Automobiles and Global Warming: Alternative Fuels and Other Options for Carbon Dioxide Emissions Reduction

by

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Abstract

Automobiles are a source of considerable pollution at the global level, including a significant fraction of the total greenhouse gas emissions. Alternative fuels have received some attention as potential options to curtail the carbon dioxide emissions from motor vehicles. This thesis discusses the feasibility and desirability (from a technical as well as a broader environmental perspective) of the large-scale production and use of alternative fuels as a strategy to mitigate automotive carbon dioxide emissions. Other options such as improving vehicle efficiency and switching to more efficient modes of passenger transportation are also discussed. These latter options offer an effective and immediate way to tackle the greenhouse and other pollutant emission from automobiles, especially as the limitations of currently available alternative fuels and the technological and other constraints for potential future alternatives are revealed.

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The basic concept of automotive engines (i.e., reciprocating internal combustion (IC) engines) has not changed much since the earlier part of the century. The combustion of the fuels that have been traditionally utilized in such engines (i.e., petroleum-derived fuels) leads to the release of pollutants as inherent by-products of this combustion process. Of these, the major pollutants are sulfur oxides (SOx), nitrogen oxides (NOx), hydrocarbons (HCs), lead, particulates, carbon monoxide (CO), and carbon dioxide (CO_2). SOx are due to the sulfur impurities in the gasoline, while the formation of NOx results from the large fraction of nitrogen that is present in ambient air used for the combustion. These two pollutants have been implicated in the acid rain issue. HCs (mainly unburned or evaporated components of gasoline) and NOx are key components in the sequence of reactions that lead to the production of photochemical smog and urban ozone. Lead emissions are a consequence of adding tetra-ethyl lead (TEL) to gasoline as an anti-knock agent. Although the use of TEL has been severely curtailed in the US, and is beginning to be eliminated from Europe, it is still widely used in other countries. Lead emissions are of concern, especially in the urban environment, since exposure can lead to increased blood lead levels which interferes with the mental development of young children. The oxides of carbon (CO and CO_2) are unavoidable if the energy conversion process is based on the combustion of carbonaceous fuels (such as gasoline). CO is known to have acute health effects, though it acts on a local scale. Last, but not least, CO_2 which has been traditionally recognized as a greenhouse gas, is of concern in the context of global warming.

Currently, motor vehicles are estimated to contribute about 14% of the global CO_2 emissions, 50-60% of the CO, HCs and lead, 30% of the NOx and about 10-20% of the particulate emissions (Faiz 1993). Air-conditioning in motor vehicles is responsible for 25% of the global chlorofluorocarbon (CFC) consumption; not only does air-conditioning significantly reduce the fuel efficiency of the vehicle, but the release of CFCs used in these systems contributes a sizable fraction (5%) of the total global greenhouse effect (due to their extremely high greenhouse potential), as well as to the stratospheric ozone depletion problem (Faiz 1993). The global vehicular emissions are estimated to be responsible for about 15% of the greenhouse effect (Faiz 1993) as well as about 50% of the photochemical air pollution and 25-40% of the acid emissions (Boyle 1990). Such statistics clearly highlight the fact that the contribution to the global environmental crisis by motor vehicles is already substantial; they cause more air pollution than any other single human activity (Faiz et al. 1990).

The pervasiveness of the automobile (like many other technological marvels of the twentieth century) is closely linked to global "development". As a result, even though car ownership in the industrialized nations is approaching saturation levels, the relative numbers of cars are much lower in most of the lesser-industrialized countries (LICs) or newly-industrialized countries (NICs). For example, the level of car ownership in the United States is 1000 times that of China and 250 times that of India; in fact, at present, only 16% of the world's population owns 81% of all automobiles (Boyle 1990). Still, in most industrializing countries, there have been rapid automobile population explosions, as the newly affluent classes move to acquire one of the most desirable of all status symbols: the car. There is no doubt that the next few decades are likely to see an enormous increase in the numbers of automobiles worldwide, especially given the fact that the global economy is desperately in need of inducting potentially gigantic consumers like India and China into the global marketplace. Projections indicate that the world wide number of vehicles is expected to double by 2020 (Faiz 1993). Even more, the number of road miles traveled increases disproportionately as the rising levels of affluence of a country lead to improvements in its basic infrastructure. Even in the US, the number of road miles traveled has been consistently increasing in the past few decades (Ross 1989).

Among the environmental issues that the transportation sector is involved in, an important one, especially for the long-term, is that of global warming. Even though the climatic implications of the greenhouse effect are still not fully understood and scientific consensus has not been reached on the exact magnitude of the global warming problem, there seems to be an increasing agreement on its potentially catastrophic nature. For this reason, global warming has captured the attention of the general public, most environmentalists, and many policy makers. Given the significant fraction of the global greenhouse emissions that are attributable to road transport, it is surprising that in the global warming debate, greater emphasis has not been laid on the contribution of the transport sector. In fact, even in industrialized countries, automotive emission inventories generally do not include greenhouse gases (Faiz 1993).

A commonly discussed approach to severely curtail or eliminate the emissions of carbon dioxide (the primary greenhouse gas) is to switch to alternative sources of fuel (or energy) for powering automobiles on a large scale. This thesis seeks to examine the feasibility and effectiveness of such an approach, especially in terms of its large-scale implementation. Successful widespread use of alternative fuels is contingent upon the development of automotive technology that allows their use, as well as the development of economically feasible fuel production technologies. Toward this end, the possible automotive technologies based on non-conventional fuels or energy sources that could mitigate greenhouse emissions, as well as the possible sources for these alternative fuels, are discussed. The advantages and disadvantages of the various options, both from a technical feasibility and a greenhouse emissions perspective are considered. For the total greenhouse gas emissions from the use of these alternatives, the tailpipe emissions from the automobile, as well as the emissions generated during the production of the fuel are taken into account in the discussion. In addition, since some other pollutants from automobiles can also have significant health and environmental impacts, the effects on such emissions from the use of these alternatives are also considered briefly. Also discussed are some of the environmental, social, and economic issues that become relevant as the large-scale use of alternative fuels is considered. Finally, adopting a broader perspective, other options and policy instruments that might be useful in mitigating the greenhouse impact of the transport sector are also discussed in some detail.

2.1 Carbon-Based Fuels

2.1.1 Alcohols: The two main fuels that come under this category are the lower alcohols, namely methanol and ethanol. The commercial use of such fuels is not a new concept; Brazil, for example, has had an extensive ethanol-based petroleum substitution program (PROALCOOL) in place since the early 1970s (Geller 1985). Similarly, in the US, corn is used as a fermentation feedstock for ethanol which is subsequently used in 90/10 gasoline-ethanol fuel blends.

For light duty vehicles (such as cars and pickup trucks), methanol and ethanol can both be used as fuels, either neat or in blends with gasoline. The composition of such fuels is described through a nomenclature such as M85 or E100 for example, where the prefix M or E denotes methanol or ethanol respectively, and the numbers following indicate the percentage of the alcohol in a blend with gasoline. Generally, it is felt that the M85, M100, E85 or E100 fuels are the most serious contenders for alternative alcohol-based fuels (OTA 1990).

Though some research has been carried out on IC engines usable with alcohols, the design of IC engines operating with pure alcohol or alcohol-gasoline blends is still far from being optimized in terms of balancing performance, economy and emissions. The physical and chemical properties of alcohols, and consequently their combustion characteristics are substantially different from those of gasoline. As a result, deriving the maximum operational benefit that alcohols can offer necessitates their utilization in IC engines designed specifically for them, as opposed to retrofitted gasoline engines or flexible-fuel-vehicles. In addition, the use of pure alcohol fuels (M100 or E100) leads to problems such as difficulty in cold starting that have not been completely worked out yet (Mills and Ecklund 1987).

The energy density per unit volume of methanol is about half, and of ethanol about two-thirds that of gasoline. However, factors such as charge cooling due to the high heat of vaporization of these alcohols, and the possibility of operation with higher possible compression ratios and leaner mixtures (higher air-fuel ratios) lead to an improved thermal efficiency of the combustion cycle (Geller 1985, Mills and Ecklund 1987, OTA 1990). In fact, the thermal efficiency of an engine designed for ethanol use is about 17-25% greater than a gasoline engine, while methanol engines have thermal efficiency gains of about 25-46% over gasoline engines (Lynd 1990). Thus, in very rough terms, the use of alcohols makes the engine operation (in an engine designed for use with the specific alcohol) much more efficient, but greater volumes of alcohols are required to provide the same energy output from the engine.

Alcohol fuels can be commercially produced by two major sets of feedstocks: fossil fuels and biomass. In the former category, fuel methanol is currently produced from natural gas, and gasification of coal has also been proposed as a potential route to methanol production. If the alcohols are fossil-fuel-derived, not much of an advantage (if any) is gained over gasoline in terms of CO_2 emissions. On the other hand, biomass-based alcohols have a significant potential to reduce CO_2 emissions from automobiles, and it is this route to alcohol production that merits detailed discussion.

Biomass-derived alcohols: The photosynthetic process in plants results in a net uptake of atmospheric carbon dioxide which is fixed as the carbon in biomass. If biomass-derived alcohols are used as energy sources, it is this carbon that is eventually released back to the atmosphere. For example, in the case of alcohol production from biomass, this release can take place during the conversion processes (such as fermentation) of the biomass to ethanol or the eventual combustion of these alcohols when used as fuels. As a result, there is no net increase in atmospheric carbon, except for the CO_2 that might have been released in the energy used for the various processes involved in the conversion cycle (such as production and transportation of the biomass etc.) but even this can be minimized by using biomass-produced fuels as the energy source wherever possible in these processes.

The Brazilian program is based on the conversion of sugarcane to ethanol by fermentation. Historically in the US, fuel ethanol has been made by fermentation of starch. However, in recent years, alternative feedstocks for the production of alcohols have been explored; ethanol production from the hydrolysis of lignocellulosic (i.e., woody or herbaceous) biomass seems to be close to commercial feasibility (Lynd 1990, Wyman and Hinman 1990) while methanol from thermo-chemical conversion of similar biomass is also possible (OTA 1990).

For the production of corn, its conversion into ethanol by fermentation (current US route to fuel ethanol) and subsequent utilization as a fuel, it has been estimated that the total greenhouse gas emission are equivalent to 12.42 - 16.45 kilograms of carbon released from the production process to produce ethanol containing one gigajoule (GJ, 10^9 joules) of energy (i.e., 12.42 - 16.45 kgC/GJ) (the exact value depending on the by-product credits). Combustion of this ethanol as a fuel results in a release of an additional 17.53 kilograms of carbon (i.e., 17.53 kgC/GJ) (Marland and Turhollow 1991). For gasoline the corresponding figures are 2.35 kgC/GJ and 18.41 kgC/GJ respectively (Marland and Turhollow 1991). It should be noted here that due to the higher thermal efficiency of ethanol engines, one energy unit of ethanol replaces 1.25 energy units of gasoline (Lynd 1990). Therefore, we see that on an equivalent energy basis, the production and use of ethanol (obtained from the relatively inefficient production technology based on starch fermentation) contributes only 48-63% of the CO_2 from gasoline-based systems. It is estimated that the external energy input required for the more efficient ethanol production process in Brazil is about 30% of the energy content of the product (Geller 1985). Newer technologies for the production of fuel ethanol from lignocellulosic biomass by acid-based or enzymatic hydrolysis seem more promising with an energy input-output ratio of about 0.2 (Lynd et al. 1991); further maturity of the technologies could possibly increase the efficiency of conversion. If we were to carry out a rough calculation as above, but with the advanced ethanol production from lignocellulose, we find that the CO_2 contribution from an ethanol-based system could theoretically drop to about 15% of a gasoline-based system. Using renewable sources of energy during the ethanol production process could make the ethanol alternative even more favorable.

Estimates based on a systems perspective analysis (considering a complete life-cycle plus other after-effects) of a methanol-from-biomass system indicate that using such methanol as a fuel in an engine results in carbon emissions of 18.82 kgC/GJ, an additional 43.64 kgC/GJ being emitted by the methanol production system (Ellington and Meo 1991). The high value for the system inputs here might be partly attributable to the detailed systems perspective that even takes into account second-order effects such as the CO_2 emissions from the materials and construction for the infrastructure required for such a process. But in the end, this result is not surprising; the production of synthesis gas from biomass, and its subsequent conversion to methanol is likely to be more energy intensive than the direct hydrolysis of biomass to ethanol.

The specific figures in the above discussion are highly dependent upon the assumptions regarding the alcohol production and utilization technologies, but they serve to indicate that the global warming potential of fuels based on alcohols or alcohol-gasoline blends vary greatly with the source and the fraction of the alcohol in the fuel. It also seems clear that the overall greenhouse emissions related to the use of biomass-based alcohols as fuels could be much lower in comparison to the base case of gasoline. On a purely technical level, probably the best option (in terms of CO_2 reduction) in switching to biomass-derived fuels would be to utilize ethanol produced from lignocellulose. As mentioned, this technology has been rapidly developing in the past few years, and is predicted to be cost-competitive with the projected costs of gasoline within a decade (Lynd et al. 1991).

Interestingly, in terms of the ambient air quality benefits derived from using alcohols as automotive fuels, the overall results may be mixed (OTA 1990). The two major contributors from automobiles to the ambient air pollution are evaporative emissions and combustion emissions. Alcohols are far less volatile than gasoline; furthermore, alcohols are far less reactive (for ozone production) than the evaporative components of gasoline. However, the presence of alcohol in blends with gasoline tends to increase the volatility of the blend, especially at high gasoline fractions. The major combustion emissions of alcohol or alcohol-gasoline blend IC engines are highly dependent upon the composition of the blend, the engine design and its operating conditions. Since the vehicles for alcohol operation (such as M85, M100, or E100) are still in the development stage, at this point it is difficult to predict exactly the levels of the pollutants from such vehicles during eventual practical use. Alcohol-operating vehicles have a large propensity to emit aldehydes (formaldehyde with methanol and acetaldehyde with ethanol), which are very active in local ozone production. The formaldehyde emission is of special concern because of its carcinogenicity. (Though the aldehyde levels can be controlled by oxidation catalysts, these catalytic converters become operational only after warming up which still allows significant release of pollutants in the case of automobiles.) In addition, the overall tropospheric ozone levels in an area can depend upon other factors such as its geography, the nature of the air pollution episode, as well as the ambient air levels of other gases (such as NO_x) participating in the ozone-forming reactions. As a result, the ozone producing potential of vehicles operating with alcohol fuels in different areas can be highly variable, though OTA concludes that alcohols do offer a potential for some reduction in urban ozone production (methanol more than ethanol) (OTA 1990). Generally speaking, the use of alcohols significantly reduces the CO, SOx, lead (as gasoline additive), and particulate emissions. Beyond the general air pollution issues, the toxic nature of methanol raises important health and safety issue relevant to its widespread use.

2.1.2 Gas: Natural gas, consisting mainly of methane, is usable directly and reasonably easily as a transportation fuel in IC engines. In fact, many countries have programs to run vehicles on natural gas (most noticeably Italy and New Zealand) to utilize their indigenous resources. Overall, there are about 700,000 natural-gas based vehicles on the roads worldwide (OTA 1990). Generally speaking, IC engines can be easily modified to run on natural gas, although to get optimal performance, it is preferable to use engines dedicated to, and designed for natural gas usage. The main drawback of natural gas is its low energy density. Therefore, its use as a fuel for vehicles necessitates its storage in a compressed form (CNG) or liquefied form (LNG). Despite the fact that CNG (at 3000 pound per square-inch) has an energy density of only about a fourth that of gasoline, it still accounts for almost all the current natural-gas vehicles. LNG, on the other hand, compares favorably with gasoline with an energy density of about 70% of gasoline, but the storage of natural gas in a liquefied form requires substantial and bulky insulation. Research is also underway on attempting to store methane through adsorption onto the surfaces of highly porous structures (adsorptents) (Sperling and DeLuchi 1989).

In terms of greenhouse gas emissions, natural gas-powered vehicles might offer a marginal benefit as compared to gasoline-powered vehicles. Higher efficiencies would probably be achievable with IC engines optimized for operation with natural gas (gains of up to 10%), but leakage of methane from the vehicles could offset these gains, especially given the higher greenhouse index of methane as compared to carbon dioxide (OTA 1990).

If the gaseous fuel is obtained by thermo-chemical conversion of lignocellulosic biomass, then it should be possible to obtain some reductions in overall greenhouse emissions (once again due to the utilization of carbon that is being fixed by plants through photosynthesis). However, if the transportation fuel is "synthesis" gas derived from coal gasification, significant increases in the overall greenhouse emissions could be expected due to the utilization of fossil carbon, as well as the energy utilized in the conversion process.

Natural (or synthesis) gas powered vehicles offer a bigger advantage in terms of reducing ambient air pollution caused by automobiles. Because of the gaseous nature of the fuel, it mixes well with the air in the combustion chamber, and therefore burns very efficiently and with no particulate emissions. Cold start problems are also avoided, thereby eliminating the major cause of CO emissions from vehicles. The absence of sulfur in the fuel also removes the possibility of SOx emissions. Methane is not photochemically reactive; therefore, the leakage of methane from the fuel tank does not contribute to the tropospheric ozone problem. Therefore in terms of local air pollution, the use of natural gas to power vehicles would offer significant benefits in comparison to gasoline (OTA 1990).

2.2 Non-Carbon Based Alternatives

Among the various alternatives to reduce CO_2 emission from automobiles, some technologies have been the focus of much attention and discussion because they have the theoretical potential to eventually eliminate the use of carbon as the basic pivot in the automotive energy cycle.

2.2.1 Electric vehicles: Of all the alternatives to the conventional automotive technology, electric vehicles have been receiving the most attention. Some of the reasons for this are obvious: there is a widespread distribution network of electric power supply that could possibly be used for recharging electric vehicles, and these vehicles do not cause any local air pollution. Probably the largest driving force for the recent widespread interest in electric vehicles is the urgent need for air pollution control in many urban areas. California has recently passed a law requiring that by 1998, 2% of the cars sold by any manufacturer in the state be zero-emission-vehicles (ZEVs), increasing progressively to 10% by 2003. ("Zero emission" is actually a misnomer in this case; a stricter description would be "zero local emission.") At present, the only technology that can feasibly satisfy this stipulation is the electric car. Such a shift towards severe pollution control is likely to become more common (along with markets for zero or low emission vehicles), at least for some urban areas in industrialized countries. In many other ways also, electric vehicles are ideally suited for the urban environment since they can be made very compact, and are not as wasteful as IC engines in stop-and-go traffic. Also, one of the biggest limitations of the electric vehicles, namely a limited range, should not pose a major problem for use in the urban environment.

One of the biggest drawbacks with most electric vehicles so far is that they have mostly been based on existing automobiles that were designed for IC engines. As an example, the first commercially available electric car from a major manufacturer, the Fiat Panda Elettra is derived directly from a petrol-driven Panda (Rogers 1991). Recently, though, has there been a major effort devoted to vehicles designed to be electric-based from the beginnings of the design process. This has resulted in pure-electric vehicles such as the GM Impact and the Nissan FEV.

The development of electric cars has significantly benefited from practical application of technologies such as DC/AC inverters that allow the use of high efficiency AC induction motors, and regenerative braking (OTA 1990, Sperling and DeLuchi 1989). Furthermore, there has also been a vast amount of research in battery technology, with a large number of options being evaluated (Appleyard 1992). In fact, finding a suitable battery with high energy storage, low cost and weight, and quick recharging is probably the biggest hurdle to electric car development. Though at the present time, lead-acid or nickel-cadmium batteries are the two major available options, technologies such as the sodium-sulfur battery (with three times the energy density of lead-acid) seem close to production. Future options with even better energy-storage capabilities such as the lithium-aluminum-iron-disulfide might be available within a decade (Howard 1992). Still, it is difficult to envision pure-electric cars as being anything more than urban vehicles in the near future, since even the highest energy-density battery options with a small car are likely to provide only a 200 kilometer range before recharging (Appleyard 1992). The possible widespread use of batteries in electric vehicles also raises questions about the environmental implications of their eventual disposal, especially for those containing elements such as sodium, lithium, and cadmium.

In terms of vehicle-use related pollution, examining the impact of pure-electric vehicles by themselves is misleading since these vehicles consume electricity that must be produced somehow. Even though the vehicle itself may emit no pollutants, there are significant emissions of both greenhouse gases and other air pollutants associated with the production of electricity. At present, 69% of the world's electricity generation is fossil-fuel based (coal 42%, oil 12%, and natural gas 15%) (Winje 1991). Coal-based generation generally leads to higher levels of pollutants than oil and gas. At present, the OECD member nations generate 43% of their electricity using coal, and only 8% using oil, and developing countries use coal-fired plants for 30%, and oil-fired plants for 22% of their electricity generation (Winje 1991). If electric vehicles were to rely on such an energy mix, it seems quite obvious that their use would still contribute to significant greenhouse gas emissions. Therefore, for electric vehicles to be truly zero or low emission, it becomes necessary to depend upon "clean" electricity production technologies that are themselves zero or low emission.†

2.2.1.1 "Clean" Electric Power Generation: This category encompasses a whole host of technologies that have been developed over the last few decades which can be divided into four major categories: nuclear, hydroelectric, wind and solar. Since the real greenhouse emissions reduction potential of electric cars is inexorably linked to the potential of clean electricity generation, a brief technical assessment of the four categories of clean generation processes follows.

2.2.1.1a Nuclear: At present, nuclear (fission) power accounts for 16% of the global electricity generation (Hafele 1990). A majority of the nuclear reactors currently in operation are light-water reactors which use ordinary water as a coolant, as well as to drive the turbines, although heavy-water reactors and gas-cooled reactors are also in use in some countries. Recent advanced reactor designs have focused on improved safety through better containment design, "passive" safety features (that independently prevent catastrophic failures without relying on immediate human intervention), and indirectly through simplified designs that allow easier and safer operation (OTA 1992, Hafele 1990). Fast breeder reactor technology to allow more efficient use of uranium has also been under development, but has not reached commercialization yet. Fusion-based nuclear technology has been the focus of significant research efforts in the past decades, but at present it is far from being applicable for power generation.

2.2.1.1b Hydroelectric: Hydroelectric generation is regarded as the quintessential clean electric power generation system since it relies on converting the kinetic energy of flowing

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† Of course, no source of energy is completely clean; the construction of the generation facilities necessary for any kind of electric power requires energy and materials. Generally, though, the CO_2 emitted during such construction represents only a small fraction of the CO_2 emissions saved over the lifetime of the clean power generation facility (Lysen 1990).

water into electricity through a simple turbine-based power generation system. In addition, hydroelectric systems can be very flexible in terms of their size, going all the way from gigawatts (large hydro) to less than 100 kilowatts (micro-hydro). Consequently, this is probably one of the best developed technologies for commercial generation of electric power, at present accounting for almost 20% of the world's electricity, over 2100 terawatt-hours (1 terawatt-hour = 10^{12} watt-hours) (Lysen 1990). Globally, there were over 36,000 dams with walls higher than 15 meters by 1986, more than a 7-fold increase since 1950. Almost two-thirds of these dams are in Asia, most of the rest being in Europe or the Americas (Economist 1992). Although the theoretical global potential for hydroelectric generation is much larger (Lysen 1990), such estimates often ignore practical issues such as costs and location (OTA 1992).

2.2.1.1c Wind: In recent years, wind power has slowly come of age. Already, in some parts of the world, it is beginning to make a significant contribution in terms of total power generation. For example, California generates 1.6 gigawatts (about 1.5% of its electricity needs) from windmills (Anderson 1991); in Denmark, over 1.5% of the national total power consumption is supplied by wind energy (Clarke 1991). A number of other countries are vigorously pursuing wind energy programs, including third-world countries like India (Clarke 1991). Recent developments in technology have dramatically improved the efficiency and the operating windows of windmills; improved blade designs, variable speed and transmission design, and overall improved reliability have quadrupled the performance of wind turbines in the past decade (Anderson 1991, Clarke 1991). This has allowed wind energy to be cost competitive with traditional sources of power generation such as coal. Further innovations in windmill related technologies (for example, using light polymer composite blades) should enhance their performance further. An added advantage of wind energy is that it can be utilized in many forms for many markets such as grid connected or stand-alone with the excess supplied to the grid due to the highly decentralized and independent nature of its production (Clarke 1991). Although there are some limitations on the proximity of windmills to each other, the overall area occupied by windmills on a wind farm is only about 1% (Clarke 1991). This allows the remaining land area on a wind farm to be utilized for other applications such as farming.

2.2.1.1d Direct Solar: It is possible to use solar power for producing electricity directly. In solar-thermal systems, this is carried out by using the sun's rays to heat a fluid to high temperatures, often using some kind of a reflector to focus the rays for enhanced efficiency. This fluid can then be used to turn water into steam that can drive the turbines for electricity generation. Most of the world's utility-scale solar power generation capacity is installed in California (about 0.160 GW), with generation plants reaching a 20-25% (solar-to-electric) average annual energy conversion efficiency (Lysen 1990). Despite the obvious appeal of such a technology, it has yet to find widespread use. Such a method of power generation is ideally suited for tropical countries that have strong sunshine almost all year round, especially for desert-like regions. In terms of land area, its requirements are not excessive. Photovoltaics (PVs) are another promising technology for converting sunlight directly into electric power. There has been an intensive research and development effort on this front in the past years, with the result that the price of photovoltaic-generated electricity has dropped a hundred fold in the past two decades, from about $30/kilowatt-hour to 30¢/kilowatt-hour (Charters 1991). With further developments, the price is expected to drop further, eventually making this option cost-competitive with other sources on the grid.

If clean electricity is to be used as an eventual power source for automobiles, probably the most effective way to do so would be to utilize the base load capacity that is generally available at off-peak hours. Unfortunately, these hours (generally at night) coincide with the times that the solar power facilities are inoperative. In fact, this is a general problem with solar or wind generated electricity; due to the variability in their supply, the tendency is to relegate them to a supplemental position in the power grid. Large-scale use of such power sources will almost certainly necessitate some kind of storage devices that are likely to increase the costs of the electricity from that source, although the amount of storage required often turns out to be surprisingly modest (Weinberg and Williams 1990).

An interesting set of alternative to pure-electric vehicles that are being explored are electric-hybrid vehicles i.e. vehicles that have electric motors along with an auxiliary power source (generally combustion-based engines) on board, and thus do not have to rely upon an external electric supply only to recharge the battery. Consequently, such vehicles have a much greater operational flexibility than the pure-electric vehicles. A parallel-hybrid design allows either the electric or the auxiliary system to drive the transmission, while in a series-hybrid combination, the auxiliary source provides power for the electric motor, which in turn drives the vehicle. This class of vehicles seems to hold substantial promise, and as a result, their commercial possibilities are being explored by many major automobile manufacturers. A particularly interesting implementation of the hybrid-vehicle idea is illustrated by Volvo's concept hybrid vehicle (ECC) which uses an on-board gasoline-driven high-speed gas turbine to constantly recharge the car batteries during travel; an electric motor drives the wheels (Simanaitis 1993). Since the gas turbine is decoupled from the transmission, it can be operated at a constant high speed, with an efficiency much higher than possible with traditional IC engines. Such a concept of a hybrid vehicle should be more likely to find use since it removes the sharp limits on the range of a pure electric vehicle, and still results in an ultra-low-emission-vehicle (ULEV); the Volvo ECC emissions easily meet the California ULEV standards (Simanaitis 1993).

2.2.2 Hydrogen: The combustion of hydrogen leads to no emissions beyond water and NOx (the latter being unavoidable since it is formed from the nitrogen present in the air used in the combustion process). Therefore, automobiles powered by hydrogen seem to offer a panacea (at least in theory) for almost all the environmental ills caused by the organic fuels in current use or under consideration. For this reason, there has been an increasing effort devoted to researching this technology (DeLuchi 1989).

There are some major hurdles on the path to practical utilization of hydrogen in vehicles, of which probably the biggest relate to the on-board storage of hydrogen. Space limitations prevent the storage of sufficient hydrogen gas on a moving vehicle even in a compressed form, since the molar density of hydrogen is very low (one-eighth of methane) (DeLuchi 1989). Currently more efficient methods of hydrogen storage are also being explored, especially in programs in Germany and Japan (DeLuchi 1989). One possibility is to store hydrogen in a liquefied form in an insulated tank at -253 °C, as in recent experimental vehicles developed by BMW and DFVLR (the German Aerospace Research Establishment) (Peschka 1986). However, the cryogenic requirements for liquid hydrogen pose problems in terms of requiring highly insulated fuel tanks, and boil-off during refueling. Another technology being explored is the chemical storage of hydrogen in the form of a metal hydride. Long-term tests on research automobiles (based on Mercedes-Benz vehicles) powered in such a fashion have demonstrated the feasibility of hydride storage (Feucht et al. 1988). This technology has drawbacks in that hydrides have a low volumetric energy density; consequently, only a very limited amount of hydrogen can be stored on-board in such a chemically bound fashion. There are also a variety of other storage methods that are being explored such as cryoadsorbents, liquid hydrides, and glass microcapsules with some limited success (DeLuchi 1989). At the present time, though, most of the on-board hydrogen storage schemes are still in various stages of development, and remain far from being implementable in a reliable and economical fashion on a large-scale. Though concerns have been raised about safety issues related to the use of hydrogen in automotive applications (especially with respect to hydrides), vehicles using hydrogen are not likely to be any more unsafe than their gasoline-powered counterparts (DeLuchi 1989) (which may not be a consolation to some people).

A different approach to use hydrogen to power automobiles that has been receiving considerable attention lately is hydrogen-based fuel cells as potential on-board electric generation system for electric vehicles (Lemons 1990, Appleby 1992). Fuel cells are basically electrochemical devices that convert the chemical energy of reaction into electricity in a very efficient, non-polluting fashion. In theory, these could offer the same performance as an IC engine with a comparable range and refueling time, but with twice the overall efficiency and much less pollution (Lemons 1990). There are a number of different fuel cells that could conceivably find application in automobiles, of which the main ones are the alkaline, the solid polymer (or proton exchange membrane (PEM)), and the solid oxide fuel cells. Since fuel cell technology is far from being mature at present, it is a matter of conjecture whether it can be successfully applied to automobiles, and if it can, which form would be most suitable. Although the alkaline fuel cell is already commercially available and has a very high energy density and efficiency, it has the major drawback of being intolerant of CO_2 in the reactants. Given the fact that air is generally used as one of the reactants, and the removal of CO_2 from air is very cumbersome, the alkaline fuel cells are constrained in their applicability. It may be possible to improve the alkaline technology to make it CO_2 tolerant (Appleby 1992). At present, it seems that such CO_2-tolerant alkaline fuel cells (if they are developed) or solid polymer fuel cells (if they are successfully commercialized) might present themselves as suitable candidates for eventual use in motor vehicles (DeLuchi and Ogden 1993). The solid oxide fuel cells may hold the potential for very high performance, but are still very much in the early developmental stages (DeLuchi and Ogden 1993). Most current fuel cells are based on the reaction of hydrogen and oxygen, and produce no chemical products other than water. For such fuel-cell-based electric vehicles, hydrogen would need to be stored on board (with the storage issues discussed above being relevant); as an alternative, it could be produced on-board by the reforming of methanol into H_2 and CO_2.

As in the case for electric vehicles, the direct CO_2 emissions from hydrogen-powered vehicles would effectively be zero, but the same cannot be said of the processes utilizable for the production of hydrogen. Large-scale production of hydrogen is most likely from an electrolytic fission of water. Therefore, the total pollution of greenhouse and other pollutants is tied to the electricity generation processes that are utilized to provide the energy for the hydrogen generation. As a consequence, hydrogen-powered vehicles would be truly pollution free during their operation only if clean electric power was used exclusively for the hydrogen production (as for electric vehicles).

The overall emissions reductions available from large-scale applications of the above-mentioned alternative fuels or technologies are still a matter of some conjecture. Estimates for such reductions are strong functions of the assumptions underlying the analyses, and different studies can yield wildly differing estimates for seemingly similar options. This is especially true of options such as ethanol, where the large variety of available production routes with large differences in process efficiencies can lead to completely different conclusions (compare, for example, Lynd et al. 1991, and Ho and Renner 1990). Therefore, instead of alluding to an alternative fuel in isolation, the ultimate source of the fuel and a specific production process must be defined in order to get a meaningful estimate of the CO_2 emissions reduction potential of the alternative. Even for a well-defined system, the uncertainty in the future projections of the current state-of-the-art can result in estimates that span a large ranges of values (Sperling 1991, DeLuchi 1993, for example). Despite all the uncertainty in the estimates, though, some overall trends are still apparent. After examining the options available as alternatives for powering automobiles, we find that the ones that could potentially offer significant relief from CO_2 emissions can be broadly divided into two classes on the basis of their primary source of energy: those that are derived from biomass, and those that require some form of clean electric power. As a result, large-scale implementation of the potential alternatives is certain to create a significant demand for biomass or clean electricity, which in turn is likely to raise other issues and concerns.

3.1 Biomass: Presently, advanced technologies to utilize biomass as a large scale source of energy for transport applications are close to commercialization, or at least reasonably well-developed. However, in simple economic terms, biomass-derived fuels are at a disadvantage when compared to fossil fuels for a number of reasons, the major one being that the traditional economic analyses rarely take into account the environmental and health externalities associated with the utilization of a resource. Furthermore, simplistic economic analyses based on the market price of petroleum miss an important consideration for the many LICs that do not have any significant domestic petroleum reserves, but face increasing demands for transportation fuels. Most often this necessitates the purchase of crude oil or refined products with borrowed foreign exchange. It is not uncommon for developing countries to quickly accumulate large debts, interest payments for which require refinancing through new loans. All of this can causes a spiraling debt burden on their economies. As a result, the real price of petroleum for many countries turns out to be far in excess of the simple market price. Fuels based on indigenous biomass could help ameliorate such a situation, at least in countries with suitable local resources.

The production of biomass-derived fuels is a highly labor-intensive industry. In fact, as the PROALCOOL program in Brazil demonstrates, both the agricultural and the production sectors employ large numbers of workers (Carvalho et al. 1979, Geller 1985). Furthermore, due to the nature of the Brazilian alcohol production system, the investment required per worker is much lower than in other traditional industrial sectors. Data from Brazil show that the oil refining-petrochemical complexes can require investment costs per worker of 10-20 times that in the ethanol production industry (Geller 1985). With the development of the micro-distilleries in Brazil, it was also possible to have a geographically well-distributed ethanol production industry. This offered the dual advantages of increasing employment in many parts of the country, as well as substantially reducing the transportation costs of the raw feedstocks. Advanced ethanol production processes have certain basic similarities with traditional starch or sugar fermentation processes; therefore, it might be expected that future ethanol production programs could be designed to carry over some of these attributes of the Brazilian model, especially since they might be particularly desirable for some developing countries.

On the down side, the use of biomass as fuel feedstock raises a number of not so favorable issues. Biomass-based fuel production raises the "food vs. fuel " issue. In most third-world countries, there is only a limited area of arable land available for cropping. In addition, in many of these countries this arable area is even decreasing, or becoming more marginal (although the exact magnitude of the problem of shortage of land in any given country also depends upon its population growth rate). On top of all this, in a number of third-world countries, the best croplands have been converted to cash crops rather than food crops for the local population. In fact, more than a quarter of the cropland in developing countries is devoted to cash crops; this situation is exacerbated by the fact that international organizations often fund programs to grow cash crops (Hall and De Groot 1985). All this contributes to a significant, and increasing, food shortage in many parts of the world. (It is projected that 64 countries might be unable to meet their populations' food needs by the end of the century (Dover and Talbot 1987)). If farming for transportation fuel feedstocks (whether for consumption in the domestic transport sector, or for exporting for cash) was also to compete with food crops for the limited area of available cultivable land, it is highly possible that the food problem in many parts of the world might be worsened. For countries with large amounts of land area, such an issue may not be that relevant, though that is more the exception than the rule. Also, for countries where the land is not particularly suitable for cultivation of food crops, but allows the cultivation of lignocellulosic biomass, fuel production from biomass may be a route to reduce the petroleum imports, and hence save foreign-exchange for importing food instead.

In many of the countries with the so-called "under-utilized" land (such as Brazil and some others in the tropics), another issue has recently caused significant concern. Very often, these undisturbed areas contain old-growth forests that are repositories of immense biological diversity, but have a fragile ecology. Rapid clearing of such areas for conversion to agricultural and other uses carries a heavy penalty in terms severe ecological disruption; these areas are also not very fertile and cannot support intense farming, necessitating a periodic shift to newly cleared lands. Overall, such practices results in significant deforestation, land degradation, and widespread ecological impacts.

Sugarcane-derived ethanol has been utilized extensively as a transportation fuel in Brazil, and ethanol produced from cellulosic biomass has been proposed as a large-scale transportation fuel for the United States (Lynd 1990, Lynd et al. 1991, Wyman and Hinman 1990). Though alcohol can be derived from excess biomass (such as ethanol from corn in the US currently or from conversion of waste cellulosic biomass such as municipal solid wastes and agricultural wastes in the future), such a supply of alcohol is bound to be limited. For example, the current US transportation energy consumption is in excess of 22 quads (1 quad = 10^{15} British Thermal Units = $1.054*10^{18}$ joules), while the estimated total production potential of the cellulosic wastes available from the agricultural, forestry and MSW sectors combined is about 3.8 quads (Lynd et al. 1991). In order to utilize ethanol produced from cellulosic biomass as a large-scale transportation fuel for the United States, large-scale farming would be required to provide suitable quantities of feedstocks. Theoretically, this is feasible for the US (or any other country with excess or potential cropland). It is suggested that the farming of perennial cellulosic energy crops might be more environmentally benign than conventional annual row crops (Lynd et al. 1991). In fact, biomass has been proposed as alternative energy source, not just for transportation, but for widespread substitution of traditional (fossil fuel) feedstocks for power generation to reduce global CO_2 emissions, with claims that this source could be tapped in some kind of a sustainable fashion (Hall et al. 1991, for example). In reality, this seems highly unlikely; a historical examination of natural resource exploitation illustrates that resources are eventually consistently overexploited for a variety of reasons (Ludwig et al. 1993). It is estimated that almost 2 billion hectares (17% of the Earth's vegetated surface) has suffered human-induced soil degradation in the last 45 years, of which over 1.2 billion hectares is considered to be moderately to extremely degraded. About 37% of the total degraded soils are attributable to deforestation and about 28% due to agricultural practices (World Resources 1992). In the past few decades, a spectrum of other problems associated with large-scale farming and forestry have also become more and more obvious (such as adverse human health and ecological effects due to pesticide applications, and contaminated groundwater supplies due to widespread fertilizer and pesticide use). Despite a recognition of these problems, there has been little movement towards farming techniques that are sustainable. It is difficult to imagine that a move towards utilizing bio-energy on a large scale could be carried out sustainably; on the contrary, it would be quite likely to result in significant adverse environmental and human health impacts.

3.2 Clean Electricity: Large hydroelectric facilities have been the cause of much public debate in the past decades due to the litany of serious problems associated with them (Biswas 1982, Goldsmith and Hildyard 1984). The flooding caused by large dams and reservoirs leads to very substantial environmental and health impacts such as inundation of land, salinization and waterlogging of surrounding areas, increased seismic activity, as well as introduction (or increased incidence) of water-borne diseases. In addition, the construction of these dams also often displaces indigenous peoples from their lands resulting in substantial social and cultural impacts. Dams also act as a barrier to the normal flow of silt in the rivers; this slowly fills up the reservoir causing loss of generating capacity, and also prevents deposition of silt downstream causing significant loss in the fertility of agricultural and other lands. Due to the strong opposition from environmental movements and local populations in both the developed and the developing worlds, large hydroelectric projects are generally becoming more and more controversial (current examples being projects in the James Bay in Canada, the Narmada Valley in India, and the Three Gorges in China). Consequently, large hydroelectric projects are not likely to play a significant role in expansion of clean electric power (Economist 1992, Swisher et al. 1993). Small and micro-hydro facilities have smaller adverse effects, but are more expensive due to the lack of economies of scale. In addition to the high capital costs, smaller hydro facilities are not grandiose, high-visibility projects and therefore often lack political appeal. Given all this, hydroelectric systems are likely to serve a useful, but only a limited role in the future as new primary sources of clean power.

In the case of nuclear energy, the safety and health issues involving the operation of nuclear reactors, transport and processing (and reprocessing) of nuclear fuels, and transport and long-term disposal of high-level nuclear waste have generated substantial public opposition in many countries. In Germany and Switzerland, there is a de facto moratorium on nuclear reactor construction, while a referendum in Sweden has indicated strong support for nuclear-free power generation by the year 2010, and in the US, there have been no new orders for nuclear reactors since 1978 (Hafele 1990). The concerns over proliferation of nuclear technology as well as the high capital costs of building nuclear power plants have also served to limit the utilization of nuclear power in many developing countries of the world. LICs such as Brazil, Mexico, Iran, and the Philippines have abandoned their nuclear programs for all practical purposes; the possibility of significant expansion of nuclear power in the LICs in the foreseeable future seems quite remote (Surrey 1988). Overall, then, it seems that the future of nuclear (fission) power is limited by a number of technological, social, institutional, and political hurdles; given the nature of some of these hurdles (such as effective international cooperation on nuclear issues), this future seems very difficult to predict, but does not seem very optimistic. Fusion-based nuclear power generation seems like a more desirable alternative in terms of many of the issues surrounding current fission-based systems, but it is far from being developed as a practically implementable technology, as mentioned earlier. Consequently, it would be unrealistic at this time to consider nuclear facilities as potential sources of large-scale clean electric power for the future.

Given this, additional clean electric power generation capacity is likely to be based mainly on wind or solar-power, at least in the foreseeable future. It is generally felt that the overall environmental and other concerns relating to these technologies are far lesser than other generation processes. (Serious concerns have been raised, though, about the environmental consequences of large-scale PV manufacture (Kuhne and Aulich 1992) especially since PV cells could be based on toxic materials such as arsenic.) In the past few decades, the economics of the renewable electric power generation (such as solar and wind power) have continued to become more and more favorable; at present, clean electricity from such sources is close to being comparable in cost to traditional power generation technologies even on simple economic terms. However, current economic pricing and market mechanisms do not take into account the externalities related to the energy sector (Hubbard 1991). For example, it has been estimated that the price of electricity from coal would need to be doubled to cover its environmental costs (Hohmeyer 1990, Flavin and Lenssen 1992). The economic pricing models must begin to take into account such calculations. In a similar vein, the conceptual idea of the "carbon tax" has been considered as a serious way to encourage technologies that allow abatement of CO_2 emissions. Implementation of such a tax would provide a strong boost to the commercial success of clean electricity production technologies (Flavin and Lenssen 1992), though such a tax rarely has broad spectrum political support, and is often strongly opposed by interest groups ranging from oil and coal producers to consumers.

The use of biomass-based alcohols to generate electricity in unpopulated areas (such that the production of aldehydes during their combustion will not pose a health risk) is another option to generate electricity using renewable resources, although once again the points raised earlier regarding the large-scale cultivation of biomass feedstocks must be kept in mind.

At present, more often than not, government policies in many countries still favor conventional technologies of power generation; this is true for countries as diverse as the US (Williams et al. 1990) and India (Hall 1991). For providing an impetus to the clean electric power generation technologies, these kinds of policies will need to be revamped, and government support for removing the institutional barriers impeding alternative technologies will need to be emphasized.

A common thread underlying many of the clean power technologies is that they tend to be heavily capital intensive. This is as true of the established technologies such as nuclear and hydroelectric as of the less utilized, but potentially implementable, clean technologies such as wind and solar power. For example, it has been estimated that the operating and maintenance costs expenses are less than 2% of the overall costs in the case of wind generation (Clarke 1991). Photovoltaics also suffer from this problem: they are a highly capital intensive (though low maintenance) power source (Charters 1991). The capital intensive nature of such technologies can prove to be particularly adverse for third-world countries which generally face a high cost of capital due to high interest rates and large debts. This sets up a dilemma in that the countries that are most likely to be rapidly expanding their electric generation capacity in the future are the least likely to be able to use the newer, less environmentally harmful generation technologies. A satisfactory solution to this dilemma will probably require some form of technology transfer, as well as favorable economic conditions for such technologies to be implemented on a large scale by developing countries. This in turn hinges upon considerable international cooperation, and significant foresight and long-term perspective on behalf of the developed and developing countries. This is not a trivial set of requirements; only the next few years will show if the North and South are capable of such joint actions. International lending institutions or multi-lateral banks are also likely to play an important role here.

Overall, a substantial replacement of traditional fossil-fuel-based generation systems by renewable- resource-based systems does not seem very probable in the near future, even for many industrialized nations. As an example, projections indicate that over the next 40 years, the current 8% contribution of renewables to the US energy supply is expected to only grow to 15-35% (Hartley and Schueler 1991).

4.1 Role of Alternative Fuels: Lignocellulose-derived ethanol using low-cost technologies such as enzymatic hydrolysis and subsequent fermentation seems to offer the best technical option among the biomass-based fuels in the near future. On the other hand, it seems clear that biomass-based options (especially if applied on a large scale) carry with them other significant pros and cons at the environmental and socio-economic levels. If applied prudently and on a limited scale (for example, such that waste biomass is used as a feedstock), such a low-capital option might be especially suitable for some LICs or NICs. Brazil's sugarcane-based ethanol program, which in some senses could be considered a precursor to possible lignocellulosic ethanol programs of the future, has shown some success in the wider perspective (Carvalho et al. 1979, Geller 1985).

Options such as electric vehicles might prove to be eminently suitable for urban use in a country like France, where over 80% of the electric generation is from nuclear sources (almost no CO_2 emissions), and there is a surplus of electric power. On the other hand, such an option, if implemented on a large scale does not make much sense for other countries where the fossil-fuel-based electric power generation is already a cause of significant local and greenhouse gas pollution. Maybe as some of the industrialized nations shift to greater renewable-resource based power-generation, electric vehicles could play a role in reducing the greenhouse gas contribution of the transportation sector. Realistically speaking, however, the scenario of a significantly increased fraction of electric power generation from clean sources is unlikely for many industrialized countries, leave alone the less affluent ones. Certainly, for LICs or NICs, a strong shift to renewable electric generation from sources such as wind or solar-thermal is highly uncertain because of its capital-intensive nature. In fact, such capital-intensive, low-labor industry may not even be desirable in many cases, given the low-capital, high-manpower distribution of resources in most LICs.†

Technologies based on hydrogen power (in IC engines or fuel cells) certainly offer some very desirable characteristics on paper, but their eventual implementation is still contingent upon a significant amount of innovation and development. At this time, it is highly unlikely that they will be commercialized for vehicular applications to any significant level in the next few decades. Therefore, these options are probably best relegated for mid-to-long term consideration. Furthermore, given the fact that these technologies need to evolve and mature substantially before they can be applied on a large-scale, it seems difficult to make accurate projections about their performance and economics, although there have been attempts to do so (for example, Plass et al. 1990, DeLuchi and Ogden 1993). Hydrogen utilization in automobiles also depends upon electricity for the fuel production; as for electric vehicles, in the absence of clean electric generation, a shift to hydrogen technology would still result in greenhouse gas (and other) emissions.

As we examine the main thrusts of automobile manufacturers in terms of alternative technologies, we find that currently the major area of development is electric cars. Almost all of the major manufacturers are falling over themselves to introduce electric cars, all the way from Japan to the US to Europe (the major driving force being the new requirements for selling cars in California's lucrative market). Since these cars are going to rely on the current energy mix (very little of which is based on clean sources), all that electric vehicles are likely to do mainly, as a result, is to transfer greenhouse gas and other pollution from areas of their use to areas of electric power generation. The other area of major research is flexible-fuel-vehicles (FFVs), i.e., vehicles that can run on pure gasoline or gasoline-

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† It should be kept in mind here, though, that importing crude or refined petroleum for powering the transport sector or for satisfying other energy requirements is already a constant cause of substantial financial burden for many LICs.

alcohol blends containing up to 85% alcohol. Although this seems like a very attractive option, in reality, it suffers from a major problem: FFVs offer a greater option in terms of fuel choice, but this comes at a significant cost to engine efficiency since these vehicles are not optimized for any of these fuel choices (Sperling 1990).

On the fuel suppliers' side, methanol appears to be the major alternative liquid fuel being proposed to replace gasoline in many parts of the US. The main motivation driving this change is the urgent requirement to deal with the ozone problem in many urban areas in the US which at present are in non-attainment of the air standards mandated by the Clean Air Act (OTA 1990). Methanol offers the major advantages of being a liquid fuel that can easily be distributed by the present fuel distribution system. The choice of methanol also eminently suits the petrochemical industry since synthesis from natural gas is the cheapest route to methanol. Therefore the petrochemical refiners are ideally placed to capture a significant share of the methanol market. Automobile manufacturers find methanol an acceptable option since IC engines need to be modified only somewhat to run on methanol. Interestingly, gasoline substitution by methanol may not even resolve the local air pollution problem for many of the urban areas (OTA 1990), leave alone tackle the global warming issue. An interesting possibility to promote desirable alternative fuels might be to get the automobile manufacturers involved in the production of such fuels; this should also provide an incentive for them to develop vehicles that might use such fuels.

Most of the alternative fuel programs currently existing or under development are either for utilizing indigenous resources (such as New Zealand's natural gas program, or Brazil's PROALCOOL program) or due to legislative pressures (such as the US Clean Air Act). The impetus for the development and implementation of alternative fuel programs to deal with air pollution has come almost exclusively from local air pollution issues (such as urban ozone). So in the end, it should not be surprising that the current major fuel alternatives have no effect on the greenhouse gas emissions from automobiles. As we expand our horizons to look at greenhouse and other environmental issues beyond urban air pollution, the whole spectrum of alternatives must be considered carefully since different fuels mean trading off between different environmental effects (within and outside the transport sector), as well as between environmental and economic considerations, and therefore might present very different criteria for successful implementation. No single alternative fuel can provide a panacea for greenhouse gas emissions as well as other environmental problems relating to the transport sector, even though fuel suppliers and automotive companies would like it to be otherwise (Sperling 1990).

4.2 Other Options: As the above discussion indicates, it is difficult to imagine alternative fuels offering by themselves a complete and sustainable solution to the greenhouse emissions from the passenger transport sector. Biomass-derived fuel or electric based options might be able to contribute to a limited extent, but it would be imprudent to rely only on these options for a solution, especially given the magnitude and the growing nature of the problem. Fortunately, although alternative fuels are among some of the most commonly considered options as possible solutions to the automobiles/global warming issue, they are by no means the only ones.

4.2.1 Improving automobile fuel efficiency: The CO_2 emissions from conventional-fuel operated automobiles can be directly reduced through an improvement of fuel economy of the vehicles in use. Recent years have seen the evolution of a host of design modifications that can significantly improve the fuel efficiency of automobiles, and therefore reduce the CO_2 emissions per vehicle-mile. Among these technologies, the more noteworthy are lean-burn engines (e.g., Honda's VTEC-E, and Mitsubishi's Vertical Vortex), 2-stroke gasoline engines (such as the Orbital), improved electronics for fuel management, advanced diesel engines, transmission improvements such as continuously variable transmission, use of lighter materials (such as aluminum and plastics), and aerodynamic body designs. Most of these technologies are incremental, but some can offer a dramatic potential for fuel savings; for example, the Volkswagen Golf Ecomatic has an electronically controlled diesel engine that shuts off when the car is standing still and restarts automatically when the accelerator pedal is depressed. In start-and-stop urban driving, this car offers a large improvement in fuel efficiency, with over 20% reduction in CO_2 emissions, and substantial reduction in other emissions as well (Frankel 1993). Some manufacturers have developed high-efficiency experimental prototypes (e.g., the Toyota AXV and the VW E-80) with highway fuel-economy of 100 or more miles-per-gallon (Bleviss 1990). Overall, it has been estimated that with implementation of the currently existing efficiency improving technologies, current carbon emissions in the transportation sector could be reduced by about a third (OTA 1992).

Unfortunately, these advanced technologies have been very slow to diffuse through the automotive industry since there is not much of an incentive for auto manufacturers to promote them in commercial vehicles, or for consumers to buy such vehicles (Hughes 1991). On top of this, the magnitude and the real costs of the environmental insults associated with the production and operation of automobiles are not completely measurable or even completely understood. Even though the choices of car buyers are eventually linked to these environmental effects, most of them are unconcerned or unmindful of the eventual effects of their choices. This manifests itself in consumption patterns such as a preference for higher vehicle performance over fuel efficiency, and for spacious, air-conditioned cars over simpler, smaller models. The automobile industry, of course, has no major problem with such a philosophy since larger, more luxurious cars are also more expensive and allow greater profit margins. As a result, many of the design improvements are applied towards increasing the performance of automobiles with almost no improvements in the fuel economy. For efficiency-enhancing designs to effectively contribute to fuel economy or other emissions reduction goals, research and development efforts that have been traditionally geared towards increasing the horsepower of automobiles, and designing high-performance vehicles need to be redirected towards the more desirable goal of improving the fuel economy while keeping the performance constant (or even lowering it to some reasonable level). Moving towards that goal requires a philosophical transition on part of the manufacturers and the consumers that is unlikely to come about on its own. Still, some automobile manufacturers are already beginning to rethink their philosophy in those terms. Honda, for example, has withdrawn after a long and highly successful career in Formula I racing to focus its engineering innovation on "green" issues (Yates 1992).

Experience with some countries has shown that strong regulations or market incentives can promote the production and use of smaller and more fuel-efficient cars. In the United States, the imposition of the CAFE standards is considered mainly responsible for almost a doubling of the new car fuel economy between 1974 and 1986 (Ross 1989) (though the road fleet average fuel economy is still about 20-30% less than many European countries (Schipper 1991)). The average fuel economy of vehicles on the road in Italy is almost 20% higher than the other major European countries (Schipper 1991); this is (at least partly) attributable to additional purchase tax being levied on cars with an engine displacement exceeding two liters, with the road tax being banded similarly (Hughes 1991). In Japan, market response to *kei* cars (current size: engine capacity less than 660 cubic centimeters, length less than 3.3 meters, and width less than 1.4 meters) has been directly related to the advantages (in taxes and otherwise) they enjoy over larger vehicles (Hughes 1991, Economist 1990).

Another possible regulatory option might be to raise the taxes on fuels, though a number of economic studies have indicated that to rely upon fuel taxes as a means for promoting the use of more efficient cars to reduce overall fuel consumption would require very substantial increases in such taxes (Jessup 1989). Fuel purchases generally make up a small fraction of the overall costs of operating an automobile; therefore with increasing fuel economy, consumers have a smaller economic incentive to buy fuel efficient cars (von Hippel 1983). Still, the price of gasoline does have a direct impact on the behavior of car users. The fewer vehicle-miles traveled per capita, as well as the greater popularity enjoyed by fuel-efficient cars in Europe (relative to the US) have been attributed at least in part to the significantly higher prices of gasoline in Europe (Metz 1991). Even within the US, the advent of stable, lower gas prices in the early 1980s can be correlated with a resurgence of consumer preferences for higher-performance, larger, and less fuel-efficient vehicles (Plotkin 1991).

The use of regulatory, economic and other incentive programs to encourage use of fuel-efficient cars seems to be crucial to modifying the behavior of both, the consumers as well as the automobile manufacturers. In the end, though, these programs are likely to be effective only if they provide unambiguous signals and do not allow circumvention through loopholes. For example, the size-based criteria for *kei* cars in Japan has led the manufacturers to develop engines small enough to qualify for that category, yet these engines produce horsepower comparable to that of bigger engines through the use of technology such as turbocharging. In the US, light trucks are not covered by the CAFE requirements; consequently the automobile manufacturers have been promoting the sales of such (inefficient) vehicles with great success. Light truck accounted for about a third of the total vehicle sales in 1990, up from 20% in 1976 (Bleviss 1990). Even when fuel economy levels are mandated, the manufacturers obtain the fuel consumption data under ideal, carefully controlled driving conditions that do not mimic the typical driving environment; these data, therefore, do not represent the fuel economy of the vehicle in normal use, but rather its most optimistic estimates.

It is often argued that taxes on fuel prices are regressive in that they have a relatively greater impact upon the less wealthy car-owners. This argument may have some truth to it, but low gasoline taxes send the completely wrong market signals to drivers; the real costs of using a resource must be borne by all users of the resource. Furthermore, uniform fuel taxes can be supplemented by a strong, progressive taxation scheme for automobiles based upon their horsepower (rather than the engine displacement) and the fuel economy.

Although there is a large gap in the efficiency of the high-efficiency concept cars developed by many automakers and the actual production vehicles in most countries, nowhere is this gap more painfully obvious than in LICs. In many of these countries, the automobiles presently in use are often outmoded and highly energy-inefficient. Although the payback periods for investments in efficiency-increasing technologies can be quite short, consumers may not often recognize this or have the necessary capital to indulge in them. Information and financing programs and other incentives might encourage greater acceptance of such technologies by consumers (Komor et al. 1993). Furthermore, since most of the efficiency-enhancing automotive technologies are developed in a few industrialized nations, their diffusion to LICs is also dependent upon suitable technology-transfer polices on the part of these countries, as well as multilateral financial institutions (Komor et al. 1993).

It must be kept in mind that while advanced automotive technologies (like many alternative fuel options) could reduce the emissions from the usage of motor vehicles, they do not reduce the number of the vehicles produced. The production of motor vehicles involves energy intensive processes, with their own associated greenhouse (and other) emissions. Though these emissions may not be as vast as those caused by the combustion of vehicle fuels, they are certainly not negligible, given the fact that each year over 30 million vehicles are being added to the global fleet (Faiz 1993).

4.2.2 Reducing Automobile Use: The issue of automobiles vis-a-vis global warming has two parts: the emissions per vehicle-mile, and the increasing numbers of vehicle-miles (the latter due to both increasing vehicle numbers and increasing travel). Most of the alternatives discussed above have a serious drawback in that they deal almost exclusively with the first part. In addition, some of these alternatives still need significant technological progress as in the case of advanced alternative fuels, or are stymied by problems of a non-technical nature as in the case of lack of implementation of fuel-efficiency improvements. However, significantly limiting the greenhouse gas emissions from automobiles hinges on a strategy that simultaneously confronts both parts of the problem. Attacking the second part of the problem (i.e., controlling the total numbers of vehicle-miles) is as (if not more) important.

At present, passenger transportation is heavily based on personal vehicles, with the overall degree of dependence (at a global level) growing inexorably. It is this pernicious trend that must be confronted if automobile use is to be controlled. Essentially, then, efforts to control the total number of vehicle-miles traveled entails a re-examination of the transport policies of the developed and the developing countries to decouple the concept of passenger transportation from the automobile (and other personal vehicles). This requires switching to more efficient modes of transportation, while providing disincentives for personal motorized transport.

In most of the LICs or NICs, the majority of the vehicles on the road are in urban and associated areas. Since many of these countries are still in the process of building their infrastructures, it is still possible for them to plan towards integrating a number of different modes of transport into their overall urban transport program such that personal vehicular traffic can be limited (OTA 1992). Mass-transit modes such as buses and light rails must be important components of such programs. They are far more efficient at transporting passengers than cars: considering direct energy use, and the indirect energy required for building the infrastructures associated with the respective modes (i.e., roads etc.), buses are ten times and light rails five times as efficient as automobiles (OTA 1992) with a concomitant reduction in the pollution associated with this energy use.† In addition, thetotal costs per passenger-mile for automobiles are two to three times higher than buses (OTA 1992). As also indicated earlier, beyond the issue of greenhouse emissions, the air pollution associated with urban vehicle use also poses health risks to large populations, as well as other significant environmental effects. Once again, this problem is likely to take on acute dimensions for developing countries with the rapid increases in motorization. It is estimated that 300-500 million people in developing countries will be exposed to unhealthy levels of pollutants by the year 2000 due to motor-vehicle caused emissions, unless significant pollution control measures are undertaken (Faiz 1993). Therefore, aggressive programs promoting mass transit should be an important component of any plan to limit the personal vehicular traffic in these areas. Such programs require careful planning, but can be very successful in curbing individual automobile use as has been shown in Curitiba in Brazil (Bleviss and Walzer 1990). The cost of installing the bus transit system in Curitiba was about 0.2% that of a subway (on a per mile basis), and it is operated without any subsidies (Worcman 1993). Even simple technologies such as bicycles can gain popularity and be effective as a means of efficient personal transportation, given the proper incentives as the Chinese experience has illustrated (Harral 1991).

Of course, the economies that have well-developed transportation infrastructures need to evaluate them critically, and focus on evolving their transportation policies to reap the benefits of switching to more efficient modes of personal transport. Unfortunately (without making sweeping generalizations) it is still probably fair to say that most of the

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† Though a detailed discussion is beyond the scope of this paper, it should be mentioned here that more efficient means of transportation can result in energy savings at all levels, not just passenger transport - for example, trains offer a much more efficient means of commercial transportation than trucking. It has been estimated that overall trains are twice as efficient as trucks in moving cargo (OTA 1992).

industrialized nations have shown no particular enthusiasm in embracing such a philosophy. On the contrary, technology-intensive programs such as intelligent vehicle highway systems (IVHS) seem to occupy a prominent position in the vision of the transportation future for many industrialized countries. Such programs, which are designed to reduce congestion, are certainly unlikely to mitigate the overall greenhouse (and other) emissions from automobiles. On the contrary, it is quite possible that increased ease in personal travel could lead to an increase in the total numbers of vehicle-miles traveled (Shladover 1993). It is imperative that the policy-makers in industrialized countries recognize the contradictions in such transportation policies, and adopt a more coherent approach. Out of necessity, planners in some cities in Europe are doing exactly this by limiting cars in crowded city centers. The most radical proposal comes from the city of Amsterdam in the Netherlands, where backed by a popular referendum, officials plan to gradually eliminate virtually all personal automobiles from the center of the city while expanding the mass transportation network as well as providing facilities to encourage bicycle use (Simons 1993).

Alternative modes of transport are likely to be more successful if at the same time concerted efforts are made to curtail personal automobile travel. This necessitates influencing the driving habits of car owners through policy tools such as high fuel prices and road and automobile taxes. Singapore provides an illustration of the judicious use of economic instruments such as high taxes on private vehicles and gasoline, combined with a strong encouragement for mass transit systems to manage the growth and use of personal vehicles (Tieng 1983) leading to savings in transport energy use (Ang and Oh 1988). Another successful example comes from the Philippines, where a number of measures were put into effect to increase the overall efficiency of the transportation sector. These included: a rail transit system for Manila, almost a doubling of fuel prices, higher fees for larger motors, and training vehicle maintenance workers. This actually caused a decline in the gasoline consumption between 1976 and 1985 by 43% while the population and the per capita income was increasing. In fact, if the consumption of gasoline per unit of GNP had been maintained at 1976 levels, the consumption of gasoline would have been more than 300% higher in 1985 than it was (Kats 1988).

4.3 Global Outlook: Adopting innovative transportation policies to introduce more efficient vehicles on the road, and to limit the number and use of automobiles and other motorized personal transportation on the roads allows for, above and beyond reducing greenhouse gas emissions, greater economic efficiency, improved resource utilization, and reduced local air pollution and its associated health effects. Overall, these options seem to offer greater flexibility and potential than the choices among the current alternative fuels. It makes sense to start considering such policies very seriously without depending solely upon future developments in alternative fuels.

At present, OECD countries are responsible for about 70% of the global CO_2 and about 75% of the global CO, HC and NOx emissions from motor vehicles; the analogous contributions from the developing countries are about 22% and 15% respectively for these sets of pollutants (Faiz 1993). This translates to per capita CO_2 emissions from the OECD nations being fifteen times those from the developing nations. In addition, the contribution to CO_2 emissions from transport in the industrialized nations is likely to be far in excess of the rest of the world for quite some while.[†] If one looks at the time-cumulative emissions

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[†] Transport energy consumption grew annually at about 2.5 % in OECD countries in the period 1973-1988, and approximately 4.8 % in developing countries between 1971 and 1988 (Grubler et al. 1993). For a rough analysis, we assume that over the near future, the average growth rate for industrialized countries will be 1.5 % (probably an optimistically low estimate, even accounting for potential implementation of efficiency improvements etc.), and that the trend for the developing countries stays constant. It can also be assumed that the carbon emissions from transport scale with the energy consumption. A quick calculation shows that it is only in 2025 that the annual transport energy consumption of all of the developing world combined will approximately equal that of the OECD nations. At that time the per capita transport energy consumption in the industrialized world would be about seven times that of the developing world (taking into account the projected populations for 2025).

from automobiles, the picture begins to look even more ludicrously unbalanced. Therefore, in terms of any debate about mitigation of the greenhouse gas emissions from the transport sector, it is obvious where the discussion should begin. Aside from the global warming issues, policy makers in the industrialized nations should also start thinking of transportation in the same terms as the rest of the energy sector, where there has been a gradual realization that conservation through increased efficiency and use reduction is highly effective, in both economic and environmental terms. Furthermore, the major automobile manufacturers must realize that their access to the global markets is going to become more and more contingent upon small, fuel-efficient cars. Traditional luxury manufacturers such as Mercedes-Benz and BMW have already started moving in this direction.

It is true that the LICs and NICs are in the process of building their infrastructure, and should be able to effectively plan their development for the future in terms of their transportation needs. Unfortunately, being able to indulge in plans based on broad and long-term assessments is generally the luxury of the wealthy. The policy-makers in LICs and NICs are often (though obviously not always) uninterested in investing their resources in programs that have diffuse, long-term benefits, and generally the people who would benefit the most from such programs have the least say in their design. It is difficult to say what the practical solution to this extremely complex problem might be, especially since these countries are making their infrastructure development choices now. Still, it is encouraging to see that many of the recent examples of successful implementation of innovative transportation programs come from LICs or NICs.

It is clear that any significantly successful approach to the automobiles/global warming problem would be one that is multi-faceted in that it does not depend exclusively on one set of solutions, and also deals with both parts of the issue (i.e., reduces the greenhouse gas emissions per vehicle-mile, but also curtails the numbers of vehicle-miles traveled). For greatest effectiveness, a whole set of complementary options must be drawn upon, commensurate with the needs of different countries, and even different regions within a country.

In the end, the success of any alternate fuel or passenger transportation program depends upon its widespread acceptance by the consumers. Strong and clear incentives are needed for consumers to accept any new transportation programs, whether they involve alternate fuels, promotion of efficient cars, or different modes of transportation. It is also crucial to gain the confidence of the consumers, which in turn can depend to a large extent upon the explicit, long-term support of the government (as illustrated by Brazil's ethanol program). Governments have also played a wider role in most transportation programs through regulatory or market-based incentives or direct intervention. In fact, significant government involvement is necessary for the introduction and subsequent success of any successful transportation program, given the generally large scale of such programs, the diffuse nature of their benefits (especially relating to the pollution-related externalities that are seldom captured by open markets), and the variety of issues that are involved in their implementation. In addition, government procurement programs could also be utilized to provide support for desirable options (such as fuel-efficient vehicles, for example).

Although alternative fuels are being given serious consideration for tackling the global warming and other environmental issues related to passenger transportation, it seems clear that currently available options are applicable mainly for a few selected scenarios rather than on a global scale, and even then primarily for local air pollution issues only. Widespread application of some potential alternative fuels could conceivably reduce the greenhouse and other emissions from the transport sector, but technologies related to their production and utilization at a commercial level still need significant innovation. Commercial application of these fuels would also involve a number of other significant environmental and social impacts that should not be ignored.

Beyond alternative fuels, a number of additional options (such as increasing the efficiency within a given mode of transportation, and switching to more efficient modes) are presently available to policy-makers that could serve as tools to effectively tackle the greenhouse emissions problem from automobiles. Most of these options do not suffer from any major technological constraints, and very importantly, also offer the possibility of ameliorating other problems (such as local air pollution, traffic congestion, high costs per passenger-mile, and inefficient resource utilization) related to personal automobile use. It is this potential to simultaneously deal with the many facets of transportation-related issues that makes these choices particularly interesting and useful.

Waiting for scientific consensus on a problem as complex as global warming before attempting to tackle it could be catastrophic; scientific consensus for prevention of resource over-exploitation has historically seldom been achieved in time to save the resource, if at all (Ludwig et al. 1993). Therefore, in terms of practical action, the best strategies for CO_2

abatement are likely to be those that also fulfill other desirable objectives (van Gool 1989) in the face of the uncertainty that surrounds the long-term effects of the increased concentrations of CO_2 in the atmosphere. In this sense, the passenger transport sector offers an almost unique possibility since an integrated approach can allow us to tackle the more immediate, often acute, problems that grow out of its current configuration based heavily on petroleum-driven personal automobiles, while also reducing its not insignificant greenhouse gas emissions. Unfortunately, such an approach to simultaneously tackle environmental and other issues related to automobiles is rarely undertaken. In contrast, the relevant transportation policies often seem to take a piecemeal approach, tackling one issue at a time. This is not only undesirable in terms of lack of efficiency, but also needless in terms of no lack of common solutions. The sooner an integrated and consistent approach to these issues is undertaken, the better it will be.

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