of transport activity, especially when other factors (like income growth) are working to keep transport activity growing.

Over periods of a few years to a decade, somewhat larger changes in transport demand patterns become feasible. People can change their job location or where they live. Manufacturers or employers can change the location of their places of business. The same survey mentioned above found that a 1% increase in the price of travel reduces travel activity by about three-tenths of one percent over periods of a few years to a decade.

It is only over periods of several decades that major shifts in personal and/or goods transport demand patterns occur. In this timescale urban areas can change their configuration, new manufacturing and merchandising patterns can emerge and new ways of moving people and goods can be developed and implemented. Quantitative estimates of the impact of individual demand channeling measures over time are not very useful – too much is changing at one time to permit individual influences to be isolated statistically. But these extended time scales are the ones that matter.

It was only in the 1960s that Europe and Japan began to achieve mass-motorization. The US interstate highway system was begun in the 1950s. With the exception of Germany, Europe's motorways developed in the 1970s. The first enclosed shopping mall appeared in the US in the mid 1950s. The Japanese "bullet train" began operating in 1964 and the French TGV in 1981. Air transport did not become a significant mode of mass long-distance travel until the 1970s. International container shipping has been a significant freight transport mode only during the past 30 years. Overnight package delivery service over distances of several thousand miles is no more than a couple of decades old.

Each of these transport innovations was responsible for major changes in the volume and/or pattern of transport activity. Each took several decades for its full impact to be felt. There are many demand-led measures that, in theory, can impact the total volume of transport activity, the modal mix of transport activity or both. But the impact of these measures over the short to medium term when aggregated at a national and/or regional level appears relatively small – meaning that their potential as a tool for directly reducing transport-related GHG emissions is likely to be quite limited.

D. Insights from the SMP spreadsheet model concerning the potential impact of various approaches for reducing transport-related GHGs

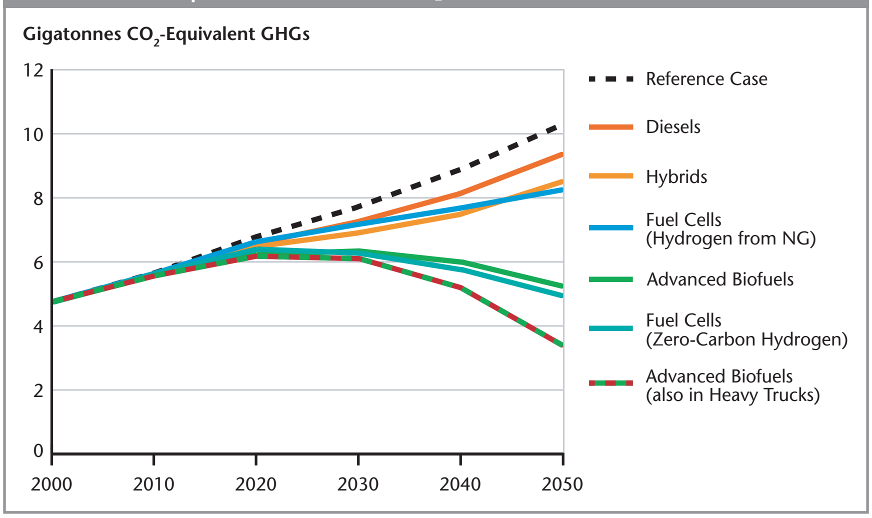
To obtain a better sense of the potential impact of various technologies and fuels in reducing transport-related GHG emissions, the SMP conducted a number of simulations using its spreadsheet model. The benchmark was the SMP reference case projection showing total transport-related CO_2 emissions doubling between 2000-2050 with most of the growth in emissions occurring in the countries of the developing world. While other analyses have examined this issue for individual developed countries or regions, to the best of our knowledge the Sustainable Mobility Project is the first to examine it for the world as a whole.

In these simulations the focus – consistent with the principal locus of our companies' expertise – was total road transport – light-duty personal vehicles, powered two- and three-wheelers, transit and intercity buses and both medium and heavy-duty trucks. Together, these categories account for about three-quarters of transport-related CO_2 emissions today.[21]

Our exercise did not examine the technical or economic feasibility of any of the actions being simulated. It was intended merely to help us understand the impact on GHG emissions from road vehicles if the actions described were taken. As will be seen below, this enabled us to compare our results with the results of other studies that likewise have not considered technical or economic feasibility in deriving their results.

We began by examining the impact of single technologies on worldwide road transport CO_2 emissions. Figure 4.7 shows results for five such technologies – dieselization, hybridization, fuel cells, "carbon neutral" hydrogen, and biofuels. It was assumed that each powertrain technology achieves as close to 100% global sales penetration as possible given the characteristics of the technology and that each fuel becomes as close to

Figure 4.7 **Hypothetical potential of individual technologies to lower road transport Well-To-Wheels CO_2 emissions relative to the reference case**



Note: Cases represent high hypothetical levels of technology penetrations, thus they cannot be added together.

Source: Sustainable Mobility project calculations.

100% of the global road transport fuel pool as its characteristics permit.

It must be emphasized that these single technology examples are purely hypothetical. It is highly unlikely in practice any single technology would achieve 100% penetration. Also, they cannot be added together. Differences in timing between the implementation of these technologies and fuels in the developed and developing worlds was largely ignored.

For both diesels and advanced hybrids, it was assumed that 100% sales penetration would be reached by 2030 and that these would be cover light-duty vehicles and medium-duty trucks.[22] In the case of fuel-cell vehicles, it was assumed that 100% sales penetration would be reached by 2050.[23] It was also assumed that the hydrogen used in these vehicles would be produced by reforming natural gas and that carbon sequestration would not be involved. The estimate of the impact of carbon neutral hydrogen was generated by changing the WTT emissions characteristics of the hydrogen used in the fuel cell case just described. To focus on the impact of biofuels, it was assumed that these fuels would be used in a world road vehicle fleet similar in energy use characteristics to the SMP reference fleet. Diesel ICE technology (using conventional diesel fuel) was assumed to have an 18% fuel consumption benefit versus the prevailing gasoline ICE technology during the entire period. The fuel consumption benefit relative to gasoline ICE technology was assumed to be 36% for diesel hybrids, 30% for gasoline hybrids, and 45% for fuel-cell vehicles.

From this single technology assessment it is evident that even if implemented worldwide, diesels and hybrid ICEs fueled with conventional gasoline and diesel fuel, or fuel cells fueled by with natural gas-derived hydrogen, can no more than slow the growth in road transport CO_2 emissions during the period 2000-2050. Only the use of carbon-neutral hydrogen in fuel cells and advanced biofuels in ICE-powered vehicles can largely or totally offset the growth in CO_2 emissions produced by the growth in road travel during the period 2000-2050.

This does not mean that vehicle energy use characteristics are irrelevant. They may not have a major impact on the trajectory of road vehicle GHG emissions over the very long term, but they will have a major impact on the amount of low-carbon or carbon-neutral fuel that must be produced to power the world's road vehicle fleet. This means that they can have a very important impact on the cost of significantly reducing GHG emissions from road vehicles.[24]

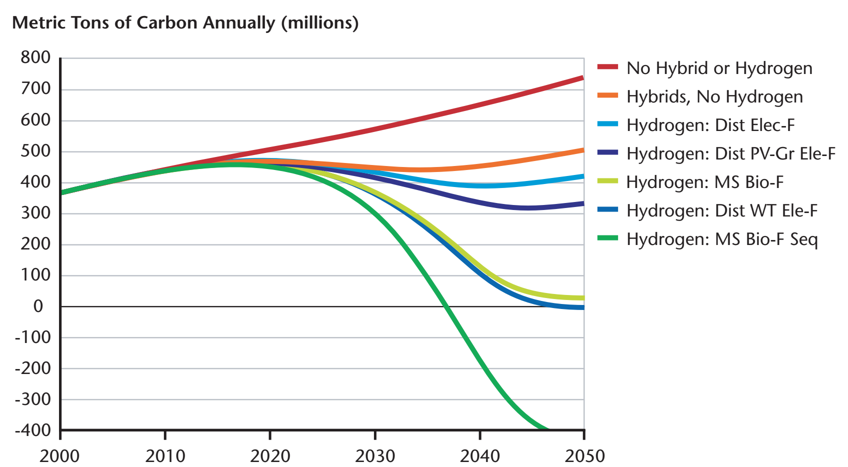
Based upon these results, the SMP conclusion is that it will only be through a combination of fuel and powertrain solutions that significant CO_2 reduction will be attained. No single technology pathway stands out enough to compel its selection as the sole long-run solution.

1. HOW THE SMP SIMULATION RESULTS COMPARES WITH SIMULATION RESULTS OBTAINED BY OTHER STUDIES

These results are not unique. Other recent studies have reached similar results after examining their specific geographic area and scope of interest. One example is the NRC study of the challenges posed for the US by a significant transition to hydrogen quoted above. This initiative was charged with exploring the entire range of potential hydrogen uses. But since a major use is in powering light-duty road vehicles, it projected the impact on CO_2 emissions for these vehicles to 2050. Figure 4.8 shows the emissions estimates. Figure 4.9 shows the sales share by vehicle technology and total fleet penetration associated with the emissions estimates in Figure 4.8.

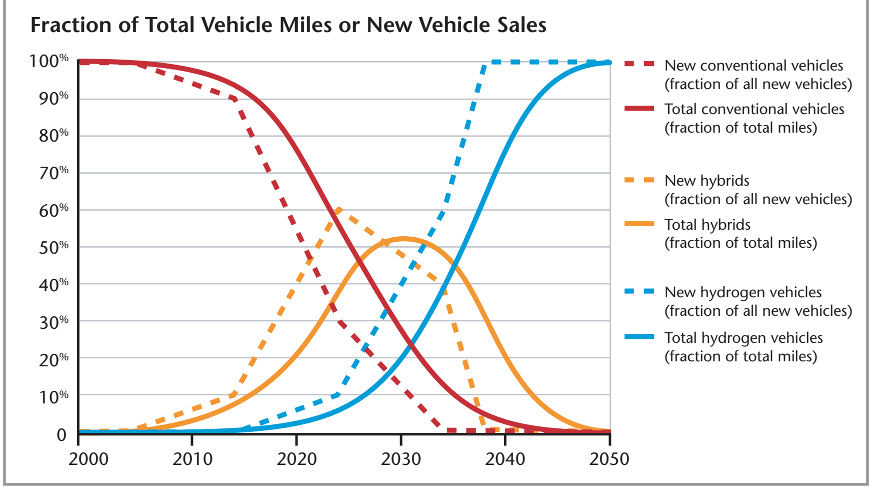
Figure 4.8 is fairly similar to the SMP's Figure 4.7. Figure 4.9 shows how rapidly the number of fuel-cell vehicles and the production of carbon-neutral hydrogen to fuel them would have to ramp up in order to permit US light-duty vehicle

Figure 4.8 **Estimated volume of carbon releases from passenger cars and light-duty trucks; possible future hydrogen production technologies (electrolysis and renewables), 2000-2050, based upon "optimistic " vision created by the NRC Committee on Alternatives and Strategies for Future Hydrogen Production and Use**



Source: **NRC 2004, Figure 6.10**

Figure 4.9 **Postulated fraction of conventional vehicles, hybrid, and hydrogen, 2000-2050, US LDV fleet, based upon "optimistic" vision created by the NRC Committee on Alternatives and Strategies for Future Hydrogen Production and Use**



Source: **NRC 2004, Figure 6.1**

CO_2 emissions to decline as illustrated by the bottom line of Figure 4.8. The NRC committee characterizes these rates of vehicle and fuels introduction and rates of growth in vehicle sales as "optimistic." Yet they are not nearly as optimistic as the ones incorporated into the SMP single technology analysis, which requires within the same time period (prior to 2050) that a ramp-up occurs worldwide and that it includes road vehicles in addition to light-duty passenger vehicles.

The NRC assumptions used in Figures 4.8 and 4.9 are worth noting:

> *"In this analysis, it is assumed that ... low-cost and durable fuel cells are available; high density of energy storage on vehicles allows reasonable range and quick refilling of the vehicles; vehicles have the same functionality, reliability, and cost associated with their gasoline- fueled competitors; hydrogen-fueled vehicles are as safe as gasoline-fueled vehicles."* *(NRC 2004, p. 6.1)* [25]

In short, the NRC study assumed that all the technological and cost challenges associated with fuel cells are overcome. This was appropriate given its mandate. (NRC 2004. pp 1.1-1.5) But in the real world these challenges will only yield to determined effort.

A second recent study was prepared by the British consulting firm E4tech (UK) Ltd. for the UK Department for Transport. This study focused on the technical potential of liquid biofuels and hydrogen from renewable resources to supply the fuel requirements of all UK road transport by 2050. It analyzed a number of possible vehicle and fuel pathways and rates of penetration. Like the NRC study, it assumed away vehicle-related technology and cost issues: "For this study it has necessarily been assumed that fuel-cell vehicles are cost competitive with conventional vehicles." *(Hark, Bauen, Chase, and Howes 2003)*

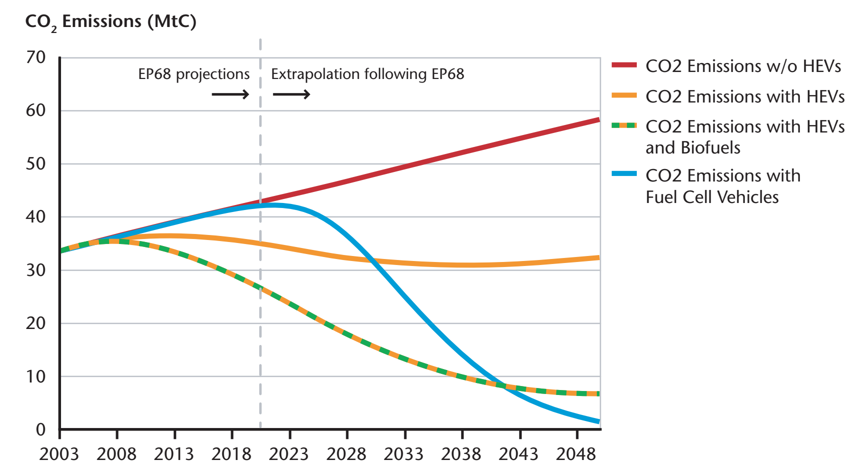
Figure 4.10 shows the projected CO_2 emissions for the total UK road vehicle fleet over the period 2003-2050 under various assumptions. The study's major conclusion was that *"if transport emissions of greenhouse gases are to be reduced significantly, it appears that improved conventional technologies will be an important part of the development, but that fuel switching will be essential."*

(Hark, Bauen, Chase, and Howes 2003, p. 12.)

2. COMBINED TECHNOLOGIES

Since the substantial reduction of CO_2 emissions from road vehicles is likely to require the widespread adoption of several advanced fuel and vehicle technologies, as well as other factors, the SMP decided to examine the combined impact of several actions including:

Figure 4.10 **A possible reduction in CO_2 emissions through rapid introduction of Hybrid Electric Vehicles (HEVs) using conventional fuels, or vehicles using renewable fuels, into transport**



Source: **E4tech 2003, p.12.**

- Fuels that are carbon neutral (which we defined as ones that reduce WTW CO_2 emissions by at least 80%)

- Powertrains that are highly energy efficient

- A change in the historical mix-shifting trend to larger vehicle categories

- Improved traffic flow and other changes in transport activity resulting from better integration of transport systems enabled, at least in part, by information technology (IT).

An illustrative target of reducing annual worldwide CO_2 emissions from road transport by half by 2050 was set. This is equivalent to a fall in yearly CO_2 emissions reductions of about 5 gigatonnes from levels that our reference case projects they otherwise would reach, and, by coincidence, returns annual road vehicle CO_2 emissions in 2050 to about their current levels.

For illustrative purposes, the illustrative CO_2 reduction target is divided into seven "increments." The timing and size of each increment is not fixed and ultimately would be decided subject to sustainability and investment choices at national, regional and global levels. The purpose of the analysis is to illustrate what might be achieved if ambitious changes were made beyond those in the SMP reference case, without any judgment as to the cost or probability of each step being taken:

Increment 1. ***Dieselisation.***
We assume that dieselisation of light-duty vehicles and medium-duty trucks rises to around 45% globally by 2030 (that is, to about current European levels). Diesel engines are assumed to consume about 18% less fuel (and emit 18% less CO_2) than current gasoline ICEs.

Increment 2. ***Hybridisation.***
We assume that the hybridisation (gasoline and diesel) of light-duty vehicles and medium-duty trucks increases to half of all ICE vehicles sold by 2030. Gasoline hybrids are assumed to consume an average of 30% less fuel than current gasoline ICEs, and diesel hybrids are assumed to consume an average of 24% less fuel than current diesels.[26]

Increment 3. ***Conventional and advanced biofuels.***
We assume that the quantity of biofuels in the total worldwide gasoline and diesel pool rises steadily, reaching one-third by 2050. Conventional biofuels (biofuels yielding a 20% CO_2 unit efficiency benefit) are capped at 5% of the total pool. The balance is assumed to be advanced biofuels (those yielding at least an 80% CO_2 unit efficiency benefit).[27]

Increment 4. ***Fuel cells using hydrogen derived from fossil fuels (no carbon sequestration).***
We assume that mass market sales of light-duty vehicles and medium-duty trucks start in 2020 and rise to half of all vehicle sales by 2050. We assume that fuel cell-equipped vehicles consume an average of 45% less energy than current gasoline ICEs.

Increment 5. ***Carbon neutral hydrogen used in fuel cells.***
We assume that hydrogen sourcing for fuel cells switches to centralised production of carbon-neutral hydrogen over the period 2030-2050 once hydrogen LDV fleets reach significant penetration at a country level. By 2050, 80% of hydrogen is produced by carbon-neutral processes.

The first five increments reflect the inherent properties of different vehicle technologies and fuels. But actual CO_2 emissions reductions will be determined not only by these properties but by the mix of vehicles that consumers and businesses buy and by how these vehicles are used on a daily basis. To reflect these two factors, two more increments were included:

Increment 6. ***Additional fleet-level vehicle energy efficiency improvement.***
The SMP reference case projects an average improvement in the energy efficiency of the on-road light-duty vehicle fleet of about 0.4% per year, with new vehicle sales showing an average of 0.5% per year fuel economy improvement. The improvement potential embodied in actual vehicles is around 1.0% per year, but about half of this potential improvement is offset because of vehicle purchasers' preferences for larger and heavy vehicles. In developing this increment, we assume that preferences relating to the mix of vehicles chosen by purchasers and the performance of these vehicles change somewhat, leading to an additional 10% average annual in-use improvement relative to our reference case. (I.e., average annual fleet-level improvement rises from about 0.4% to about 0.6%.

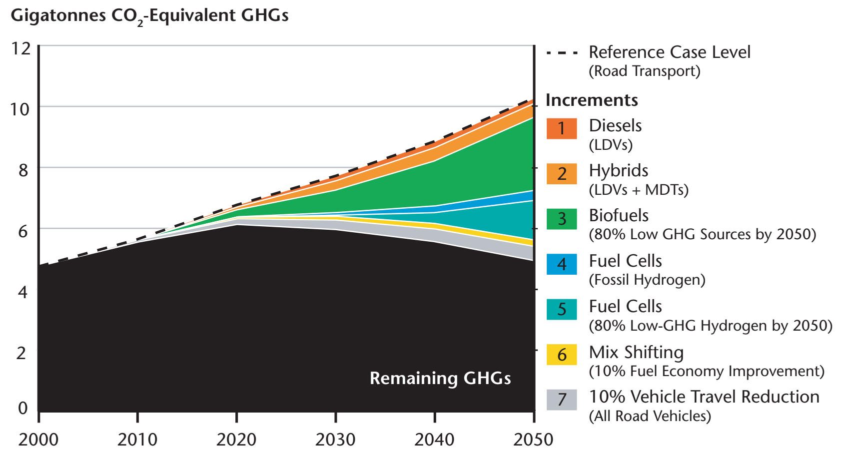
Increment 7. ***A 10% reduction in emissions due to better traffic flow and other efficiency in road vehicle use.***
We assume that the gap between on-road energy-use performance and the technological improvements embodied in vehicles narrows. How might this happen? For one thing, there are a number of opportunities relating to the increased use of IT in transport systems that might enable the better management of travel demand. Improved routing information might permit trips to be shortened. Improved information about road conditions might reduce the amount of time that motorists spend in their vehicles while

idling in traffic. For another, more accurate and current information about when public transport vehicles will arrive and how long they will take to get to their destinations might encourage additional public transport use. Individually, none of these improvements would be major. And almost certainly there would be offsets. But combined, we assume that such factors could produce an additional 10% reduction in road vehicle CO_2 emissions.

Figure 4.11 shows the results of the SMP "combined technologies" analysis just described. It confirms the impression conveyed by the three single technology analyses discussed above that it would required the widespread adoption of a combination of fuel and vehicle technologies (plus other factors) to return 2050 CO_2 emissions from road vehicles to their 2000 level.

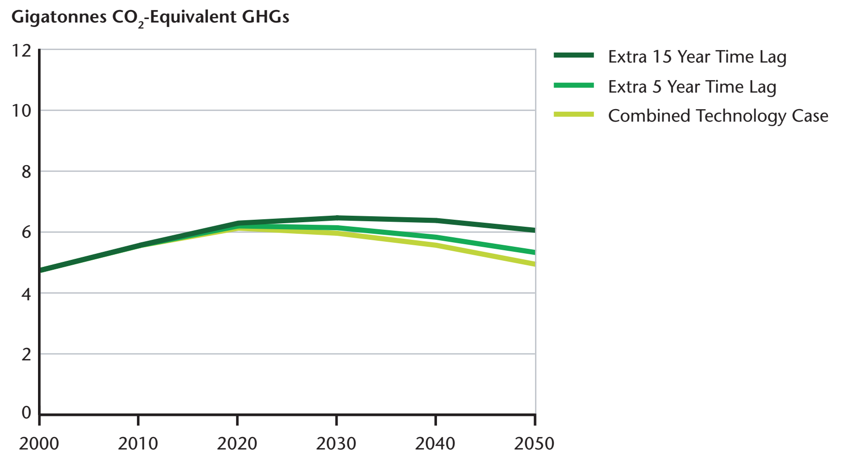
Both our single technology analyses and the combined technologies analysis assume that adoption rates for vehicle and fuel technologies would be about the same in both the developed and developing worlds. But as we saw with regard to the goal of reducing transport-related emissions of conventional pollutants, the developing world typically has lagged behind the developed world in adopting such technologies. How would differences in adoption in the developed and the developing worlds impact the results just shown?

Figure 4.11 **Combined technology case**



Source: Sustainable Mobility Project calculations.

Figure 4.12 **Combined technology case with various time lags in technology implementation in non-OECD regions**



Source: Sustainable Mobility Project calculations.

To find out, we conducted two additional runs of our combined technologies case. One assumed that implementation in the developing world would be lagged by five years relative to what had been assumed in the original combined technology case. The second assumed an additional fifteen-year lag. Table 4.4 shows the resulting lags for each increment as well as the lag (if any) assumed in our original combined technology case and our reference case. Figure 4.12 shows the result of the model run.

Table 4.4 **Developing countries- Assumed technology implementation time lags in the cases**

	Reference Case	Combined Technologies Case	... with Additional 5 Year Lag	... with Additional 15 Year Lag
Diesel Sales Reach 50%	5 years	no lag	5 years	15 years
Hybrid Sales Reach 50%	10 years	5 years	10 years	20 years
Fuel Cell Sales Reach 50%	n.a.	10 years	15 years	25 years
Biofuels Blend Levels Reach 33%	5 years	5 years	10 years	20 years
Biofuels Low-GHG Share Reaches 80%	n.a.	no lag	5 years	15 years
Hydrogen Low-GHG Share Reaches 80%	n.a.	no lag	5 years	15 years
Additional 10% Fuel Economy Improvement	no lag	no lag	5 years	15 years

Source: Sustainable Mobility Project

The importance of the assumed length of lag in developing world adoption of these combined vehicle technologies and fuels is evident. With the 15 year time delay, rather than peaking about 2020 and returning to its 2000 level by 2050, GHG emissions from road transport peak in about 2030 and by 2050 are approximately 1 Gt per year above their level of 2000.

E. The timing and magnitude of GHG reductions in road transport versus other GHG emissions sources

This project is titled "Sustainable Mobility," and the sustainability issues examined so far have been viewed almost totally through the lens of the transport sector. The goals stated in this chapter are therefore intended to be goals for the transport sector.

It has been noted at several places in this report that a kilogram of GHGs released anywhere in the world in connection with any transport mode contributes equally to GHG concentrations in the atmosphere.[28] But this is also true for a kilogram of GHGs emitted by any other anthropogenic activity. For this reason it is important to discuss the relationship between actions taken to reduce GHGs emitted by transport-related activities and actions taken to reduce GHGs impacting other sectors.

In a recent presentation, Robert Socolow of Princeton University's Global Carbon Mitigation Initiative estimated that "business as usual" (BAU) global carbon emissions from all energy-related uses will roughly double over the next 50 years. (Socolow 2004) He reported that if BAU emissions continue unabated for 50 years before actions sufficient to stabilize emissions are taken, atmospheric CO_2 concentrations will reach approximately 800 ppm - more than double their present level of about 350 ppm. However, if worldwide energy-related carbon emissions could be stabilized at or near current levels, atmospheric CO_2 concentrations could be held between 500-550 ppm.

To illustrate what would be required to stabilize worldwide energy-related carbon emissions at or near their present levels, Socolow identifies a number of "slices," each of which represents a cumulative 25 Gt reduction in carbon emissions (91.7 Gt of CO_2 emissions) over the 50-year period. Each slice has

Table 4.5 **Potential "slices" each yielding a cumulative 25 Gt of carbon reduction over the time period 2004 and 2054**

Activity	*Level of Effort Needed for One Slice*
Road Transport Related	
• Internal combustion engine efficiency improvements (1)	*2 billion gasoline and diesel cars with 60mpg rather than 30mpg*
• Hydrogen used as a fuel in motor vehicles (1)	*1 billion H2 cars displace 30mpg gasoline/diesel vehicles*
• Biofuels displace petroleum in road transport	*Annually, plant and sustain 4 million new hectares of high-yield (15 t/ha-yr) crops, back out gasoline and diesel: by 2050 have planted area equal to US cropland (200 million hectares)*
Coal Displacement In Electricity Generation	
• Gas displaces coal in electricity generation	*By 2054, build 1400 GW baseload power plants fueled by gas instead of coal*
• Solar photovoltaic electricity generation displaces coal-fired generation	*1000 X current capacity, i.e. 5 Million hectares*
• Wind generation displaces coal-fired generation	*Install 40,000 1 MW_{peak} windmills each year and maintain until 2054*
• Nuclear generation displaces coal-fired generation	*Over 50 years, add 700 GY (twice current capacity): requires 14 new 1-GW plant/year*
Carbon Capture/carbon Sequestration	
• Carbon sequestration employed in coal-fired or gas-fired electric generating or H2 production plants	*Carbon capture and storage at 800 GW coal or 1600 GW natural gas, or equivalent H_2 plants*
• Geological carbon storage	*70 Sleipner equivalents (2) installed every year and maintain until 2054*
Natural Stocks	
• Forest-related	*Reduce tropical deforestation by 100% instead of 50% by 2054 (i.e., from 1.0 GtC/yr to 0 Gt/Cyr instead of to 0.5 GtC/yr plus rehabilitate 400 million hectares temperate or 300 million hectares tropical forest*
Other	
• Generalized energy efficiency improvements	*Carbon intensity per $GNP drops 0.2% faster than in past*

(1) In the SMP reference case, the global light duty vehicle fleet in 2050 is projected to be 2 billion vehicles

(2) A carbon capture and storage (CCS) project might typically be made up of 1-3 CO2 injection wells in a gas field. The Sleipner project in Norway is an example where CCS trials are being carried out.

Source: SMP calculations using **Socolow 2004** and other sources annual carbon emissions reductions starting at zero in 2004 and increasing linearly to 1 Gt of carbon (3.7 Gt of CO_2) in 2054.

Table 4.5, adapted from Socolow's presentation, indicates the level of effort required to produce a single slice. The slices identified in Table 4.5 are not the only ones possible and some are duplicative. Nor is there any assumption that the slices are equivalent in terms of the cost of producing them.

What Socolow shows is that in order to reduce energy-related carbon emissions over the next 50 years by enough to stabilize atmospheric CO_2 concentrations at 500-550 ppm, emissions reductions equivalent to seven slices must be found. The approaches discussed in this section might yield between one and two slices if implemented. Eliminating all transport-related (road and non-road) GHG emissions growth worldwide between 2000 and 2050 would yield about four slices.

Clearly, actions focusing on the transport sector cannot come close to stabilizing atmospheric CO_2 concentrations by themselves. Moreover, based on the SMP's understanding of the cost-effectiveness of various GHG reduction approaches, applying a disproportionate share of total GHG emissions reductions to transport-related activities might not be desirable for the world economy.

F. Summary assessment

In road transportation it appears technically feasible to reduce growth in worldwide GHG emissions significantly – and, eventually, to reduce the absolute volume of these emissions – by the introduction of advanced power-trains and fuels. At least six technology

possibilities exist (in addition to improvements in mainstream gasoline engine technology) that appear capable of contributing to stabilization – dieselisation, hybridisation, advanced bio-fuels, fuel cells, carbon-neutral hydrogen, and non-powertrain vehicle efficiency improvements.

Some of these technologies and fuels are beginning to be introduced. Others may not be ready for introduction for several decades, if then. Also, the time required from the introduction of each technology lever to the deployment of enough vehicles using that technology to have a significant impact on GHG emissions varies widely (between 10-50 years).

No single new technology can provide a stabilization solution by 2050. It will only be through combinations of new fuels, powertrains, and vehicles that such a stabilization solution may eventually be reached. Making combinations of this sort work will require close and continuing cooperation between the automobile and fuel industries.
The time lag between the widespread use of these technologies in the developed world and their widespread use in the developing world has an important impact on the trajectory of GHGs emissions from road vehicles.
It is important to begin consideration of how the length of this lag can be reduced without making road transport in the developing world unaffordable.

Demand channeling has a role to play in reducing transport-related GHG emissions. But this is not something that can be achieved quickly, inexpensively, or easily.

The changes in demand patterns that would need to occur for demand channeling measures to have a large and relatively rapid impact on transport- related GHG emissions would be extremely expensive and highly disruptive.

IV.

Significantly reduce the total number of road vehicle-related deaths and serious injuries from current levels in both the developed and the developing worlds

In Chapter 2 the SMP concluded that between 2000-2050 the number of road-related deaths and serious injuries should fall across the OECD and in some upper-middle level income countries. But road-related deaths and serious injuries seem likely to rise for a few decades (and perhaps longer) in lower-income countries where growth in motorized road transport is relatively rapid. In this section we discuss how the worldwide outlook for road-related deaths and serious injuries might be improved.

As detailed in Chapter 2, see especially Figures 2.26 and 2.27, the problem of road-related deaths and serious injuries differs in countries that are heavily motorized and countries that are in the early stages of motorization. In the former, death and injury rates are already quite low by historic standards and are projected to decline further. The total number of road-related deaths and serious injuries is also quite low and falling although there is still considerable room for improvement. Vehicle occupants constitute the majority of crash victims (Figure 2.27).

In lower-income developing countries, death and accident rates are higher by a factor of ten or more than the OECD average. These higher death and injury rates combine with large populations to produce total numbers of deaths and injuries that far outstrip the numbers of deaths and serious injuries in the OECD. While death and injury rates in these countries are often declining, the growth of personal/freight transport activity is so rapid that total deaths and serious injuries are rising, sometimes steeply. And pedestrians, bicyclists, and (in some places) operators of powered two- and three-wheelers, constitute a large majority of crash victims.

With these distinctions in mind, the SMP asked their own and outside safety experts[29] to identify approaches that (a) would help OECD countries attain their stated goal of significantly reducing the number of road-related deaths and serious injuries, and (b) would lower rates of death and serious injuries in developing countries significantly more rapidly than projected in our reference cases.

Table 4.6 **Risks per vehicle kilometres on road types in the Netherlands, 1994 and Germany, 1993**

Road Type	Speed Limit		Mix Fast /Slow Traffic	Crossing / Opposite Traffic	Inury Rate per 10^6 km		Fatality Rate per 10^8 km	
	Netherlands	*Germany*			*Netherlands*	*Germany*	*Netherlands*	*Germany*
Calming Area	30	-	yes	yes	0.20	-	0.3	-
Residential Roads	50	50	yes	yes	0.75	1.75	1.0	1.7
Urban Arteries	50 / 70	50 />50	yes / no	yes	1.33	1.37	2.3	2.1
Rural Roads	80	100	yes	yes	0.64	0.44	3.6	2.8
Rural Arteries	80	100	no	yes	0.30		1.8	
Rural Motor Roads	100	100	no	yes / no	0.11	0.26	1.0	0.8
Motorways	100 / 120	no	no	no	0.07	0.15	0.4	0.5

Source: **Koornstra 2003, p.14.**

A. Potential safety improvements in OECD countries

With respect to the OECD countries, the suggestions fell into three major categories: (1) improvements in road infrastructure, (2) changes in road user behavior, and (3) changes in vehicle design.

1. IMPROVEMENTS IN ROAD INFRASTRUCTURE

Road infrastructure contributes to road safety in several ways. Injury risk is highest on roads where relatively high differences in traffic speeds and direction occur in combination with moderate speed limits (50 or 70 km/h limit, mixed slow and fast traffic, intersection crossings, opposing traffic). Fatality risk is highest where these conditions are present and, in addition, speed limits are high (80 or 100 km/h limits on roads with mixed traffic, intersection crossings, and opposing traffic without mid barriers).

Table 4.6 illustrates how the infrastructure design and traffic rules of roads determine traffic complexity for road users and, therefore, the risk differences between road types. These differences are explained mainly by the effects of different average impact speeds in crashes, especially in collisions involving vulnerable road users (pedestrians and cyclists), and by the effects of speed differences on crash frequency.

According to European safety specialists we consulted, road safety in Europe could be significantly improved if:

- Mixing of fast and slow traffic is not allowed on roads and crossings with car speeds higher than 30 km/h. Where 30km/h roads intersect with surrounding 50km/h roads, speed limits on roundabouts should be 30km/h. Where vulnerable road users use 50km/h routes, proper foot and cycle paths should be provided.
- Roads with speed limits between 50-80 km/h should have no intersection crossings for cars and instead use roundabouts that physically reduce the car speeds.
- Separation barriers and graded intersection crossings should be used on roads with speed limits higher than 80 km/h.

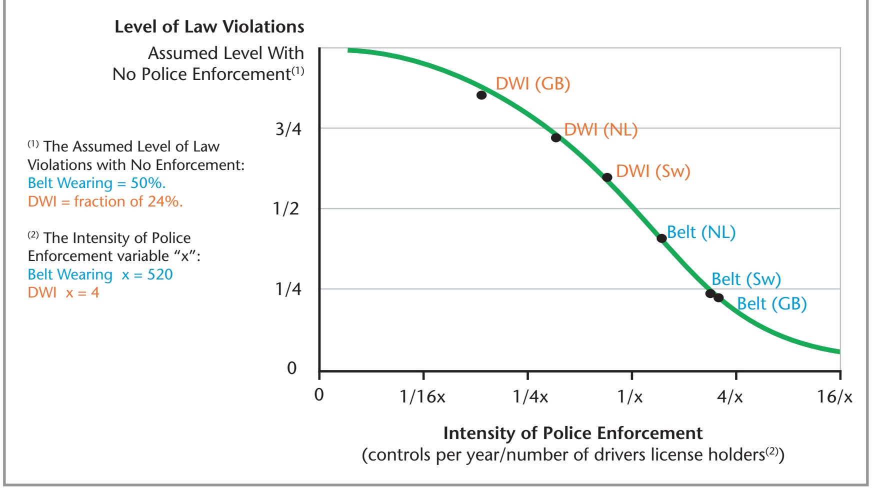
Some European safety specialists have estimated that by redesigning road infrastructure this way there could be a reduction in "slow traffic" fatalities (i.e., fatalities of pedestrians and bicyclists) of as much as 90% while motorised road-user fatalities on urban and rural roads could be cut by up to 80%. The decline on motor roads (not motorways) could be as much as 60%. In total, 80-90% of fatalities might be avoided by such a road redesign. Full reconstruction would be costly and would take more than two decades. But according to these specialists the most effective and least costly measures could be implemented before 2020 and might reduce fatalities by as much as 40%.

2. CHANGES IN ROAD USER BEHAVIOR

Four types of behavior by vehicle users contribute in a major way to a high fatality and injury risk: (1) failure of car occupants to wear seat belts, (2) failure of drivers and passengers of motorized two-wheelers to wear helmets, (3) driving while intoxicated, and (4) speed limit violations. Each of these types of behavior could be substantially reduced through more intensive police enforcement, saving lives and injuries.

How much more intensive would police enforcement have to be? Koornstra and his colleagues have attempted to provide an estimate based upon data relating to violation levels and enforcement intensity in Sweden, the UK, and the Netherlands – the three EU countries with the lowest motor vehicle death rates. *(SUNflower 2002)* Figure 4.13 shows data for each of these countries for two types of violation – driving while intoxicated and driving ("DWI") and failure to wear seat belts ("Belt"). Figure 4.13 is a generalized relationship. To calibrate it in order to project required enforcement levels for a specific

Figure 4.13 **Police enforcement intensity and its effectiveness**



Source: Adapted from **Koornstra 2003**.

type of violation, one must supply data on the assumed level of the violation with minimal police enforcement (Z) and, for an actual observed violation level, the number of controls per license holder per year (X).

The impact of enforcement on increasing seat belt use. For the countries studied, with no police controls the level of seat belt violation is estimated to be about 50%, while at a level of just one annual control per 65 license holders, the violation level falls to about 6%. If this experience were transferable to the United States, improved belt-enforcement intensity could save more than 35% of all road fatalities.[30]

The impact of enforcement on reducing the incidence of driving while intoxicated (DWI). Many studies have shown that the fatality probability increases exponentially with the blood alcohol content (BAC) of the driver. With no police control the violation level of drink/driving above 0.1% blood alcohol content (BAC) in weekend nights is generally about 24%. This level is associated overall with about 40% of the national road fatalities in the three countries studied. Most developed countries now have 0.05% or 0.08% BAC laws. But if the legal BAC-level were lowered to 0.02%, and if police enforcement intensity by random breath testing could be increased to as high as 1 annual control per license holder, possibly 25% of all road fatalities could be prevented. In Sweden, where the legal BAC-level is 0.02% and the level of enforcement is one annual control per every four license holders, fatal accidents from drinking have been reduced to below 12%.

The impact of increased enforcement of speed limits. Koornstra and his colleagues estimate that speed limits are violated by approximately half of all drivers when police enforcement is low. In the Netherlands in 2000, an enforcement level of about 3 million speeding fines for 7 million license holders (i.e., 0.43 fines per license holder) was associated with a violations level of about 33% on main urban and inter-urban roads. Using these data to calibrate the generalized enforcement curve enables one to estimate that it would take an enforcement level of about 3 speeding fines per 2 license holders per year (i.e., 1.5 fines per license holder, or more than three times the actual Netherlands rate in 2000) to reduce the violation level to 10%. They calculate that for Sweden, this level of enforcement would reduce total road fatalities by 17%.

Education, training, and publicity (ETP) as a complement to enforcement. In the analysis described above, one of the key parameters was the violation level assumed to exist in the absence of significant police enforcement. This violation level was found to differ by violation type. It also differs by country. Some of this difference no doubt is due to differences in objective factors such as geography, population density, etc. But some likely is due to differences in the road safety “culture” of the countries. This culture can be influenced by education, training, and publicity.

The authors of the SUNflower report note that when Sweden switched in 1967 from left to right hand traffic, there was a major safety education campaign to prepare the population. This campaign appears to have had an impact on road safety attitudes in Sweden, though the influence of this campaign has declined over time. They also note the impact that programs aimed at young and drivers have had some impact.

It is difficult to measure quantitatively the impact of ETP activities. Overall, the SUNflower authors estimate that it contributed less than five percent of the fatality saving of car occupants between 1980 and 2000 in the three countries studied. (This estimate does not include any impact that such activities may have had in fatality reductions due to reduced DWI and seat belt wearing.) However, this influence may have been limited by the relatively limited use of ETP activities. Moreover, as the authors' note: *“A certain level of ETP is a prerequisite for any road safety policy that needs parliamentary approval and thus acceptance by the public. Public acceptance is certainly doubtful without ETP.”* *(SUNflower 2002, pp 138-139)*

3. CHANGES IN VEHICLE DESIGN

The SUNflower Project estimated that improvements in passive vehicle safety have reduced occupant fatalities by 15-20% over the last two decades in the three countries. Koornstra estimates that the introduction of new passive safety devices, combined with the introduction of additional passive and active vehicle safety systems, might cut fatalities by as much as 40% more in the decades ahead. Among potential passive safety devices, candidates for consideration include an automatic ignition block if someone is not belted, soft-nose car construction for vulnerable road user protection, car compatibility requirements and freight vehicle under-ride protection. Potential active safety technologies deserving examination include intelligent speed adaptors, automatic daytime running lights (DRL) and collision avoidance assistance devices.

4. THE IMPACT OF INSTITUTIONAL AND SOCIAL DIFFERENCES AMONG COUNTRIES IN THE POTENTIAL FOR IMPROVING ROAD SAFETY

The proposal that automatic ignition blocks be used to prevent a vehicle being started when someone in the vehicle is unbelted raises the important issue of public acceptability. Automatic ignition blocks were mandated by law for new cars sold in the US in the early 1970s and proved to be effective in increasing the rate of seat belt use. However, they generated major public opposition. In addition, many motorists found ways to disable or defeat the interlocks. This outcry forced Congress eliminate the requirement for their installation, and that requirement has never been reinstated.

Public acceptability is an issue that all governments contemplating various safety measures must take into account. The authors of the SUNflower final report acknowledge:

> *"It is likely that the public acceptance of measures to improve behavior (with respect to speeding, drinking and driving, motorized two-wheelers, and novice car drivers) may be highly dependent on national perceptions, attitudes, and beliefs with respect to safety in general, and road safety measures in particular."* *(SUNflower, 2002, p. 126)*

This has two important implications. First, it underscores the care that should be taken in trying to infer the impact that a particular measure or group of measures might have in one country based upon the experience of another. Second, it emphasizes the need for research on how national perceptions, attitudes, and beliefs with respect to road safety measures are formed and might be changed.

5. THE IMPACT OF OFFSETTING BEHAVIOR

One reason that safety-enhancing measures sometimes turn out to produce results that are less than predicted is that motorists modify their behavior in ways that tend to offset the safety-enhancing potential of the measure. This is known as "risk compensation." They also react inappropriately to the cues generated by a safety technology with which they are relatively unfamiliar.

Discussion of the unintended consequences of some road-safety measures goes back more than a quarter of a century. Peltzman probably was the first person to point out that drivers who wear seat belts might be expected to drive more aggressively, offsetting some of the expected safety benefits. *(Peltzman 1975)*

The same argument has been made concerning antilock brakes. Antilock brake technology has become common in US light-duty vehicles. The evidence seems clear that antilock brakes have proved beneficial to occupants of other vehicles, pedestrians, and bicyclists. But they have not yielded the benefits for vehicle occupants that were expected. Indeed, some studies have found that the risk of a vehicle occupant experiencing a fatal accident has risen in vehicles equipped with antilock brakes. There are a number of possible reasons. Some analysts attribute this "anomaly" to risk compensation. Others argue that it is due to driver unfamiliarity with the requirements of the technology, especially in situations where a driver's reactions may be impaired due to, for example, to drinking. *(Harless and Hoffer 2002)*

Many of the potential safety technologies described in this report are intended to provide drivers with more information about their surroundings. Some may even "protect" the driver against "bad decisions." As these technologies move towards the marketplace, issues of risk compensation and inappropriate driver response due to unfamiliarity will become increasingly significant.

No society should reduce its efforts to decrease deaths and serious injuries resulting from road crashes through the incorporation of new technologies into vehicles and the road infrastructure. But it is important to understand that behavioral responses may offset some of the projected benefits – an unfortunate reality that needs to be taken into account when deciding which road-safety technologies are implemented and how resources should be allocated.

B. Additional considerations related to the road safety prevention-learning potential for developing countries

Road-traffic safety in developing countries has the potential for very significant improvements since at present the lowest-income countries have an average fatality risk per vehicle about 75 times greater than that of the safest countries of the world.[31] In many low and middle-income countries, road safety does not get treated as a priority, and there is little or no systematic measurement of safety consequences. In an effort to rectify this situation, efforts are being made to highlight the importance of deaths and injuries from road crashes as a worldwide public health problem. In August 2003, the United Nations General Assembly published a report by the Secretary-General titled "Global Road Safety Crisis." *(UN 2003.)* The theme of World Health Day in 2004 was road safety. And on that day, the World Health Organization and the World Bank issued a joint study on road traffic injury prevention. *(WHO 2004)*

Application to the developing world of the factors identified above (i.e., improved infrastructure, improved behavior, and improved vehicles) would lead to major improvements in road safety. However, given the mix of road users in lower and middle-income countries, the emphasis on the various factors will need to be quite different. As Mohan and Tiwari have observed, since a majority of the road traffic injury victims in the lower and middle income countries are vulnerable road users (see Figure 2.27 above), major reductions in road traffic injuries will not come from technologies making vehicle occupants safer, but rather from a combination of road design, urban land use policies, and vehicle technologies that makes vulnerable road users safer. *(Mohan and Tiwari 2003, p. 7.)* They identify several measures as a starting point to improve road safety policy in the developing world:

- Establish national or regional road safety agencies. This is a precondition for improvements to be implemented. Such agencies should be staffed with trained professionals and be responsible for accident data surveillance and analysis, funding of research activities, setting vehicle and road standards, and developing appropriate traffic engineering approaches.

- Develop safety standards for the front ends of vehicles (including buses, trucks, cars, three-wheeled taxis, tuk-tuks, becaks) to make them less hazardous for pedestrians and bicyclists.

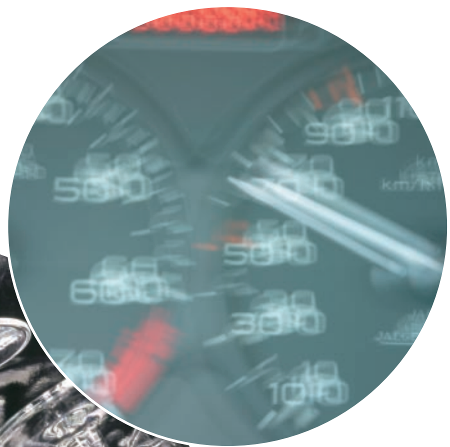
- Develop appropriate human resources. Fewer than a dozen road safety and environmental professionals work in each of the less motorized countries at present. Training programs should be institutionalized. But this will happen only if and when road safety and transportation research bodies are set up in selected universities and research institutions.

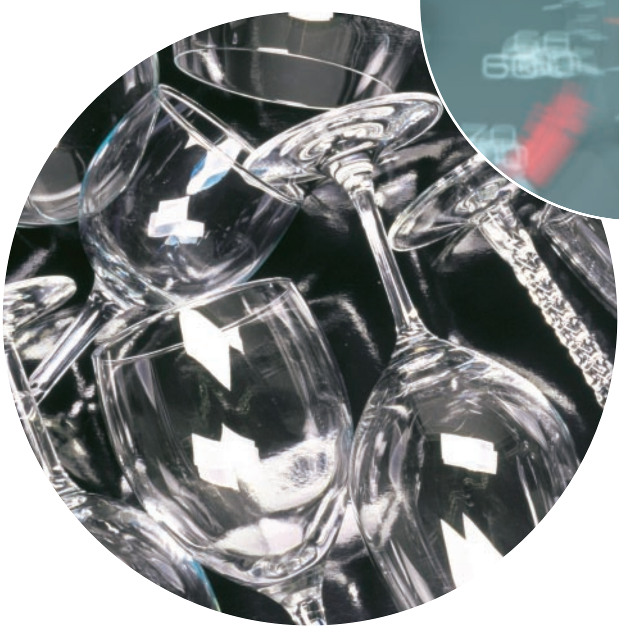
C. Summary assessment

Traffic-related deaths and serious injuries can be reduced substantially below the levels projected in the SMP reference case in both the developed and developing worlds. Improved vehicle design and improved infrastructure design have a role to play in both areas. But neither represents a complete solution.

One key to progress in both developed and developing regions is to improve the behavior of vehicle operators and passengers. In the developed world, establishing and strictly enforcing speed limits appropriate to road location and condition, strengthening and strictly enforcing laws against driving under the influence of alcohol or other substances, and enforcing the wearing of seat belts would each result in significant reductions in road fatalities and serious injuries. ITS technologies could contribute to effective enforcement although the willingness to use such technologies will vary widely. In the same way there are great variations in the willingness of countries to employ enforcement strategies such as the routine, random stopping of vehicles to detect drivers operating under the influence of alcohol or drugs.

In the developing world, the most important contemporary safety issue is the effective protection of vulnerable populations (pedestrians, bicyclists, and users of motorized two-and three-wheelers) from death or injury by the growing number of cars, light trucks and heavy-duty vehicles using the streets of rapidly urbanizing areas and roads connecting these urban areas with rural areas and other towns and cities. Educating everyone on the need to observe rules of the road is essential as are police efforts to enforce these rules. So is improved infrastructure design that separates motorized vehicles from pedestrians and bicyclists.





V.

Reduce transport-related noise

If climate change is the prototypical global public good, transport-related noise can be said to be the prototypical local public good.

Transport-related noise generates external costs and cannot be controlled effectively either voluntarily or by the unaided market. But its costs are felt locally rather than regionally, nationally, or globally. For this reason, the priority assigned to the goal of reducing transport-related noise differs around the world. Many European countries appear to be attaching increasing priority to it as an element of sustainable mobility. *(Directive 2002/49/EC)* The same seems to be true for Japan. *(Ministry of Land, Infrastructure and Transport 2001)* In some other countries and regions, it seems to be a lower priority.

Transport-related noise, like transport-related deaths and serious injuries, is the product of many factors. Therefore, any drive to reduce transport-related noise must be multifaceted if it is to be effective. Some elements must deal with unlawful behavior by vehicle operators, since this is one of the most important sources of noise in densely populated urban areas. Some must deal with road conditions and choice of materials for road surfaces since these also have a major impact on transport-related noise. Some must deal with the inherent noise-generating characteristics of the vehicles themselves.

Box 4.1 identifies the major elements of one such multifaceted approach to

Box 4.1 **Elements of the Mayor of London's ambient noise reduction strategy**

Three Key Issues

Securing good, noise reducing surfaces on Transport for London's roads.

Securing a night aircraft ban across London.

Reducing noise through better planning and design of new housing.

Other Initial Priorities

Extending good, noise reducing surfaces across all roads where they would be effective, along with less disruptive and better reinstated streetworks.

Encouraging quieter vehicle technologies.

Building in noise reduction in day-to-day traffic management – to maximise gains from reducing stop-start driving as congestion falls, smoothing traffic flow, allocating street space better, and other transport measures.

Improving noise environments through 'Streets for People', in Home Zones, in town centres, and in exemplar Public Space projects.

Developing a Traffic Noise Action Programme for the 580 kilometres of roads which Transport for London manages, including targeted traffic noise reduction projects.

Trialling fuel cell buses, seeking to trial hybrid-electric buses, and seeking smoother and quieter driving, including through driver training.

Establishing a London Ambient Noise Fund for exemplar noise reduction projects, and a London Domestic Noise Fund to improve internal and external noise, especially in poorly converted flats.

Seeking improved railway track quality and maintenance on National Rail and Underground as soon as organisation and funding allow.

Securing support for exemplar noise barrier-integrated photovoltaic power generation along suitable east-west roads and railways, and noise screening from safety and security fencing.

Promoting development alongside or over suitable roads and railways, protecting wider areas from noise.

Ensuring that 'polluter pays' levies compensate those affected by aircraft noise and other effects, such as through Aviation Environment Funds for each airport.

Reducing noise through better planning and design, where London's growth in people and jobs presents challenges, but redevelopment and refurbishment also offer opportunities - high density, mixed-use development can create quiet outdoor spaces away from traffic.

Examining the scope for a Mayor's Silver Sound Award, and promoting exemplar City Soundscape projects.

Source: **City Soundings 2003, pp.xii-xiii** noise reduction – the Mayor of London's strategy for reducing ambient noise, published in March 2003. The items on this list are influenced by the Mayor's authority to influence noise-generating activities. Some directly target technology, others relate to needed changes in behavior, still others appeal to civic pride. Nevertheless the list illustrates the wide range of elements that a comprehensive noise-reduction program must include.

A. Vehicle owners and operators

Much of the road-related noise in urban areas is a result of unlawful activity. Vehicle owners modify their vehicles to defeat the noise-reducing technologies that have been installed by manufacturers.[32] They operate their vehicles in ways that generate much higher noise levels than a properly operated vehicle would produce. Dealing with this situation requires making enforcement of existing anti-noise measures a police priority. For a variety of social and political reasons, many societies are not willing to do this. In other societies, noise regulations are observed without the need for much enforcement.

B. Roadway design and maintenance

A roadway's surface is a major determinant of the noise produced by vehicles traveling over it. Two approaches can be used to deal with this type of noise. First, different materials can be used to surface roads. Second, barriers can be constructed alongside the road to contain the noise.

Different road surfaces generate different levels of noise when traveled over by the same volume and mix of traffic. When new, porous asphalt surfaces can reduce noises by 3-5 dBA compared with dense asphalt surfaces. In the Netherlands there is a large national program to replace old dense asphalt surfaces with porous asphalt surfaces. In Japan, the use of porous surfaces has become mandatory and already more than 1000 km of roads are reported to be covered with such surfaces. Other significant road surface replacement projects exist in the UK, New Zealand, Italy, France, and Spain. *(Sandberg 2001)*

At the 2004 meetings of the Transport Research Board, the development of a porous elastic road surface (PERS) that could reduce road noise by up to 10 dBA was reported. PERS has a porous structure composed of granulate rubber made from old used tiers as its aggregate and urethane resin as its binder. The concept was first proposed in Sweden in the 1970s but, according to the TRB paper, was not put into practice until recently in Japan. The share of Japanese urban highways that meet noise limits, currently 13%, could rise to 90% using this road surfacing material. *(Meiarashi 2004)*

Noise barriers are used in many countries to reduce noise from motorways in urbanized areas. In the US, more than 1,800 km of such barriers had been constructed through 1998. Table 4.7 shows the estimated level of effectiveness of barriers in reducing noise within approximately 60 meters of a highway. However, noise barriers are costly. The average cost of the barriers constructed in the US through 1998 was almost $700,000 per linear kilometer.

Table 4.7 **Impact of noise barriers**

Sound Level Reduction	Acoustic Energy Reduction	*Degree of Difficulty to Obtain Reduction*
5 dBA	70%	*Simple*
10 dBA	90%	*Attainable*
15 dBA	97%	*Very Difficult*
20 dBA	99%	*Nearly Impossible*

Source: **US DOT 2000, p.10.**

C. Smoothness of traffic flow

Another roadway-related issue is the smoothness with which traffic operates. This is discussed in the section on congestion mitigation.

D. Vehicle design

Most developed countries require new vehicles sold within their borders to meet noise limits. These limits have been strengthened over the years so that properly operated and maintained vehicles today are quieter than they were. It is possible that more could be done – for example (as described in Chapter 3) by improving tires.

E. Summary assessment

Numerous opportunities exist to reduce the annoyance caused by road noise. Among the most important seem to be enforcing noise regulations, building noise barriers, and adopting less noisy road surfaces. Congestion mitigation (see below) can also contribute to road noise reduction by smoothing traffic flow. New propulsion systems such as fuel cells have the potential to reduce noise, though noise reduction is unlikely to be a major impetus for their adoption.

VI.

Mitigate congestion

Congestion can never be eliminated, but its adverse impacts can be mitigated. Congestion occurs when infrastructure capacity is inadequate to accommodate demand at a particular point in time. It manifests itself in two related ways. The average time required to complete a typical trip lengthens, and the variability in trip time increases significantly. Transport users can offset the first (at additional cost) by increasing the time they allow for the trip. But the second is much more difficult and expensive to offset since it cannot be predicted.

Congestion can be mitigated by reducing the demand for and/or by increasing the supply of infrastructure capacity, particularly during peak travel hours. "Reducing demand" does not necessarily mean reducing the total number of vehicles using a piece of infrastructure – smoothing out the peaks and valleys in demand during the day is often sufficient. "Increasing capacity" does not necessarily mean building new infrastructure. Existing infrastructure can be used more efficiently.

However, any strategy to mitigate congestion must contend with induced demand. Typically, when a congested road is improved and traffic flows faster, drivers who were using alternative routes, drivers who had shifted their trips out of peak hours, and commuters who were previously using other transport modes (but who then shift to driving) will all soon redirect to the improved route. The "induced" increase in the demand for the road space can sometimes equal the new capacity of the roadway.[33]

In terms of moderating the effects of induced demand, strategies that reduce demand may prove more successful than those that increase infrastructure supply. But it is unlikely that demand changes alone will be sufficient to handle projected growths in vehicle travel or maintain infrastructure supply and demand in equilibrium.

A. Reducing the demand for infrastructure access

Strategies to reduce demand for infrastructure access can focus on affecting the total numbers of vehicles using the available capacity or on redistributing usage, thereby reducing peak demand. It is seldom the case that a road or bridge is congested all the time. Congestion generally is worse at certain times of the day or night and at certain "choke points." If demand can be smoothed, and if the pressure on "choke points" can be reduced, congestion can be mitigated.

1. REDUCING VEHICLE TRIPS

Lessening the total amount of passenger vehicle travel involves removing the underlying need for travel – for example, by increasing the availability of telecommuting, or reducing distances between destinations by accommodating the travel through some other form of transport. Changes in urban and regional planning and improvements to public transport or intermodal connections may thus have a positive effect on congestion levels despite the fact that such developments take time to have any significant effect.

Although behavioral changes often prove extremely difficult to induce, increasing loads can be a means of reducing the total number of vehicles using a road for both passenger and freight travel. For the former, ride sharing (car pooling), or trip chaining are behaviors that reduce trips. High Occupancy Vehicle (HOV) lanes or restricted urban entry zones accessible only to vehicles with a minimum number of occupants are two other examples although their success is unclear. Parking cash-out programs in which employees (usually receiving free parking) who opt to ride share or choose another travel mode receive some financial benefit, are another. For freight travel, improvements in logistics-handling through IT or regional distribution centers can lead to reduced numbers of commercial trips.

2. SMOOTHING DEMAND

Tools that focus on curbing peak time demand at "choke point" locations include the higher pricing of infrastructure access during peak usage periods, in-car information technologies that inform drivers about less-congested routes, and the alteration of business or retail hours to redistribute or smooth out peak times.

In principle, managing capacity during peak congestion hours by externalizing the cost and shifting it to road users provides a financial incentive to adjust travel times, choose alternate routes, ride sharing, combine trips, or eliminate them entirely. Various road pricing schemes have been implemented around the world, typically in the face of public opposition. On other occasions public opposition has prevented implementation. Despite this, and despite other concerns (such as the impact on lower-income individuals), road pricing appears to be effective in reducing peak-hour congestion in some situations.

The two best-known examples of congestion charging in congested urban zones are to be found in Singapore and London. Singapore's began as a simple system in which drivers purchased permits and posted them in their vehicle windows. It has evolved into an electronic system that can vary charges in real time.

London's congestion charge system is not as advanced technologically. It is noteworthy primarily for being the first case in which elected officials of a large European metropolis have taken the political risk of imposing charges on road use. Motorists must pay £5 a day to enter a designated area of central London on weekdays. After one year of operation, traffic delays inside the charging zone were 30% less than before charging was introduced. Buses in and around the charging zone were experiencing up to 60% less disruption by traffic delays. There was a 15% reduction in traffic circulating within the zone and an 18% reduction in traffic entering the zone during charging hours. A report published in February 2004, one year after the imposition of the congestion charge, found no evidence of significant adverse traffic impacts from the scheme outside the zone. And surveys by Transport for London have found little evidence to support the concern that the charge might adversely impact business. *(Transport for London 2004)* [34]

3. INCREASING INFRASTRUCTURE SUPPLY

Building additional infrastructure capacity. The building of new roads or expanded lanes, particularly where there are identified "choke points" and in areas of high transport demand growth, means that in the short term the infrastructure will accommodate more vehicles during peak travel periods resulting in fewer bottlenecks and shorter periods of congestion. Within a regional network where new roads are built or expanded, parallel routes may also experience lower congestion levels. But it is likely that the expanded road capacity will see some of the effects of induced demand and may over time congest again to previous levels or beyond.

Building additional infrastructure capacity is not, therefore, a total solution to congestion problems. But it can be an important element in a congestion mitigation strategy when (a) the demand for transport is increasing rapidly as a region experiences strong economic growth or is integrating or (b) when rural or "fringe" areas are being urbanized or (c) when previously useable capacity becomes unusable. The first is typical not only of the rapidly urbanizing areas in many developing countries but also in Europe as EU integration proceeds. The second is typical of the rapidly growing developing countries as well as much of North America and Europe. The third has no geographic basis but is associated with a shift in transport demand that alters the nature of the service that a part of the infrastructure provides. [35]

Rapidly growing countries in Asia are engaged in massive infrastructure construction programs. According to the People's Daily newspaper, China added a total of 46,000 km of new roads in 2003, including 4,600 km of expressways. This brought the country's total road mileage to 1.81 million km, of which 30,000 km are expressways. *(People's Daily Online, 2004)* Rapidly growing Chinese cities are especially active in infrastructure construction. In April 2002, Shanghai outlined a transport plan for the next 20 years. Among other things, it envisages increasing arterial road capacity from 2.7 million vehicle km/h to 4.1 million km/h by 2005 and to 6.5 million km/h by 2020. *(Embarq 2003)* Over this same period, Shanghai is planning to build six new tunnels and bridges across the Huangpu River bringing the total number of river crossings to 16. *(People's Daily Online, 2003)*

4. INCREASING THE SUPPLY OF INFRASTRUCTURE THROUGH MORE EFFICIENT INFRASTRUCTURE USE

Where it is not feasible or desirable to build new roads, the capacity of existing infrastructure can often be improved by dedicated lanes, infrastructure design changes, advanced vehicle and communication technologies, and comprehensive traffic management strategies and systems.

One of the factors contributing to congestion (and road traffic accidents) is the difference in speed and acceleration among different vehicles. If all vehicles traveled at the same speed, capacity and safety would improve substantially. Dedicated lanes are useful as a means

of separating different traffic flows. They also ensure under most circumstances that target vehicles travel congestion-free, even when the main road is blocked. Lanes can be dedicated specifically for cars, taxis, freight trucks or buses or for through traffic only as express lanes. Traffic in adjacent non-dedicated lanes often sees traffic flow improvements, too. Technologies to mark dedicated lanes, and to change their status dynamically, are in use and are expected to be improved.

In some cases in the US, HOV lanes are being transformed into High Occupancy Toll (HOT) lanes. Vehicles access the less congested dedicated HOV lanes by paying a fixed or adjustable toll despite carrying less than the minimum number of occupants. In one example of dynamic HOT lane pricing, charges on Interstate-15 highway in San Diego can fluctuate every 6 minutes in $.50 increments from $0.50 to $8.00 per trip, depending on the price required to keep traffic in the HOT lanes moving at a designated speed. Road users of all incomes may choose HOT lanes during peak congestion periods if the reduced travel time is worth the premium. The characteristic of choice that defines HOT lanes often makes them more acceptable than fixed and non-variable pricing schemes such as toll roads which may have a disproportionate effect on lower-income drivers.

Minimizing delays and stops on all roads whether, in the form of road or rail intersections or road construction or repairs, will yield improvements in congestion conditions. Thus the design and maintenance of the infrastructure system itself can improve its capacity and performance. Technologies like Electronic Toll Collection (smart cards, scanners and electronic management systems) can also reduce delays by easing toll and fee collections and the management of dedicated lanes.

Because driver behavior also affects traffic flow, reducing (and enforcing) maximum speeds can increase road capacity, as can reducing the amount of vehicle lane changing. In the future, the distance between vehicles (head-way) may be maintained not by drivers, but by vehicles themselves. Innovations in automated vehicles or automated highways and intelligent cruise control may someday enable vehicles to safely maintain shorter headways at higher speeds. For now there are still technical, social, and regulatory challenges to be met before these technologies are unveiled on public roads, whether on dedicated lanes or not.

Where there are physical barriers to building new lanes to existing roads to increase capacity, it may be possible to create additional lanes by dedicating shoulder or safety lanes of existing roads to general traffic. During peak hours these shoulders can be used as extra lanes, provided that the road is being carefully monitored, and the extra lane can be closed again (through electronic signals) in case of a vehicle breakdown. The use of shoulders as an extra lane is seen as a relatively inexpensive method of increasing capacity. The Ministry of Transport in the Netherlands is currently investing €380 million in 150 km of so-called "peak hour lanes" (€2.5 million / km). Another potential option may be to narrow lanes in order to provide new lanes. For safety reasons the implementation of narrower lanes may prove dependent on the widespread uptake of advanced vehicle lane-keeping technologies or the types of automated vehicles/highways mentioned above.

Other advances in Intelligent Transport Systems (ITS) have the potential to increase safety and reduce congestion by increasing the effective capacity of existing infrastructure. These information technologies extend the capabilities of regional traffic management systems to develop traffic management strategies for the whole network in a region. Traffic managers are able to improve traffic flow by monitoring real time-capacity usage and responding through signals, signage, and lane allocation.

Actions to redistribute traffic can include traffic signal optimization, dynamic speed signs, ramp metering, and direction reversal of commuter lanes or one-way streets. In Paris information on traffic movement relayed by taxis ("floating car data") is being used as an alternative to costly induction wires embedded in roads.

Information technologies also enable traffic managers to respond rapidly and remove accidents that lead to significant reduction in travel times and congestion levels from major roads. Cellular phones may offer another practical option for incident detection. The coverage areas for cellular phones are far greater than the areas that can be monitored with traditional detection methods such as cameras and induction loops. In-vehicle GPS systems that enable the ability to track and compare speeds of many vehicles at a time may also be an effective tool for detecting traffic incidents, speeding up response, and reducing delays in the future.

The Dutch Ministry of Transport claims that implementation of traffic management systems over the last 25 years has increased effective road capacity by 5%, resulting in a reduction in congestion of 15-20% relative to what it would have been without such measures. *(Middelham 2003)* With ongoing innovations in information and on-board vehicle technologies, further experience gained from implementation of new value pricing projects, and the development of networked traffic management strategies, a diverse set of tools to make more efficient use of existing and new infrastructure will soon exist.

B. Summary assessment

Congestion can be mitigated by reducing infrastructure demand during critical periods and by increasing infrastructure capacity. A number of approaches, many of which rely on some form of pricing, show considerable promise in reducing infrastructure demand. Infrastructure capacity can be increased by building additional infrastructure especially at "choke points," and by expanding the effective capacity of existing infrastructure through the use of technologies such as ITS. To a degree, increases in infrastructure capacity will always be offset by induced travel demand.

VII.

Narrow the "mobility opportunity divides" that inhibit (A) the inhabitants of the poorest countries, and (B) members of economically and socially disadvantaged groups within nearly all countries from achieving better lives for themselves and their families

So far in this chapter, the sustainability goals have been focused on mitigating – and in some cases eliminating – certain negative consequences associated with the growth of mobility. This clearly is important. But by itself it is not sufficient to make mobility sustainable. According to our definition, sustainable mobility not only requires that "essential human or ecological values not be sacrificed today or in the future." It also requires that "society's needs to move freely, gain access, communicate, trade, and establish relationships" be met. The SMP's sixth and seventh goals are intended to ensure that mobility continues to fulfill its indispensable role in improving the living standards of the global population by reducing disparities in mobility opportunities between and within countries and by providing enhanced mobility alternatives to the general populations of countries in both the developed and developing worlds.

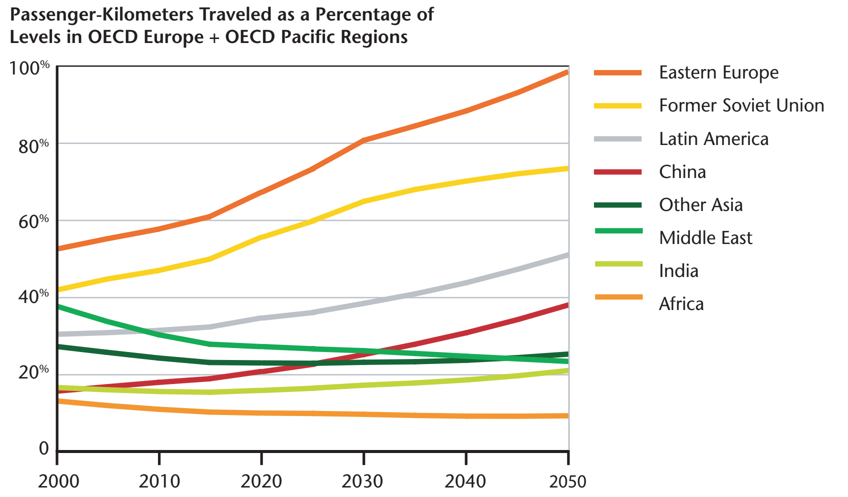
A. Narrowing the "mobility opportunity divide" between the poorest developing countries and developed countries.

The SMP projections of personal and freight transport activity 2000-2050 given in Chapter 2 show that both personal and freight transport activity will grow, with expansion being especially rapid in certain parts of the developing world. However, these projections also demonstrate that the growth will not be adequate to provide the average citizen of some of the poorest developing nations and regions with mobility opportunities that are in any sense comparable to those experienced today by the average citizen in the developed world. We referred to this disparity as the "mobility opportunity divide."

In the SMP's view, this mobility opportunity divide must be narrowed.

This statement does not imply that the average African should travel as many kilometers each year as the average North American, European or Japanese. The mobility opportunity divide will cease to exist when people everywhere have comparable opportunities to "move freely, gain access, communicate, trade, and establish relationships."

Figure 4.14 **Average per capita travel per year relative to that of residents of OEDC Europe and OEDC Pacific regions**



Source: Sustainable Mobility Project calculations.

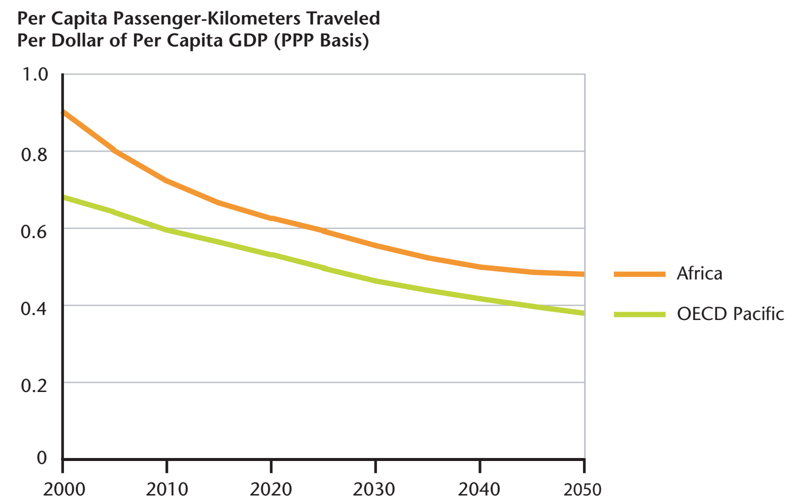
Figure 4.14 is intended to provide a rough sense of the present magnitude of the mobility opportunity divide and how it may evolve if present trends continue. Each line in Figure 4.14 shows for the region identified the average per capita number of kilometers traveled annually as a percent of the average per capita number of kilometers traveled annually in OECD Europe/ OECD Asia.

By 2050, Eastern Europe and the Former Soviet Union will have closed the gap with OECD Europe and OECD Asia in terms of personal mobility opportunities. Latin America will show a significant narrowing of its gap. But per capita travel by the average inhabitant of Other Asia, India and the Middle East will remain at about 20% of the OECD Europe/OECD Asia level. Annual travel by the average African – in 2000 only 13% percent of the annual travel of the average inhabitant of OECD Europe/OECD Asia – will decline by 2050 to 8%. In other words, for the average inhabitant of Africa (and also the Middle East), the mobility opportunity divide is projected to widen.

One relevant comparison is between India and China. In 2000 both countries show similar levels of per capita travel relative to OECD Europe/OECD Asia – 17% for India, 16% for China. By 2050 India has changed relatively little (to 20%) while China has more than doubled (to 37%). Why the difference?

The projections of transport activity in the SMP reference case are determined primarily by the rate of real per capita economic growth projected for each region or state. Some variation is assumed in regional travel intensities (measured as passenger kilometers per capita per dollar of real per capita GDP). But it is differences in per capita real income, rather than differences in travel intensity, that largely determine the magnitude of the mobility opportunity divide. This can be seen by comparing travel intensity for the OECD Pacific and Africa regions. (Figure 4.15) In 2000 travel intensity for Africa was greater than for OECD Pacific. This difference is projected to narrow, and from about 2025-2050 the travel intensities are nearly identical, even though in 2050 the average inhabitant of Africa is projected to travel only one-eighth as many kilometers per year as the average inhabitant of OECD Pacific.

Figure 4.15 **Personal travel intensity: OEDC Pacific and Africa**



Source: Sustainable Mobility Project calculations.

1. APPROACHES TO NARROWING THE DIVIDE

There are two ways to narrow the mobility opportunity divide. The first is to boost the poorer country's or region's growth rate of real per capita income. The second is to increase the mobility opportunity obtainable per dollar of real per capita income in the poorer country.

Earlier in this report (Chapter 1) the SMP described how improved mobility opportunities can enable economic growth, especially in regions now experiencing the worst mobility opportunities. But by themselves improved mobility opportunities are unlikely to prove sufficient to raise real per capita economic growth rates significantly. Instead they must be part of a range of actions, most of which are beyond the scope of this report. That said, there is one obvious way of increasing mobility opportunities per dollar of real per capita income – lower the cost of travel.

a) Lowering the cost of travel by improving basic road infrastructure

One of the most important ways of lowering the cost of travel in the poorest rural areas of the developing world is to provide people in these areas with basic means of access.

According to the World Bank, around 900 million rural poor – about one third of the world's total number of rural poor – lack access to an all weather road. *(World Bank 2003)* In a recent article, Jeffrey Sachs cataloged some of the important infrastructure deficiencies of six African countries -- Ethiopia, Ghana, Kenya, Senegal, Tanzania, and Uganda. Among the most serious of these deficiencies was the lack of paved roads. The six countries listed above average 0.01 kilometers of paved road per person. In contrast, all non-African developing countries average 4.49 kilometers per person. *(Economist 2004, p. 20)*

Just how difficult is travel in some parts of Africa? In an article provocatively titled "The Road to Hell is Unpaved," a writer for *The Economist* decided to experience first hand just how bad roads in poor rural developing areas are and the costs that they impose on the victims:

> *Visitors from rich countries rarely experience the true ghastliness of third-world infrastructure. They use the relatively smooth roads from airports to hotels, and fly any distance longer than a hike to the curio market.*
>
> *But the people who actually live and work in countries with rotten infrastructure have to cope with the consequences every day. They are as profound as they are malign. So to investigate how bad roads make life harder, this correspondent hitched a ride on a beer truck in Cameroon, a pleasant, peaceful and humid country in the corner of the Gulf of Guinea....*
>
> *The plan was to carry 1,600 crates of Guinness and other drinks from the factory in Douala where they were brewed to Bertoua, a small town in Cameroon's south-eastern rainforest. As the crow flies, this is less than 500 km (313 miles) – about as far from New York to Pittsburgh, or London to Edinburgh. According to a rather optimistic schedule, it should have taken 20 hours, including an overnight rest. It took four days. When the truck arrived, it was carrying only two-thirds of its original load.*
>
> *(Economist 2002, p. 37)*

The correspondent counted 47 road-blocks where the truck was stopped "for inspection," each of which required the payment of a bribe to pass. He also reported that there were three occasions that the road – one of Cameroon's major arteries - was blocked by rain, causing delays of up to four hours each time.

How much does poor infrastructure add to the cost of products? A bottle of a well-known soft drink costs 300CFA in the town where it is bottled. At a town 125 km further the price rises to 315CFA. At a smaller village 100 km further on, it is 350CFA. The three locations just mentioned are all on the main road. Once one leaves the main road, prices rise sharply.

What was true of bottled drinks was also found to be true of more or less any other manufactured good. Soap, axe-heads and kerosene were all much more expensive in remote villages than in the big cities. Even lighter goods that do not cost so much to transport, such as matches and malaria pills, were significantly dearer. At the same time, the products that the poor have to sell – yams, cassava, and mangoes – sold for less in the villages than they did in the towns. Peasant farmers were doubly squeezed by bad roads. They paid more for what they bought and received less for what they sold.

The SMP has already noted how China is devoting large resources to improving its road infrastructure. A significant share of this spending is going to improve rural roads. In contrast, not much money is going into improving rural roads in Africa. The World Bank estimates that at least $18 billion needs to be pumped each year into African infrastructure (roads plus other infrastructure elements) if the continent is to attain the sort of growth that might lift large numbers of people out of poverty.

Improving rural roads is not a panacea. As the Cameroon example shows, security must also be improved. But assuring that people in remote rural areas can reach the outside world is an important factor in helping them to escape poverty.

b) Making available inexpensive vehicles that also meet basic safety standards and emissions limits

Once access to the outside world becomes easier, inhabitants of rural areas normally take advantage of the improved opportunities for travel and trade. In doing so, they make use of a wide range of personal and goods vehicles, most of which are motorized. The lower the cost of obtaining and operating these vehicles, the greater the mobility opportunities. This raises a dilemma. To reduce transport cost, there is a strong temptation to avoid "luxuries" such as emissions controls and safety features on motorized vehicles used in poorer developing regions. Within limits, such tradeoffs may be appropriate provided the people making them understand the consequences. But when these tradeoffs produce significant negative externalities, individuals acting solely for themselves will not make decisions that reflect full costs.

As discussed earlier, motorized two- and three-wheelers play an important role in providing inexpensive mobility opportunities in certain regions of the world. But as also noted, these vehicles are responsible for a disproportionate share of "conventional" emissions and are involved in a significant share of serious road crashes. In this context it is clearly important that technologies for reducing emissions and improving safety be affordable and compatible with two- and three-wheel vehicles.

However, motorized two-wheelers are not the only vehicles capable of providing inexpensive mobility opportunities in rural areas of developing countries. In China an entire industry has developed to manufacture inexpensive three and four wheeled motorized vehicles designed to haul goods. These vehicles use simple, locally developed technology. Most of the manufacturers are small backyard operations though a few are sophisticated industrial companies. The Chinese government classifies these businesses not as motor vehicle producers but as producers of farm machinery.

Daniel Sperling and two of his colleagues at the Institute for Transportation Studies at the University of California at Davis recently published the first systematic report about this industry – the Chinese Rural Vehicle (or CRV) industry. *(Sperling, et. al., 2004)* They estimate that annual CRV production grew from almost nothing in the mid-1980s to 1.1 million in 1992 and 2.3 million in 1995. Annual production peaked at 3.2 million in 1999, and dropped about 7% a year from 2000-2002. In 2001, the CRV population is estimated to have totaled about 22 million vehicles. Sales of the more expensive and more sophisticated four-wheeled CRVs rebounded in 2002, posting a 7% gain. The researchers attribute this to increasing regulation and intervention by the Chinese government that reduced the profitability and viability of the less sophisticated three-wheeled CRVs.

Though the data are fragmentary, Chinese CRVs appear to account for a significant share of Chinese road transport energy consumption. About 80% of the 22 million CRVs are powered by single-cylinder diesel engines originally designed for stationary agricultural machinery. These one-cylinder engines are very inefficient, especially in mobile applications. Different estimates led the researchers to conclude that CRVs accounted for 21% of total Chinese diesel fuel consumption in 2000. Highway transportation as a whole (excluding CRVs) accounted for 24%.[36]

The conventional emissions performance of CRVs is even more difficult to assess. By combining different bits of information, the researchers estimated that CRVs emit as much air pollution as all other motor vehicles in China combined. Due to their high emissions they are banned by local authorities from entering many urban areas.

The CRV industry is unique in its size, scope, and vigor. But Sperling and his colleagues report the existence of somewhat similar industries in Thailand, India, and Crete.[37] In each case they note that the local industry has not survived once it is exposed to external competition. This may or may not happen in China. But either way, the rapid emergence of a CRV industry testifies to the strong desire for motorized mobility in fast-growing developing countries. It also underscores the importance of making it as inexpensive as possible for vehicles in the poorest regions of the world to be equipped with basic emissions controls. The fuels required by these controls must also be available and affordable. Failure to do so will raise the cost of transport above what it otherwise might be, so worsening the mobility opportunity divide.

c) Won't any additional narrowing of the mobility opportunity divide between the poorest developing countries and the developed world increase transport-related GHG emissions?

Most of the increase in transport-related GHG emissions projected to occur between 2000-2050 will originate in the developing world. But the growth in developing world transport activity associated with this growth in developing world GHG emissions will not appreciably narrow the mobility opportunity divide between the poorest countries and the countries of the developed world. If additional steps are taken to narrow this divide, won't the world see an even greater volume of developing world transport-related GHG emissions? Perhaps, but not necessarily.

One way of preventing any such increase– a way that the SMP considers unacceptable – would be to constrain development by preventing developing countries and regions from realizing the improved mobility opportunities required to lift their citizens out of poverty.

In the SMP's view, if global sustainable mobility is to be achieved it must be made possible both for non-OECD regions to substantially improve their living standards and for worldwide challenges such as climate change to be addressed effectively.

The first of these objectives requires more attention be given to providing affordable transport systems – both vehicles and infrastructure – to citizens of the developing world. The second requires that the developed world not base strategies for reducing transport-related GHG emissions on the assumption that growth and development in non-OECD countries and regions will be constrained. Instead, in the SMP's view, developed states should be prepared to take steps to help the poorest developing countries grow more rapidly without creating unacceptable global environmental concerns.

B. Narrowing the "mobility opportunity divides" that exist within almost all countries

Significant mobility opportunity disparities also exist within most countries and regions -- regardless of their stage of economic development. A number of such intra-country and intra-regional "mobility opportunity divides" contributing to the social exclusion of older people, the handicapped, the poorest, and disadvantaged ethnic

minorities were identified in Chapter 2 in connection with our discussion of equity concerns.

A British study – "Social Exclusion and the Provision of Public Transport" – identifies several ways in which lack of adequate mobility opportunity can contribute to social exclusion:

- ***Spatially,*** because without adequate mobility opportunities, individuals have no way of reaching places they wish (or need) to reach;
- ***Temporally,*** because they cannot get there at the appropriate time;
- ***Financially,*** because they cannot afford to get there;
- ***Personally,*** because they lack the mental or physical equipment to handle the available means of mobility.

Individuals excluded in any or all of these dimensions find it difficult to obtain and hold jobs, receive needed medical care, realize educational opportunities, obtain social services, access a wide choice of goods at competitive prices, visit friends and relatives, participate in public events, etc. Once high mobility levels have become a fact of life, those who face a significant shortfall in mobility opportunities are excluded from many of the activities that those with good mobility opportunities take for granted.

1. THE ROLE – AND LIMITATIONS – OF PUBLIC TRANSPORT IN PROVIDING ACCESSIBILITY FOR SOCIALLY-EXCLUDED GROUPS

The British study we have just referenced focused on how public transport might be used to offset social exclusion. Such a focus is understandable since, as we showed in Chapter 2, the groups identified above and in Chapter 2 all rely disproportionately on public transport. Moreover, Britain has a relatively well-developed public transport system, and, within limits, that system's equipment, routes and fares can be tailored to contribute to reducing social exclusion. The same is true for other urbanized areas having high-quality, relatively affordable public transport systems -- the centers of most large European cities, large parts of Japan, and the centers of a few large North American cities.

However, public transport services are inadequate to fulfill this role in the majority of urbanized areas of the developed and developing worlds – even including most areas outside the center of those large urban areas where public transport plays a very important part in providing personal mobility. In such areas, the present quality of public transport services is not sufficient to provide a meaningful mobility alternative for the general population, let alone for these socially-excluded groups. In some cases, it may be financially and technologically feasible to expand the coverage and quality of conventional public transport by enough to provide the general population with such a mobility alternative. In these cases, it also may prove feasible to design these services to make them especially useful to socially excluded groups. But the number of such cases is likely to prove limited. For most urban areas, other measures will need to be found.

We will discuss two possible measures that would primarily benefit the general population in connection with our final goal. But there is one approach – paratransit – that should be singled out in connection with providing mobility opportunities to socially-excluded groups.

2. PARATRANSIT [38]

Generally speaking, paratransit refers to an urban passenger transportation service, usually consisting of road vehicles operated on public streets and highways in mixed traffic. In principle, it includes all public and private mass transportation in the spectrum between private automobile and conventional transit. Some paratransit services are restricted to certain groups of users such as the elderly and disabled. Usually they are available to the general public, mostly in areas of low density or at night or during the weekend.

A common feature of paratransit systems is their ability in varying degrees to adapt routing and scheduling to individual users' desires. In the developed world, the use of the term "paratransit" is normally limited to demand-responsive systems such as shared-ride taxis, dial-a-ride systems and subscription buses. In developing countries, "paratransit" is used to refer to any service that operates outside the conventional fixed route, fixed schedule public transport system. Vehicles used can range from simple non- motorized human or animal powered vehicles to motorized minibuses.

a) Paratransit in the developed world

The late 1960s and early 1970s saw a surge of interest in paratransit, especially in the US. At that time, many conventional public transport systems were struggling to cope with the impact of suburbanization. It was believed that computerized dispatching and scheduling would make possible systems capable of providing service levels of six to eight passengers per vehicle-hour. This proved to be optimistic. Paratransit evolved into the means by which public transport systems could meet a legal requirement to provide access to disabled and elderly individuals. In Europe many paratransit services developed either to complement regular public transport services or were launched by communities for social purposes.

Telecommunications and information technologies have advanced enough now that paratransit might be able to fulfill its earlier expectations. Several relevant information technologies are in use or planned, including digital radio frequency data communication, mobile data terminals and computers, vehicle location devices, mapping software and geographic information systems, card-based data storage and transfer media, computerized order-taking, scheduling and dispatching, and telephone or Internet-based technologies.

In general, this new technology makes possible many enhancements that might improve service and lower costs. Notable possibilities include automatic communication with riders during trip reservation and just before pickup, transfer coordination, and use of information on real-time traffic conditions in scheduling and dispatching.

Improvements in vehicles will help improve the performance of paratransit. Vehicles used at present include sedans, vans, ramp- and lift-equipped vans, minibuses and low-floor buses. The accessible taxi sedan pioneered in London is one of the latest trends in paratransit vehicles. The latest small bus designs allow the internal configuration to be changed quickly. This allows the same vehicle to be used to carry multiple wheelchairs, to carry able-bodied persons to a trunk route, in rural transit operations, and for package delivery – all in the course of one 24-hour period.

b) The dilemma created by the growth of paratransit in the developing world

The last quarter century has seen an explosive growth in paratransit in the developing world. Motorized paratransit is estimated to provide between 20-50% of public transport services in cities such as Manila, Jakarta, Kuala Lumpur, and Bangkok. In these cities paratransit supplements conventional public transit systems by providing more flexible and frequent services at relatively low fares to small settlements through narrow streets. Sometimes they operate where no other service is available. But they may also operate on the same routes as regular buses, relying on higher speed or frequency to compete. As a result, in parts of Latin America and Africa, paratransit systems are viewed not as a supplement to conventional public transport but as a major threat to public transport's financial viability.

One reason is that paratransit services are widely deemed to be unsafe, insecure, and a major contributor to congestion. The innovations in telecommunications and information technology referred to above may help to improve matters. So may certain innovative new vehicle designs. But a resolution of the deeper issue concerning the relative roles to be played by paratransit and conventional public transport probably is a higher priority.

C. Summary assessment

The inhabitants of the poorest developing countries need to have their mobility opportunities substantially enhanced if they are to break the cycle of poverty in which they are trapped. Disadvantaged groups in wealthier countries – countries that, on average, already enjoy high levels of mobility – need to have the mobility opportunities available to them enhanced if they are to play a fuller role in society.

If mobility opportunities are enhanced, individuals presently experiencing restricted mobility will take advantage of them and become more mobile. Improved mobility, and the increased economic growth it enables, will cause these individuals to increase their demand for goods and services. This increase is likely to stimulate additional transport activity demand.

Were nothing else to happen, this extra demand for personal and goods mobility could exacerbate pollution, greenhouse gas emissions, road-related deaths and serious injuries and congestion. This possibility should not cause those who already benefit from good mobility opportunities to try to limit the mobility opportunities of those who presently lack them. Rather, they should work to make the technologies developed to reduce transport-related external costs in their own societies available and affordable to newly-mobile individuals elsewhere.

VIII.

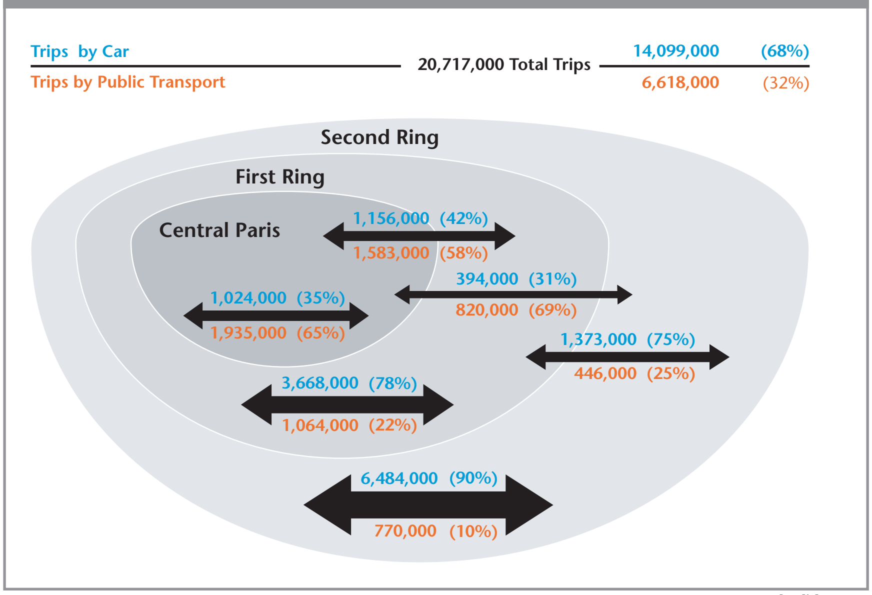
Preserve and enhance mobility opportunities for the general population of both developed and developing-world countries

The mobility opportunities available today to the general population of most developed-world countries (and in many developing-world countries) greatly exceed those of any period in the past. However, the changes in urban living patterns that have been noted above as adversely impacting the mobility opportunities of the poorest, the elderly, the handicapped and disabled, and the disadvantaged also threaten to erode the mobility opportunities of many average citizens. In particular, the ability of conventional public transport systems to perform their vital role in providing personal mobility is being threatened.

During the next several decades, a primary goal of governments should be to preserve this important mobility option. London, Paris, Tokyo, Berlin, and New York are only a few of the developed world cities that could not exist without public transport. And, as the survey of developing world cities we sponsored makes clear, public transport systems are even more essential in many developing world urbanized areas.

In many urban areas in both developed and developing countries the SMP believes that there are important opportunities for increased utilization of bus and "bus-like" systems (including paratransit) to take advantage of the flexibility inherent in road-based systems. Advantage should also be taken of opportunities to incorporate new vehicle technologies (including propulsion systems) and new information technologies into these "bus-like" systems.

Table 4.9 **Daily trips by mode in the Paris region**



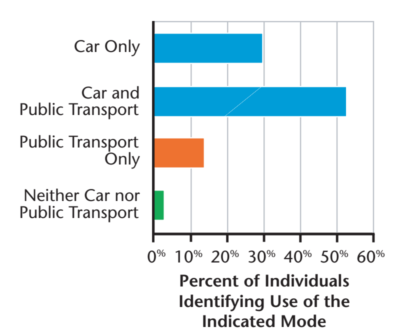
Source: **Renault Slides, p. 2.**

A. How adequately can public transport fulfill personal transport needs? The extent of multimodalism in urban areas having access to high-quality public transport services

Even in urban areas where individuals have ready access to high quality public transport, it often is unable to fulfill their personal mobility needs totally. Research exploring transport choices of individuals living in and around the Paris region show a surprisingly high degree of multimodalism – the use by individuals of different transport modes for different trip purposes at different times of the day and week.

In this research, the Paris region was divided into three concentric "rings" – Central Paris (Arrondissements I – XX), the Petite Couronne (the Departments of Hauts de Seine, Seine Saint Denis, and Val de Marne) and the remainder of the Ile de France region. Table 4.9 shows the variation in public transport modal share depending upon where within this region the trip began and ended. Trips within Central Paris, or between the Central Paris and the first or second ring, were predominantly by public transport. However, Transport between these two rings or within them was predominantly by car. Moreover, the total number of daily trips in each category varied widely, with trips not involving a journey to or from Central Paris being made primarily by car.
In Central Paris and the Petite Couronne, where there is an extremely high level of public transport supply, the public transport share of all motorized transport is about 60%. Yet only 14% of those surveyed rely exclusively on public transport. Thirty percent rely exclusively on cars. And more than half (53%) use multiple modes. (Figure 4.17) About 75% of people use cars exclusively to reach commercial centers. Over 50% use public transport exclusively to travel to and from work or study, for "administration," or to shop in Paris. (Table 4.10)

Figure 4.17
Personal transport mode usage in Paris (Central Paris and First Ring)



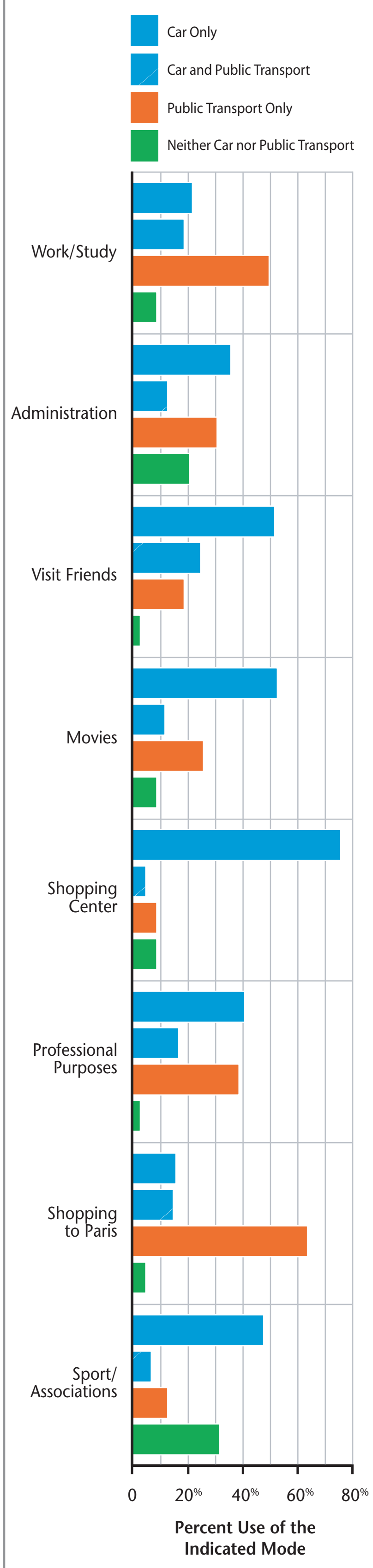
Source: **Renault Slides, p. 1.**

As we have already pointed out, it does not seem either technologically or financially feasible to provide a high enough level of conventional public transport service to meet even the majority of the typical urban resident's personal mobility needs in many urbanized areas. So the real choice is not between relying totally on public transport or totally on a car. What is needed is a broader spectrum of mobility options. We have already discussed one – paratransit. We will now consider another that is presently available in limited situations but that could be significantly improved and expanded -- shared-use vehicle services (i.e., car sharing). Finally, we will consider a category of mobility options that might exist in the future -- entirely new transport solutions incorporating various new technologies.

B. Shared-use vehicle services (car sharing)

"Car sharing" is a service that provides a fleet of available vehicles to local household or commercial users on an as-needed basis. Though payment structures vary, car-sharing users generally pay for the use of a vehicle based on the time used and/or mileage driven, with some providers also charging an additional monthly membership fee. Through their usage fees, customers pay the service providers for the costs of the vehicle purchase or lease, fuel, vehicle maintenance and cleaning, parking, registration, taxes, insurance, and the administration of the venture itself. Before becoming active users of the service, car-sharing customers, or "members", usually go through an upfront application process that can

Table 4.10
Modal choice by trip purpose- Paris (Central Paris and First Ring)



Source: **Renault Slides, p. 4.**

include reviews of driving records, credit/ billing set-up, information sessions and distribution of keys, codes, or smart cards.

1. ORIGINS OF CAR SHARING

The origins of car sharing go back to 1948 and a Swiss cooperative. In the late-1980's new car sharing ventures (primarily in Europe) emerged. Over the last decade momentum seems to have grown in many regions, with exponential growth in some. *(Shaheen, Schwartz, and Wipyewski 2003)* Though many car-sharing organizations may have started (and ended) at grass roots level, today's providers range from experimental research programs and small-scale non-profit organizations to multicity private business ventures in Europe, Japan, Canada, the US and elsewhere. The largest going organizations include Mobility Car Sharing Switzerland and StadtAuto Drive in Europe, CommunAuto in Canada, and CityCar Share, Flex Car and ZipCar in the US, each offering services in multiple cities.

The majority (though not all) of car-sharing schemes have been supported by startup or ongoing contributions (public and private) on the basis of social or environmental goals. Zipcar, launched in the US in June 2002 without public funds, has grown in a short time on a for-profit basis to serve more than 10,000 members with 250 cars in a number of cities (Boston, Washington, DC, New York, and Chapel Hill). It plans to continue expanding. *(Grimes 2004)* To get a sense of scale of Zipcar's growth, in 1999, all US car-sharing organizations claimed a total of around 1,600 members and 115 vehicles. *(Shaheen, Sperling, and Wagner 1999)* Launched in 1987, Mobility Car Sharing Switzerland, one of the world's largest car-sharing organizations, today serves over 52,000 members with approximately 1,700 vehicles. *(Car Clubs 2004)*

2. POTENTIAL ADVANTAGES OF CAR SHARING FROM THE VIEW-POINT OF CAR SHARING USERS

Car-sharing users obtain the benefits provided by the private automobile (including flexibility and comfort) and the benefits of public transportation – low (or no) fixed costs, depreciation or maintenance responsibilities. Unlike traditional car rentals, shared use vehicles can be reserved for as little as an hour and sometimes less, are parked within neighborhoods close to the users (or at transit stops) and require no paperwork or administration other than an internet or phone reservation.[39] Shared-use vehicle services spread the high fixed vehicle ownership costs across multiple users, a benefit for both personal and commercial users. They often offer different vehicles types to suit customers' varying needs or desires such as delivery or pick-up of goods, or transporting any number of passengers or clients.

In effect, rather than having access to one vehicle that they own, car-sharing customers can have access to a larger fleet of vehicles and can choose whichever best matches each particular trip need. The vehicle usage efficiency of those services catering to both household and business users is improved because their respective demand distributions are for the most part non-overlapping. And commercial use tends to be concentrated during working hours, as opposed to evenings or weekends when personal use is higher.

Car-sharing services can be very cost-effective, particularly as a replacement for vehicles driven below a certain distance threshold each year. But as costs of vehicle ownership vary dramatically among regions and users (the threshold is usually around 10,000 km/year) exact comparisons are difficult. Car-sharing services seem to work best for users who do not require a personal vehicle for daily commuting. Many users see shared use vehicle services as a sort of "mobility insurance" – it's there if they need it. Typically, personal use customers tend to be highly educated and professionally employed. So while these services have the potential to expand mobility access to lower-income groups, the evidence suggests that barriers to their uptake remain. These barriers include low awareness of the service, limited local vehicle availability, the application processes and the reality that deposits are usually required.

Most surveys characterise commercial car sharing as a predominantly inner urban-area phenomenon. This can be explained by the fact that sharing instead of owning a car becomes economically attractive for people who do not need a car every day. This is more likely to be the case in the inner-urban area, where most activities can be reached quite easily by transport modes other than the car. In outer urban areas people are more often dependent on the car due to more distant activities and fewer alternative transport modes. Trips from the periphery often cover longer distances. Because costs for such journeys tend to mount up rather quickly, car sharing appears best suited for short or middle-range trips, not least because of the lack of parking for private cars in inner urban areas. To exploit this, some car-sharing systems offer guaranteed parking along with the ability to use a car. For journeys longer than 40 km car rental seems the more economical option. Car-sharing projects that do develop in outer urban areas usually have a more informal and cooperative character and often become an alternative to the purchase of a second household vehicle.

As well as these "public" neighbourhood systems, car-sharing systems may be "closed." Such systems offer services at locations where a group of people have specific mobility needs such as transit points. In this way shared-use vehicle services act as a complement to existing transport infrastructures including private vehicle ownership (or lease), taxis and traditional car rentals as well as public and non-motorized modes of transport.

Shared cars also act as an additional link in the transport chain. They can be a first link, allowing the user get from front door to public transport access, or a last link - from public transport drop-off to destination. Given this, the positioning of car sharing as a complement to public transport is important. In some Swiss and German cities, public transport and car sharing have become part of an integrated transport system with linked ticketing and service. Additionally, it can reduce the need for costly parking infrastructure or slow its development. Researchers in the US and Europe have found impressive reductions in car sharing users' vehicle miles traveled, with annual vehicle mileage declining in most cases between 30-70%.

3. CAR-SHARING OPERATIONAL CHALLENGES

A number of challenges exist to the successful operation of car-sharing services and their long-term viability remains in doubt despite strong recent growth. High insurance costs, difficulties in finding and maintaining viable member/vehicle ratios and costly investments in new technologies are three current issues. About 30% of US car-sharing fleets consist of gasoline-electric hybrid and alternative-fuel vehicles, including electric vehicles. Some recent car-sharing initiatives have been complicated by difficulties related to the use of such vehicles. *(Shaheen, Schwartz, and Wipyewski 2003)*

Assuring availability of vehicles where and when they are needed is another challenge. Usually a car-sharing member drives the car back to the station where he or she picked it up. But with systems that permit vehicle pick-up at one point and drop-off at another, some method of redistributing vehicles becomes necessary. The use of human "jockeys" is one option. But this increases operating costs significantly. A variety of ITS-based approaches are being explored to minimize the the need to reposition vehicles. Eventually, automatic relocation by means of electronic platooning of vehicles between stations may be possible.

Car-sharing faces quite different challenges in the developed and developing worlds. In the developed world, the challenge is to find ways of reshaping the image of a "shared vehicle." To do this car sharing must show that it can overcome the perceived disadvantages of the private car and/or it must create public transport offerings where inadequate options exist. In the developing world, car-sharing pilot projects are needed to demonstrate the concept and to prove its technical and commercial viability.

Despite strong recent growth, car-sharing represents a very small fraction of global vehicle miles traveled, not reaching 1% in any region. However, this might change if certain of the technologies described in Chapter 3 (and immediately below) could be applied to this transport concept.

C. Entirely new transport solutions incorporating a range of new technologies

The next 50 years may see the emergence of entirely new transport solutions. These would offer either a completely new mode of transport or would make use of a new combination of existing transport modes. New transport solutions become possible when mobility demand, in combination with support from government, the availability of the required technology and economic benefits for all stakeholders – make such solutions more attractive than those that exist.

Entirely new transport solutions do not appear overnight. To become available after 2030, development work would need to begin almost immediately. Numerous issues have to be addressed in advance, public acceptance obtained, and pilot projects organized. Meantime developed and developing world stakeholders would likely place differing requirements in such areas as cost, infrastructure, reliability, geographical application, and logistics.

So-called "Cybernetic Transport Systems" (CTS) composed of road vehicles with fully automated driving capabilities are one new possibility. A fleet of such vehicles would form a transportation system for passengers or goods on a network of roads with on-demand and door-to-door capability. Cars would be under control of a central management system in order to meet particular demands in a particular environment. The size of the vehicle could vary from 1-20 seats, depending on the application. This concept is similar in many respects to another concept known as PRT (Personal Rapid Transit). But CTS offer the advantage of being able to run on normal road infrastructure. This makes them cheaper and more flexible. Existing technologies allow a relatively inexpensive "grid" to be placed over a geographic area to be served. Software drives the routing and management of the fleet of vehicles.

The potential of systems like CTS is great. In effect it is a high-quality public transport service that offers on-demand, door-to-door service. Moreover, the most expensive component of public transport, the driver, has been substituted. If vehicles turn out to be clean and silent, the implementation of such systems in urban areas would simultaneously reduce pollutants, noise, and congestion, improving the livability of the city. CTS also offers real mobility solutions to those who cannot drive or do not own their own vehicles. The elderly and disabled, in particular, would become mobile.

An internet survey in the CyberMove project with more than 3,000 respondents indicated that most (more than 80%) would use a fully automated vehicle, not least because it could help solve a current parking problems. *(Janse et. al. 2003)* Technologies already exist to allow CTS systems to run under controlled circumstances - for example, at Schiphol International Airport and Capelle aan den IJssel in the Netherlands. Improvements will be necessary to develop the performance of these systems at higher speeds and to spread the use of less expensive components.

Despite the potential, CTS must overcome many hurdles before they can be introduced widely. A major one concerns legal and liability issues and public acceptance. For example, the Vienna Convention and traffic laws of all countries require the driver always to be in control of his or her vehicle while the vehicle is operating on public roads.

In vehicles capable of automatic operation sensors, obstacle detection and vehicle controllers take over the main function that human beings bring to driving a vehicle – observing, analyzing/deciding, and executing these decisions. Today no standards exist to determine the conditions under which such a "takeover" might be permitted although several European projects including CyberCars, CyberMove, and Response are addressing the issue.

Public acceptance almost certainly would require that CTS be integrated into existing transport systems. For this to happen, CTS would have to fulfill the needs of end users and system operators. Recent work within the CyberCars and CyberMove projects has offered a glimpse of what these needs might be. For system users, they include "solving" parking problems and providing links from parking lots to historical city center or central business district. For system operators, they include lowering system costs, permitting use of existing infrastructure and enhancing system flexibility.

Implementing a CTS would also require examining the transport needs of users in a particular geographic area and designing a system in such a way that it provided a useful additional transport service, not simply a "ride." That could well imply encouraging transport system users to evolve from a unimodal focus (often consisting almost totally of the use of a private vehicle) to multi-modal (using public transport for some trips, leaving the private vehicle at home) to intermodal (deciding each day the best individual traffic solution.) Under such an evolution, customers would not always prefer a car, but might use a transit pass for basic mobility needs or pay in advance for a transit access discount. Second-generation applications might be in niches, usually urban, where the systems could gain a foothold in terms of public acceptance by addressing a specific need such as parking in a useful way.

D. New transport systems as an alternative to requiring people to adjust their living patterns to fit the technological constraints imposed by conventional public transport systems

The pattern of urban areas influences the total volume of transport demand and the mix of transport services used to satisfy that demand. The reverse is true too – transport system characteristics influence the pattern of urban areas. Indeed, it has been argued that the principal force shaping the world's urbanized areas in the twentieth century was the automobile and the truck:

> *"As important as prior transportation innovations have been, the car has*

had a more dramatic effect on the city than anything before it. Unlike the earlier transportation innovations, the car has radically reshaped cities because it eliminates walking almost entirely. People who took streetcars in 1900 still had to walk from the streetcar stop to their homes or their jobs. As such, businesses and homes needed to crowd against public transportation stations. Routine shopping and many other non-work related activities were generally done on foot before the automobile. As such, stores, schools and restaurants needed to be within ready walking distance of consumers. Public transportation made it possible for consumers to live far from their work, but they still needed to live at high densities. Cars have changed that and, as a result, unalterably changed city living forever." *(Glaeser and Kahn 2003)*

The authors of the last paragraph above regard the impact of cars on urban life as broadly positive. Others disagree. Indeed, some transport and urban planners contend that for urban mobility to become sustainable, the role played today by motorized vehicles in urban areas must be sharply curtailed and that rapidly growing urban areas in the developing world must be prevented from becoming as auto-dependent as most urban areas in the developed world. They support such an outcome even if transport-related conventional emissions can be eliminated as a major public health concern, even if transport can be largely eliminated as a major source of greenhouse gas emissions, and even if the number of deaths and serious injuries related to road crashes can be reduced significantly everywhere.

The reasoning behind such views can be summarized as follows: Mobility cannot become sustainable unless it is accessible and affordable (as well as achieving the other goals). But accessibility and affordability cannot be achieved as long as public transport is not readily available. Public transport cannot be readily available if people are geographically dispersed. Since it is the automobile that enables and encourages the geographic dispersal that undermines the viability of public transport, dependence on the automobile should be severely curtailed. How such a restrictive outcome could be achieved is a source of a disagreement among urban planners holding this view. One group believes that the answer lies in establishing "appropriate" land-use policies. They contend that such policies will:

- Reduce the need to travel by increasing the density of the built-up area. According to this idea, the more people and activities are located in close proximity, the lower the trip distances and the lower the negative transport externalities. It is also claimed that lower trip distances help to enable new transport systems. Mixing housing, shopping, and working areas can also produce shorter trip distances.

- Alter the design of the localities where people live. Neighborhoods are often designed for car users. During their development, not much attention is paid to non-motorized modes (bicycling and walking), public transport or new mobility systems. By providing shorter and more attractive routes for these transport modes, it is argued that their usage could be stimulated.

- Alter regional accessibility to stimulate new mobility systems. Stockholm is lauded as an urban area in which the built-up area is clustered around the public transport system, providing optimal access to alternative transport modes to most of the residents. This has enabled the city to exploit a high quality and competitive alternative for car travel, preserving mobility opportunities for all of its residents. *(TNO 2004)*

Others contend that there is little evidence that land-use policies have ever proved effective in reducing communities' dependence upon the automobile. Rather, they believe that direct controls over vehicle ownership and use are necessary. According to this view:

- Land-use and transport policies are only successful with respect to criteria essential for sustainable urban transport (reduction of travel distances and travel time and reduction of share of car travel) if they make car travel less attractive (that is, more expensive or slower).

- Land-use policies to increase urban density or mixed land-use without accompanying measures to make car travel more expensive or slower have little effect as people will continue to make long trips to maximise opportunities within their travel cost and travel time budgets. In the long run these policies may be important as they create preconditions for a less car-dependent urban way of life.

- Transport policies to improve the attractiveness of public transport in general have not led to a major reduction of car travel, have attracted little development at public transport stations and have contributed to further suburbanisation of population. *(TRANSLAND 1999)*

As far as the SMP knows, no controlled experiment has been (or, probably, could be) conducted to determine the validity of either of these viewpoints.

The closest to a "natural experiment" is probably the efforts of Singapore over the last several decades to discourage private automobile ownership and use.

In a review of Singapore's experience, Willoughby concluded that neither land use policies nor transport policies were adequate by themselves to discourage auto ownership and use. Singapore required both strong land-use policies that lead to most citizens living in clusters of high-rise buildings and draconian charges levied on the ownership and use of private motor vehicles to achieve its exceptionally low levels of motorization. *(Willoughby 2000)* Singapore has limited motor vehicle ownership largely to the wealthy. The public transport system is quite good and quite inexpensive. But for most people it is the only alternative.

Singapore is an extreme example of the use of a wide range of public policies to shape the living and working patterns of a large urbanized area to fit the technological and economic constraints of current public transport systems. But it does represent the logical conclusion of the argument that accessible, affordable mobility is incompatible with a society's becoming heavily auto-dependent.

The SMP thinks that, rather than drastically restrict auto ownership and use, society should encourage the use of approaches such as the ones described earlier in this section to increase the range of mobility options available to the residents of urban areas, whether they live in the "core" of these areas or in the lower-density areas that typically surround it. By making such technologies available, and by pricing transport services appropriately, mobility can be made sustainable.

E. Summary assessment

Both developed and developing regions that already enjoy high levels of mobility opportunities, as well as regions that are seeking to realize substantial mobility opportunity improvements, should be encouraged to experiment with new mobility options. These may be as simple as car sharing and bus rapid transit, or as complex as self-driving vehicles and automated highways. To the extent possible, new mobility options should be designed to increase transport system flexibility. Society's goal should be to fit transport systems to people's desired living patterns rather than to fit people's desired living patterns to transport systems.

IX.

The roles of "building blocks", "levers" and "institutional frameworks" in achieving the above goals

In describing approaches for achieving the above goals, we have alluded to roles that different stakeholders – private business firms, governments at different levels, individuals, and others – might play. As we end this chapter, we consider how the actions of different stakeholders might either reinforce or undercut goal achievement. To do this, we need to formalize some of the terminology we have already introduced.

In the previous chapter a "building block" was defined as something that has the potential to generate change if it can be utilized effectively. The building blocks we concentrated on were vehicle technologies and fuels. However, building blocks cannot act by themselves. To move, they require the use of "levers." These are either policy instruments such as pricing, voluntary agreements, regulation, subsidies, taxes and incentives or they are changes in a society's underlying attitudes, and values. Some of these levers and what we know about their effectiveness has been described in this chapter. The third element, "institutional frameworks," consists of the economic, social, and political institutions that characterize a particular society. We have mentioned these briefly – e.g., in our discussions of differences in the willingness of different societies to accept "intrusive" traffic safety enforcement policies such as speed cameras and self-reporting by vehicles to regulatory authorities that they are emitting conventional pollutants at excessive levels. Now we want to concentrate more on these vital elements in the quest to achieve sustainable mobility.

Why worry about institutional frameworks? *"Institutions are the rules of the game in a society or, more formally, are the humanly devised constraints that shape human interaction... In consequence, they structure incentives in human exchange, whether political, social, or economic."* (North 1990) In our specific context, institutions establish the context by which a country or region determines which sustainable mobility goals to pursue and the priority given to each; which levers are acceptable to use to achieve any particular goal; how intensively these levers can be used; and the constraints that may be imposed on their use. In short, they are the ultimate determinant of whether and how sustainable mobility is achieved.

In *Mobility 2001*, the importance of institutional frameworks was emphasized as follows:

"Most discussions of the challenges to making mobility sustainable tend to focus on the role that technology is expected to play. We imagine energy-efficient "supercars," transportation fuel systems that are hydrogen- rather than petroleum-based, and magnetically-levitated trains that speed people between cities using relatively little energy. We envision telecommunications technologies that tell us how to avoid congestion as we drive and that automatically charge us for the full external costs of our personal mobility choices.

As intriguing as these technological possibilities might seem, history suggests that something far more mundane will actually determine the pace and direction of change in mobility systems. That something is institutional capability. Political institutions determine which transportation modes get favored through subsidies, regulations, and protection from competition. Political and social institutions exert enormous influence over whether infrastructure can be built, where it can be built, and what it costs to build. Economic institutions – especially large corporations – can either take the lead in encouraging change or drag their feet and make change difficult and expensive. (Mobility 2001 pp. 7-9.)

Institutional frameworks influence mobility choices in many ways: They affect the time and effort required to reach consensus about whether to address a particular issue and how aggressively to address it. They affect the ability of a government to formulate long-term approaches and the credibility of its commitments. They affect the instruments that governments use to enforce a society's laws and norms as well as the ways in which these instruments are used. They affect whether a government can or will undertake policies and approaches whose success requires joint action and agreement with other governments. They determine the social acceptability of certain products and services as well as the social acceptability of different patterns of product use and the range of different patterns that are tolerated. They affect the apportionment of responsibility and cost within society to achieve a desired result. They encourage or discourage voluntary collaboration across a range of stakeholders.

Achieving sustainable mobility is almost certain to require changes in personal and goods transport systems and in how society uses them. The size and type of changes that may be needed may put great pressure on some societies' political, cultural, and economic institutions. For example: Some approaches might require governments to impose policies that previously had been deemed to be "impractical" or "politically unacceptable". Some might require governments to make extremely long-term (more than 50 years) commitments. Some might require the public to accept levels of government intrusiveness regarding vehicle use that in the past have been considered unacceptable. Some might require governments to undertake types and levels of spending – for example, on infrastructure – that previously had been considered unconventional or objectionable. Some might require segments of the population to be favored relative to other segments. Some might require certain societies to accept restrictions on long-standing legal rights. Some might require certain societies to cooperate with other societies in ways that had previously been deemed unacceptable. Some might significantly impact (or preclude) traditional patterns of purchase and use of certain products.

There is no guarantee that different societies will be able (or willing) to undergo these changes. When a society encounters a mismatch between a goal it has declared important and its willingness (or ability) to employ the levers that might be needed to achieve that goal, it faces a dilemma. It can declare certain policies or efforts to change behavior to be "unthinkable," thereby effectively (if not actually) abandoning achievement of the goal. It can risk adopting policies that are "difficult" for various groups to accept and try to encourage (or force) acceptance after the fact. It can try to change the acceptability of certain policies prior to adopting them through publicity, broad stakeholder involvement in their design, or by agreeing to compensate actual or perceived "losers."

Moving towards sustainable mobility will involve paying as much attention to institutional frameworks as to the inherent potential of any vehicle technology or fuel or the theoretical "effectiveness" or "ineffectiveness" of any particular policy lever or action. Consider, for example, the challenge of developing fully-automated vehicles. In an interview published in July, 2002, Michael Parent, Head of Research at INRIA (the French National Institute for Research in Computer Science and Control) characterized this challenge as follows:

> *"The barriers are not technological, but rather regulatory. The regulatory environment, by its very nature, always trails innovation. In France, for instance, current legislation states that the driver is responsible for his vehicle. What would be the case if the vehicle drove itself? Then, if we want to have automated vehicles driving in an urban environment, access for traditional cars will have to be limited. This starts to encroach on the idea of freedom of movement, very dear to the Latin mentality in particular."*
> *(Renault R & D Review 2002)*

Differences in their institutional frameworks are likely to cause different nations, collections of nations, or subunits of nations to approach the goals we have stated in different ways. In some cases, they may assign different priorities to the attainment of an individual goal. In other cases, they may employ different levers to manipulate a given building block.

In Chapter 1 the extent to which such differences can be accommodated was outlined. We identified goals such as the reduction of transport-related noise and the mitigation of congestion as ones that offer room for considerable difference both in the weight given to the goal and the levers that might be applied. Control of greenhouse gas emissions (GHGs) was identified as the goal permitting the least latitude. No single country or region can control worldwide GHGs on its own, yet anything less than worldwide control will not produce the GHG stabilization levels needed to mitigate global climate change. Countries and regions may differ legitimately about which levers they wish to use to control greenhouse gas emissions and how to apply these levers. Nevertheless, in this case, some form of global and international commitment is likely to be unavoidable.

X.

How companies like ours can contribute to achieving the goals we have identified

Most of the issues described in this report are not new to our companies. As the report indicates, we have made considerable progress in providing the fuels and vehicles to control transport-related conventional emissions and are within sight of eliminating these concerns in the developed world. All our companies are involved in programmes to address road safety issues, whether through active safety systems in vehicles, through driver training programmes in schools and elsewhere, and through a wide variety of education programmes encompassing drivers, passengers and pedestrians.

The picture on greenhouse gases is more complex as we move to reduce not only the emissions from our own operations, but also the much more challenging task of those arising from the use of our products – fuels and vehicles – by our customers. The fundamental aim is to reduce fuel consumption of our products while working to develop the future fuels and vehicles that will provide for a carbon neutral outcome. This is an area of both competition and collaboration, but our companies are involved, for example, in joint initiatives such as the California Fuel Cell Partnership and in demonstration projects with hydrogen and fuel cell vehicles in both developed and developing countries.

However, the extreme importance of transport to our societies and the fact that transport-related considerations have some impact on almost everything done within them means that our ability to act independently in many areas is extremely limited.

Regarding the control of conventional emissions, we can continue to improve the effectiveness and reliability of the emissions control equipment in our vehicles. We can encourage aggressive efforts to detect "high emitters" and to require these vehicles to be fixed or removed from service. In the developing world, we can strive to reduce the cost of emissions control equipment and increase the "robustness" of this equipment to poor maintenance and poor quality fuels. We also can work to reduce the added cost and to increase the availability of the necessary fuels. However, we cannot force our customers to maintain their vehicles properly or to scrap their older, more polluting vehicles and replace them with newer, less polluting ones. That is something that only governments can do. And in determining whether or not to do so, governments must consider more factors than merely the effectiveness of emissions control.

Our role in achieving the goal of reducing transport-related GHGs to sustainable levels is also limited. We can and will continue to improve mainstream technologies and develop and implement new technologies. However, from a business perspective, we cannot justify production of vehicles that customers won't buy or produce and distribute fuels for which there is little or no demand. If the costs of the vehicles and fuels required to reduce GHG emissions from road vehicles are greater than our customers are willing to pay, and if society requires action to be taken, then it is up to governments to provide the necessary incentives, either to us or to our customers, to permit us to make these vehicles and fuels available. We can engage in the public debate, encourage governments to adopt such incentives, and help them understand which will and won't be effective. As far as advanced technologies and fuels are concerned, we can work together and with governments to increase understanding of what is technically feasible and work to reduce the technological and economic uncertainties described in detail earlier in this report.

Regarding road safety, we can support the adoption of appropriate, effective safety-related vehicle technologies. We can encourage more aggressive enforcement of traffic laws. We can undertake programs to educate motorists about how to operate their vehicles more safely and vulnerable users about how protect themselves. We can support the construction of infrastructure designed to separate motorized vehicles from vulnerable users and to encourage vehicle speeds appropriate to road and location conditions. But as we have noted above, the safety consequences of how our products are used by our customers are even less subject to our control than are the emissions consequences. The most extreme example of where we have limited leverage is in narrowing the mobility opportunity divides described above. We can support efforts by the World Bank and other institutions to provide basic road access for individuals living in rural regions of the poorest countries. But we have no role to play in actually providing such roads. We can support efforts to encourage new approaches to providing improved mobility opportunities in urbanized areas (e.g., car sharing, paratransit, and new mobility systems). But we have little influence over whether societies will choose to adopt such approaches or whether they will be successful if adopted.

XI.

The way forward

By collaborating on this project our companies have advanced their own understanding of the key areas to be addressed in moving towards more sustainable patterns of mobility, a much better sense of where the solutions lie, and what needs to be done to deliver them.

An important purpose of this report is to be a catalyst for advancing the sustainable mobility agenda within the companies. And in reviewing the conclusions of their work prior to publication of the report, the companies have looked at what could be done to accelerate progress on the goals beyond the extensive and diverse activities on which they are already engaged. There are clearly opportunities, but they must sensibly be the result of wider consultation both within the companies and with others. We therefore need to debate both internally and with a range of stakeholders to determine where and how best to focus our activity. This we are committed to do because we recognize both the imperative and the opportunity that the report sets out. The goals clearly set out the focus for attention and recognize the variety of timescales and choices to be considered.

In addition to the report itself, we are making available the underpinning work and material from which the report is drawn, including the scenarios we used to help guide our efforts. (These scenarios were described briefly at the end of Chapter 2.) We also are making available the spreadsheet model and explanatory documentation which was developed jointly with the IEA. This will we believe provide a basis for others to initiate further work.

As the CEO's of the companies point out in the Foreword, enhanced mobility is critical to progress, but can bring with it a set of impacts that must be resolved. Much has been achieved and we are now developing a clearer understanding of how better to resolve the issues leading to more sustainable mobility. For us, and we hope for others, the work of this project will be an important contribution, and we anticipate working with others to deliver the progress, which is clearly possible.

[1] Different analysts define "high emitter" differently. The USEPA defines them as vehicles emitting a level of emissions at least twice (for some pollutants, three times) the standards to which they were certified. In the work of Professor Stedman and his colleagues, they are defined as the "dirtiest 10%" of vehicles.

[2] A good description of these challenges in the Mexico City Metropolitan Area is contained in Molina and Molina.

[3] The number of miles and/or time period over which manufacturers must certify that vehicles they sell will meet the emissions standards to which they have been certified have been substantially lengthened. Vehicles falling out of compliance during this period must be repaired at the expense of the manufacturer.

[4] According to The Wall Street Journal, two years ago, an "angry tycoon" in central China took a sledgehammer to his new SLK230 Mercedes-Benz because it kept breaking down. The culprit, according to Mercedes-Benz, was poor-quality gasoline. *(The Wall Street Journal, December 11, 2003)*

[5] We are speaking here of the general population. Some individuals may, for various reasons, choose to incur these additional costs. But unless this is true of the great majority of the population, and unless this willingness endures indefinitely, transport-related GHG emissions will not be reduced significantly.

[6] Perhaps the most complete compendium of studies that have investigated these issues can be found at the website of the On-Line TDM Encyclopedia **(http://www.vtpi.org/tdm/)**.

[7] According to Automotive News, as of Autumn 2003, "on average, a car with a medium-sized diesel costs about $1087 more than one with a gasoline-powered engine." "Debate over diesels still sizzles in Europe," Automotive News, September 8, 2003, page 20D.

[8] In France, the initial purpose of the lower tax on diesel was to help offset higher costs faced by those who had to travel much more than the typical motorist in the course of their business. At that time, most light-duty diesel vehicles were owned and operated by small businessmen.

[9] "Bright future of diesel engines forecast," citing the study, "Global Markets for Diesel Powered Vehicles to 2015." Story dated September 15, 2003, accessed on "just-auto.com" website.

[10] In the mid-1980s, about 75% of new vehicles produced in Brazil were alcohol-powered. This fell rapidly as subsidies were eliminated. Even so, as of 1998 some 4.5 million Brazilian cars were alcohol-powered and another 16.75 million used a blend of 24% alcohol and 76% gasoline *(Ribiero & Younes-Ibrahim, 200?)*.

[11] Brazilian analyses also attribute benefits from employment creation and foreign exchange saving to the alcohol fuels program.

[12] "Popular cars" were cars with a displacement of up to 1.0 liter.

[13] Manufacturers are allowed to "carry back" or "carry forward" credits that they earn for exceeding the standards in a particular year, though only for a limited number of years.

[14] Over the past 15 years or so, US customers have chosen to take nearly all the potential annual efficiency improvements available to them in terms of increased performance and other vehicle characteristics rather than in the form of increased fuel economy.

[15] Recall that the reference vehicle is a 2002 compact European sedan powered by a port-injected spark ignition gasoline engine. The retail price of this vehicle is assumed to be €18,600.

[16] The authors of the study assume that, where a dedicated fuel infrastructure is needed, it would be necessary to equip 20% of the fueling stations in the EU-25 (approximately 20,000 stations) with the ability to dispense those alternative fuels requiring different dispensing arrangements in order to provide adequate fuel availability to the equivalent of approximately 5% of the EU-25 fleet.

[17] Recall from Figure 3.3 that the well-to-wheels emissions of GHG from vehicles using hydrogen produced by these technologies are about the same as for current gasoline- or diesel-powered ICE vehicles.

[18] This figure is from a British study identifying European resources. It therefore excludes sugar cane, the crop used in Brazil to produce ethanol.

[19] Growth in transport activity explains more than 100% of the projected increase. Projected improvements in transport vehicle energy efficiency offset some of the impact of the growth in transport activity. Changes in the GHG emissions characteristics of transport fuels have hardly any impact due to their limited penetration in the reference case.

[20] This is not inconsistent with the finding that pricing approaches can produce significant short-term congestion relief. Congestion is not usually a manifestation of too much demand in total, but rather too much demand for use of a particular element of infrastructure at a particular point in time. Pricing approaches can be used to shift the timing of demand or to boost the effective capacity of an element of infrastructure without significantly affecting the total volume of transport activity.

[21] Non-road transport (air, water, and rail) accounts for the remaining quarter of transport-related CO_2 emissions. In the SMP reference case, this share is projected to rise to about 30% by 2050.

[22] A very high proportion of heavy trucks and buses are already diesel powered. We assumed that hybrid technology would not find significant use in heavy-duty over-the-road trucks and buses because of their operating characteristics. As discussed in Chapter 3, public transport buses are already being seen as prime candidates for hybridization. These were not included in our calculation, but their omission makes relatively little difference to the results.

[23] We made the same assumptions concerning the type of vehicles to which fuel cells might be applied as we did for hybrids.

[24] The fuel economy benefit relative to gasoline ICE technology was assumed to be 36% for diesel hybrids, 30% for gasoline hybrids, and 45% for fuel cell vehicles.

[25] The study then states: "With respect to vehicle cost for the three vehicle types considered in the analysis – hydrogen, conventional gasoline, and gasoline hybrid electric vehicles (GHEVs) – the committee has assumed that vehicles having equivalent performance will have equal cost. This cost equivalence is a goal for the auto industry. In making this assumption, however, the committee has not conducted its own analysis or projection of whether this goal will be achieved. The advantage of assuming equivalence among the three vehicle types is that it permits comparisons strictly of fuel supply systems without judgments as to the success or failure of vehicle developments underway. However, the total cost of a hydrogen economy compared to a hybrid or conventional vehicle economy is left undetermined."

[26] It is generally acknowledged that, due to the diesel's initial superior energy efficiency, any additional benefit from hybridizing a diesel is likely to be less than the extra benefit from hybridizing a gasoline engine.

[27] This implies that these advanced biofuels are either gasoline from lignocellulosic sugar fermentation or diesel from biomass gasification/ Fischer Tropsch synthesis.

[28] This assumes, as we have been, that emissions of all GHGs are measured in terms of their appropriate CO2 equivalents.

[29] The outside safety experts the SMP consulted were Dr. Matthijs Koornstra of the SWOV Institute for Road Safety Research, the Netherlands; Dr. Leonard Evans, President, Science Serving Society, USA; and Professor Dinesh Mohan, Transportation Research and Injury Prevention Program, Indian Institute of Technology.

[30] In the most recent year for which US data are available (2003), about 30% of vehicle occupants were wearing seat belts. However, about 60% of people in fatal accidents weren't. *(The Wall Street Journal, April 29, 2004)*

[31] These are the "Group 8" countries in Table 3.x – the UK, Sweden, The Netherlands, and Norway.

[32] In a 1996 report, the International Motorcycle Manufacturers Association (IMMA) estimated that in Europe, 35% of motorcycles and 65% of mopeds had been equipped with illegal replacement exhausts or had had their existing exhaust systems altered illegally by their owners. The majority of these vehicles were found to be operating at 10 – 15 dB (A) over the legal noise limit. The report estimated that the illegal systems resulted in a seven-fold increase in the noise output of motorized two-wheelers in Europe. (IMMA 1996).

[33] There is a large literature on just how much of any increased capacity will be offset and just how soon the offset will occur. Cervero reviews the results of these prior studies and conducts a new one using different analytical techniques. He finds evidence for significant induced demand, but the amount of induced demand he finds is less than in many previous studies. These studies often found that within a couple of years, induced demand had "used up" all the additional capacity. *(Cervero, 2001)*

[34] Though Londoners appear to support the charge, there continue to be concerns about its impact on business. Retail and leisure businesses inside and immediately around the charging zone were typically reporting a 2% reduction in sales for the first half of 2003, with food and confectioner-tobacconist-newsagent businesses typically reporting reductions of 6%. When retail businesses were asked about the influences that might have led to these reductions, economic and tourism factors were reported most frequently, though congestion charging constituted about a fifth of the reported influences. In contrast, only about 1 in 15 service sector respondents cited congestion charging as an influence. For all surveyed businesses, the share was 12%. *(Transport for London 2004, pp. 21-22)*.

[35] An example of the third situation is where a bridge can no longer safely handle the weight of the traffic crossing it, even though traffic volume may not have changed all that much.

[36] These two uses together total 31 MMT of diesel. In 2000, total Chinese gasoline use was 38 MMT.

[37] The authors distinguish these industries from industries in countries such as the Philippines that install locally-constructed vehicle bodies on foreign-produced chassis. The CRV industry and similar industries in the other countries mentioned construct the entire vehicle, using local components and technology.

[38] The following discussion of paratransit is taken largely from Lave & Mathias and Shimazaki & Rahman.

[39] Some car-sharing systems require no reservations and offer direct access to the vehicles.

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