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THE IMPORTANCE OF FUEL CELLS TO ADDRESS THE GLOBAL WARMING PROBLEM

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Introduction: overview of the problem

During the last decade petroleum supply disruptions and cost increases sent a shock wave through the world which dramatically accelerated interest in more efficient motor vehicles. The need for remedies became a high priority for many countries and investigations were initiated into possible alternative fuels, new technologies and use of highly efficient conventional approaches. As the crises passed, oil prices dropped and interest in these alternatives for energy reasons dwindled; at the same time interest began to increase for environmental reasons. This is especially true for motor vehicles.

Motor vehicles, using petrochemical fuels, emit significant quantities of carbon monoxide, hydrocarbons, nitrogen oxides, fine particles and lead, each of which in sufficient quantities can cause adverse effects on health and the environment. Because of the growing vehicle population and the high emission rates from these vehicles, serious air pollution problems have become an increasingly common phenomenon in modern life. Initially, these problems were most apparent in center cities but recently lakes and streams and even forests have also experienced significant degradation. As more and more evidence of man made impacts on the upper atmosphere accumulates, concerns are increasing that motor vehicles are contributing to global changes which could modify the climate of the entire planet [1 - 8].

In an effort to minimize the motor vehicle pollution problem, emission rates from cars have been limited since the 1980s. Starting in 1975, the pace of control was accelerated with the introduction of catalytic converters on cars in the United States. Initial oxidation catalysts have been replaced by three way converters which can lower carbon monoxide, hydrocarbons and nitrogen oxides simultaneously and increasingly this technology is being applied to vehicles all across the world. Catalytic technology using platinum is now routinely applied to vehicles in Austria, Australia, Canada, Federal Republic of Germany, Japan, Netherlands, South Korea, Sweden, Switzerland, and the United States. Within the next few years, Brazil, Mexico and Taiwan along with most of Europe are scheduled to join their ranks.

The primary impetus for these controls to date has been concerns regarding tropospheric or low level pollution. However, evidence now shows

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that control of CO, HC and NOx is also important for reducing the risk of global warming.

With regard to carbon dioxide emissions which are also important in this regard, serving as a blanket to trap heat close to the planet, very little progress is occurring. The governmental push of the late 1970s and early 1980s toward improved vehicle fuel efficiency has stalled and market competition now appears to be focused primarily on performance improvements rather than fuel economy gains. Since consumption of each gallon of gasoline results in about 6 pounds of carbon (C) or 22 pounds of CO_2, it is easy to see why CO_2 overall is increasing. As illustrated in Fig. 1, based on projected increases in vehicles and their use around the world, motor vehicle CO_2 emissions will skyrocket over the next forty to fifty years. Modest efficiency improvements on the scale of 1% per year would barely reduce this growth. Most observers would agree that motor vehicles already play a significant role in local, regional and global environmental problems and have the potential to play an even greater role in the future. In addition, vehicles are the major consumer of increasingly scarce oil throughout the world. The purpose of this analysis is to examine their role in these problems and likely future directions. It will show that these problems are directly linked; more vehicles leads to more vehicle miles travelled which leads to more oil consumption and more local and global air pollution. Further more global air pollution especially global warming will exacerbate local and regional pollution problems and vice versa.

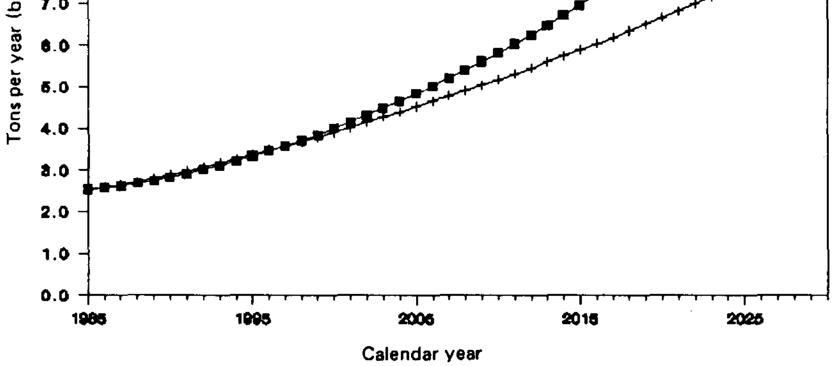

Fig. 1. Global motor vehicle CO_2 emissions, assumed 2% annual VMT growth: ■, constant efficiency; +, 1% annual m.p.g. gain.

First, the next section will assess the important greenhouse gases and the current significance of vehicle emissions. Then, historical and likely future trends in vehicles and their use will be summarized. Finally, the potential benefit from increased use of fuel cells in the transport sector will be summarized.

The role of the motor vehicle in climate modification

Important greenhouse gases

Important greenhouse gases include carbon dioxide (CO_2), CFC 11, CFC 12, methane (CH_4), nitrous oxide (N_2O), ozone (O_3) and the compounds which cause ground level ozone to form, hydrocarbons (HC) and the oxides of nitrogen (NOx). On a global level, each of these gases has been increasing.

As noted in the WMO report [9]:

"The concentrations of halocarbons, methane, nitrous oxide (N_2O), odd nitrogen and carbon monoxide appear to be increasing at present on a global basis, by 5% per year for CFC 11 and CFC 12, 7% per year for CH_2CCl_3, 1 percent a year for CH_4, 0.2% per year for N_2O and 1 to 2% per year for CO."

Concentrations of ground level ozone are increasing, and stratospheric ozone is being destroyed globally. During the Antarctic spring a 'hole' the size of North America is depleted of ozone and, at certain altitudes, is destroyed almost completely because of man made chemicals [10]. Researchers who recently reanalyzed a European data set on tropospheric ozone concentrations from the turn of the century concluded that ozone concentrations had doubled over the past 100 years [11]. One commentator described the finding "as remarkable as the observation of a hole in the stratospheric ozone layer over Antarctica and potentially is just as consequential" [12]. An analysis of several sites indicates that tropospheric ozone background levels are increasing at a rate of 1 to 3% per year with overall NOx increases the controlling factor [13].

Likely effects of climate modification

Over the next fifty years, increasing concentrations of tropospheric ozone and other greenhouse gases are projected to increase the global average temperature between 1.5 and 4.5 °C. Changes likely to accompany this temperature increase include stratospheric cooling; global mean precipitation increase; reduction of sea ice; polar winter surface warming; summer continental dryness; high latitude precipitation increase; and, rise in global mean sea level. Most of these changes should occur gradually (*e.g.*, EPA's recent estimate that average sea levels will rise 5 to 15 inches above current levels by 2025 [14]) if events develop as anticipated; however, the Antarctic ozone hole experience reinforces the anxiety that is associated with any such significant and poorly understood phenomena because of the risk that chemical modifications once initiated may proceed at a faster rate than anticipated.

Carbon monoxide also plays a role

Some of these compounds react with each other in ways only recently understood. For example, hydroxyl radicals (OH) which scavenge many anthropogenic and natural trace gases from the atmosphere, are themselves removed by carbon monoxide [15, 16]. As summarized by Ramanathan recently [17]:

"The highly reactive OH is the primary sink for many tropospheric gases and pollutants including O_3, CH_4, CO, and NO. Hence, increases in CH_4, such as those during the last century [135% increase] could have caused a substantial (20 to 40%) reduction in OH, which in turn, could cause an increase in tropospheric O_3 by as much as 20%. Since CH_4 oxidation leads to the formation of H_2O, an increase in CH_4, an important greenhouse gas, can lead to an increase in H_2O in the stratosphere. Likewise, an increase in the CO concentration can tie up more OH in the oxidation of CO. Thus, through chemical reactions, an increase in either a radiatively active gas such as CH_4 or even a radiatively inactive gas such as CO can increase the concentration of several important greenhouse gases."

Thus carbon monoxide emissions are very important for climate modification. This point was reinforced by MacDonald in a recent analysis:

"Carbon monoxide could thus be indirectly responsible for increasing greenhouse warming by 20 to 40% through raising the levels of methane and ozone. Carbon monoxide participates in the formation of ozone, and also in the destruction of hydroxyl radicals, which are principal sinks for ozone and methane greenhouse gases. Because carbon monoxide reacts rapidly with hydroxyl, increased levels of carbon monoxide will lead to higher regional concentrations of ozone and methane. Measures to reduce carbon monoxide emissions will assist in controlling greenhouse warming." [18]

This is especially significant in view of the evidence that *global* CO levels are now also increasing. As recently noted by Khalil and Rasmussen:

"the average tropospheric concentration of CO is increasing at between 0.8% and 1.4% per year, depending on the method used to estimate the trend, and the 90% confidence limits of the various estimates range between 0.5% and 2.0% per year." [19]

Motor vehicles emit many of these gases

Motor vehicles generate more air pollution than any other *single* human activity. Hothouse gases emitted by (or attributable to) motor vehicles include CFCs, carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and the precursors to ground level ozone, hydrocarbons and nitrogen oxides [20].

CFCs. These are the most potent hothouse gases, now contributing about 15 to 20% of the total global warming effect. About 40% of the United States production of CFCs and 30% of European production is devoted to air conditioning and refrigeration. Mobile air conditioning accounted for 56 500 metric tons of CFCs, 28% of the CFCs used for refrigeration in the United States, or about 13% of total production. In contrast, home refrigerators accounted for only 3800 metric tons [21]. Thus, approximately one of every eight pounds of CFCs manufactured in the U.S. is used, and emitted, by motor vehicles. (CFCs are also used as a blowing agent in the production of seating and other foamed products but this is a considerably smaller vehicular use.)

Carbon dioxide. CO_2 is the other major hothouse gas. A single tank of gasoline produces between 300 and 400 pounds of CO_2 when burned. Overall, the transport sector uses approximately 56 quads of energy each year. The consumption varies considerably between regions of the world, with the U.S. far and away the largest consumer, using over 35% of the world's transport energy. Transport consumes almost one thrid of the total energy consumed in the world, again highly variable by region. It is important to note the already significant proportion of energy consumption by transport in many rapidly developing areas of the world.

Because of this high overall energy consumption, it is not surprising that motor vehicles emit over 1100 Tg of carbon, approximately 25% of the world's output [22].

CO, HC and NOx. During 1987, transportation sources were responsible for 40% of U.S. nationwide lead emissions, 70% of the CO, 34% of the volatile organic compounds (HC), 45% of the NOx and 18% of the particulate. In some cities, the mobile source contribution is even higher. Even these contributions do not include the impact of 'running losses', gasoline vapors emitted from the vehicle while it is driving. Accounting for these emissions, the vehicle contribution rises significantly. Including running losses, the overall contribution of transportation to total nationwide HC emissions rises to approximately 50%.

Motor vehicles also dominate the emissions inventories of most European countries, as well. OECD recently noted that,

> "The primary source category responsible for most NOx emissions is road transportation roughly between 50 and 70%... Mobile sources, mainly road traffic, produce around 50% of anthropogenic VOC emissions, therefore constituting the largest man made VOC source category in all European OECD countries." [23]

Beyond the U.S. and Europe, Table 1 shows that, for OECD countries as a whole, motor vehicles are the dominant source of carbon monoxide, oxides of nitrogen and hydrocarbons [24].

These pollutants cause other adverse effects

Many of the same pollutants which cause or contribute to global warming, also contribute substantially to adverse health effects in many individuals, in addition to harming terrestrial and aquatic ecosystems, causing crop damage and impairing visibility. Some of these other effects will be described below.

TABLE 1

Motor vehicle share of OECD pollutant emissions (1000 tons, 1980)

Pollutant	Total emissions	Motor vehicle share
NOx	36019	17012 (47%)
HC	33869	13239 (39%)
CO	119148	78227 (66%)

Tropospheric ozone

Photochemical smog results from chemical reactions involving *both* hydrocarbons and nitrogen oxides in the presence of sunlight. While historically the major strategy for reducing smog has focused on tight restrictions on hydrocarbon emissions, NOx control is also necessary. As recently noted by a prominent researcher in this field:

"Recent research results from our research group indicate there is a critical need to consider controls on *both* nitrogen oxides and reactive hydrocarbons if overall oxidant levels are to be lowered... A critical implication of these findings is that without controls on nitrogen oxides the current control policies will simply change the urban ozone problem into a regional scale one." [25]

The ozone problem is a special concern. First, the problem is widespread and pervasive and appears likely to be a long term problem in many areas of the world unless significant further controls are implemented. For example, over 100 million Americans currently reside in areas which exceed the current air quality standard [26, 27]; many of these individuals suffer eye irritation, cough and chest discomfort, headaches, upper respiratory illness, increased asthma attacks, and reduced pulmonary function as a result of this problem.

In addition, the current air quality standard tends to understate the health effects. For example, as noted in testimony before the U.S. Congress in 1987 by EPA, new studies indicate:

"that elevated ozone concentrations occurring on some days during the hot summers in many of our urban areas may reduce lung function, not only for people with preexisting respiratory problems, but even for people in good health. This reduction in lung function may be accompanied by symptomatic effects such as chest pain and shortness of breath. Observed effects from exposures of 1 to 2 h with heavy exercise include measurable reductions in normal lung function in a portion (15 - 30%) of the healthy population that is particularly sensitive to ozone." [26]

Other studies presented at the recent U.S. Dutch Sumposium on ozone indicate that healthy young children suffer adverse effects from exposure to ozone at levels below the current air quality standard [28]. Numerous studies have also demonstrated that photochemical pollutants inflict damage on forest ecosystems and seriously impact the growth of certain crops [29].

It is important to note that global warming may have a significant impact on local ozone air pollution episodes. As recently pointed out by the American Lung Association:

"the increase in ultraviolet D radiation resulting from even a moderate loss in the total ozone column can be expected to result in a significant increase in peak ground based ozone levels." The ALA continued, "these high peaks will occur earlier in the day and closer to the populous urban areas in comparison to current experience, resulting in a significant, though quantitatively unspecified, increase in the number of people exposed to these high peaks." [30]

Further, tropospheric ozone is a greenhouse gas. Ozone absorbs infrared radiation and increased ozone concentrations in the troposphere will contribute to climate modification.

Carbon monoxide

Exposure to carbon monoxide results almost entirely from motor vehicle emissions. (In some localized areas, wood stoves also significantly affect CO levels.) While there has been progress in reducing ambient CO levels across Europe, Japan and the United States, the problem is far from solved. For example, approximately 35 major metropolitan areas in the U.S. with a population approaching 30 million currently exceed the carbon monoxide air quality standard. In fact, EPA indicated in Congressional testimony (February 1987) that as many as 15 areas in the U.S. may have intermittent carbon monoxide (CO) problems that could prevent attainment for many years [26].

The CO problem is important because of the clear evidence relating CO exposure to adverse health effects. For example, in a recent assessment conducted under the auspices of the Health Effects Institute, it was concluded that:

"These findings demonstrate that low levels of COHb produce significant effects on cardiac function during exercise in subjects with coronary artery disease." [31]

Further, in another recent study of tunnel workers in New York City, the authors noted:

"Given the magnitude of the effect that we have observed for a very prevalent cause of death, exposure to vehicular exhaust, more specifically to CO, in combination with underlying heart disease or other cardiovascular risk factors could be responsible for a very large number of preventable deaths." [32]

In addition, as noted earlier, recent evidence indicates that CO may contribute to elevated levels of tropospheric ozone [18].

Oxides of nitrogen

NOx emissions from vehicles and other sources produce a variety of adverse health and environmental effects. NOx emissions also react chemically with other pollutants to form ozone and other highly toxic pollutants. Next to sulfur dioxide, NOx emissions are the most prominent pollutant contributing to acidic deposition.

Exposure to nitrogen dioxide (NO_2) emissions is linked with increased susceptibility to respiratory infection, increased airway resistance in asthmatics, and decreased pulmonary function [33]. While most areas of the U.S. currently attain the annual average national air quality standard, short term exposures to NO_2 have resulted in a wide ranging group of respiratory problems in school children (cough, runny nose and sore throat are among the most common) as well as increased sensitivity to bronchoconstrictors by asthmatics [34, 35].

The World Health Organization concluded that a maximum 1 hour exposure of 190 - 320 micrograms per cubic meter (0.10 - 0.17 ppm) should be consistent with the protection of public health and that this exposure should not be exceeded more than once per month. The State of California has also adopted a short term NO_2 standard, 0.25 ppm averaged over one hour, to protect public health.

Oxides of nitrogen have also been shown to affect vegetation adversely. Some scientists believe that NOx is a significant contributor to the dying forests throughout central Europe [36]. This adverse effect is even more pronounced when nitrogen dioxide and sulfur dioxide occur simultaneously. Further, nitrogen dioxide has been found to cause deleterious effects on a wide variety of materials (including textiles dyes and fabrics, plastics, and rubber) and is responsible for a portion of the brownish colorations in polluted air or smog.

Acid deposition results from the chemical transformation and transport of sulfur dioxide and nitrogen oxides. NOx emissions are responsible for approximately one third of the acidity of rainfall. Recent evidence indicates that the role of NOx may be of increasing significance with regard to this problem:

"Measurements of the nitrate to sulphate ratio in the atmospheric aerosol in southern England have shown a steady increase since 1954. The nitrate content of precipitation averaged over the entire European Air Chemistry Network has steadily increased over the period 1955 to 1979. The nitrate levels in ice cores from South Greenland have continued to increase steeply from 1975 to 1984, whilst sulphate has remained relatively constant since 1968. The 'Thousand Lake Survey' in Norway has recently revealed a doubling in the nitrate concentration of 305 lakes over the period 1974, 1975 to 1986, despite little change in pH and sulphate." [37]

Several acid deposition control plans have targeted reductions in NOx emissions in addition to substantial reductions in sulfur dioxide. Furthermore, the ten participating countries at the 1985 International Conference of Ministers on Acid Rain committed to "take measures to decrease effectively the total annual emissions of nitrogen oxides from stationary and mobile sources as soon as possible". [38]

Conclusions

Motor vehicle emissions of HC, CO and NOx, therefore, can be seen as a major source not only of climate modification but also of adverse health and other environmental effects from ground level pollution. In addition, tropospheric pollution and climate modification have been found to be directly linked by a variety of mechanisms. To deal with these problems in a coordinated fashion requires the minimization of carbon monoxide, carbon dioxide, hydrocarbons, nitrogen oxides and chlorofluorocarbons.

On a global scale, emissions of these pollutants depends on the number of vehicles in use and their emission rates. In turn, their actual emission rates depend on their fuel efficiency and their use of control technologies which are available.

Increased population and economic activity in the future holds the potential to increase the problem. Whereas the number of people in Europe and the U.S. is increasing slowly, the global population is expected to double (compared to 1960 levels) by the year 2000, driven by more than a doubling in Asia and an almost 150% increase in Latin America. Beyond the overall growth in population, an increasing portion of Asia's and South America's people are moving to cities, driving up the global urban population. One result is that global automobile production and use are projected to continue to grow substantially over the next several decades.

The Toronto conference on global warming which took place last year concluded that in the short term, *i.e.*, over the next 15 years, global CO_2 reductions in the order of 20% will be necessary to restrain global warming; over the longer term, reductions of approximately 50% *from current emissions rates* appear necessary to stabilize the global climate. Experience gained during the 1970s and 1980s in the U.S. suggests that the dual goals of low emissions (CO, HC and NOx) and improved energy efficiency (and therefore lower CO_2) are not only compatible but mutually reinforcing as illustrated in Fig. 2. However, continuing air pollution and the emergence of the global warming phenomena, indicate that it is now time to look for the next technological leap forward.

Fuel cells: the energy/environment solution [39 - 52]

Fuel cell technology is essentially just a battery, using an external supply of fluids as its energy source, and solids to separate those fluids, connected to an electric motor. Unlike a battery, however, a fuel cell does not run down or require recharging; it will operate as long as both fuel and oxidant (oxygen in air) are supplied to the electrodes and the electrodes remain separated by the electrolyte. The electrodes act as catalytic reaction sites where the fuel and oxidant are electrochemically transformed, producing d.c. power, water, and heat. Since fuel cells are not limited by Carnot's theory of heat engines (as are all conventional engines), their potential efficiency is much greater.

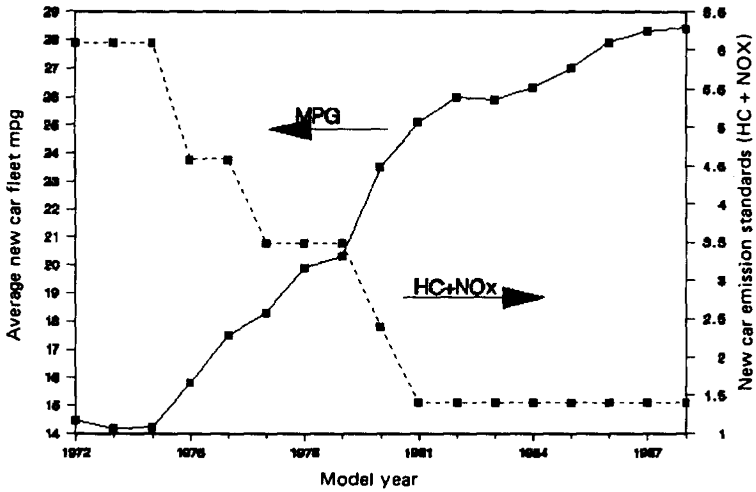

Fig. 2. U.S.A. emissions and fuel economy trends.

Studies have demonstrated that fuel cells have the potential to approximately double vehicle fuel efficiency. Less fuel consumption for the global fleet is the real key to lower CO_2 emissions. This energy conservation can take the form of less miles driven per vehicle per year, or less total vehicles, or more efficient vehicles; ultimately it will probably require some combination of each.

At the same time, fuel cells have the potential to substantially lower if not eliminate some of the conventional pollutants. For example, NOx production is due to interactions between the oxygen and nitrogen in the air at high temperatures; since fuel cells operate at much lower temperatures than conventional combustion engines, they should emit less NOx. Hydrocarbon production is mainly due to incomplete combustion; fuel cells do not rely on combustion, except in auxiliary systems which produce warm gases which are recycled into the system.

Potential impact of fuel cells on CO_2 emissions

Figure 3 shows the likely trend in fuel consumption by the worldwide vehicle fleet over the next forty years under alternative growth scenarios and based on current vehicle fuel economy trends. Based on historical trends, global VMT growth of at least 2% per year is likely. Should this occur, Fig. 4 shows the potential impact on global CO_2 emissions from the vehicle fleet.

Figure 5 illustrates the potential impacts of several alternative strategies to address this concern. It shows that a 1% annual improvement in new vehicle fuel efficiency starting in 1990 can start to *reduce the rate of growth in carbon dioxide emissions but is not sufficient to reverse the trend.* Alternatively, conversion of 1% of the new vehicle fleet by the year 2000 to

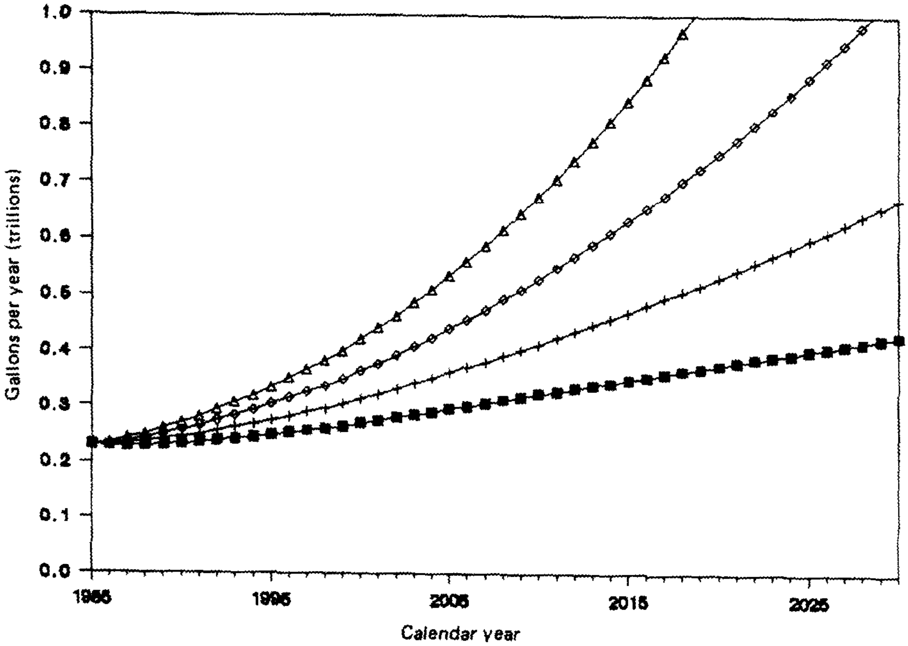

Fig. 3. Global auto fuel consumption, alternative VMT growth rates: ■, no growth; +, 1% growth; ◇, 2% growth; △, 3% growth.

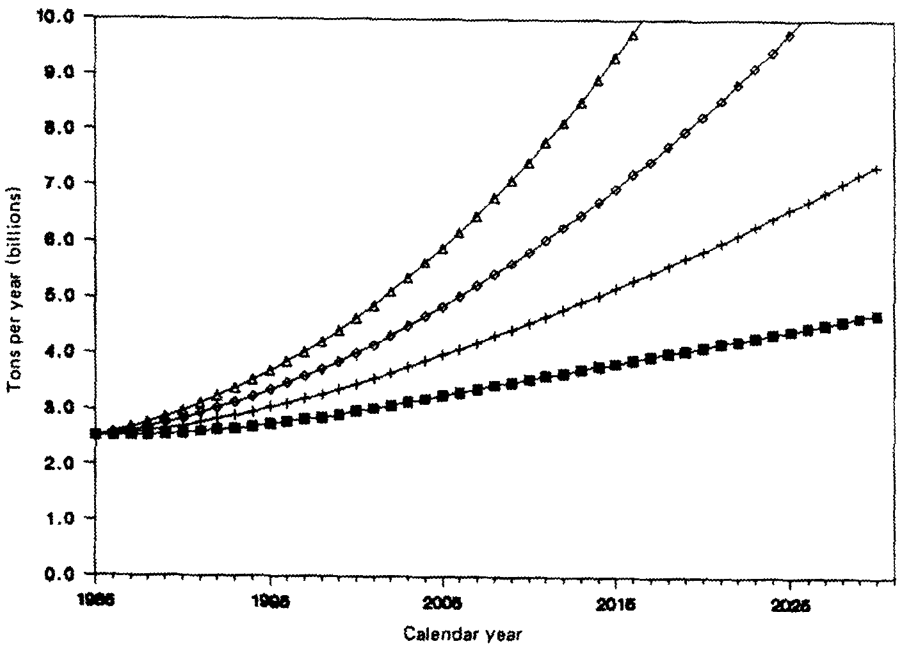

Fig. 4. Global auto CO_2 emissions, alternative VMT growth rates: ■, no growth; +, 1% growth; ◇, 2% growth, △, 3% growth.

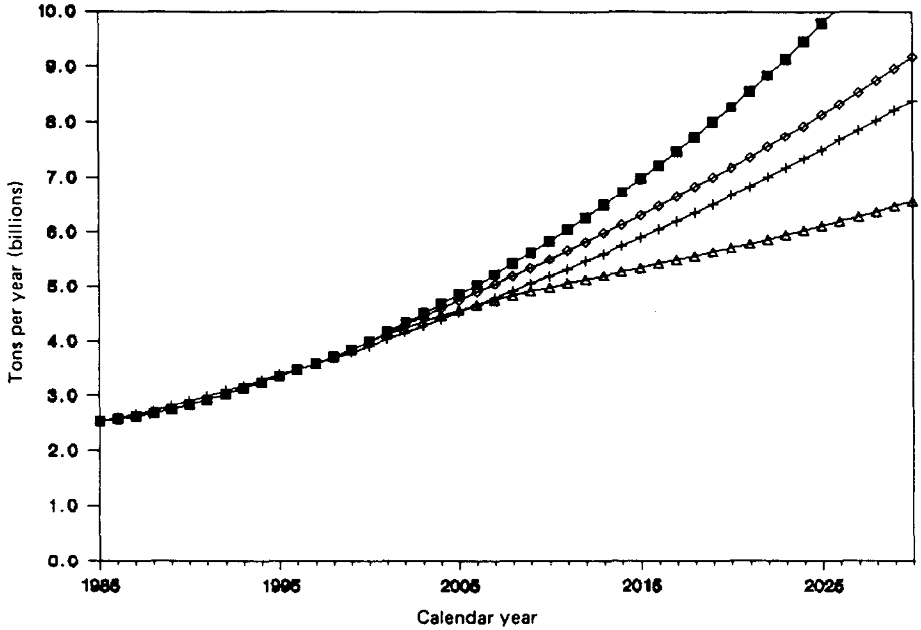

Fig. 5. Global auto CO_2 emissions, alternative strategies: ■, base; +, 1% efficiency gain; ◇, 1% fuel cells; △, 3% fuel cells.

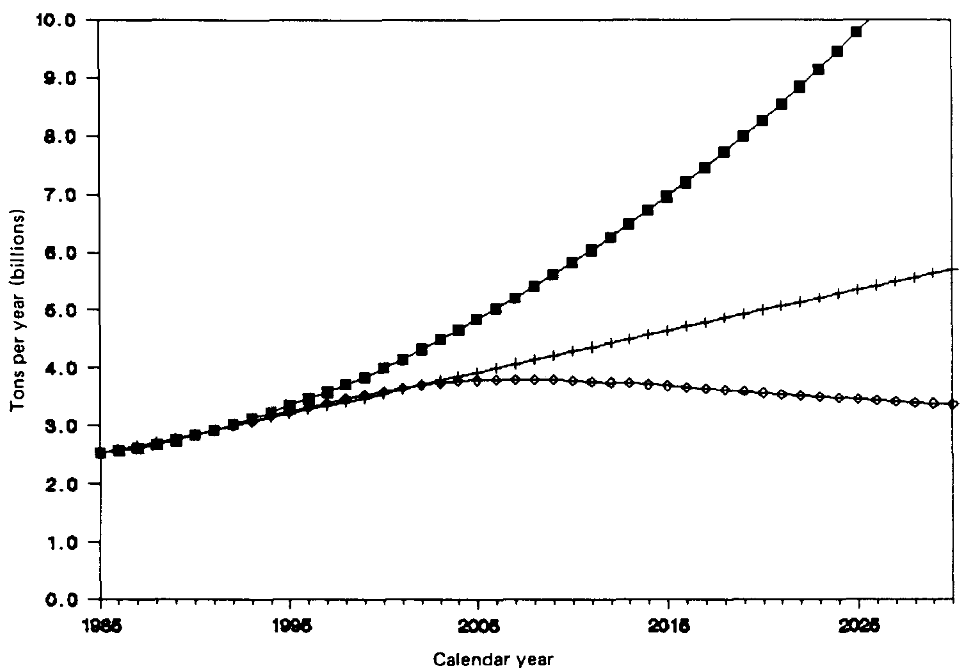

Fig. 6. Global auto CO_2 emissions, combined strategies: ■, base; +, 2% efficiency gain; ◇, 3% fuel cells.

operate with fuel cells, increasing at a rate of 1% per year after 2000, can also start to lower the rate of growth in CO_2 emissions. If this rate of conversion could be increased to 3% per year, the overall impact would be even more substantial. However, none of these strategies alone are sufficient to overcome expected vehicle growth.

Figure 6 shows the potential impact of a combination of strategies. Specifically, if 'conventional' new vehicles were to improve at a rate of 2% per year starting in 1990 and 3% of the fleet were to convert to fuel cells and achieve twice the efficiency of conventional vehicles starting in the year 2000, it would be possible to actually start to reduce the global CO_2 remissions from the global vehicle fleet.

The overall policy to address air pollution and global warming

The correct policy to minimize local and global environmental problems from vehicles in the future would have the following elements.

(1) Stringent emission standards for CO, HC and NOx such that all new vehicles sold around the world are equipped with 'state of the art' catalytic emissions controls. This state of the art should continue to move toward lower and lower levels. In the short term, at a minimum, these levels should be no higher than those already adopted by the State of California. Longer

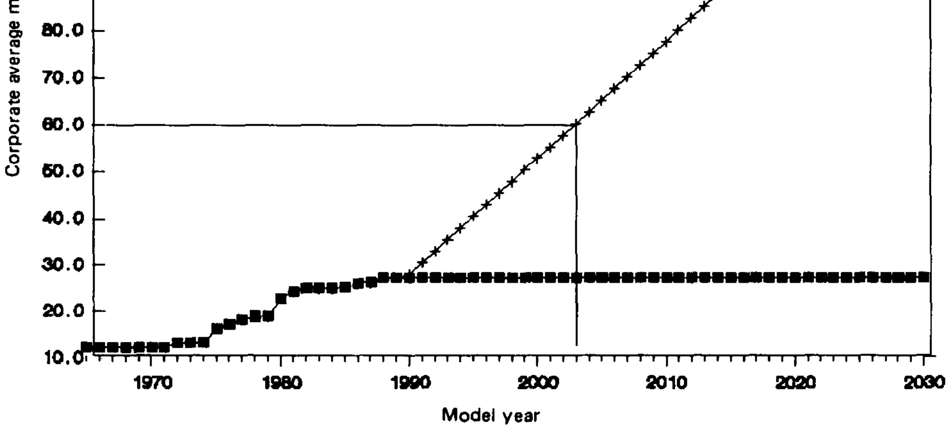

Fig. 7. CAFE requirements to achieve CO_2 target compared to 1988 base: ■, base m.p.g.; +, improved m.p.g.

term, even lower levels should be mandated as advanced technologies such as fuel cells enter production.

(2) Carbon dioxide standards which will be sufficient to lower global fleet emissions by 20% in the short term and 50% in the longer term (taking into account not only the direct emissions but also the emissions associated with the entire extraction, manufacture and distribution of the fuel). As shown in Fig. 7, for the U.S. this likely means fuel efficiency levels for gasoline fueled cars approaching 60 m.p.g. by the year 2000 and 125 m.p.g. by 2030.

Fuel cells clearly have great potential to play a significant role in addressing both these objectives and therefore should be receiving much greater attention. While energy concerns should continue to be a major motivation, local, regional and global air pollution concerns may be an even more significant reason to aggressively pursue this advancement.

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