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The Passenger Car and the Greenhouse Effect

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ABSTRACT

Concern is mounting over the possibility of global warming from the greenhouse effect. Carbon dioxide from the combustion of fossil fuel is a major greenhouse gas, and automobile exhaust is one of its contributors. The only way to decrease carbon dioxide emissions from a car consuming carbonaceous fuel is to decrease its fuel consumption. The best alternative fossil fuels offer a carbon dioxide reduction of about 20%. Without introducing any new greenhouse-gas controls, it is projected that the total greenhouse-gas contribution of the average car will be halved from recent levels just through fleet turnover and already planned elimination of the current air-conditioning refrigerant. If global warming develops into a serious problem, cars can be operated without fossil fuel. Leading options include battery-electric cars using nuclear power and engine-propelled cars burning biomass-derived alcohol or hydrogen extracted from water with solar cells or nuclear power.

A TRANSPARENT SHIELD of tropospheric greenhouse gases encompasses the earth. This layer of trace gases intercepts a fraction of the infrared radiation redirected skyward from the earth and reflects it back to the earth's surface, keeping our world at an inhabitable temperature averaging 288 K (59 F). Without the warming effect of that reflected radiation, the average temperature of the earth would be 253 K (-4 F). The greenhouse gases of significance include water vapor (occurring naturally and not a global-warming concern), carbon dioxide, methane, nitrous oxide, and CFCs (chlorofluorocarbons). A review of sources of the gases of concern aids in understanding the greenhouse effect.

Combustion of fossil fuels is the principal anthropogenic source of carbon dioxide. That makes engines burning gasoline and diesel fuel one of the prime targets for countering the possibility of global warming.

An estimated 40% of atmospheric methane comes from natural sources [1] -- oceans and lakes, wetlands and tundra, termites and other insects, and the digestive tracts of wild animals. Methane sources attributable to human activity include natural gas and mining losses, rice paddies, biomass burning, solid waste, and the digestive systems of domesticated animals like cattle.

Most nitrous oxide (N_2O) comes from the action of bacteria in the soil [1]. Some has been attributed to the use of nitrogen-based fertilizers, and fossil-fuel combustion is another source. N_2O is not to be confused with the NOx emitted from automotive vehicles, which is not a significant direct contributor to global warming.

All CFCs are attributable to human activity. Insofar as the automotive industry is concerned, the traditional uses of CFCs have been as the refrigerant in air conditioners, and in making foam cushions, degreasing parts, and cleaning microelectronic components.

Although the earth would be uninhabitable without the greenhouse protection of water vapor and the historic inventory of carbon dioxide, human activity has been adding new carbon dioxide and other greenhouse gases at a rate that has triggered alarm. The expectation is that if greenhouse-gas concentration in the atmosphere becomes excessive, the increased earthward reradiation of infrared energy will cause additional global warming. Atmospheric modelers have projected that a doubling of carbon dioxide, expected to occur by the middle of the 21st century, would cause an average global-temperature increase of 1.5 to 4.5°C [2]. It has been estimated that this could cause a rise in sea level on the order of 1 m, alteration of climatic patterns, changes in distribution of precipitation, and major agricultural dislocations. Some scientists fault the models for inappropriately treating feedback mechanisms that moderate warming tendencies and point out that recent temperature measurements fail to show evidence of global warming. Other scientists in turn fault the measurements for being unreliable. The present purpose is not to judge the validity of global-warming predictions, but rather to review the relationship of the automobile to the mounting concern about possible global warming.

Within the U.S., 32% of the carbon dioxide derived from fossil-fuel combustion comes from the transportation sector, with the balance attributable to electric utilities, manufacturing, and residential and commercial use [2]. In 1987, automobiles consumed about 40% of the national transportation energy budget, with trucks and buses accounting for another 33% [3]. Accepting the approximation that carbon dioxide produced in these applications is proportional to energy consumed, cars were responsible for about 13% of this carbon dioxide inventory, with trucks and buses accounting for another 11%.

In 1986, 24% of the worldwide emission of carbon dioxide from fossil-fuel combustion was attributed to the U.S. [4]. In the decade of the 1980s, carbon dioxide was charged with 49% of the greenhouse-gas contribution to global warming [2]. It follows from all these estimates that U.S. passenger-car engines are responsible for about 1.5% of the world's anthropogenic contribution to global-warming potential, with another 1.2% being charged to U.S. trucks and buses. Thus it can be argued that draconian steps to decrease the carbon dioxide from U.S. highway vehicles cannot have much effect on global climate change. On the other hand, however, no single source nor geographical location dominates the total contribution of anthropogenic greenhouse gases, so none should escape scrutiny.

To put the carbon dioxide produced by fossil-fuel combustion into perspective, consider the following identity:

$$CO_2 = \frac{\text{carbon dioxide}}{\text{technology}} \times \frac{\text{technology}}{\text{population}} \times \text{population} \qquad (1)$$

The first term on the right side of Eq. 1 is the technology factor considered in the present work. The second term is a socio-economic characteristic. It reflects the historically evident urge for people to upgrade their standards of living at a rate paced by their economic well being. The third term accounts for population growth, which is a cultural matter. The second and third terms lie outside the scope of this paper. What Eq. 1 shows is that just to stabilize the addition of anthropogenic carbon dioxide to the atmosphere would require technology to improve at a rate sufficient to counteract worldwide population growth and the aspirations of people to increase their quality of life.

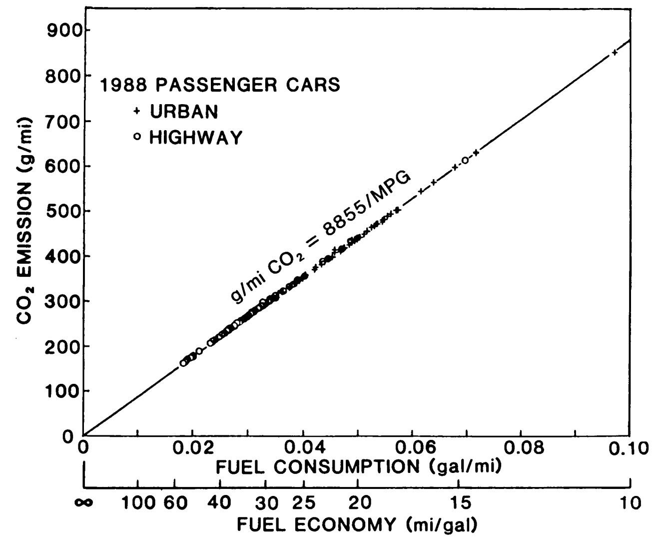

Fig. 1 - Carbon dioxide emissions from gasoline-fueled cars as a function of fuel consumption.

In dealing with the technological aspects of this issue from the viewpoint of the automobile, the relationship between carbon dioxide and fuel economy is first reviewed. Then the significance of fuel choice is explained. Next the role of CFCs from car air conditioners is examined. Finally, two opposite extremes to the control of automotive greenhouse-gas emissions are considered -- the "laissez-faire" strategy, in which no special effort is initiated specifically to counter the possibility of global warming, and the "ban-fossil-fuel" strategy, in which global warming is judged to be so serious that the use of petroleum, natural gas and coal must be terminated.

CARBON DIOXIDE AND FUEL ECONOMY

For a specified fuel containing carbon, tailpipe carbon dioxide emissions are inexorably tied to fuel consumption. In Fig. 1, carbon dioxide emitted on the EPA driving schedules is plotted against fuel consumption in gal/mi for 86 different gasoline-fueled cars from the 1988 model year. The crosses are for the urban schedule, the circles for the highway. The car, the engine, the transmission, the driving schedule -- none of those matter. The g/mi of carbon dioxide is seen to be directly proportional to fuel consumption. (It should be noted that in the following discussion, emissions are treated on a per car basis, as they are in regulations. Changes in vehicle-miles traveled lie outside the scope of this treatment.)

For those more accustomed to the inverse of consumption, namely fuel economy in mi/gal, that parameter is shown on the scale along the bottom of Fig. 1. This scale makes a point. Suppose a 25% reduction in g CO_2/mi is sought in a car averaging 15 mi/gal. That calls for a 5-mi/gal increase in fuel economy, to 20 mi/gal.

In a more fuel-efficient car averaging 30 mi/gal, however, that same 25% reduction in carbon dioxide requires a 10-mi/gal increase in fuel economy.

The data points of Fig. 1 fall along the line,

$$\text{g } CO_2/\text{mi} = 8855/(\text{mi/gal}) \quad (2)$$

The constant of 8855 is typical of gasoline. For an engine operated on diesel fuel, the expression becomes

$$\text{g } CO_2/\text{mi} = 10{,}000/(\text{mi/gal}) \quad (3)$$

Primarily because of the greater density of diesel fuel, for a specified fuel economy, a car operated on diesel fuel emits more carbon dioxide. However, the superior thermal efficiency of the diesel engine overcompensates for this fuel characteristic, so a typical diesel car emits less carbon dioxide than a comparable car with a gasoline engine. This topic is dealt with in greater detail subsequently.

The historical trend in average carbon dioxide emissions from the U.S. new-car fleet is shown in Fig. 2. As driven on the EPA combined urban and highway schedules, the output of carbon dioxide has been halved over the last 15 years.

EFFECT OF THE FUEL

The carbon dioxide emission can be expressed as

$$\frac{\text{g } CO_2}{\text{mi}} = \frac{EICO_2}{\text{mi/gal}} \times \frac{\text{kg fuel}}{\text{gal}} \quad (4)$$

where $EICO_2 = CO_2$ emission index (g CO_2/kg fuel). The CO_2 emission index of a fuel is an inherent characteristic of its chemical composition.

$EICO_2$ OF HYDROCARBONS - Representing gasoline or diesel fuel as C_mH_n, and assuming complete combustion of a stoichiometric mixture,

$$C_mH_n + (m+n/4)O_2 + 3.76(m+n/4)\ N_2 \Rightarrow \quad (5)$$

$$mCO_2 + (n/2)\ H_2O + 3.76(m+n/4)\ N_2$$

Introducing the molecular weights of appropriate species,

$$EICO_2 = \frac{44{,}000}{12 + (n/m)} \text{ g/kg fuel} \quad (6)$$

The hydrogen/carbon ratio n/m varies only within a range of about 1.5 to 2.0 for commercial gasolines, with most gasolines centered somewhere between those extremes. From Eq. 6, then, $EICO_2$ for commercial gasolines should vary within ±2% of the mean.

Eq. 6 was developed for complete combustion of a stoichiometric mixture. If the mixture is lean, the expression is still valid because the excess oxygen cannot affect the production of carbon dioxide, since there is no extra carbon with which it can combine. If the mixture is diluted with exhaust gas rather then excess air, Eq. 6 is similarly unaffected. If the mixture is fuel-rich, then some of the carbon is tied up in carbon monoxide, and carbon dioxide production is decreased. Considerations of fuel economy and exhaust emissions discourage rich operation, however.

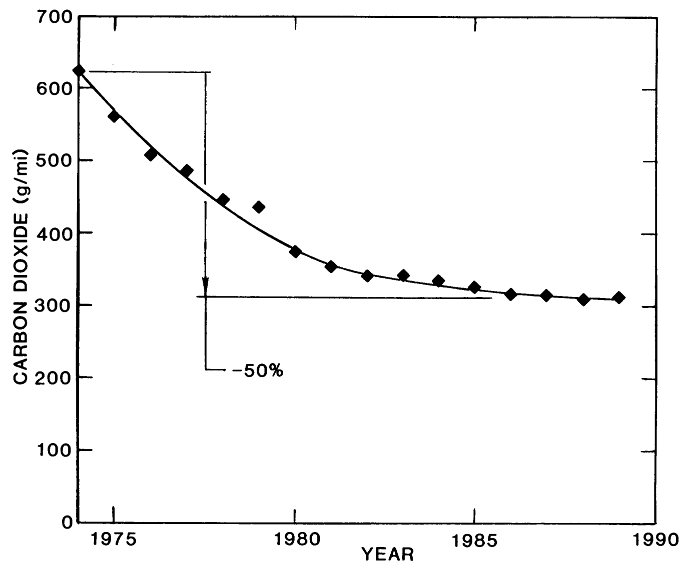

Fig. 2 - New-car fleet-average carbon dioxide emissions from U.S. passenger cars.

Eq. 6 is predicated on complete combustion, but the fact that emission standards are necessary for unburned hydrocarbons and carbon monoxide underscores the existence of incomplete combustion. Consider a contemporary car operated at current emission standards of 0.41 g/mi HC and 3.4 g/mi CO. Assuming an average HC-emission composition of propane, that amounts to 0.34 g/mi of carbon tied up in unburned HC. The CO contains 1.46 g/mi of carbon. If the resulting 1.8 g/mi of carbon had been converted to CO_2 instead, the associated carbon dioxide would have amounted to 6.6 g/mi. This is only 2% of the 322 g/mi of CO_2 emitted by a car averaging 27.5 mi/gal.

Gasoline and diesel fuel are blends of many different liquid hydrocarbon compounds. An interesting question is to what extent the individual hydrocarbon compounds affect production of carbon dioxide. Eq. 6 can be used to compare them on an emission index basis, but it is important to recognize that insofar as the effect on the environment is concerned, there is more to the question than emission index alone. This broader perspective is treated subsequently.

The curve of Fig. 3 shows $EICO_2$ as a function of atomic carbon-hydrogen ratio. This

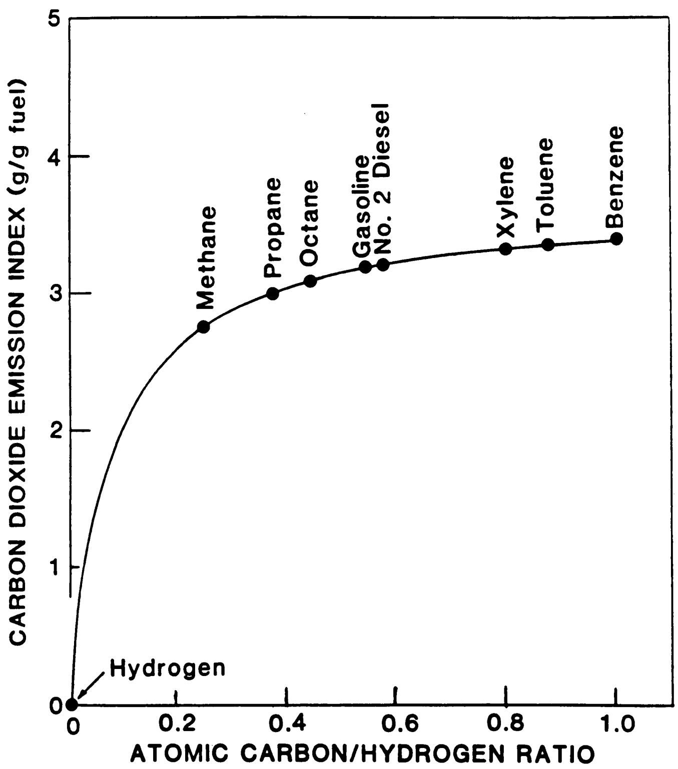

Fig. 3 - Carbon dioxide emission index of hydrocarbon fuels as a function of atomic carbon/hydrogen ratio.

inversion of the hydrogen-carbon ratio used above allows hydrogen to be included as the limiting case. With respect to production of carbon dioxide, hydrogen is the perfect fuel, of course, because its combustion produces no CO_2.

Selected hydrocarbons are spotted along the curve of Fig. 3. Typical gasoline, with a H/C ratio of 1.85, has an $EICO_2$ of 3177 g/kg fuel. Typical number 2 diesel fuel, with a H/C ratio of 1.75, has a slightly higher $EICO_2$ of 3200. Benzene, with a H/C ratio of 1.0, is the poorest of the hydrocarbons, having an $EICO_2$ of 3385. The most common gaseous fuels are natural gas, which is typically 90+% methane, and LPG, which is mostly propane. Methane and propane are seen to have lower emission indices than the liquid hydrocarbons. It is interesting to note that the maximum possible variation in $EICO_2$ for hydrocarbon fuels, as represented by the ratio of benzene to propane, is 1.23. The emission indices of the fuels marked in Fig. 3, along with other relevant properties, are provided in Table 1.

$EICO_2$ OF OXYGENATES - Complete stoichiometric combustion of the common alcohols can be represented by

$$C_mH_{n-1}OH + \left(m + \frac{n}{4} - \frac{1}{2}\right)O_2 + 3.76\left(m + \frac{n}{4} - \frac{1}{2}\right)N_2 \Rightarrow$$

$$mCO_2 + \frac{n}{2}H_2O + 3.76\left(m + \frac{n}{4} - \frac{1}{2}\right)N_2 \qquad (7)$$

Recognizing that for the simple alcohols (methanol, ethanol, propanol, butanol), n = 2m + 2, Eq. 7 yields

$$EICO_2 = \frac{22{,}000}{7 + (9/m)} \qquad (8)$$

In Fig. 4, the emission index curve for the alcohols from Eq. 8 is added to the hydrocarbon curve of Fig. 3. Points are also shown for MTBE (methyl tertiary butyl ether) and ETBE (ethyl tertiary butyl ether), two additional oxygenates of current interest. On an emission index basis, all of these oxygenates show an advantage over gasoline in terms of production of carbon dioxide, but emission index is only one of the essential considerations. Emission indices of the oxygenates considered are listed, along with other relevant properties, in Table 1.

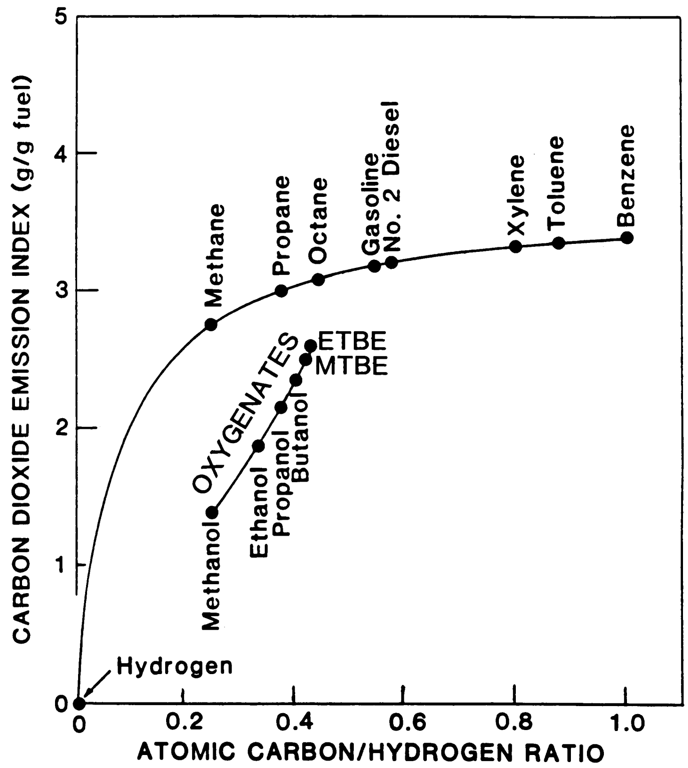

Fig. 4 - Comparison of carbon dioxide emission indices for oxygenated fuels and hydrocarbon fuels.

ENERGY-SPECIFIC CO_2 - For a more realistic assessment of the propensity of a fuel as it resides in the vehicle fuel tank to form tailpipe carbon dioxide, its energy content has to be considered. This involves its $ESCO_2$ (energy-specific carbon dioxide) in g CO_2/MJ, where the appropriate energy factor is the lower heating value (LHV) of the fuel.

$ESCO_2$ is plotted against atomic C/H ratio in Fig. 5 for the fuels of Fig. 4.

TABLE 1 - PROPERTIES OF SELECTED FUELS

	Atomic H/C	Lower Heating Value (MJ/kg)	Density at 20°C (g/mL)	Octane MON/RON	CO_2 Emission Index (g/kg fuel)
Hydrogen	∞	120.02	--	--/--	0
Methane	4.00	50.22	--	120/120	2750
Ethane	3.00	47.90	--	99/115	2933
Propane	2.67	46.55	0.501	97/111	2999
Butane	2.50	46.04	0.579	89/94	3034
Isooctane	2.25	44.56	0.692	100/100	3088
Gasoline (typ.)	1.85	43.49	0.739	83/92	3177
Diesel No.2 (typ.)	1.75	42.79	0.852	--/--	3200
p-Xylene	1.25	40.70	0.861	110/116	3321
Toluene	1.14	40.61	0.867	109/120	3349
Benzene	1.00	39.98	0.877	115/>120	3385
Oxygenates					
Methanol	4.00	20.10	0.791	89/109	1375
Ethanol	3.00	26.99	0.789	90/109	1913
n-Propanol	2.67	30.93	0.804	--/--	2200
n-Butanol	2.50	33.22	0.810	--/--	2378
MTBE	2.40	35.09	0.741	98/115	2500
ETBE	2.33	36.02	0.740	105/118	2588

Comparison with Fig. 4 shows that now the advantage the oxygenates had over gasoline has almost disappeared. Also, there is much less difference among the oxygenates on an energy basis (Fig. 5) than on a mass basis (Fig. 4).

SYSTEM CONSIDERATIONS

Different fuels provide different thermal efficiencies when burned in an engine. Thus the tailpipe emission of carbon dioxide for a given vehicle operated on a specified driving schedule with alternative fuel "x" can be related to the emission when burning gasoline by

$$(g\ CO_2/mi)_x = (g\ CO_2/mi)_g \frac{(ESCO_2)_x}{(ESCO_2)_g} \frac{1}{\epsilon_x} \qquad (9)$$

where $ESCO_2$ = energy-specific CO_2 production (g/MJ)

ϵ_x = thermal-efficiency ratio, fuel x/gasoline

Subscripts g and x denote gasoline and fuel x, respectively.

The typical thermal-efficiency ratios estimated for this study are listed in Table 2. The ratio for gasoline, the baseline of comparison, is unity by definition.

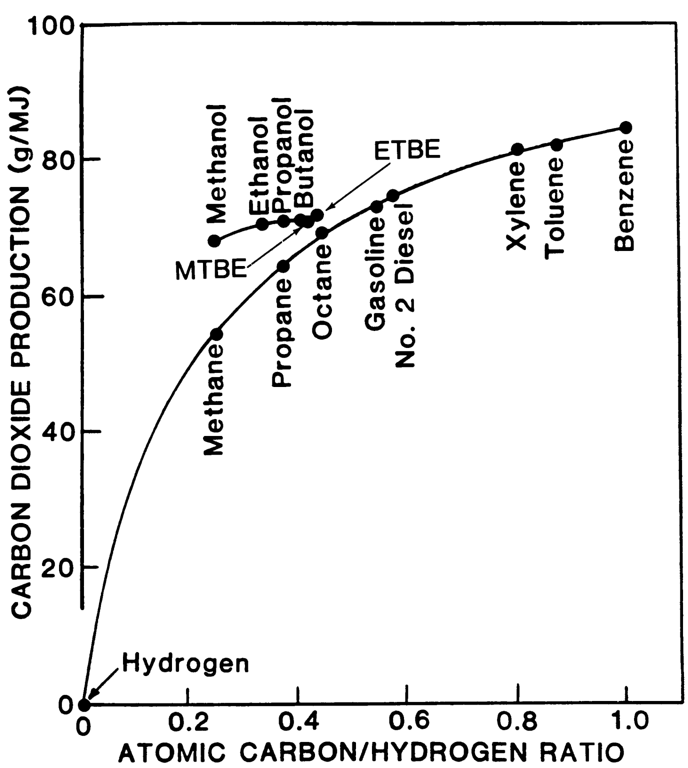

Fig. 5 - Energy-specific carbon dioxide emissions of hydrocarbon and oxygenated fuels.

TABLE 2

ASSUMED EFFICIENCY RATIOS
FOR SELECTED FUELS

Gasoline	1.00
Diesel	1.18
Natural gas	1.00
Methanol	
Variable-fuel vehicle	1.06
Dedicated vehicle	1.18

The ratio for diesel fuel burned in a compression-ignition engine is taken as 1.18. Allowing for a 13% greater energy content in a gallon of diesel fuel than in a gallon of gasoline, this corresponds to a 33% advantage in mi/gal for the diesel engine. The magnitude of this assigned advantage is favorable to the diesel when the passenger-car application is considered because past passenger-car diesels meeting emission standards showed mi/gal gains closer to 25% on an equal-performance basis. Thus the ratio selected comprehends the additional gain in fuel economy accompanying a switch from the indirect injection approach used on past passenger cars to the direct-injection approach of heavy duty diesels. So far, direct-injection diesels have not demonstrated the ability to meet U.S. passenger-car emission standards.

Compressed natural gas is assigned a thermal-efficiency ratio of unity. Although the high octane rating of natural gas permits use of a higher compression ratio for increased thermal efficiency in a dedicated natural-gas vehicle, that benefit is counteracted by the lower volumetric efficiency encountered with gaseous fuel in a naturally aspirated engine, a result of gas in the manifold that occupies space normally devoted to air. To maintain the same performance capability, then, engine displacement must be increased, and that entails increased frictional losses.

Two values of thermal-efficiency ratio are assigned to methanol. The 1.06 corresponds to a variable-fuel vehicle capable of accepting any fuel from M85 to gasoline. Because of both poor cold-starting characteristics and initial supply and distribution problems, early vehicles accepting methanol are expected to be of this type. The thermal-efficiency ratio of 1.18 corresponds to a dedicated methanol vehicle. In this case a higher compression ratio is possible that utilizes the increased octane rating of methanol. In contrast to the situation with natural gas, the high latent heat of methanol cools the intake charge, increasing volumetric efficiency. This factor combines with the higher compression ratio to allow a smaller-displacement engine for the same performance, with an associated reduction in friction work.

The thermal-efficiency ratios for the alternatives listed in Table 2 are not fundamental constants but are subject to upward or downward movement as more experience is gained. For the moment, though, they are believed at the least to rank the fuels in the proper order.

When considering the greenhouse impact of alternative fuel "x", a systems perspective is required. Not only is carbon dioxide produced through combustion of the fuel in the engine, but also in extracting the resource from which the finished fuel is made and transporting it to a refinery site, in processing that feedstock into usable fuel, and in distributing the finished fuel to the vehicle-fueling site. The carbon dioxide created in production, transportation and distribution depends both on geographic factors, such as the proximity of the original resource to the refinery and of the refinery to the fueling site, and on technological factors, such as the technique used in refining the fuel and the methods used in transportation and distribution. Typical values developed in a study done for the California Energy Commission are used here [5]. With the groundwork thus laid, the carbon dioxide emissions of a variety of alternative-fuel options are compared in Fig. 6 [5]. The bar at the left is for the base case of gasoline processed from crude oil and burned in a spark-ignition engine. The lower part of the bar represents the tailpipe emission, and the upper addendum accounts for production, transportation, and distribution of the fuel before it can be consumed in the vehicle.

The second bar is for a diesel engine and shows a nominal 10% reduction in total production of carbon dioxide.

The third bar is for compressed natural gas. The range in the top segment of the bar reflects differences in transportation and distribution. A nominal reduction of 20% is seen.

The fourth bar is for methanol made from natural gas and burned in a variable-fuel

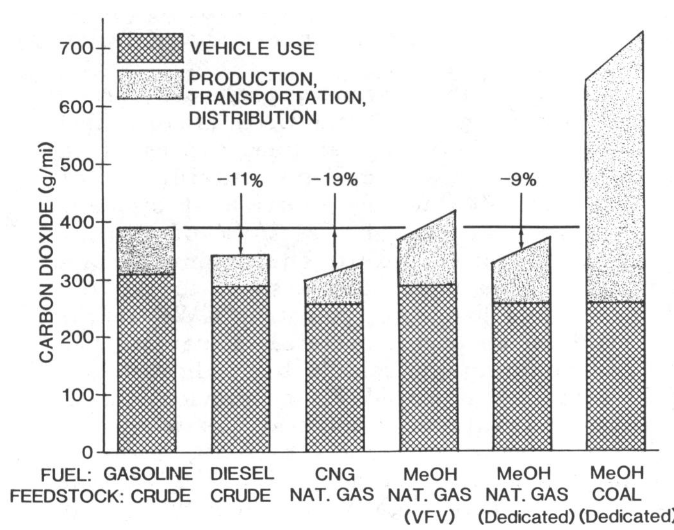

Fig. 6 - Carbon dioxide emissions from vehicles using various fuels, including the contribution from production, transportation and distribution.

vehicle. On average, no benefit in carbon dioxide production is seen relative to the baseline gasoline case. The gain shown for tailpipe emission is lost to increased carbon dioxide production in conversion from natural gas to methanol. The fifth bar indicates that if methanol is burned in a dedicated vehicle, the higher thermal-efficiency factor lowers the tailpipe emissions. The reduced fuel consumption also lowers the carbon dioxide associated with production, transportation and distribution. As a result, a nominal 10% reduction in total emission is noted.

The final bar is for methanol produced from coal. With established conversion technologies, the carbon dioxide made in producing the methanol exceeds that emitted from the tailpipe. If the energy consumed in coal conversion were to come from renewable resources, however, methanol from coal might be more competitive with petroleum-derived fuels on a carbon dioxide basis [6].

From Fig. 6 it appears that among the leading alternative-fuel options, natural gas is the most attractive from the standpoint of carbon dioxide. Carbon dioxide is not the only significant greenhouse gas, however. Methane, which is the principal constituent of unburned-fuel emissions from engines operated on natural gas, is also a contributor. Global climate models have been used to project the effect on temperature of anticipated increases in the concentration of a range of greenhouse gases [7]. From the ratios of predicted temperature increase to predicted concentration increase from 1980-2030, a mass-based methane global warming factor (GWF) relative to carbon dioxide of about 80 can be derived. Some have criticized this approach for ignoring the short lifetime of methane in the atmosphere compared to that of carbon dioxide. On a mass basis, the GWF of methane has been estimated in the literature to range from 16 to 116 [5]. For present purposes, factors of 80 and 16 are used. Most recent methane GWF estimates have fallen nearer the lower factor.

In Fig. 7, the previously presented carbon dioxide bars for gasoline and CNG are modified to show the effects of methane, expressed in terms of equivalent carbon dioxide. For gasoline, the left bar, the emission of methane is so small that even for a GWF of 80, the effect when converted to equivalent carbon dioxide adds no more than a sliver to the top of the original bar. Applying that GWF to the exhaust from an engine operated on natural gas, the addendum to the middle bar indicates that if 80 were the proper GWF, the previous global warming advantage of natural gas would be nullified. If the proper GWF is 16, however, the third bar indicates a continued advantage for CNG, although slightly less than when only carbon dioxide was considered. One of the reasons that the natural gas-fueled engine is so significantly affected by accounting for tailpipe methane is that methane has proven remarkably resistant to oxidation in the catalytic converter.

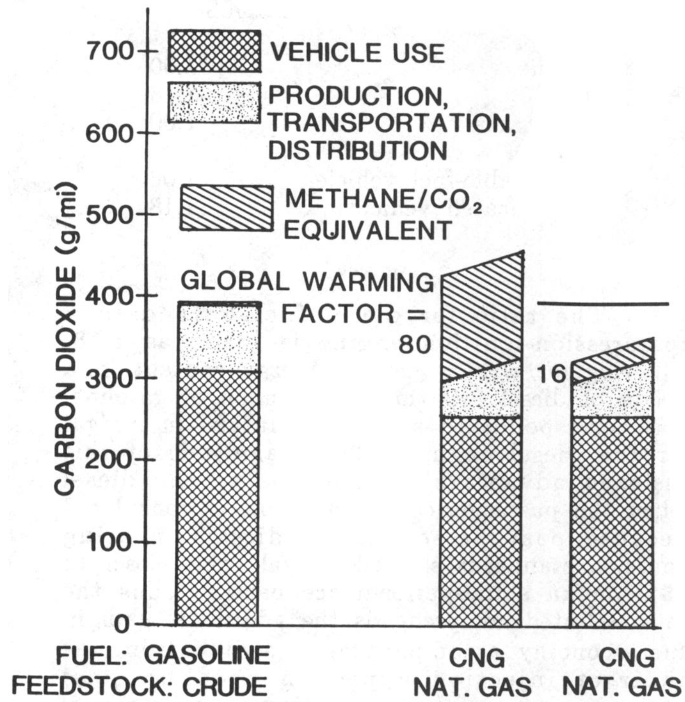

Fig. 7 - Global warming potential of gasoline and natural gas vehicles, expressed in equivalent carbon dioxide, when tailpipe methane emissions are included.

AIR CONDITIONING

About nine out of every ten new cars in the U.S. are air conditioned. The refrigerant used is CFC-12. Mass-based global warming factors, relative to carbon dioxide, of 3600, 10,300 and 16,000 have appeared in the literature [5]. For present purposes, a median value of 10,000 is employed.

A car air conditioner contains about 1.36 kg (3 lb) of CFC-12. During the 100,000-mi lifetime of an average car, it is typically taken in for air-conditioner service three times. This service has been customarily started by venting into the atmosphere the CFC-12 remaining in the system. When the car is scrapped, the remaining charge is again released to the atmosphere. Thus 5.45 kg (12 lb) of CFC-12 is released during the typical lifetime of a car. If the car meets a 27.5 mi/gal CAFE standard and achieves 85% of that value in actual service, it then emits 380 g/mi of carbon dioxide. For this set of conditions, the greenhouse effect of the air conditioner is greater than that of the carbon dioxide emitted from the tailpipe during the lifetime of the vehicle.

The U.S. automotive industry is moving rapidly to phase out CFC-12 in new-vehicle air conditioners, with 1994 being the likely year of initiation [8]. This action is being taken as part of the Montreal Protocol to reduce chlorine in the stratosphere, which threatens to destroy the stratospheric ozone shield that protects the earth from excessive ultra-violet solar radiation. Ozone depletion is a different issue from global warming.

The leading CFC-12 replacement candidate for mobile air conditioning is a chlorine-free hydrofluorocarbon, HFC-134a (1-1-1-2 tetrafluoroethane). The greenhouse effect of HFC-134a is estimated to be only about 10% that of CFC-12. Thus, as HFC-134a is phased in and vehicles requiring CFC-12 are retired from service, a substantial reduction in greenhouse-gas emissions from cars will result.

In addition, serious steps are being taken to discontinue the venting of CFC-12 at dealerships during servicing. Instead, the refrigerant will be collected and processed for re-use. Typically, leakage of 0.5 kg of refrigerant from an air conditioner is enough to cause the driver to seek service. Under this scenario, then, the mass of CFC-12 lost to the atmosphere during the lifetime of a car would be nearly halved. A further reduction in released CFC-12 would be realized if the refrigerant were also recovered when the vehicle was scrapped. If half of the car-lifetime consumption of CFC-12 had been recovered for recycling during servicing in 1987, this would have been the greenhouse equivalent of increasing the in-use average fuel economy for that year from 19.1 to 46.4 mi/gal.

THE LAISSEZ-FAIRE STRATEGY

The laissez-faire strategy is one in which no special actions aimed specifically at decreasing greenhouse gases are taken. As far as carbon dioxide is concerned, this means that the CAFE standard is fixed at 27.5 mi/gal. Then the mass emitted from the average car will automatically decrease as old cars are scrapped.

The effect this has on the tailpipe emissions of carbon dioxide is shown in Fig. 8, where vehicle carbon dioxide in g/mi is plotted against years. The solid line traces the history of the in-use fleet up to a base year of 1987. In a given year the average fuel economy of the in-use fleet [9] is, of course, poorer than the new-car average for that year because of the population of old cars. Allowing fifteen years for fleet turnover and no increase in CAFE above 27.5 mi/gal, tailpipe carbon dioxide emissions will follow some trajectory ending at the solid circle plotted for 2002. In calculating the average emission for 2002, the fuel economy was discounted 15% from the 27.5 mi/gal standard to allow for the fact that the typical driver does not do as well on the road as a professional test driver does in following the EPA urban and highway schedules on a chassis dynamometer. The tailpipe emission in 2002

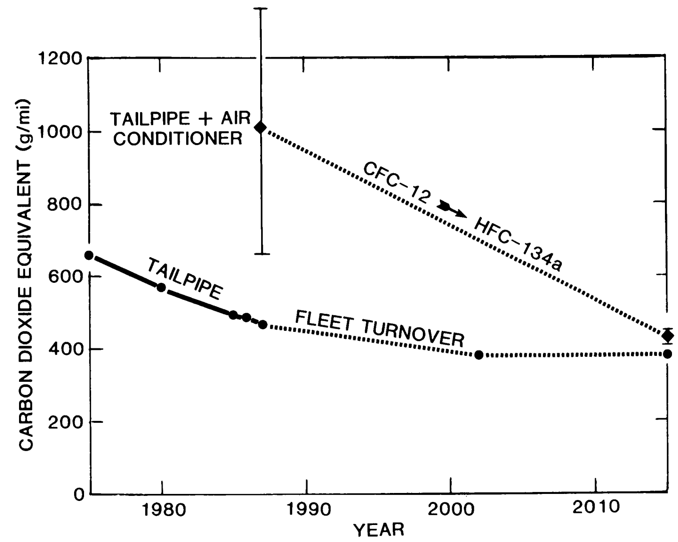

Fig. 8 - Historical trend in average tailpipe carbon dioxide emissions from the U.S. in-use passenger car fleet, exptrapolated into the 21st century without further improvement in fuel economy, and equivalent carbon dioxide supplement attributable to vehicle air conditioning, including reduction from CFC-12 phase-out.

represents an 18% reduction from 1987 even though the fuel economy standard has remained constant.

The solid diamond for 1987 represents the sum of the tailpipe carbon dioxide and the carbon dioxide equivalent of the CFC-12 lost from the air conditioner, as discussed above. In determining this point, it was assumed that CFC-12 was 10,000 times as significant a greenhouse gas on a mass basis as carbon dioxide. The error bar around this point marks the range of global warming factors from 3600 to 16,000, as mentioned previously.

Assuming the switch from CFC-12 to HFC-134a begins on schedule in 1994 for new vehicles and is completed by 2000, and allowing for a 15-year fleet-turnover time, yields the solid diamond at 2015. Thus it appears that even if no special measures are taken to decrease greenhouse emissions from cars, the greenhouse-gas effect of the U.S. passenger car will be halved from its 1987 level by early in the next century.

THE BAN-FOSSIL-FUEL STRATEGY

It was indicated in Eq. 1 that the world production of carbon dioxide depends on global population, per capita use of technology, and the status of technology. Global population is presently about five billion and is projected to double during the 21st century [10]. Energy per capita, which might be considered a first approximation to quality of life, rose from the turn of the century until the 1973 oil embargo, after which it showed some sign of leveling off [11]. This encouraging change in energy-consumption habits reflects the beneficial effects of conservation, primarily in developed countries, rather than a marked reduction in quality of life. Because demographic studies suggest that population will grow faster in the underdeveloped countries than in the developed ones, it seems questionable that the recent conservation-inspired leveling in per capita energy consumption can be sustained on a worldwide basis. If it cannot, then with the projected doubling of population, halving the carbon dioxide production, for example by doubling energy conversion efficiency with fossil fuels, would be insufficient to stabilize global carbon dioxide.

In the U.S., electric utilities account for roughly a third of carbon dioxide from fossil-fuel combustion. The best electric-utility powerplant reached a thermal efficiency of 42% in 1965, although regulation has since caused some retreat from that figure [12]. To more than double that value in fossil-fueled steam powerplants would, with reasonable temperature limits, exceed the bounds of cycle thermodynamics. Therefore, halving the carbon dioxide per technology (Eq. 1) solely through improvements to fossil-fueled electric generating plants is out of the question. There is room for lowering carbon dioxide through improved end-use efficiency, of course, e.g., through the use of more efficient lighting and better refrigerators. Halving carbon dioxide production from the electrical sector by that route in a reasonable time frame seems problematical, however.

In the U.S., transportation accounts for roughly another third of carbon dioxide production from fossil fuels, and automobiles dominate that fraction. Carbon dioxide from the passenger car during powered modes, i.e., when the accelerator pedal is depressed, is given by

$$\text{g } CO_2/\text{mi} = ESCO_2 \times (1/\eta_e \eta_d Q_f) \times (E_{tr}/S) \qquad (10)$$

where η_e = average engine brake thermal efficiency
η_d = average drivetrain efficiency
Q_f = fuel lower heating value (MJ/kg)
E_{tr} = vehicle tractive energy required (MJ)
S = distance traveled (mi)

$ESCO_2$ is a function of the fuel chosen. As shown previously, with the leading alternative fuels derived from fossil sources, a maximum carbon dioxide reduction of about 20% is anticipated from fuel changes alone. The two efficiency terms in Eq. 10 depend on the technology used. With current gasoline engines showing a peak brake thermal efficiency of about 33% and the ideal fuel-air cycle (constant-volume combustion, no friction, no heat loss) showing a calculated maximum efficiency of about 47% with a stoichiometric mixture at a compression ratio of 10, it is clear that more than doubling the efficiency of the engine is an unreasonable expectation. Similarly, average drivetrain efficiency cannot be doubled because it is already well over 50%.

Although none of these factors acting alone can effect a sufficient gain to cancel anticipated increases in the second and third terms of Eq. 1, a significant improvement accrues from combining moderate but reasonable improvements in each, since they interact in a multiplicative manner. To cut carbon dioxide emissions by a factor greater than two, however, a reduction in vehicle tractive-energy requirement becomes necessary.

The average car of today has already experienced a substantial decrease in tractive-energy requirement, through reduced mass, improved aerodynamics, and better tires. Because of their even lower tractive-energy requirements, a few new cars on the road today emit only half of the fleet-average carbon dioxide. This achievement is normally accomplished by making the car smaller and/or by sacrificing performance capability.

As demonstrated by sales statistics, such cars are unable to satisfy the wants of most American drivers. If such drastic reductions in carbon dioxide emissions as suggested above prove to be necessary, therefore, attention will turn toward nonfossil fuels. In the limit, complete elimination of fossil fuels from the transportation fleet has already been discussed by some. In this section, some options for eliminating fossil-derived automotive fuels are considered.

The number of possibilities is large. From that list, those few judged to be the leading options in terms of demonstrated technological feasibility and potential energy capacity are represented in Fig. 9. The primary-energy sources, at the left, are either nuclear or solar. As indicated, the media for

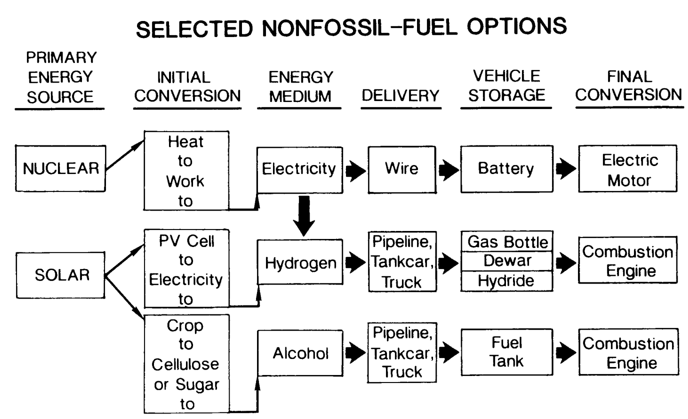

Fig. 9 - Selected nonfossil-fuel options for eliminating carbon dioxide emissions from the automotive fleet.

energy transmission and ultimate storage in the car are electricity, hydrogen, and biomass-derived alcohol. Final energy conversion into mechanical work for vehicle propulsion is accomplished with either an electric motor or a combustion engine, as indicated at the right in Fig. 9

ELECTRIC VEHICLES - Of the options illustrated in Fig. 9, the electric vehicle is the recipient of much attention because it avoids tailpipe emissions. If such a vehicle is to counteract global warming, however, the electricity must be generated with nonfossil fuel. A DOE projection of how electricity will be generated in the U.S. in 2010 is shown in Fig. 10 [13]. About two-thirds will involve combustion of fossil fuel -- coal, oil and natural gas. Nuclear power accounts for only 20%,

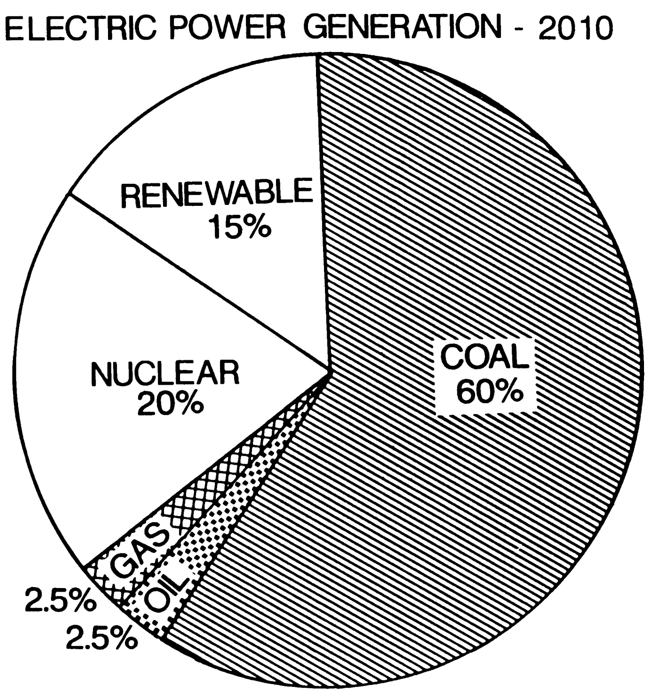

Fig. 10 - Distribution of primary energy sources for U.S. electricity production in 2010.

with the remainder coming from such renewable resources as water power, wind and geothermal energy. The potential for large expansions of these particular renewable resources is restricted, so a quadrupling of the nuclear-power energy fraction is required to eliminate the use of fossil fuels. Given the unfavorable public image of nuclear power, and the time and cost associated with construction of a nuclear powerplant, this presently seems a gigantic undertaking.

To improve the public acceptability of the nuclear power station, three hurdles must be overcome. First, the reactor needs to be passively safe. That is, in case of an accident it should shut itself down without the need for external mechanisms or control systems, which are subject to potential failure. Second, it should breed new replacement fuel in order to avoid depletion of world uranium resources. Third, it needs, at the least, to eliminate production of waste products that remain dangerously radioactive for a million years. The Integrated Fast Reactor, a subject of ongoing research and development, is intended to address these barriers [14], although concerns about management of shorter-life nuclear wastes remain.

Given such a primary-energy source, as illustrated in Fig. 9, the heat generated is normally converted into work to drive an electric generator, the output of which is transmitted by wires to the battery through a battery charger. The battery is presently the biggest shortcoming of the electric car. It has a number of characteristics that are worth reviewing, both because they are unfamiliar to many who are accustomed to the internal combustion engine as the vehicle prime mover and because they demonstrate areas of challenge for engineers engaged in improving the electric vehicle as it exists today.

Batteries are often characterized on a plot of power density in W/kg versus energy density in W-h/kg, as shown in Fig. 11. Energy density is indicative of range, power density of performance capability. The individual data points indicate the reported 1988 status of various types of battery modules being developed by DOE contractors [15]. The lead/acid (gel-cell), nickel/cadmium, nickel/iron and iron/air modules cited all operate at room

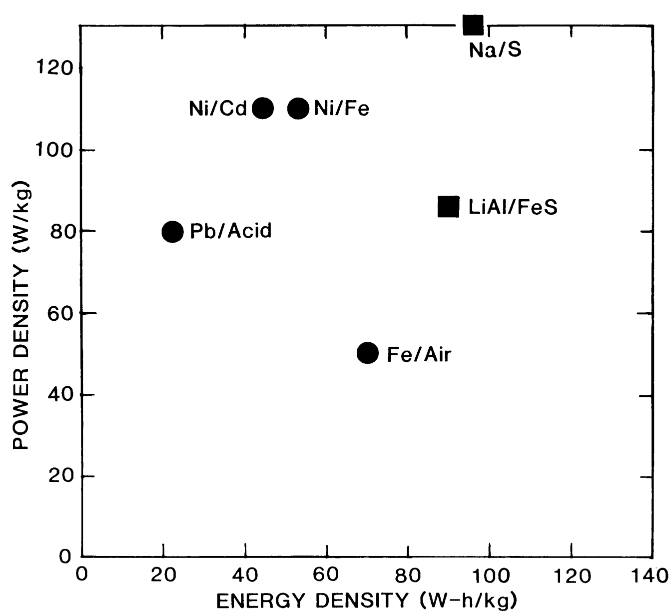

Fig. 11 - Status of advanced batteries in the DOE research program as of 1988, represented in terms of energy density, and power density at 50% depth of discharge. Circular points are for room-temperature batteries, square points for high-temperature batteries.

temperature. The elements of the other two modules operate in the molten state. Sodium/sulfur functions in the 300-350°C (570-660 F) range, lithium aluminum/iron sulfide in the 400-500°C (750-930 F) range. Although these high-temperature batteries demonstrate the best combination of range and performance of all those illustrated, they obviously entail an extra safety concern. In addition, if used in a private car that is parked, say for a week or two, at an airport in a northern winter climate, the elements have to be unfrozen before the battery can function.

Such plots are helpful for comparing batteries if the measurements are made under consistent conditions. The power densities of all batteries represented in Fig. 11 are quoted at 50% depth of discharge. Fresh batteries do better, with power density decreasing at an increasing rate as discharging proceeds.

A shortcoming of such a two-dimensional plot is that it ignores the aspect of battery life. Fast battery discharge can both accelerate depletion of its stored energy, as shown below, and shorten the number of times the battery can be charged and discharged before it must be discarded. The severity of these effects depends on battery type.

The effect of depth of discharge on power density of a modern lead-acid battery pack is illustrated in Fig. 12 with data from tests on a battery-electric van [15]. This deterioration in performance with battery use stands in contrast to the characteristic of an engine-powered vehicle, in which performance remains essentially independent of the quantity of fuel remaining in the tank until the fuel supply has been exhausted. In fact, performance actually increases slightly as fuel mass is consumed.

Energy density, as manifested by range on a charged battery, is drive-schedule dependent, as illustrated for the same van in Fig. 13 [15].

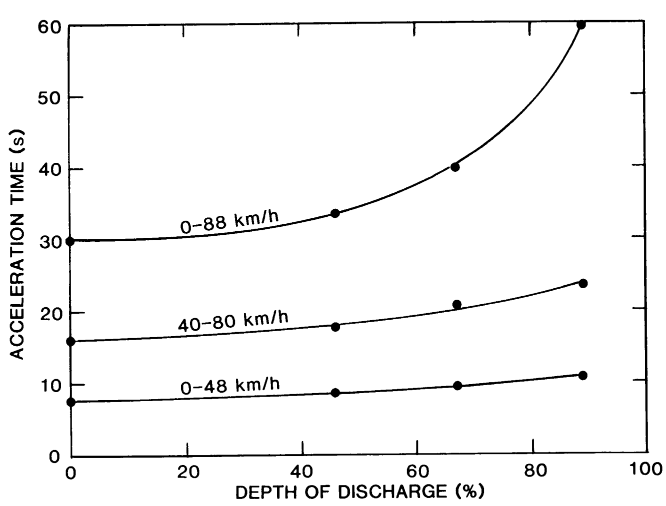

Fig. 12 - Typical electric-vehicle performance deterioration with increasing depth of discharge (lead-acid battery).

The circular data points are for transient driving and are discussed subsequently. The solid line through the square data points shows how range deteriorates at constant driving speed as the speed is increased. There are two major reasons for this.

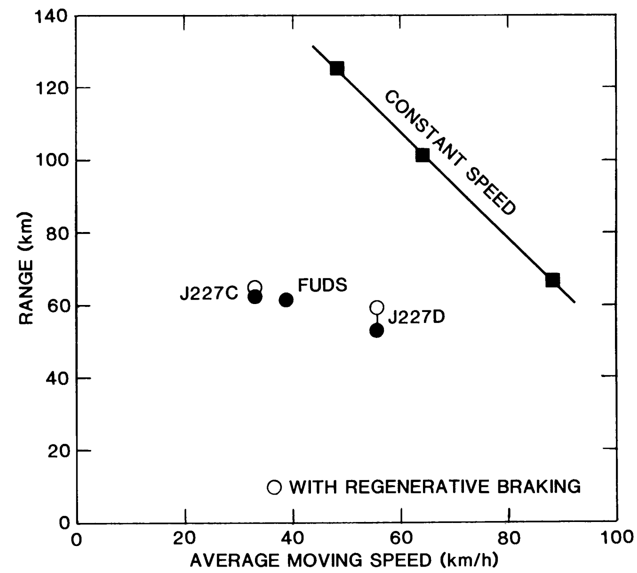

Fig. 13 - Effect of average driving speed on range of an electric vehicle on both constant-speed and transient driving schedules (lead-acid battery).

One is that the energy required to propel a vehicle increases with speed. This characteristic is shared with an engine-driven vehicle, for which range on a tank of gasoline is normally less at highway speed than at a more modest cruising speed.

The second is the effect of discharge rate on energy capacity, which is sensed by the driver as range between charges. For the constant-speed data in Fig. 13, the time required to consume the energy available from the battery decreased from 2.6 h to 1.6 h to 45 min as the vehicle speed was increased from 48 km/h (30 mi/h) to 64 km/h (40 mi/h) to 88 km/h (55 mi/h). This characteristic is unique to the battery-electric car and is equivalent to driving an engine-powered vehicle in which the fuel tank shrinks as the vehicle speed is increased. Additional "shrinkage" of the battery occurs as it ages in service.

The effect of discharge rate on energy capacity is illustrated in Fig. 14. The solid curve represents energy (W-h) available from a typical lead-acid traction battery subjected to continuous discharge at room temperature, normalized to the energy available during a steady 4-h room-temperature discharge. It is

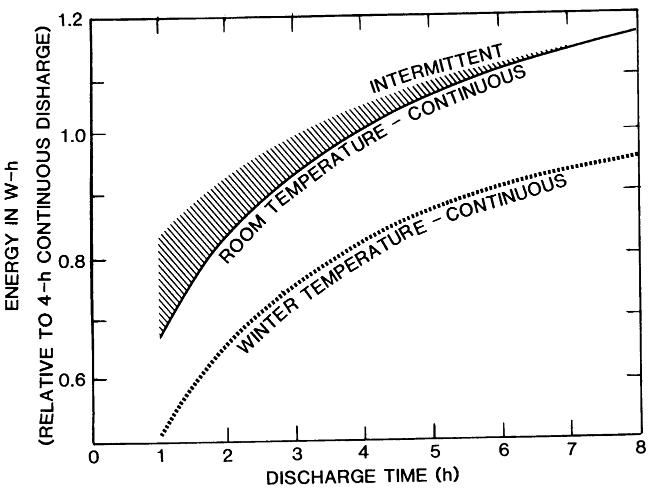

Fig. 14 - Effects of rate of discharge and battery temperature on energy available from a lead-acid traction battery, normalized to energy available for a continuous 4-h discharge at room temperature.

plotted versus discharge duration. For a given battery, this curve changes with certain conditions. For example, the shaded range above the solid curve indicates that the energy extractable from the battery before it is considered discharged increases if the battery is operated intermittently during the time that current is withdrawn from it. In other words, the charged battery will carry the car further on a given driving schedule if the schedule is interrupted occasionally and the battery allowed to rest.

The lower, dotted curve shows that the energy available decreases at low battery temperatures. That is, other factors being fixed, car range is less in winter than in summer. Not illustrated in Fig. 14 is the fact that these energy-availability curves drift downward over time as the battery approaches the end of its useful life.

Returning to Fig. 13, the filled circular points are for standard transient driving schedules. The J227a schedules, often used to evaluate electric cars, involve accelerations from rest to a specified speed, a steady cruise at that speed, a deceleration to zero speed, and a period of rest. The specified cruising speeds are 48 km/h (30 mi/h) and 72 km/h (45 mi/h) for the C and D schedules, respectively. The 12-km (7.5-mi) federal urban driving schedule (FUDS) involves 18 different cycles separated by periods of zero speed, and often with resting time, with the peak speed being 88 km/h (55 mi/h). The data points for the three transient driving schedules are plotted at the average speed for the time the vehicle is actually moving. The filled circular points indicate that because of the energy consumed in accelerating vehicle mass on a transient driving schedule, over and above the energy required to overcome aerodynamic drag and tire rolling resistance, range can suffer severely in transient driving compared to constant-speed driving at the same average moving speed. This means that range quoted for constant-speed driving, as is sometimes done, must be interpreted with caution.

An advantage the electric car has over the traditional engine-driven car is that during stopping, the vehicle kinetic energy normally dissipated in the brakes can be at least partially recovered by operating the propulsion motors as generators that return energy to the batteries. The hollow circles for the two J227a schedules in Fig. 13 show the range increase effected by such regenerative braking. The gain is greater for the D schedule, with its higher maximum speed, because the kinetic energy stored in the moving vehicle increases as the square of speed, and because as the vehicle speed approaches zero, the voltage generated by the motor acting as a generator is insufficient to charge the batteries. One of the reasons the gains from regenerative braking are so modest is because the efficiency of energy transfer from the moving vehicle back into the battery is typically poor.

To relate the battery points of Fig. 11 to the automobile of today, they are replotted on a different scale in Fig. 15 within the bubble at the lower left. On this plot the coordinates for the battery data points have been adjusted to include both a 10% energy-inefficiency deduction and a 15% mass penalty for addition of the controller and motor to the system.

The circle labeled "gasoline" in the upper right corner of Fig. 15 is for the power system of a conventionally powered car. (Circles plotted for other energy-storage media are discussed subsequently.) Included in the mass

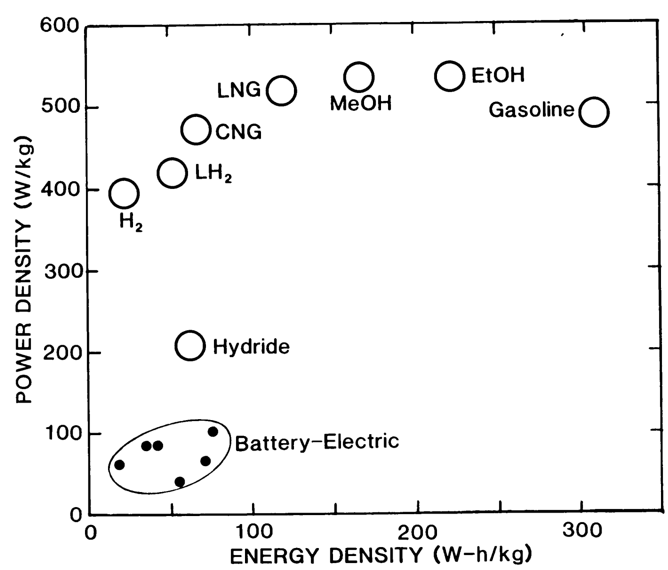

Fig. 15 - Power density, a measure of performance capability, versus energy density, a measure of range, for various internal-combustion-engine/fuel combinations (solid circles) and for an electric vehicle with various batteries (solid circles).

that appears in the denominators of the energy-density and power-density coordinates for the gasoline point are a 150-kg (330-lb) powertrain, a 9.1-kg (20-lb) fuel tank and 53 L (14 gal) of fuel. In addition, the powertrain has been burdened with a 13% overall thermal efficiency from the fuel tank to the powered wheels on the car. The magnitude of the difference between the gasoline point and the battery-electric points accounts for the inferior range and performance generally attributed to the battery-electric car.

The recently demonstrated GM Impact concept car, which accelerates to 97 km/h (60 mi/h) in just 8 s, shows that if engineering attention is focused on performance, the electric car need not be sluggish. Such outstanding performance is attributable in large part to the design of the vehicle, which has about half the mass, half the aerodynamic drag, and half the rolling resistance of many production cars. Together, its two electric motors are capable of 85 kW (114 hp) for the brief periods required for acceleration. When combined with a vehicle curb weight of only 990 kg (2200 lb), the remarkable performance is understandable. When fresh, its recombinant lead-acid batteries are rated at 230 W/kg at 83% of open-circuit voltage with an energy density of 34 W-h/kg. This power density is above the range of Fig. 11 (in which the power densities are at 50% depth of discharge), but less impressive relative to the options on Fig. 15. Being a two-seater with limited luggage space, the Impact is targeted for the urban commuter. A current shortcoming receiving attention is its estimated operating cost, about double that of a conventional car today. This disadvantage could be erased by a future sharp increase in the price of automotive fuel.

One of the reasons for the cost disadvantage of the electric car is the cost of the batteries, which is aggravated by inadequate battery life. In their present state, the modules of Fig. 11 have lives in laboratory testing that range from 130 to 800 cycles when discharged to 80% depth [15]. An individual battery from the Impact module has reached 700 cycles when laboratory tested to 30% depth of discharge. There are a number of subtleties about such reports not always understood by those unfamiliar with electric propulsion.

First, life is sensitive to depth of discharge. Although the Impact has demonstrated a range of 193 km (120 mi), that involves exploiting the full capacity of the battery. Occasional deep discharges may be acceptable, but to approach a reasonable battery life, normal discharges should be limited to a 30 to 50% depth. That translates into a daily range of 48-97 km (35-60 mi) for a vehicle capable of a 193-km (120-mi) range. Of course, drawing energy from the batteries for air conditioning or heating depreciates range.

Second, the electric vehicle operates on a module of many batteries joined in series, each comprised of a number of individual cells in series. Thus a module may contain over a hundred individual series-connected cells. All cells do not age at the same rate. Each time a cell falls short of average performance, the load on the other cells is increased. An analogy might be drawn to a multi-strand steel cable subjected to a fixed load. When one strand fails, the others must carry more than their share. In a module of batteries, the extra load on the properly functioning cells accelerates their deterioration.

Third, laboratory tests are a necessary first step in battery development, but do not necessarily translate into real-world experience. Batteries in vehicular use experience vibration, temperature extremes, careless maintenance, and general abuse that do not happen in a typical laboratory setting. That is why evaluations must ultimately occur in actual vehicular service.

One final characteristic of the battery that presently precludes the battery-electric vehicle as a complete replacement for the engine-powered car stems from its limited range. That characteristic is recharging time. An empty gasoline tank is typically refilled in a few minutes, but the recharging time for a discharged battery is measured in hours. Recharging a lead-acid battery too quickly heats the electrolyte to the point where battery life is impaired. For this reason, the battery-electric concept is best suited for such applications as commuter cars and city delivery vans. In its present form, it is not suitable for cross-country travel.

Several proposals have been advanced to overcome this handicap. One is battery exchange at service stations distributed along travel routes. This approach faces several drawbacks. First, exchanging modules involves greater labor intensity than refueling a gasoline tank. Along interstate highways, it is not unusual for five motorists to be refueling their own vehicles concurrently, but it seems likely that motorists would be unable to exchange their own battery modules (weighing 395 kg/870 lb in the Impact). Consequently, a crew of service station employees needs to be on hand at such a location. Second, the above-ground space requirements for storing freshly charged and spent batteries in numbers corresponding to the frequency of vehicle stops for refueling at a given station would impose a difficult new requirement on existing stations. Third, to make quick changes of battery modules reasonable, a high degree of standardization would be desirable. This could discourage the upgrading of battery modules as technological progress is made. Finally, there is the question of how to satisfy drivers who turn in a reasonably new battery that needs recharging and are given a poorly maintained battery with poorer performance and range in exchange.

Another proposal is to structure roads so that electricity can be picked up as it is used while the vehicle is being driven. The now nearly extinct electric trolley car proves this can be done. A modern concept is to bury coils in the roadbed such that electricity could be acquired inductively by means of an on-board pickup. This scheme may have particular merit for mass transit. For private vehicles, however, batteries would still have to be carried to accommodate travel off the system, for example, on residential streets, up a home driveway and into a garage. For efficiency, the vehicle pickup, which is currently very massive, must be within about 50 mm of the road. That is inadequate road clearance for operation off of the specially maintained electrified roadbed, requiring provision for retracting the pickup.

Another shortcoming of extensive use of this approach is the timing of the load on the electric utilities. Charging the batteries of electric cars is generally envisioned as an overnight operation that extracts electricity from the system at times separated from peak utility loads. Nighttime battery charging thus constitutes a load-leveling technique for the utilities. In contrast, if the electricity for transportation is extracted as it is consumed, its demand is superimposed on the peaks of demand for other uses, raising questions about the need for increased electric generating capacity.

Another possibility is development of a mechanically rechargeable battery. Twenty years ago General Motors built a dual-battery electric car having lead-acid batteries under the hood for their superior power density and zinc-air batteries in the rear for better energy density [16]. The zinc-air batteries were recharged by physically replacing the zinc electrodes, as well as the electrolyte. While this was a cumbersome operation, it was accomplished faster than normal electrical recharging.

Recently Lawrence Berkeley Laboratory announced work on a zinc-air battery in which the zinc anode is in the form of particles. The objective with such a battery, in replenishing its spent energy, would be to develop a system in which used electrolyte and remaining particles would be withdrawn from the cell by suction for renewal and would be replaced with a slurry of fresh particles and electrolyte.

A nearer-term approach to the problem of limited range is the combustion-engine/electric hybrid, in which an on-board combustion engine is available to run a generator for battery charging as the vehicle is being driven. There are many potential mechanical arrangements for such a system, and they are being researched in a number of quarters. To fit the strategy of no fossil fuel, however, the engine cannot use petroleum-derived fuel or natural gas. Such options exist, as discussed below.

A longer-range possibility is the fuel cell, which carries its own fuel for on-board conversion to electricity. In principle, this eliminates the range limitation of the battery-electric vehicle, with range now being determined by the size of the fuel tank. Current leading fuel candidates are methanol and hydrogen. If methanol is used, it is reformed on board the vehicle to provide hydrogen for the fuel cell. To avoid addition of new carbon dioxide to the environment, the methanol would have to come from biomass, as discussed below. If the hydrogen is stored directly on board instead, it would have to be nuclear- or solar-sourced. Because fuel cells are expected to have about double the efficiency of the internal combustion engine, the space requirement for hydrogen storage would be eased.

Fuel cells have a way to go before they could be considered seriously for widespread automotive application. The DOE is developing a phosphoric acid fuel cell, fueled from a methanol reformer, for propulsion of a small urban bus. Because of the inability of the reformer to manage the transient nature of the typical automotive driving schedule, the fuel cell is combined with a storage-battery system to comprise an electric hybrid. Presence of the batteries also allows partial recovery of vehicle kinetic energy during decelerations. In a recent review of vehicle fuel-cell propulsion, an energy density of 67 W/kg was quoted for this fuel cell [17]. When the entire supporting system was included, the energy density fell to 33 W/kg. Such energy densities are not very impressive on Fig. 15. The PEM (proton exchange membrane) fuel cell is quoted at 150 W/kg [17]. Potential exists for substantial improvement over these presently representative specifications.

BIOMASS FUELS - As suggested by the bottom line of Fig. 9, solar energy can be used to grow crops that supply cellulose, starch or sugar for conversion into alcohol, either ethanol or methanol. The alcohol can be transported by pipeline, tankcar, and/or truck to service stations for transfer to and storage in the vehicle fuel tank, with the propulsion energy being developed in a conventional internal combustion engine.

The justification for biomass-derived alcohol as a means of avoiding injection of new carbon dioxide into the atmosphere is illustrated in simplified form in Fig. 16 for the case of methanol from wood. (Approaching this closed loop in practice requires that all fossil-fueled equipment involved in planting, growing, harvesting and transporting the wood product be converted to biomass fuel or its equivalent.) Starting with the conversion plant at the upper right, the methanol it produces fuels the automobile. The carbon dioxide exhausted is taken up by trees, which are in turn harvested as feedstock for the methanol plant. The increment of carbon dioxide produced through inefficiency of the conversion process is also absorbed by the replacement trees.

Circles are plotted in Fig. 15 for methanol (MeOH) and ethanol (EtOH) for the same powertrain chosen to represent gasoline. In this comparison the volume allowed for fuel storage

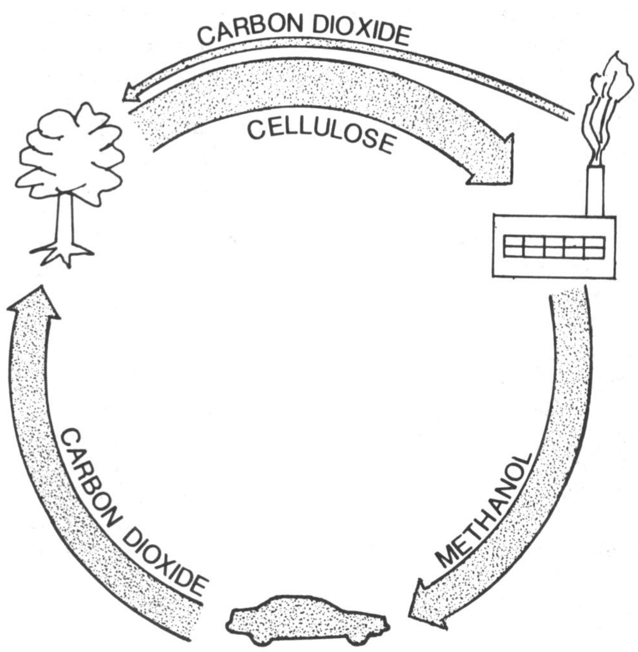

Fig. 16 - The closed carbon cycle for a vehicle fueled with methanol from wood.

has been held constant. Under these circumstances, dedicated alcohol vehicles offer higher power density than gasoline because their higher octane rating allows use of an increased compression ratio, and because their higher latent heat helps volumetric efficiency. Both fuels are inferior in energy density, hence range, however, because of the lower energy content of a fixed-volume fuel tank. Ethanol appears preferable because of its smaller sacrifice in range.

Because of their carbon content, both alcohols would also be expected to have greater adverse local effects on urban environments than nuclear electricity, and perhaps also than hydrogen, although hydrogen combustion can produce NOx. Partial oxidation of carbon results in tailpipe carbon monoxide. Other undesirable carbon-containing compounds that contribute to ozone formation, hence smog, can also result. Formaldehyde, a reactive compound that has shown up in the exhaust of methanol-fueled vehicles in 5 to 10 times its abundance in gasoline-engine exhaust, and has so far proven comparatively resistant to exhaust aftertreatment, is particularly worrisome in this regard. Ethanol may be somewhat preferable insofar as minimization of smog is concerned, although its use has received less study than that of methanol.

Other concerns about methanol include safety issues -- its toxicity, its greater propensity for inflammation in the fuel tank compared to gasoline, and its invisible flame. Near-term, the latter two issues are countered with M85, which contains 15% gasoline, but that option would disappear with a ban-fossil-fuel strategy.

Despite the arguments favoring ethanol, when faced with proven methods of alcohol production, methanol presently appears preferable for eliminating new carbon dioxide because of production-volume limitations on biomass-derived ethanol, as discussed below. The major sources of renewable biomass suitable for methanol production are crop residue, forage crops, and wood.

Crop residue consists of the stalks, stems and leaves remaining after a farm crop is harvested. Much of the residue is left on the ground as protection against erosion by wind and water, or as fertilizer. Most of the recoverable residue in the U.S. results from farming corn and grain in the Midwest. Unfortunately, the period for residue collection comes during the narrow time window between crop harvesting at the end of the growing season and fall plowing. This taxes the resources of the average farmer.

Forage crops include grass, clover and alfalfa. Grown for animal feed, these crops generally receive the minimal attention required to satisfy animal needs. Higher yields are possible through fertilization and increased cutting frequency. Unlike crop residue, harvesting forage crops does not invite erosion damage. Moreover, the gathering of forage crops can be timed to avoid interference with the annual crop harvest.

A third major source of feedstock is wood. Nearly 40% of U.S. land area is devoted to forests, and most are commercial stands. Branches and small trees abandoned at logging sites comprise one untapped resource. Residue from the woodproduct industry might also help. Annual surplus growth in commercial forestland could also be made available. To expand availability, tree plantations on which fast-growing trees are planted, raised like a crop, and harvested every few years would provide a large increase in wood resources.

A rough estimate has been made of the quantity of methanol that might be produced in the U.S. if it were to become a necessity for counteracting global warming [18], as illustrated by the bar in Fig. 17. The low estimate

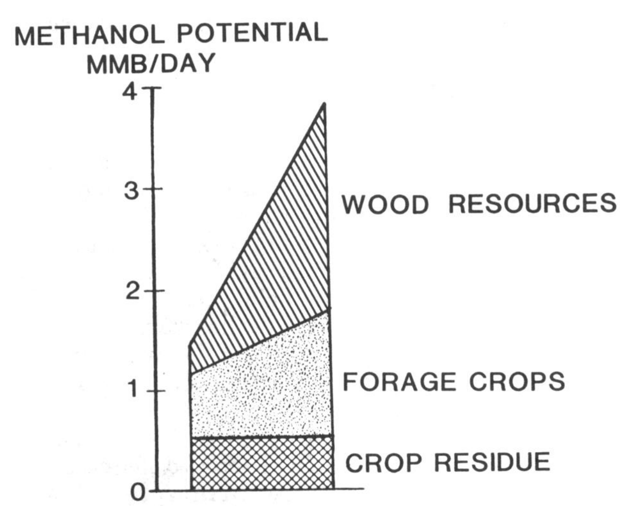

Fig. 17 - Estimate of U.S. methanol potential from wood in millions of barrels per day.

forming the left boundary of the bar represents the current situation. The right-boundary high estimate comprehends special farming of forage crops, and tree plantations. The high-estimate tip of the bar, 3.8 million barrels of methanol per day, is the energy equivalent of about a quarter of the total highway use of gasoline in 1988.

A wide latitude for error exists in such projections, so more refined studies in this area are certainly warranted. The potential yield from carefully managed tree plantations and the long-range role of genetic improvements are especially worthy of study. Most past assessments suggest, though, that domestic biomass-derived methanol alone cannot support the U.S. transportation fleet as we know it today.

Now turning to ethanol, it has been made in limited quantities from farm crops for many years. Brazil has demonstrated that government support can force the use of ethanol in cars. In 1988 ethanol provided 21.7% of Brazil's transportation energy, with 19.9% coming from gasoline and 58.4% from diesel fuel [19]. Impressive as that ethanol penetration is, it amounts to 2% of U.S. gasoline consumption on an equivalent-energy basis. Brazilian ethanol is made from sugar cane, but in the U.S. the preferred feedstock is corn.

Given current oil prices, corn-based ethanol is not economically competitive. An important factor helping to narrow its cost disadvantage is the economic value of such byproducts as animal feed and corn oil. In 1985, ethanol sales in the U.S. accounted for less than 0.5% of transportation energy consumption [18]. A Congressional commission has estimated that if presently used and economically obtainable biomass resources were converted to ethanol, production could be increased tenfold, to about 4% of energy consumption by the U.S. transportation fleet [18]. Excessive expansion of corn-for-ethanol production is expected to increase the price of corn by placing into cultivation less desirable farmland. Also, the supply of cost-offsetting byproducts would then exceed the demand, depressing their market value and further increasing the cost of ethanol. Given presently proven production technologies, therefore, wood-based methanol seems to offer a greater opportunity to decrease the production of new carbon dioxide. Ongoing work to produce ethanol from wood could alter this situation, however.

HYDROGEN FUEL - Hydrogen made by hydrolyzing water is seen as a long-range option. As indicated in Fig. 9, the electricity for hydrolysis could come from nuclear powerplants, or alternatively from solar photovoltaic (PV) cells provided they continue to increase in efficiency and decrease in cost as projected. The supply of PV electricity poorly matches the demand of the battery-electric car because solar cells produce energy only when the sun is shining, but recharging electric-car batteries is primarily a nighttime event. Hydrogen therefore provides a means of storing the solar energy until needed.

In the laboratory, the efficiency of amorphous-silicon solar modules has increased from 2.5% in 1980 to 12.5% in 1988 [20]. The efficiency of commercial modules has climbed similarly with time, but always lagged about 5 percentage points behind. It has been estimated that if and when commercial modules reach an efficiency of 15%, double their 1988 level, then with an 84% electrolyzer efficiency, PV hydrogen will require about a tenth the land area needed for an equivalent amount of bioenergy [20]. To replace annual U.S. oil consumption would require devoting 20% of the area of New Mexico to solar collection. The aesthetic acceptability of mile after mile of solar collectors is problematic, but it would be preferable to disperse separate sites over the nation for economy of distribution anyhow. However, preferred locations would be in the Southwest, where the annual average insolation is 1.5 to 2 times that of northern locations like Boston, Chicago, and Portland, Oregon.

With appropriate modification of the automotive powerplant, hydrogen is an acceptable fuel for the spark-ignition engine. The high flame speed of hydrogen is attractive, and its lean limit allows operation at much leaner mixtures than with gasoline. Both provide possibilities for increased thermal efficiency. On the other hand, the space occupied by the gaseous fuel in the intake manifold reduces volumetric efficiency significantly, decreasing the engine power at a given equivalence ratio. Although the lean-mixture capability of hydrogen is beneficial at light loads, in order to approach the power capability of gasoline at heavy loads, the mixture has to be enriched. This often causes engine backfiring as the incoming fuel-air charge comes in contact with the hot residual gas and ignites prematurely. This tendency has been counteracted by taking extra precautions to avoid hot spots on the combustion-chamber walls, by timed port fuel injection, by water injection, and/or by adopting a more complex fueling system that delays introducing the fuel into the cylinder until the intake valve has been closed.

From an emission viewpoint, hydrogen fuel eliminates carbon monoxide emissions, and also hydrocarbon emissions, except for the small amount associated with the lubricating oil. It has no special NOx advantage, though, except for that accruing from ultra-lean operation. Since the engine cannot always be operated that lean, NOx control becomes necessary, e.g., with EGR. As long as a lean mixture is used, the reducing catalyst responsible for keeping tailpipe NOx emission of the current gasoline engine acceptable will not function properly.

Achieving satisfactory engine operation seems a small problem alongside that of on-board fuel storage. In principle, the hydrogen can be stored as a gas, a liquid, or in a metal hydride. Estimates of the corresponding energy densities and power densities are shown in Fig. 15. Again, the fuel-storage volume has been limited to that for the gasoline option, and the engine and fuel tank have been included in the mass. All of the hydrogen choices suffer from low energy density.

Even when stored at 20 MPa (3000 lb/in.^{2}), gaseous hydrogen is seen in Fig. 15 to have an extremely poor energy density. Such a high pressure is simply unable to compensate for the inherently low density of hydrogen compared to liquid gasoline, even though hydrogen has nearly three times the heating value of gasoline on a mass basis.

Liquid hydrogen appears to be the best choice in Fig. 15, but it has some problems. It is seen to be vastly inferior to gasoline as an energy storage medium. Moreover, it must be kept at 20 K (-423 F) to avoid boiloff. When stored in an automotive dewar, boiloff losses amount to 0.5-3%/day [20] and could create a safety concern in enclosed spaces like garages. Moreover, 10-25% of the fuel boils off during refueling [20]. Liquid hydrogen cannot be transmitted through pipelines economically for any great distance, and liquefication at a service station is very expensive. For these reasons, liquid hydrogen seems a poor choice for passenger-car use.

Hydrogen can be stored in a metal hydride, where it is bound in the metal and released upon heating, typically by engine exhaust gas. Low-temperature hydrides can store only 1-2% of their mass as fuel. Hence this approach carries a heavy weight penalty, which contributes to the poor placement of the hydride point in Fig. 15. High-temperature hydrides store 7-8% of their mass as fuel but operate at a temperature above that for a typical passenger-car engine under many driving conditions.

CLOSING REMARKS - It has been shown that if eventual global warming necessitates abandonment of fossil fuels, other options are available for the automobile. However, three important points emerge from their consideration.

First, each option has features that will displease the consumer. For example, one shortcoming shared by the three leading alternatives discussed is restricted operating range. This situation is recapped in Fig. 18, where range on a given energy charge is plotted for the most likely options. In all cases the nonfossil-fuel choices involving a combustion engine have been restricted to the same fuel-storage volume as for the baseline gasoline case. The maximum range of the battery-electric bar for an advanced lead-acid battery is shown in broken lines. A lesser range is shown shaded to indicate what is practical if reasonable battery life is sought. Clearly, range can be increased for any of the alternatives shown by

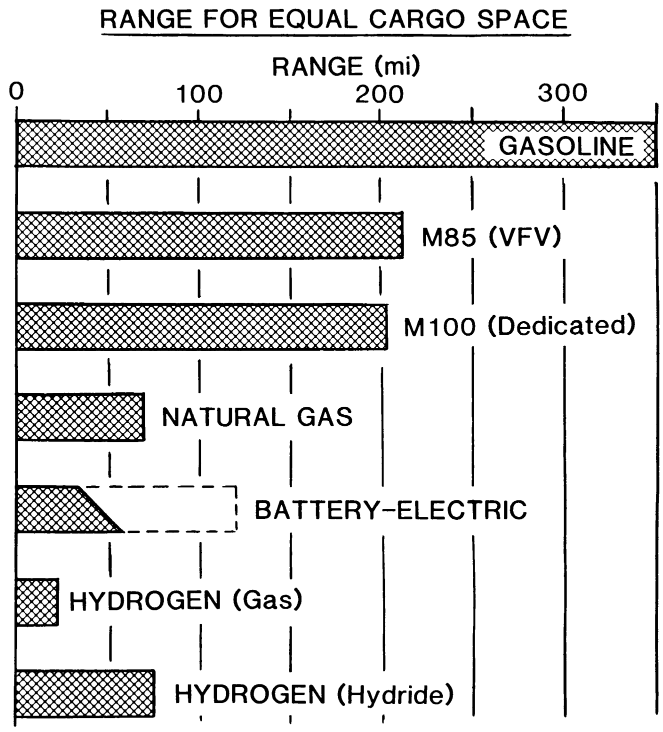

Fig. 18 - Estimated vehicle range for various alternative propulsion systems. (Fuel storage volume is held constant for engine-driven options.)

providing additional on-board energy-storage space, but given the low energy densities of the battery-electric and hydrogen options in particular, this will require some major changes in the way vehicle design is approached today. For the battery-electric option, the limited range is aggravated by slow recharging. Research and development are under way on alternative batteries to improve upon the limitations of those currently available.

The second underlying point is the enormity of the energy resource feeding the national automotive fleet. This is brought home by prospects of quadrupling the use of nuclear power, or of finding that projected future biomass resources might handle less than half of the needs of the current automotive fleet, or of contemplating the equivalent of covering 20% of New Mexico with solar collectors.

The third point is economics. This extremely important factor was not treated in this review for two reasons. First, the review was intentionally focused on technological aspects of the issue. Second, most of the nonfossil-fuel options are still at such an early development state that economic estimates are very tenuous. When one ponders the possible impact of the above actions, however, major economic dislocations could result. It therefore seems prudent to intensify efforts toward clarification of the remaining rather significant uncertainties regarding the seriousness of the global warming phenomenon while research on the transportation options discussed is continued, and before one of them is singled out prematurely for accelerated development.

CONCLUSIONS

1. The significant greenhouse gases emitted by the current automobile are carbon dioxide from the tailpipe and chlorofluorocarbons associated with the air conditioner.

2. In the U.S. presently, the automobile is responsible for about 13% of the carbon dioxide from fossil-fuel combustion, and trucks and buses are responsible for another 11%.

3. On a worldwide basis, carbon dioxide from U.S. cars and trucks account for about 1.5% and 1.2%, respectively, of the global warming potential.

4. For a specified fuel, the mass of carbon dioxide emitted from the engine is directly proportional to fuel consumption, or inversely proportional to fuel economy.

5. Tailpipe carbon dioxide from the average new U.S. car has already been halved over the last 15 years due to improvements in fuel economy.

6. If the U.S. fuel-economy standard is kept at its current level, carbon dioxide emissions emitted per mile by the average in-use car will decrease an additional 18% by early in the next century just due to fleet turnover.

7. For hydrocarbon fuels, the mass of carbon dioxide produced per unit of energy released in combustion (energy-specific carbon dioxide) increases monotonically with the carbon/hydrogen ratio of the fuel.

8. Despite their favorable carbon/hydrogen ratios, the energy-specific carbon dioxide emissions of methanol and ethanol are only slightly lower than for commercial gasoline and diesel fuel because of the reduced heating values of the alcohols.

9. When the likely effects of fuel choice on engine efficiency, and of the carbon dioxide created in processing and transportation of the feedstock and the finished fuel, are considered, reductions in total new carbon dioxide produced from the level using current gasoline amount to about 10% for the diesel, 20% for natural gas, zero for a variable-fuel vehicle operated on methanol from natural gas, and 10% if that methanol is used instead in a dedicated methanol vehicle. If the methanol is made instead from coal, the total emission of carbon dioxide is nearly doubled.

10. The appropriate global warming factor for Freon involves considerable uncertainty. Using a median mass-based value of 10,000 for the current CFC-12 air-conditioner refrigerant, the global-warming contribution of the air conditioner is greater than that of the engine exhaust over the lifetime of a typical car.

11. With the scheduled phasing out of air-conditioning refrigerant CFC-12 in favor of refrigerant HFC-134a, the global warming contribution of the passenger car is expected to be halved from recent levels by early in the next century.

12. If global warming should materialize to the point where restrictions on the use of fossil fuel become necessary, the currently leading options for operating automobiles in the extreme limit of zero fossil fuel are battery-electric cars operated on nuclear electricity, biomass-fueled internal combustion engines, and internal combustion engines fueled with hydrogen from nuclear or solar primary-energy sources.

13. Limited range and excessive recharging time restrict the utility of the battery-electric vehicle to applications like commuter cars and city delivery vans. Improvements in batteries are needed.

14. Public acceptance of the nuclear-based battery-electric vehicle would be enhanced by development of advanced reactors that are passively safe and solve the long-life radioactive-waste problem.

15. Fuel cells and mechanically rechargeable batteries offer some hope for overcoming the recharge-time handicap of the current battery-electric car, but neither is yet an accepted certainty.

16. With demonstrated conversion technologies, biomass-based methanol seems superior to biomass-based ethanol from corn in the U.S. on grounds of potential supply, although ethanol has advantages in other respects. Alcohol fuels do not inherently avoid such local air-quality concerns as carbon monoxide and ozone the way that nuclear electricity does and solar hydrogen may.

17. In principle, hydrogen made by electrolyzing water with either nuclear or solar primary energy can be used to fuel internal combustion engines, but the associated vehicle-range limitation is severe. This is especially true of high-pressure gaseous storage. Hydrogen can be stored in metal hydrides, but at a large mass penalty. On-board liquid-hydrogen storage is unattractive for several reasons.

18. If fossil fuel were to become unacceptable, the alternatives under consideration for automotive propulsion could cause economic dislocations. As research on these alternatives proceeds, therefore, it seems prudent to avoid

singling out one of them prematurely for massive action until atmospheric scientists have the opportunity to address some of the serious uncertainties surrounding the global-warming threat.

SUMMARY

The earth is made inhabitable by greenhouse gases, but their current rate of increase is causing concern about the potential for global warming. Automotive vehicles are responsible for about a quarter of the national anthropogenic production of carbon dioxide, which is the principal greenhouse gas. However, that is estimated to account for less than 3% of the worldwide global-warming potential attributable to combustion of fossil fuels. For the U.S., a switch to fossil fuels other than gasoline promises a maximum reduction in carbon dioxide from automotive vehicles of no more than 20%. About the same reduction will occur in the current passenger-car fleet by early in the next century just from fleet turnover. When the effect of the current air-conditioning refrigerant is factored in, the global warming potential of the automobile per mile driven could be halved by early in the next century as a result of switching to an alternative refrigerant. If even that reduction proves insufficient, automotive vehicles can be operated on energy from nonfossil sources, thus eliminating their carbon dioxide contribution. However, the leading candidates entail major concerns about public acceptability and economic consequences. It therefore becomes important to establish that global warming really necessitates elimination of the remaining few percent of the worldwide global warming potential contributed by U.S. vehicles before draconian countermeasures are initiated.

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