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ALCOHOL FUELS

The use of alcohols as motor fuels gained considerable interest in the 1970s as substitutes for gasoline and diesel fuels, or, in the form of blend additives, as extenders of oil supplies. In the United States, most applications involved the use of low level ethanol (qv) [64-17-5] blends in gasoline [8006-61-9] (see Gasoline and other motor fuels). Brazil, however, launched a major program to substitute ethanol for gasoline in 1976, beginning with a 22% alcohol ethanol—gasoline blend and adding dedicated ethanol cars in the 1980s. By 1985 ethanol cars accounted for 95% of new car sales in Brazil. By 1988 Brazil had 3,000,000 automobiles, about 30% of the total automobile population, dedicated to ethanol. The United States has demonstration vehicles using alcohols (mostly methanol (qv) [67-56-1]), but otherwise has not yet passed beyond the use of limited amounts of alcohols and of ethers produced from alcohols as gasoline components. However, proposals continue to be made to implement alcohol programs similar to that of Brazil (1). Other nations such as New Zealand, Germany, and Sweden also investigated the use of alcohols as a transportation fuel.

The benefits of alcohol fuels include increased energy diversification in the transportation sector, accompanied by some energy security and balance of payments benefits, and potential air quality improvements as a result of the reduced emissions of photochemically reactive products (see Air pollution). The Clean Air Act of 1990 and emission standards set out by the State of California may serve to encourage the substantial use of alcohol fuels, unless gasoline and diesel technologies can be developed that offer comparable advantages.

1. Properties of Alcohol Fuels

Table 1 summarizes key properties of ethanol and methanol as compared to other fuels. Both alcohols make excellent motor fuels, although the high latent heats of vaporization and the low volatilities can make cold-starting difficult in vehicles having carburetors or fuel injectors in the intake manifold where the fuel must be vaporized prior to being introduced into the combustion chamber. This is not the case for direct injection diesel-type engines using methanol or ethanol. Both methanol and ethanol have high octane values and allow high compression ratios having increased efficiency and improved power output per cylinder. Both have wider combustion envelopes than gasoline and can be run at lean air-fuel ratios with better energy efficiency. However, ethanol and methanol have very low cetane numbers and cannot be used in compression-ignition diesel-type engines unless gas temperatures are high at the time of injection. Manufacturers of heavy-duty engines have developed several types of systems to assist autoignition of directly injected alcohols. These include glow plugs or spark plugs, reduced engine cooling, and increased amounts of exhaust gas recirculation or, in the case of two-stroke engines, reduced scavenging. Additives to improve cetane number have been effective as have dual-fuel approaches, in which a small amount of diesel fuel is used as an ignitor for the alcohol.

There are particular alcohol fuel safety considerations. Unlike gasoline or diesel fuel, the vapor of methanol or ethanol above the liquid fuel in a fuel tank is usually combustible at ambient temperatures. This poses the risk of an explosion should a spark or flame find its way to the tank such as during refueling. Additionally, a neat methanol fire has very little luminosity and, consequently, fire fighting efforts can be difficult in daylight.

Table 1. Properties of Fuels[a]

Properties	Methanol	Ethanol	Propane	Methane	Isoctane	Unleaded gasoline	Diesel fuel #2
constituents	CH_3OH	CH_3CH_2OH	C_3H_8	CH_4	C_8H_{18}	$C_nH_{1.87n}$ (C_4 to C_{12})	$C_nH_{1.8n}$ (C_8 to C_{20})
CAS Registry Number	[67-56-1]	[64-17-5]	[74-98-6]	[74-82-8]	[540-84-1]	[8006-6-9]	
molecular weight	32.04	46.07	44.10	16.04	114.23	≈110	≈170
element composition, wt %							
C	37.49	52.14	81.71	74.87	84.12	86.44	86.88
H	12.58	13.13	18.29	25.13	15.88	13.56	13.12
O	49.93	34.73	0	0	0	0	0
density at 16°C and 101.3 kPa[b], kg/m^3	794.6	789.8	505.9	0.6776	684.5	721–785	833–881
boiling point at 101.3 kPa[b], °C	64.5	78.3	6.5	−161.5	99.2	38–204	163–399
freezing point, °C	−97.7	−114.1	−188.7	−182.5	−107.4		< − 7
vapor pressure at 38°C, kPa[b]	31.9	16.0	1.297	0.5094	11.8	48–108	negligible
heat of vaporization, ΔH_v, MJ/kg[c]	1.075	0.8399	0.4253	0.5094	0.2712	0.3044	0.270
gross heating value, MJ/kg[c]	22.7	29.7	50.4	55.5	47.9	47.2	44.9
net heating value							
MJ/kg[c]	20.0	27.0	46.2	50.0	44.2	43.9	42.5
MJ/m^3[d]	15,800	21,200	23,400		30,600	32,000	35,600
stoichiometric mixture net heating value, MJ/kg[c]	2.68	2.69	2.75	2.72	2.75	2.83	2.74
autoignition temperature, °C	464	363	450	537	418	260–460	257
flame temperature, °C	1,871	1,916	1,988	1,949	1,982	2,027	1,993
flash point, °C	11	13			4	−43 to −39	52–96
flame speed at stoichiometry, m/s	0.43		0.40	0.37	0.31	0.34	
octane ratings							
research	106	107	112	120	100	92–98	
motor	92	89	97	120	100	80–90	
cetane rating	0–5						>40
flammability limits, vol % in air	6.72–36.5	3.28–18.95	2.1–9.5	5.0–15.0	1.0–6.0	1.4–7.6	1.0–5.0
stoichiometric air–fuel mass ratio	6.46	8.98	15.65	17.21	15.10	14.6	14.5
stoichiometric air–fuel volumetric ratio	7.15	14.29	23.82	9.53	59.55	55	85
water solubility	complete	complete	no	no	no	no	no
sulfur content, wt %	0	0	0	0	0	<0.06	<0.5

[a] Refs. (2–7).
[b] To convert kPa to psi, multiply by 0.145.
[c] To convert MJ/kg to Btu/lb, multiply by 430.3.
[d] To convert MJ/m^3 to Btu/gal, multiply by 3.59.

However, low luminosity also implies low radiative fluxes from the fire. This, combined with the high latent heat of vaporization, means that the heat release of a methanol fire is low relative to one of gasoline or diesel fuel. Because methanol or ethanol are both water-soluble, fires can be successfully controlled by dilution with large amounts of water, a tactic that simply spreads gasoline fires. Nevertheless, fire-extinguishing foams (see Flame retardants) are the preferred alcohol fire-fighting method.

Some potential problems of alcohol fuels have been addressed by adding small amounts of gasoline or specific hydrocarbons to the fuel, reducing the flammability envelope and providing luminosity in case of fire.

2. Uses of Alcohol Fuels

Early applications of internal combustion engines featured a variety of fuels, including alcohols and alcohol-hydrocarbon blends. In 1907 the U.S. Department of Agriculture investigated the use of alcohol as a motor fuel. A subsequent study by the U.S. Bureau of Mines concluded that engines could provide up to 10% higher power on alcohol fuels than on gasoline (8). Mixtures of alcohol and gasoline were used on farms in France and in the United States in the early 1900s (9). Moreover, the first Ford Model A automobiles could be run on either gasoline or ethanol using a manually adjustable carburetor (1). However, the development of low cost gasoline pushed other automobile fuels into very minor roles and the diesel engine further solidified the hold of petroleum fuels on the transportation sector. Ethanol was occasionally used, particularly in rural regions, when gasoline supplies were short or when farm prices were low.

Methanol has been used as a motor racing fuel for many decades. Its high latent heat of vaporization cools the incoming charge of air to each cylinder. Increasing the mass of air taken into each cylinder increases the power developed by each stroke, providing a turbocharger effect. Furthermore, methanol has a higher octane value than gasoline allowing higher compression ratios, greater efficiency, and higher output per unit of piston displacement volume. These power increases are advantages in racing as is the simple means by which methanol fuel quality and uniformity can be verified.

The transparency of methanol flames is usually a safety advantage in racing. In the event of fires, drivers have some visibility and the lower heat release rate of methanol provides less danger for drivers, pit crews, and spectators.

Partly for these reasons, methanol has been the required fuel of the Indianapolis 500 since 1965. Methanol is also used in many other professional and amateur races. However, transparency of the methanol flames has also been a disadvantage in some race track fires. The invisibility of the flame has confused pit crews, delayed fire detection, and caused even trained firefighters problems in locating and extinguishing fires.

Low level blends of ethanol and and gasoline enjoyed some popularity in the United States in the 1970s. The interest persists into the 1990s, encouraged by the exemption of low level ethanol-gasoline blends from the Federal excise tax as well as from state excise taxes in many states.

3. Energy Diversification and Energy Security

The ethanol program in Brazil addressed that country's oil supply problems in the 1970s, at times improved the balance of payments, and served to strengthen the economy of the sugar production portion of the agricultural sector. Although the benefits are difficult to quantify because of the very high inflation rate (10) the Brazilian ethanol program generally met its goals. Ironically the inability of ethanol to substitute successfully for diesel fuel in the heavy-duty truck sector necessitated keeping refinery outputs up to provide sufficient available diesel fuel. Thus gasoline was in surplus in Brazil and oil imports were not as much affected as originally hoped. The Brazilian program demonstrated that petroleum substitution strategies need to address the "whole barrel" product slate of oil refineries.

In the 1990s world events precipitated renewed interest in energy diversification strategies for the U.S. transportation sector. However, few measures are in place to encourage fuel alternatives outside of the exemption from the Federal excise tax on motor fuel granted to ethanol blends. The Alternative Motor Fuels Act of 1988 did extend credits to automobile manufacturers in the calculation of corporate average fuel economy (CAFE) for vehicles that use methanol or ethanol or natural gas; electric vehicles had previously been granted such a credit. Under the Act's provisions, neither ethanol nor methanol is counted as fuel consumed in the calculation of fuel economy. Thus vehicles that use alcohol have very high fuel economy ratings, reflecting the value of these vehicles in reducing oil imports. The credits take effect in model-year 1993. The fuel economy calculation assumes that methanol and ethanol fuels in commerce contain 15% by volume gasoline. Vehicles that can use either alcohol fuels or gasoline receive a reduced CAFE credit. The maximum credit that can be earned by a manufacturer for selling vehicles capable of using petroleum fuels is capped because alcohol fuels usage by these vehicles is not assured.

4. Alcohol Availability

4.1. Methanol

If methanol is to compete with conventional gasoline and diesel fuel it must be readily available and inexpensively produced. Thus methanol production from a low-cost feed stock such as natural gas [8006-14-2] or coal is essential (see Feedstocks). There is an abundance of natural gas (see Gas, natural) worldwide and reserves of coal are even greater than those of natural gas.

4.1.1. Natural Gas Reserves

U.S. natural gas reserves could support a significant methanol fuel program. 1990 proved, ie, well characterized amounts with access to markets and producible at current market conditions U.S. resources are 4.8 trillion cubic meters (168 trillion cubic feet = 168 TCF). U.S. consumption is about one-half trillion m^3 (18 TCF) or 18 MJ equivalents per year, but half of that is imported. Estimates of undiscovered U.S. natural gas reserves range from 14 to 16 trillion m^3 (492 to 576 TCF) or roughly a 30-year supply at current U.S. consumption rates. Additional amounts of natural gas may become available from advanced technologies (see Fuels, synthetic).

If 10% of the U.S. gasoline consumption were replaced by methanol for a twenty year period, the required reserves of natural gas to support that methanol consumption would amount to about one trillion m^3 (36 TCF) or twice the 1990 annual consumption. Thus the United States could easily support a substantial methanol program from domestic reserves. However, the value of domestic natural gas is quite high. Almost all of the gas has access through the extensive pipeline distribution system to industrial, commercial, and domestic markets and the value of gas in these markets makes methanol produced from domestic natural gas uncompetitive with gasoline and diesel fuel, unless oil prices are very high.

It is therefore more relevant to examine world resources of natural gas in judging the supply potential for methanol. World proved reserves amount to approximately 1.1×10^{15} m^3 (40,000 TCF) (11). As seen in Figure 1, these reserves are distributed more widely than oil reserves.

Using estimates of proven reserves and commitments to energy and chemical uses of gas resources, the net surplus of natural gas in a number of different countries that might be available for major fuel methanol projects has been determined. These are more than adequate to support methanol as a motor fuel.

4.1.2. Coal Reserves

As indicated in Table 2, coal is more abundant than oil and gas worldwide. Moreover, the U.S. has more coal than other nations: U.S. reserves amount to about 270 billion metric tons, equivalent to about 11×10^{16} MJ (1×10^{20} BTU = 6600 quads), a large number compared to the total transportation energy use of about 3.5×10^{14} MJ (21 quads) per year (11). Methanol produced from U.S. coal would obviously provide better energy security benefits than methanol produced from imported natural gas. At present however, the costs of producing methanol from coal are far higher than the costs of producing methanol from natural gas.

4.1.3. Biomass

Methanol can be produced from wood and other types of biomass (see Chemurgy; Fuels from biomass). The prospects for biomass reserves are noted below.

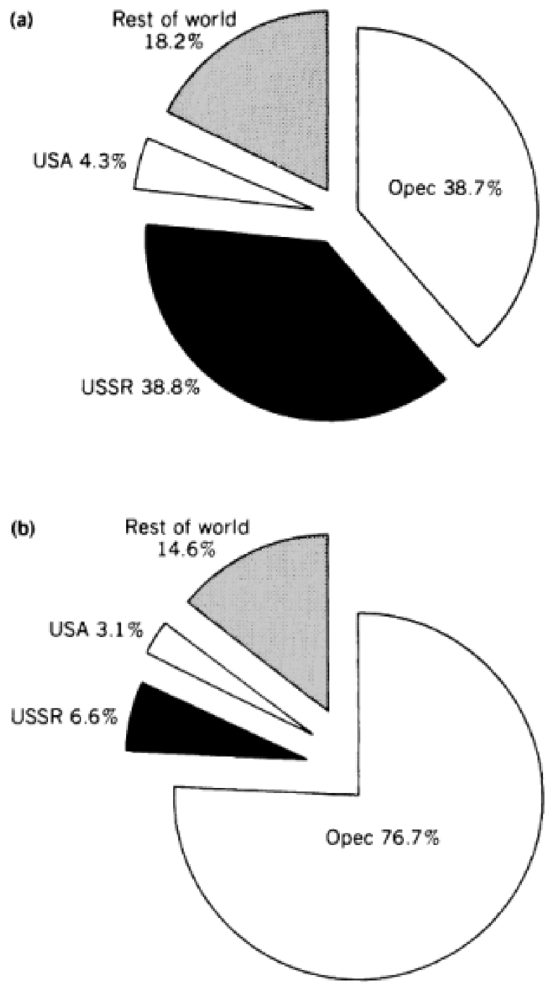

Fig. 1. Distribution ofd the world proven gas and oil reserves as of January 1, 1988. (**a**) $107.5 \times 10^{12}\ m^3$ (3,800 TCF) natural gas; (**b**) 140 m^3 (890 barrels) oil.

4.2. Ethanol

From the point of view of availability, ethanol is extremely attractive because it can be produced from renewable biomass. Estimates of the amount of ethanol that could be produced from biomass on a sustained basis range from about 3×10^{13} to more than 8×10^{14} MJ/yr (2–50 quad/yr), about half of which would derive from wood crops (11).

5. Economic Aspects

5.1. Alcohol Production

Studies to assess the costs of alcohol fuels and to compare the costs to those of conventional fuels contain significant uncertainties. In general, the low cost estimates indicate that methanol produced on a large scale

Table 2. World Estimated Recoverable Reserves of Coal in Billions of Metric Tons[a]

Location	Anthracite and bituminous coal[b]	Lignite[c]	Total
North America			
Canada	4.43	2.42	6.85
Mexico	1.91		1.91
United States	231.13	32.71	263.84
Total	*237.47*	35.13	*272.60*
Central and South America			
Total	*5.13*	*0.02*	*5.15*
Western Europe			
Total	*32.20*	*58.23*	*90.43*
Eastern Europe and USSR			
USSR	150.19	94.53	244.72
Total	*182.82*	*139.17*	*321.99*
Middle East			
Total	*0.18*		*0.18*
Africa			
Total	*64.67*		*64.67*
Far East and Oceania			
Australia	29.51	36.20	65.71
China	98.79		98.79
Total	*130.39*	*38.61*	*169.00*
World total	*652.86*	*271.16*	*924.02*

[a] Ref. 12.
[b] Includes subanthracite and subbituminous.
[c] Includes brown coal.

from low cost natural gas could compete with gasoline when oil prices are around 14¢/L ($27/bbl). This comparison does not give methanol any credits for environmental or energy diversification benefits. Ethanol does not become competitive until petroleum prices are much higher.

5.2. Methanol

5.2.1. Produced from Natural Gas

Cost assessments of methanol produced from natural gas have been performed (13–18). Projections depend on such factors as the estimated costs of the methanol production facility, the value of the feedstock, and operating, maintenance, and shipping costs. Estimates vary for each of these factors. Costs also depend on the value of oil. Oil price not only affects the value of natural gas, it also affects the costs of plant components, labor, and shipping.

Estimates of the landed costs of methanol (the costs of methanol delivered by ship to a bulk terminal in Los Angeles), vary between 8.9 and 15.6 cents per liter (33.6 and 59.2 cents per gallon). Estimates range from 7.9 to 11.1 cents per liter (30 to 42 cents per gallon) in a large-scale established methanol market and 11.9 to 19.3 cents per liter (45 to 73 cents per gallon) during a small volume transition phase (18).

Estimated pump prices must take terminaling, distribution, and retailing costs into account as well as any differences in vehicle efficiency that methanol might offer. Estimates range from no efficiency advantage to about 30% improvement in fuel efficiency for dedicated and optimized methanol light-duty vehicles. Finally, the cost comparison must take into account the fuel specification for methanol. Most fuel methanol for light-duty vehicles is in the form of 85% methanol, 15% gasoline by volume often termed M85.

The sum of the downstream costs adds roughly 7.9 cents per liter (30¢/gal) and the adjustment of the final cost for an amount of methanol fuel equivalent in distance driven to an equal volume gasoline involves a multiplier ranging from 1.6 to 2.0, depending on fuel specification and the assumed efficiency for methanol light-duty vehicles as compared to gasoline vehicles. The California Advisory Board has undertaken such cost assessment (11).

A cost assessment must also take into account the volume of methanol use ultimately contemplated. A huge methanol program designed to replace most of the U.S. gasoline use would be likely to increase the value of even remotely located natural gas. A big program would also tend to decrease the price of oil, making it more difficult for methanol to compete as a motor fuel. Nevertheless, a balanced assessment of all the studies appears to indicate that a large scale methanol project could provide a motor fuel that competes with gasoline when oil prices are not less than about $0.17/L (1988 U.S. $27/bbl).

In small volume transition phases, methanol cannot compete directly in price with gasoline unless oil prices become very high, with the possible exception of a few scenarios in which low cost methanol is available from expansions to existing methanol plants currently serving the chemical markets for methanol. Energy diversification benefits have not been quantified but the potential air quality benefits have been studied in the work of the California Advisory Board on Air Quality and Fuels. The investment required to introduce methanol might well be justified on air quality grounds, at least in those areas such as California where air pollution programs involve substantial costs. However, the relative advantage of methanol depends on the emissions levels from future vehicles and on the costs of cleaner gasolines that might be able to offer environmental benefits that compete at least to some extent with the environmental benefits of methanol.

5.2.2. Produced from Coal

Estimates of the cost of producing methanol from coal have been made by the U.S. Department of Energy (DOE) (12, 17) and they are more uncertain than those using natural gas. Experience in coal-to-methanol facilities of the type and size that would offer the most competitive product is limited. The projected costs of coal-derived methanol are considerably higher than those of methanol produced from natural gas. The cost of the production facility accounts for most of the increase (11). Coal-derived methanol is not expected to compete with gasoline unless oil prices exceed $0.31/L ($50/bbl). Successful development of lower cost entrained gasification technologies could reduce the cost so as to make coal-derived methanol competitive at oil prices as low as $0.25/L ($40/bbl) (17) (see Coal conversion processes).

These cost comparisons do not assign any credit to methanol for environmental improvements or energy security. Energy security benefits could be large if methanol were produced from domestic coal.

5.2.3. Produced from Biomass

Estimates for methanol produced from biomass indicate (11) that these costs are higher than those of methanol produced from coal. Barring substantial technological improvements, methanol produced from biomass does not appear to be competitive.

5.3. Ethanol

Accurate projections of ethanol costs are much more difficult to make than are those for methanol. Large scale ethanol production would impact upon food costs and have important environmental consequences that are rarely cost-analyzed because of the complexity. Furthermore, for corn, the most likely large-scale feedstock, ethanol costs are strongly influenced by the credit assigned to the protein by-product remaining after the starch has been removed and converted to ethanol.

Cost estimates of producing ethanol from corn have many uncertainties (11). Most estimates fall into the range of $0.26 to 0.40 per liter ($1 to 1.50/gal), after taking credits for protein by-products, although some estimates are lower. These estimates do not make ethanol competitive with oil until oil prices are above $0.38/L ($60/bbl) (17).

For these reasons, ethanol is most likely to find use as a motor fuel in the form of a gasoline additive, either as ethanol or ethanol-based ethers. In these blend uses, ethanol can capture the high market value of gasoline components that provide high octane and reduced vapor pressure.

5.4. Impact of Incremental Vehicle Costs

The costs of alcohol fuel usage may include other costs associated with vehicles. Incremental vehicle costs have been estimated by the Ford Motor Company for the fuel-flexible vehicle that can use gasoline, methanol, ethanol, or any mixture of these, to be in the range of $300 per vehicle assuming substantial production (14). This cost may or may not be passed along to the consumer, because of incentives provided to the manufacturer by the Alternative Motor Fuels Act of 1988. There also may be incremental vehicle operating costs resulting from increased lubrication or increased frequency of oil changes.

5.5. Infrastructure Requirements

In general, infrastructure requirements resulting from the expanded use of alcohol fuels are not especially greater than those involved in the production and refining of oil. However, for a corresponding delivery of energy, the capital costs of alcohol infrastructure would presumably be larger, as capital costs of production facilities appear to be larger than corresponding oil refinery costs for an equivalent amount of energy output. Moreover, infrastructure costs for storage and distribution facilities could be higher. Facilities for hydrocarbon fuels are generally not compatible with methanol and ethanol. Thus a program to introduce substantial amounts of alcohol fuel might well require existing infrastructure modifications. These changes can be especially difficult and costly for underground pipelines and tanks, which need to be replaced or modified.

In California, the South Coast Air Quality Management District has implemented a local rule requiring that one new or replacement underground tank at each gasoline retail facility must be suitable for methanol. Replacement of an existing tank can cost $50,000 and perhaps more. But many small retail outlets are being replaced by larger more efficient ones, and many older underground tanks (qv) are being replaced to prevent possible leaks and hence underground contamination. Therefore the compatibility rule allows for the gradual development of a methanol-compatible infrastructure at low costs. The extra costs for methanol-compatible storage ranges from negligible to about $4000 per tank and dispenser, depending on the technical choices that would otherwise be made for gasoline-only facilities.

6. Vehicle Technology and Vehicle Emissions

One of the reasons that U.S. automobile manufacturers showed more interest in alcohols as alternative fuels in the late 1970s and early 1980s is because alcohol's energy density is closer to gasoline and diesel than other alternatives such as compressed natural gas. They reasoned that consumers would be more comfortable with liquid fuels, envisioning little change in the fuel distribution of alcohols. Most of the research in the 1970s focused on converting light-duty vehicles, to alcohol fuels. Towards the late 1970s, researchers also began to turn their attention to heavy-duty applications. In heavy-duty engines the emissions benefits of alcohols are far clearer than in light-duty vehicles. However, it is also much harder to design heavy-duty engines to use the low cetane number alcohols.

It was not until the early 1980s that the potential air quality benefits of alcohol fuels started to be investigated. It was about five years later that proponents argued that alcohols could provide significant air quality benefits in addition to energy security benefits. Low level blends of ethanol and gasoline were argued to provide lower CO emissions. The exhaust from light-duty methanol vehicles was thought to be less reactive in the formation of ozone. Uses of alcohols fuels in heavy-duty engines showed substantially reduced mass emissions in contrast to light-duty experience which showed about the same mass emissions but a reduced reactivity of the exhaust components.

6.1. Light-Duty Vehicles

6.1.1. Use of Low Level Blends

The first significant U.S. use of alcohols as fuels since the 1930s was the low level 10% splash blending of ethanol in gasoline, which started after the oil crisis of the 1970s. This blend, called gasohol, is still sold in commerce although mostly by independent marketers and distributors instead of the major oil companies. EPA provided a waiver for this fuel allowing for a 6.9 kPa (1 psi) increase in the vapor pressure of gasohol over that of gasoline.

In the first years of gasohol use some starting and driveability problems were reported (19). Not all vehicles experienced these problems, however, and better fuel economy was often indicated even though the energy content of the fuel was reduced. Gasohol was exempted from the federal excise tax amounting to a $0.16/L ($0.60/gal) subsidy. Without this subsidy, ethanol would be too expensive for use even as a fuel additive.

Nearly four billion L/yr of ethanol are added to gasoline and sold as gasohol (18). The starting or driveability difficulties have been solved, in part, by the advances in vehicle technology employing fuel feedback controls.

Methanol was also considered as a gasoline additive. Table 3 summarizes some of the oxygenated compounds approved by EPA for use in unleaded gasoline. EPA waivers were granted to Sun Oil Company in 1979 for 2.75% by volume methanol with an equal volume of tertiary butyl alcohol [75-65-0] (TBA) up to a blend oxygen total of 2% by weight oxygen; ARCO in 1979 for up to 7% by volume TBA; and ARCO in 1981 for the use of the blends containing a maximum of 3.5% by weight oxygen. These last blends are gasoline-grade TBA (GTBA) and OXINOL having up to 1:1 volume ratio of methanol to GTBA. Petrocoal was also granted a waiver to market up to 10% by volume methanol and cosolvents in gasoline but this waiver was revoked in 1986 after automobile manufactures complained of significant material compatibility problems and openly warned consumers against gasolines containing methanol. A waiver was issued to Du Pont in 1985 which allowed addition of up to 5% methanol to gasoline having a mixture of 2.5% cosolvents. None of these additives became very popular (20).

6.1.2. Vehicle Emissions

Gasohol has some automotive exhaust emissions benefits because adding oxygen to a fuel leans out the fuel mixture, producing less carbon monoxide [630-08-2] (CO). This is true both for carbureted vehicles and for those having electronic fuel injection.

Urban areas such as Denver, Phoenix, and others at high altitudes have problems complying with health-based carbon monoxide standards in part because of automobile emissions. Vehicles calibrated for operation at sea level that are operated at high altitudes run rich, producing more CO. Blends such as gasohol cause the engine to operate leaner because of the oxygen in the fuel. There are larger CO reductions using oxygenated blends in older, carbureted engines. But even the newer technology vehicles have lower CO emissions using gasohol and other oxygenated fuels because of periods of open loop operation, especially during cold starts.

Blended fuels increase the vapor pressure of the resulting mixture so that more hydrocarbons are evaporated into the atmosphere during operation, refueling, or periods of extended parking. Although these hydrocarbons can react with NO_x emissions in sunlight to form ozone, atmospheric modeling has indicated that ozone is probably not increased as a result of the higher fuel volatility for two reasons (see Atmospheric modeling). First, CO is also an ozone precursor so reducing CO reduces ozone. Second, the hydrocarbon species are somewhat less reactive because of the lower reactivity of ethanol. Furthermore, programs for oxygenated fuel use are focused at high CO occurrences during the year. These usually occur in the wintertime, whereas

Table 3. EPA Approved Oxygenated Compounds for Use in Unleaded Gasoline[a]

Compound[b]	Broadest EPA waiver	Date	Maximum oxygen, wt %	Maximum oxygenate, vol %
methanol	substantially similar	1981		0.3
propyl alcohols	substantially similar	1981	2.0	(7.1)[c]
butyl alcohols	substantially similar	1981	2.0	(8.7)[c]
methyl *tert*-butyl ether (MTBE)	substantially similar	1981	2.0	(11.0)[c]
tert-amyl methyl ether (TAME)	substantially similar	1981	2.0	(12.7)[c]
isopropyl ether	substantially similar	1981	2.0	(12.8)[c]
methanol and butyl alcohol or higher mol wt alcohols in equal vol	substantially similar	1981	2.0	5.5
ethanol	gasohol	1979, 1982	(3.5)[c],[d]	10.0
gasoline grade *tert*-butyl alcohol (GTBA)	ARCO	1981	3.5	(15.7)[c]
methanol + GTBA (1:1 max ratio)	ARCO (OXINOL)	1981	3.5	(9.4)[c]
	Du Pont[e]	1985	3.7	[f]
methanol at 5 vol % max + 2.5 vol % min cosolvent	Texas methanol (OCTAMIX)[g]	1988	3.7	[f]

[a]Ref. 21
[b]All blends of these oxygenated compounds are subject to ASTM D 439 volatility limits except ethanol. Contact the EPA for current waivers and detailed requirements, U.S. Environmental Protection Agency, Field Operations and Support Division (EN-397F), 401 M Street, S.W., Washington, D.C. 20460.
[c]Calculated equivalent for avaerage specific gravity gasoline (0.737 specific gravity at 16°C, NIPER Gasoline Report). Calculated equivalent depends on the specific gravity of the gasoline.
[d]Value shown is for denatured ethanol. Neat ethanol blended at 10.0 vol % produces 3.7 wt % oxygen.
[e]The cosolvents are any one or a mixture of ethanol, propyl, and butyl alcohols. Corrosion inhibitor is also required.
[f]Varies with type of cosolvent.
[g]The cosolvents are a mixture of ethanol, propyl, butyl and higher alcohols up to octyl alcohol. Corrosion inhibitor is also required.

most areas violate ozone standards in the summer months. Therefore, oxygenated fuel programs, as a CO control strategy, do not generally interfere with ozone attainment strategies. However, programs should be individually evaluated (20).

Ethanol blends can also have an effect on NO_x emissions. Scattered data indicate that NO_x may increase as oxygenates are added to the fuel.

Other countries have also investigated the use of low level alcohol blends as an energy substitution strategy as well as to reduce exhaust emissions of lead (qv) (22, 23). Brazil implemented low level ethanol-gasoline blends throughout the twentieth century during times of oil shortages or as a hedge against international fluctuations in sugar prices. Blends ranged from 15 to 42%. In 1975 Proalcool, Brazil's ethanol fuel program, was initiated and required the blending of 20% by volume of ethanol in gasoline. This was not totally achieved throughout Brazil until about 1986 when a 22% ethanol–gasoline blend was standardized. Once the fuel was standardized, engine modifications for new vehicles were made, including higher compression and adjustments to the carburetor and timing (22).

Germany also evaluated the gasoline–alcohol blends using methanol. Early programs used 15% methanol added to gasoline (M15). This program required vehicles to be designed for this fuel. Modifications included changes to the fueling system for air–fuel control and vehicle material changes to be compatible with the higher methanol concentrations. The program ended in 1982. M15 was concluded to be feasible if higher vehicle costs could be offset by the possibility of lower fuel costs (24). Lower level blends were also investigated using up to 3% methanol with 2 or more percent of a suitable cosolvent. Unlike M15, gasoline vehicles could use this blend without any modifications (25). Germany has for several years now used low level blends of methanol in their gasoline.

6.1.3. Retrofits

Retrofits are vehicles designed for conventional fuels modified so that the vehicles can operate on alcohol. Generally, because both ethanol and methanol have lower energy densities, the quantity of fuel entering the engine must be increased to get the same power. Also, because the alcohols have slightly different combustion characteristics, engine parameters such as ignition timing need to be adjusted. To optimize performance and fuel economy the compression ratio of the engine should be increased. However, the economics of these conversions are such that the least amount of changes are made and adjustments to engine compression ratio is typically not done.

Retrofits were popular at the beginning of alcohol fuel programs. Kits were introduced that modified only the fuel flow rate into the engine, but material changes were also necessary because both ethanol and methanol are more corrosive to metals than gasoline. Retrofitting allowed maximum market penetration without having to wait for fleet roll over or for manufacturers to market new vehicles. There was some success in converting light-duty vehicles to methanol. Bank of America operated a fleet of 292 converted Ford and Chevrolet vehicles in the late 1970s and into the 1980s before oil prices collapsed. A conversion kit for these vehicles included hardware, material changes, and a fuel additive to help minimize corrosion (26, 27).

The California Energy Commission (CEC) evaluated the conversion of 1980 Ford Pintos equipped with 2.3-L four-cylinder engines, feedback-controlled carburetors, and three-way catalysts. Four vehicles were left unmodified, four converted to methanol, and four converted to ethanol. The basic changes required to use the alcohols were: the terneplate coating in the fuel tanks was stripped; fuel level sending units and carburetors were chromated to inhibit corrosion; and the air–fuel ratio, timing, and fuel vaporization mechanisms were recalibrated for proper combustion of alcohol fuels and to comply with emission standards. Two methanol- and two ethanol-fueled engines had special pistons installed to raise compression ratios from 9:1 to 12:1 for better efficiency. These vehicles were operated for 18 months accumulating 272,000 km (169,300 miles). The methanol conversions averaged 25,000 km; ethanol conversions, 21,700 km; and gasoline controls, 22,100 km. Although both the methanol and ethanol vehicles were designed to operate on 100% alcohol, they utilized M94.5 (94.5 vol % methanol and 5.5% isopentane [78-78-4] added to improve cold starts and engine warmup) and CDA-20 (ethanol denatured using 2 to 5% unleaded gasoline) (28, 29).

This conversion program indicated that vehicles could be converted to alcohols. Good fuel economy was obtained; methanol vehicles averaged 4.7 km/L (11.0 mpg) or 9.1 km/L (21.3 mpg) on an equivalent energy basis compared to 8.3 km/L (19.5 mpg) for the gasoline control vehicles. No driveability problems were reported and vehicles had no problems starting (lowest temperature was -1.1°C). Both the ethanol and methanol Pintos showed increased upper cylinder wear over gasoline engines. Poor lubrication from using alcohols and excess fueling because of carburetor float problems contributed to the higher wear rates. Hydrocarbon, carbon monoxide, and NO_x emissions were less for methanol, 0.14, 3.2, and 0.3 g/km, respectively, than for gasoline, 0.25, 5.6, and 0.6 g/km.

The biggest problems of the CEC Pinto fleet were that vehicle conversions were expensive and alcohol fuels were more expensive than gasoline. Changes to the fuel tank, fuel lines, and the carburetor were too labor-intensive to be done cheaply. However, these changes if designed, could be made during the vehicle manufacturing at little additional cost (30). Brazil priced ethanol at 65% the cost of gasoline (10) so that conversions could be cost-effective because of the savings on the fuel costs.

Other significant disadvantages of retrofits were the quality of the conversion kits and the ability of the conversions to meet emission regulations over the useful vehicle life. The initial phases of the Brazilian ethanol program also suffered because of poor quality vehicle retrofits. The quality was so poor that the program almost failed after a fairly substantial number of vehicles were converted and the ethanol fuel infrastructure was in place. Further incentives and automobile manufacturers introducing new vehicles designed for ethanol stabilized the program (31).

For these reasons, CEC and DOE concluded that the only cost-effective method of getting alcohol fueled vehicles would be from original equipment manufacturers (OEM). Vehicles produced on the assembly line would have lower unit costs. The OEM could design and ensure the success and durability of the emission control equipment.

6.1.4. Dedicated Vehicles

Only Brazil and California have continued implementing alcohols in the transportation sector. The Brazilian program, the largest alternative fuel program in the world, used about 7.5% of oil equivalent of ethanol in 1987 (equivalent to 150,000 bbl of crude oil per day). In 1987 about 4 million vehicles operated on 100% ethanol and 94% of all new vehicles purchased that year were ethanol-fueled. About 25% of Brazil's light-duty vehicle fleet (10) operate on alcohol. The leading Brazilian OEMs are Autolatina (a joint venture of Volkswagen and Ford), GM, and Fiat. Vehicles are manufactured and marketed in Brazil.

In contrast the California program has some 600 demonstration vehicles (32). Both Ford and Volkswagen participated in the dedicated vehicle phase of the California program. In 1981 Volkswagen provided the first alcohol vehicles produced on an assembly line, forty (19 methanol, 20 ethanol, and 1 gasoline) VW Rabbits and light-duty trucks were manufactured. Design incorporated continuous port fuel injection, 12.5:1 compression ratio, a new ignition system calibration, and a heat exchanger for faster oil warmup. The entire fuel system was designed using materials compatible with methanol and ethanol. These vehicles operated until 1983 and logged 728,000 km of service. This fleet used the same fuel as the ethanol and methanol Pinto retrofits.

In 1981 Ford also provided CEC with 40 Escorts designed to operate on M94.5 and 15 gasoline vehicles to serve as controls. These vehicles had accumulated over 3.4 million km of service as of March 1986. The 1981 Escorts were modified to use methanol. The 1.6-L gasoline engine had a production piston used in European 1.6-L engines to raise the compression ratio to 11.4:1. Other field modifications included spark plug change, a carburetor throttleshaft material change, carburetor float redesign, and the replacement of tin-plated fuel tanks with ones of stainless-steel.

In 1983 the methanol fleet was expanded with the purchase of 506 Ford Escorts. These vehicles are equipped with engines and fuel systems redesigned from Ford's standard 1.6-L gasoline-fueled Escort. Ford also produced five advanced technology vehicles equipped with electronic fuel injection and microprocessor control, with the goal of improving fuel economy and reducing NO_x emissions to 0.25 g/km. The emissions control on these vehicles used the same technology as on the carbureted gasoline versions: standard three-way catalyst, exhaust gas recirculation, and air injection. The 1981 and 1983 Escorts have logged over 48 million km in service and some vehicles have reached gasoline equivalent fuel usage per kilometer over the lifetime of the vehicle.

The methanol fuel specification was changed for the Escorts, at the end of 1983 from M94.5 to a blend of 90% methanol and 10% unleaded gasoline (M90). In the summer of 1984 the fuel was further modified to include 15% gasoline (M85). This change from isopentane was made because gasoline was cheaper. In addition, M85 has a gasoline odor and taste, and in daylight the flame is more visible than either M94.5 or M90. Another safety benefit of the added gasoline is the increased volatility creating a richer air–vapor mixture much less likely to burn or explode in closed containers than neat or 100 percent methanol.

The results of the California fleet demonstrations indicated that fuel economy on an energy basis was equal to or better than gasoline, especially using vehicles having higher compression. None of these engines, however, was fully optimized for methanol so additional improvements are possible. Driveability was also good for the methanol vehicles. An acceleration test of two 1983 methanol-fueled vehicles and a similar 1984 model resulted in: 1983 fuel injection (EFI) methanol, 14.53 s; 1983 carbureted methanol, 15.51 s; and 1984 carbureted gasoline, 19.10 s.

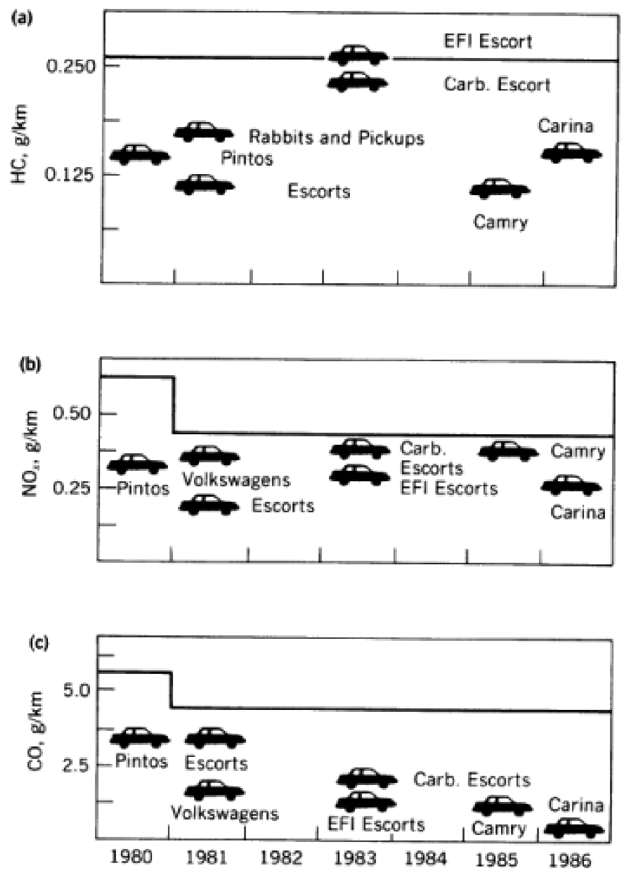

Fig. 2. CEC methanol-fueled vehicle exhaust profile for (**a**) HC, hydrocarbons; (**b**) NO_x; and (**c**) CO. Solid line represents State of California standard maximum emissions. Methanol HC emissions are calculated as $CH_{1.85}$ and not corrected for flame-ionization detector response.

Tests demonstrate that methanol vehicles can meet stringent emission standards for HC, CO, and NO_x as indicated in Figure 2. The primary benefit of methanol, however, is not the amount of hydrocarbons emitted but rather that methanol-fueled vehicles emit mainly methanol which is less reactive in the formation of ozone than the variety of complex organic molecules in gasoline exhaust. Formaldehyde [50-00-0] emissions from methanol vehicles are increased in comparison to gasoline vehicles. Tests of 1983 Escorts showed tailpipe levels as high as 62 mg/km, well above typical gasoline levels of 2 to 7 mg/km. The 1981 Rabbits ranged from about 6 to 14 mg/km and the 1981 Escorts had levels less than 7 mg/km. All results were obtained on relatively low mileage vehicles. Deterioration of catalyst effectiveness could increase these emissions.

The vehicles investigated were mostly adaptions of gasoline technology. For example, automobile manufacturers recommended that catalytic converters designed for gasoline automobiles be installed on vehicles in Brazil to control acetaldehyde [75-07-0] emissions. Brazil decided against catalysts because gasoline vehicles at that time did not have these systems. Similarly, California adopted M85 to aid in cold starting and to provide some measures of perceived safety. Research to find other additives that would assist in cold starting and provide safety characteristics at a reasonable price have been relatively unsuccessful (33). But another way to overcome the issue of cold starting is to design and optimize engines to operate on 100% methanol (M100).

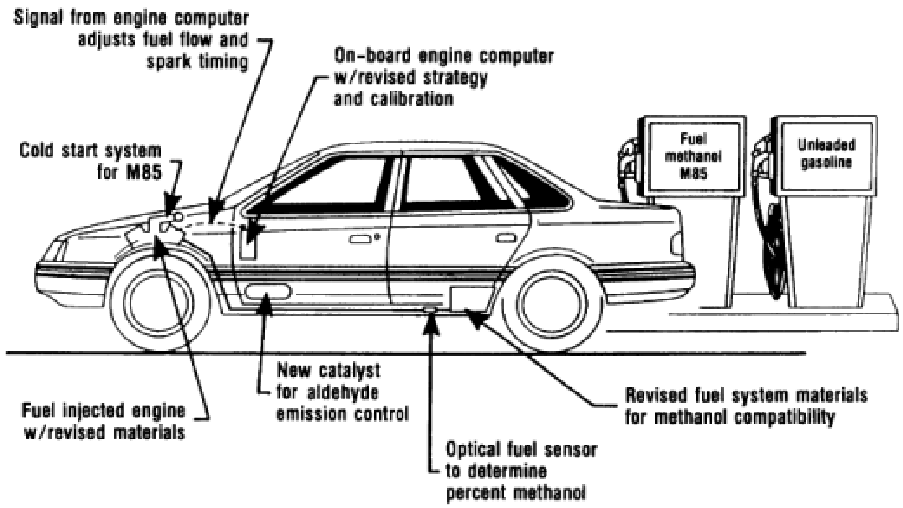

Fig. 3. Components of a Ford flexible fuel vehicle (FFV).

EPA has been pursuing M100 for several years with good success (34). Cold starting is not a problem for direct injected engines where high pressure is used to atomize the fuel and results indicate that a light-duty, direct injection engine can attain very low emissions having good fuel economy and driveability. However, safety concerns of using M100 in general commerce need to be addressed (35).

6.1.5. Fuel Flexible Vehicles

Using dedicated alcohol fuel vehicles pointed to the importance of a wide distribution of fueling stations. Methanol-fueled vehicles require refueling more often than gasoline vehicles.

In 1981, the Dutch company TNO in cooperation with the New Zealand government converted a gasoline engine to a flexible fuel vehicle by adding a fuel sensor. The sensor determined the amount of oxygen in the fuel and then used this information to mechanically adjust the carburetor jets. The initial mechanical system was crude, but the advancement of engine and emission controls, in particular the use of electronics and computers, has brought about substantial refinement (36).

Ford first tried the flexible fuel system on an Escort and called it the “flexible fueled vehicle” or FFV. As seen in Figure 3, the system included building into the electronics any necessary calibrations for gasoline and methanol fuels, adding a sensor to determine the amount of methanol in the fuel, and making necessary material changes to fuel wetted components. The sensor is one of the most critical parts of this system: its output determines parameters such as the amount of fuel to be injected and engine timing. Fuel injectors must also have a wider response range. The engine compression ratio was not changed because the vehicle is designed to operate as well on gasoline as on methanol.

Of course, FFV drivers do not have to use methanol. Emissions benefits are not obtained if methanol is not used, and fuel economy is not optimized for methanol nor are emissions. However the State of California has concluded that advantages offered by the flexibility of the FFV far outweigh the disadvantages (37).

Many U.S. and foreign automobile manufacturers are developing a fuel flexible vehicle in the 1990s. Ford has developed FFVs for 5-L engines used in Crown Victorias and for 3.0-L engines used in their Taurus car line. GM followed Ford with a variable fueled vehicle (VFV) and applied this technology first to the 2.8-L engine family used in the Corsica, and more recently to the 3.1-L engine family in the Lumina (see Fig. 4). Prototype flexible fuel vehicles are also being developed by Volkswagen, Chrysler, Toyota, Nissan, and

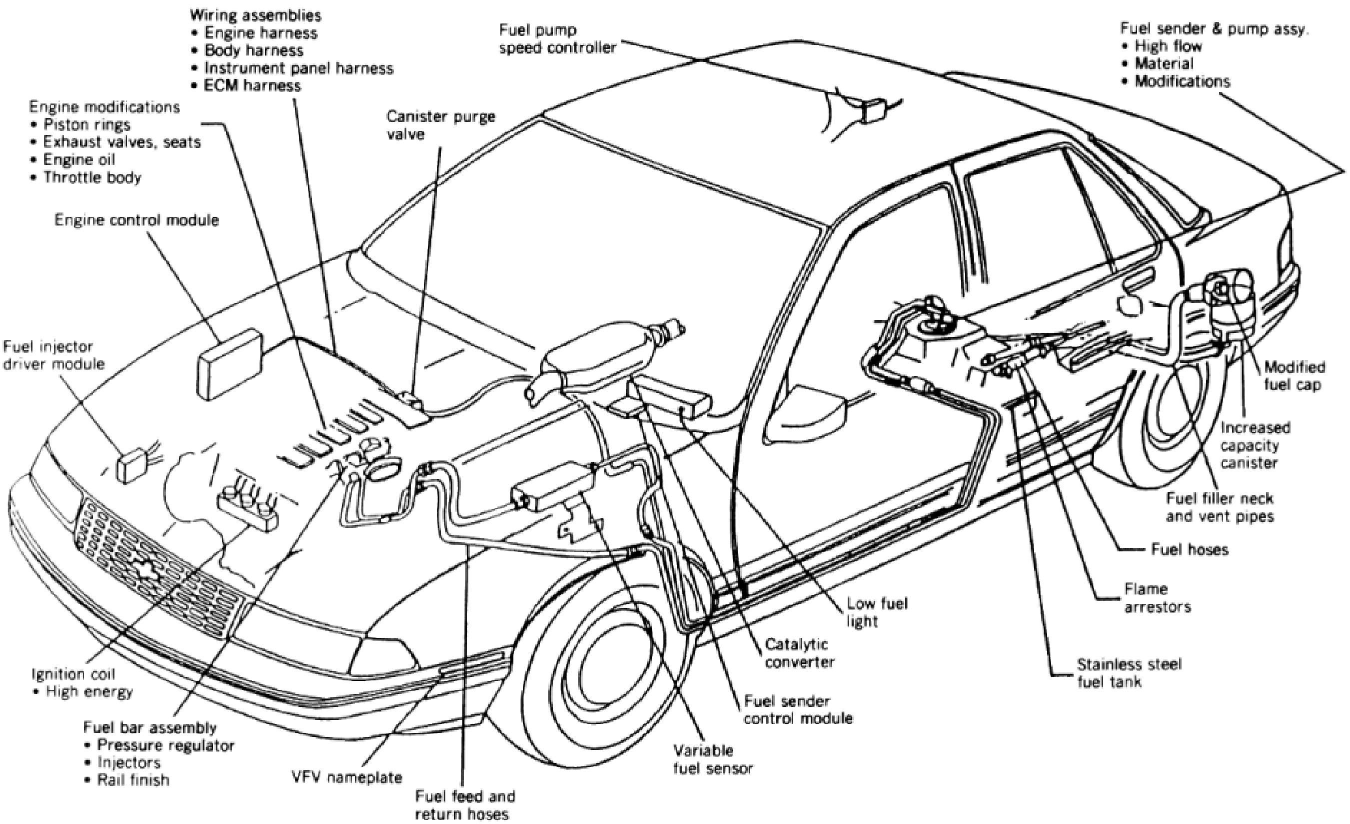

Fig. 4. Components of a Lumina methanol variable fueled vehicle (VFV).

Mitsubishi. California is in the process of obtaining an additional 5,000 of these vehicles in the next several model years (MY92 and MY93) to be used by government and private fleets.

The experience using fuel flexible vehicles has been surprisingly successful. California is operating about 200 vehicles and driveability is excellent on whatever fuel is used. Tests performed on a Ford Crown Victoria showed slightly better fuel economy (4%) and better acceleration (6%) on methanol than gasoline (38). The fuel flexible technology is not limited to methanol but with electronic calibration changes also works for ethanol and gasoline combinations. Changes can be made by adjusting the engine maps in the computer.

EPA, the Air Resources Board (ARB), and others are investigating the possible emission benefits of alcohol fueled vehicles. EPA and ARB adopted regulations for hydrocarbon mass emissions which accounted for the oxygen components in the exhaust, so-called organic mass hydrocarbon equivalent (OMHCE). The regulations required methanol vehicles to meet the same OMHCE value as gasoline hydrocarbons, which in California is 0.155 g/km in 1993. The trend is to account also for the total mass and the reactivity of individual hydrocarbon species and the measure being proposed for total mass is non-methane organic gases or NMOG. Reactivity of the individual species that make up NMOG are estimated (39) to give a value of ozone/km.

Vehicle emissions have been monitored over the last several years on fuel flexible vehicles and depending on when the tests were performed, reported in total hydrocarbons, OMHCE, or NMOG. The vehicle testing performed to date has shown that methanol FFVs can provide emissions benefits. Figure 5 shows the emissions from a GM Corsica for various gasoline methanol mixtures (40). This vehicle was designed to meet the California

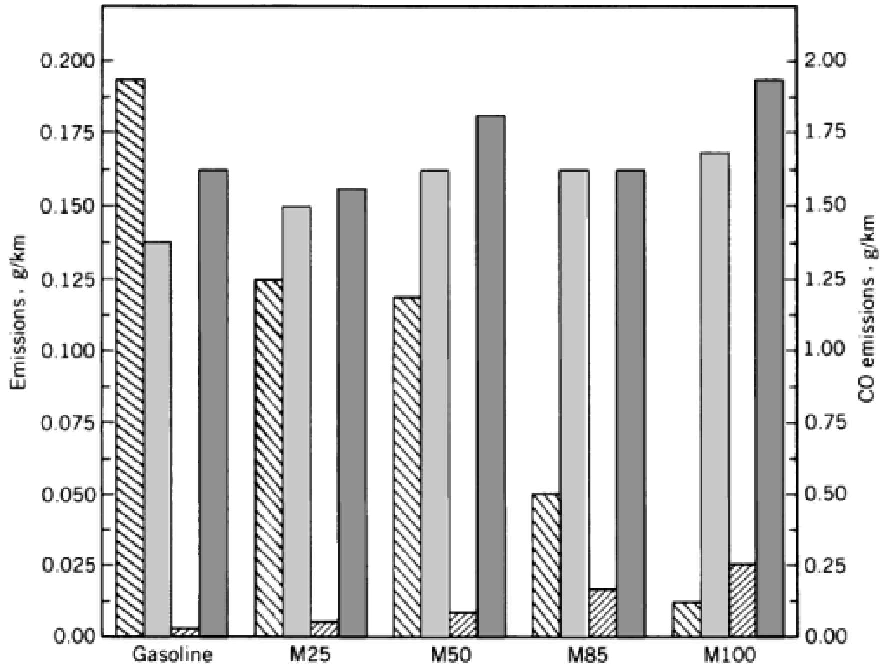

Fig. 5. Emissions from a GM Corsica VFV for gasoline and gasoline–methanol mixtures where represents total organic material, including hydrocarbons, methanol, and formaldehyde; represents NO_x; formaldehyde; and carbon monoxide.

standards of 0.155 g/km hydrocarbon, 2.1 g/km CO, and 0.25 g/km NO_x. In addition California requires methanol vehicles to meet a formaldehyde standard of 9.3 mg/km. The total organic emissions decrease with increasing methanol, whereas formaldehyde increases. NO_x and CO vary but appear unaffected by methanol content. The Corsica data were taken on a green catalyst (low vehicle mileage) and some deterioration of these emissions levels can be expected with age.

Figure 6 shows data for four vehicles operated on gasoline and M85, two having an electrically heated catalyst (EHC). The two vehicles equipped with EHC both showed low values of NMOG and estimated ozone production. These data seem to indicate that methanol vehicles result in less ozone than comparable gasoline vehicles. However, the data only include exhaust emissions and not evaporative or running losses. These later sources of emissions should be lower using methanol because of the lower reactivity of the alcohols.

6.2. Heavy-Duty Vehicles

The use of alcohols in heavy-duty engines developed more slowly than in light-duty engines primarily because the majority of heavy-duty engines are diesels. Diesels are unthrottled, stratified charge engines which autoignite fuel by heat generated during compression. Engine speed and load are modulated by varying the quantity of fuel injected into the cylinder rather than by throttling the fuel-air mixture as done in the Otto cycle or spark-ignition engine. Unthrottled air aspiration reduces pumping losses which in turn increases the engine's thermal efficiency. Diesel engines also are designed for higher compression ratios resulting in further efficiency improvements. The higher efficiency and excellent reliability and durability of these engines make them attractive for heavy-duty applications in trucks, buses, and off road equipment. Unfortunately, their low cetane number limited the compatibility of alcohol fuels with diesel engines without modifications to assist ignition.

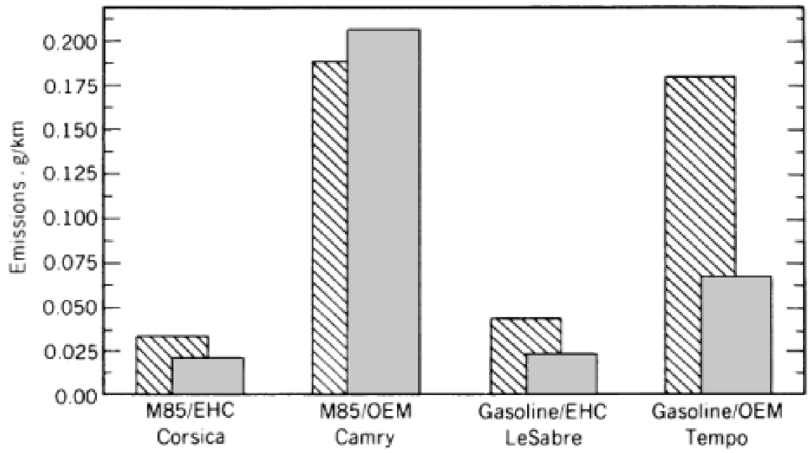

Fig. 6. Comparison of M85 and gasoline emissions (including ozone) corresponding to ▧ estimated ozone (ref. 40) and □ NMOG for vehicles having an electrically heated catalyst (EHC) or not (OEM) (ref. 41).

Not until the early 1980s were prototype heavy-duty engines developed to operate on methanol and ethanol, having efficiencies equal to or better than corresponding diesel engines. These engines were quieter and had considerably cleaner exhaust emissions. Mass emissions of NO_x and particulates were substantially lower when the cleaner alcohol fuels were used, overcoming the inherent NO_x-particulate tradeoff of diesel engines. The biggest challenge facing engine manufacturers in the 1980s and 1990s was to make the alcohol engines as reliable and durable as heavy-duty diesel engines which operate in the range of 0.3 to 0.5 million kilometers without major engine maintenance and repair.

6.2.1. Technology Options

Because alcohols are not easily ignited in diesel-type engines changes in engine hardware or modifications to the fuel are needed. Engine modifications can include the addition of a spark ignition system or an additional fuel injection system to provide dual fuel capabilities. Fuel modifications involve the addition of cetane improvers. Low level blends do not work because methanol and diesel fuels are not miscible. Some research to emulsify diesel and alcohols was carried out, but was never successful (42). Other investigations involved adding a separate fuel system including two fuel tanks, fuel lines, injection pumps, and injectors. In this approach diesel was used to ignite the fuel mixtures, and at low speeds–low loads diesel was the primary fuel. At high speeds—high loads alcohol was the primary fuel. This dual fuel approach was both cumbersome and expensive (43).

One successful method for using alcohols was fumigation. In this technique alcohol is atomized in the engine's intake air either by carburetion or injection. Diesel is directly injected into the cylinder and the combined air-alcohol and diesel mixture is autoignited. Diesel consumption is reduced by the energy of the alcohol in the intake air. This approach, although technically feasible, also requires separate fuel systems for the diesel and alcohol fuels. Additionally, the amount of alcohol used is limited by the amount that can be vaporized into the intake air. This approach is more appropriate as a engine retrofit where total energy substitution is not the primary objective (44).

Other possible technologies involve either assisted ignition or cetane improvers. Assisted ignition approaches can be divided between direct injection, stratified charge type engines, and engines converted back to Otto cycles, by throttling and lowering engine compression.

6.2.2. Dedicated Vehicles

As late as 1982, researchers were still arguing the worthiness of alcohols as fuels for heavy-duty engines (45). Pioneer work on multifuel engines led to modifications in diesel engines to burn neat or 100% alcohol. The German manufacturers were the first to provide prototype methanol engines. Daimler-Benz modified their four stroke M 407 series diesel engine to operate on 100% methanol, by converting the diesel version to a spark-ignited, Otto cycle engine. This required lowering the compression, adding a spark ignition system, and carburetion (throttling). To get back some of the efficiency loss caused by going to a throttling and lower compression, the Daimler-Benz design incorporated a heat exchanger to vaporize the methanol using engine cooling water. Vaporized methanol was introduced into the engine using a standard gaseous carburetor-mixing device.

The M 407 hGO methanol engine is a horizontal, water-cooled, inline six-cylinder configuration (46). Basic combustion is similar to the conventional spark-ignition Otto cycle with one significant exception. Lean combustion at part load is possible for two reasons: because of methanol's favorable flammability limits and because methanol is vaporized and introduced as a gas. Equivalence ratios (air–fuel ratio relative to stoichiometric) greater than 2 are possible without misfire, and minimum fuel consumption is obtained at an equivalence ratio of about 1.8. In the higher load range, the engine is controlled by the air–fuel ratio, rather than by intake throttling, so efficiency is increased relative to the conventional spark-ignition engine. Intake throttling is used for control in the lower load range.

The first methanol bus in the world was placed in revenue service in Auckland, New Zealand in June 1981. It was a Mercedes O 305 city bus using the M 407 hGO methanol engine. This vehicle operated in revenue service for several years with mixed results. Fuel economy on an equivalent energy basis ranged from 6 to 17% more than diesel fuel economy. Power and torque matched the diesel engine and drivers could not detect a difference. Reliability and durability of components was a problem. Additional demonstrations took place in Berlin, Germany and in Pretoria, South Africa, both in 1982.

The world's second methanol bus was introduced in Auckland shortly after the first. This was a M.A.N. bus with a M.A.N. FM multifuel combustion system utilizing 100% methanol. The FM system, more similar to a diesel engine, is a direct injection, high compression engine using a spark ignition. Fuel is injected into an open chamber combustion configuration in close proximity to the spark plugs which ignite the air–fuel mixture. Near the spark plugs the air–fuel mixture is rich and combustion proceeds to the lean fuel air mixtures in the rest of the cylinder. The air–fuel charge is thus stratified in the cylinder and these types of engines are often called lean burn, stratified charge. Engine hardware is similar to the diesel version including a high pressure injection pump and a compression ratio comparable to diesel (19:1). This technology was applied to M.A.N.'s 2566 series engines, an inline 6-cylinder engine, and for buses is configured horizontally (47). Like the Mercedes, it is a four stroke engine.

This technology was tested using diesel fuel, gasoline, methanol, and ethanol. A M.A.N. SL 200 bus having the M.A.N. D2566 FMUH methanol engine was also demonstrated in Berlin. Results of these tests were somewhat mixed. Fuel economy was 12% less than a comparable diesel bus, but driveability was very good. Because the methanol fueled bus was not smoke limited at low speeds, higher torque was possible and bus drivers used this advantage to accelerate faster from starts. Emissions results indicated a considerable advantage in using fuels such as methanol. CO and NO_x were reduced compared to diesel engines and particulates were virtually eliminated.

The success of the New Zealand and German programs were instrumental in implementing a similar bus demonstration in California in 1982 (48). The primary objective was to assess the viability of using methanol in heavy-duty engines. The project focused on evaluating engine durability, fuel economy, driveability, and emissions characteristics. CEC also initiated a demonstration project for off-road heavy-duty vehicles using a multifuel tractor capable of operating on either neat methanol or ethanol (30).

M.A.N. and Detroit Diesel Allison, now Detroit Diesel Corporation (DDC), agreed to participate in the California bus program. DDC provided a methanol version of their 6V-92TA engine, which along with the DDC 71 series, is the most commonly used bus engine in the United States. The engine is a compression-ignited, two-stroke design having a displacement of 9.1 liters and power rating of 20,700 W (277 hp). Several design changes were incorporated for operation on methanol, including electronic unit injectors (EUI) for more precise fuel control, an increased compression ratio, a bypass blower, and glow plugs. Compression ignition is achieved by maintaining the cylinder temperatures above the autoignition temperature of methanol. Air is diverted around the blower, reducing the amount of air entering the cylinders. Glow plugs are used as a starting aid and also at low speeds and low loads to maintain the cylinder temperatures necessary for autoignition. The methanol-fueled engine is turbocharged and equipped with a blower (supercharged).

The engine was the first to incorporate compression ignition of alcohols (7). Low cetane fuels can autoignite, however, provided the in-cylinder temperature is high enough and fuel injection correctly timed. This compression ignition works for methanol as well as ethanol and gasoline.

The California bus program was run at Golden Gate Transit District (GGTD) and continued through late 1990 (49). M.A.N. supplied two European SU 240 coaches for this project, one diesel powered and one methanol powered. DDC provided a GM RTS coach powered by methanol. GGTD already had a RTS diesel powered coach. Results indicate that methanol is a viable fuel for heavy-duty engines in general and transit in particular. Driveability including starting, full and partial throttle acceleration, and deceleration was as good or better using the methanol buses as compared to their diesel counterparts. Figure 7 illustrates the comparison of full throttle acceleration. Detailed fuel economy tests were also performed. Figures 8 and 9 compare steady-state and transient fuel consumption tests, respectively. The transient tests were performed using the Fuel Consumption Test Procedure, Type II (50). Methanol is comparable to diesel in steady-state fuel usage tests, but methanol consumption is higher at idle and during accelerations. The idle fuel consumption is higher because methanol can not burn as lean as diesel fuel. Higher transient fuel consumption is a result of poor combustion factors resulting from poor fuel atomization, air control, and over fuelling. The methanol engine should not inherently be worse than the diesel engine during accelerations, if good combustion can be maintained.

The biggest problem of the GGTD program was engine and vehicle reliability and durability (see Fig. 10). Components needing the most frequent replacement were electronic unit fuel injectors and glow plugs, followed by the electronic control system (controlled power to the glow plugs), throttle position sensor, fuel pump, and fuel cooler fans. Other problems included increased engine deposits and ring and liner wear (51). The M.A.N. engine had similar but fewer problems; the components having the lowest lifetime were spark-plugs.

California continued the development of methanol powered vehicles primarily because of the substantial emission benefits (52). Then in 1986, the U.S. EPA promulgated technology-forcing standards for on-road, heavy-duty diesel engines which had been basically uncontrolled (53). These standards were also adopted in California by the ARB for buses in 1991 and all heavy-duty engines in 1993. Diesel engine manufacturers have made significant improvements in technology and new diesel engines are projected to meet standards without a particulate trap. These improvements have made the diesel engine more competitive with alcohol fueled engines.

In 1987 Seattle Metro purchased 10 new American built M.A.N. coaches powered by methanol. Six GM buses powered by DDC methanol engines entered revenue service at Triboro Coach in Jackson Heights, New York, 2 GM buses in Medicine Hat Transit in Medicine Hat, Manitoba, and 2 Flyer coaches in Winnipeg Transit, Winnipeg, Manitoba, Canada. An additional 45 DDC powered methanol buses were introduced in California as indicated by Table 4. Figure 11 shows the distance accumulation of alternate-fueled buses in the four California transit properties.

Many of the development problems identified in the first bus programs were carried into the more recent demonstration projects. Spark-plug life continued to be an issue at Seattle Metro and the project was terminated in 1990 because of costs of replacement parts. Costs were compounded when M.A.N. decided to discontinue

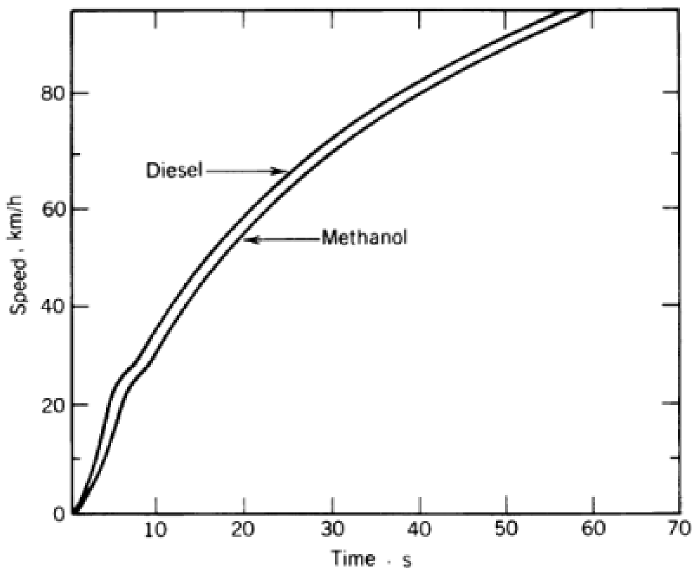

Fig. 7. Full-throttle acceleration for diesel and methanol-powered GM RTS coaches having simulated full-seated passenger loads of 43 passengers.

manufacturing buses in the United States. DDC engines also continued to have problems with fuel injectors and glow plugs. Unit injectors were failing for a variety of reasons but the biggest problem was plugging injector tips. Injectors on some buses had to be changed at mileages as low as 1600 to 3200 km compared to diesel injectors which last up to 100 times as long. DDC and Lubrizol have since developed a fuel additive that when added to methanol at 0.06% by volume substantially reduces injector failures (see Fig. 12).

Many improvements have been made in both combustion and emissions control from the first experimental engine operating at GGTD (54). The new DDC preproduction engines have increased compression, 23:1 compared to 19:1, allowing the glow plugs to function only during starting. The rest of the time the cylinder temperatures are high enough to autoignite methanol. This revision increased the life of glow plugs from an average of 11,900 to 22,100 km between failures. Fuel economy has also improved as have exhaust emissions. Tests performed on an engine dynamometer following the federal test procedure are many times better than California's 1991 bus standard as shown in Table 5.

Because of the success of these various alcohol fuel programs, heavy-duty demonstrations have been extended to other applications as shown in Table 4. The majority of applications are still either in transit or school buses, but California has also begun a program to utilize methanol engines in heavy-duty trucking applications (55). Domestic engine manufacturers participating in this program include Caterpillar, Cummins, DDC, Ford, and Navistar. The Caterpillar and Navistar engines are four stroke engines having glow plugs to assist in igniting methanol. These engines are very different from the two stroke DDC engine and from each other. The Navistar (56) uses a shield glow plug which neither Caterpillar (57) nor DDC do. Navistar claims these glow plugs provide both good combustion and long life. The combustion chambers and fuel control schemes differ from manufacturer to manufacturer. Ford converted a diesel engine to an Otto cycle and added electronically controlled port fuel injection, throttling, and a distributorless spark-ignition system.

Methanol has been shown to be a viable fuel for a variety of trucking applications in a local yet fairly large geographical area (58). And although the results focus primarily on dedicated methanol engines and vehicles in the United States, the conclusions are nearly transferrable to ethanol fuels. DDC's 6V-92TA methanol

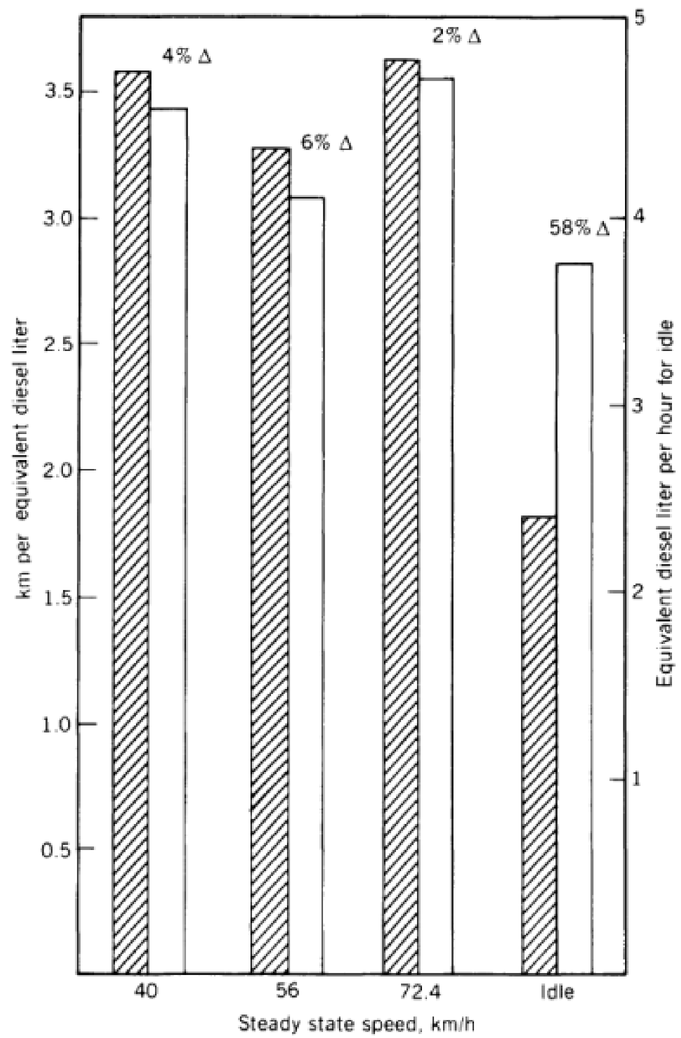

Fig. 8. Fuel consumption for GM RTS coaches using ▨ diesel and □ methanol as fuel. Differences in fuel consumption are indicated by the symbol Δ. To convert km/L to mpg, multiply by 2.35.

engine operates on ethanol using a different engine calibration optimized for good performance and emissions. Additional hardware modifications are not anticipated.

6.2.3. Cetane Improvers

Compared to dedicated alcohol engines, fewer hardware changes need to be made to heavy-duty engines using cetane improvers. The early research on using cetane improvers and alcohol fuels for heavy-duty diesel engines was performed by the Germans in the late 1970s-early 1980s (59). The possibilities of using cetane improvers with ethanol for heavy-duty vehicles operating in Brazil were investigated (60). The work indicated that nitrates are the most effective cetane improvers for alcohols (61) and the Brazilian program focused on nitrates that could be manufactured from sugar cane, the feedstock for ethanol production. Additives considered included butyl nitrate, isoamyl nitrates, 2-ethoxyethyl nitrate, and ethylene glycol nitrates. The selection of

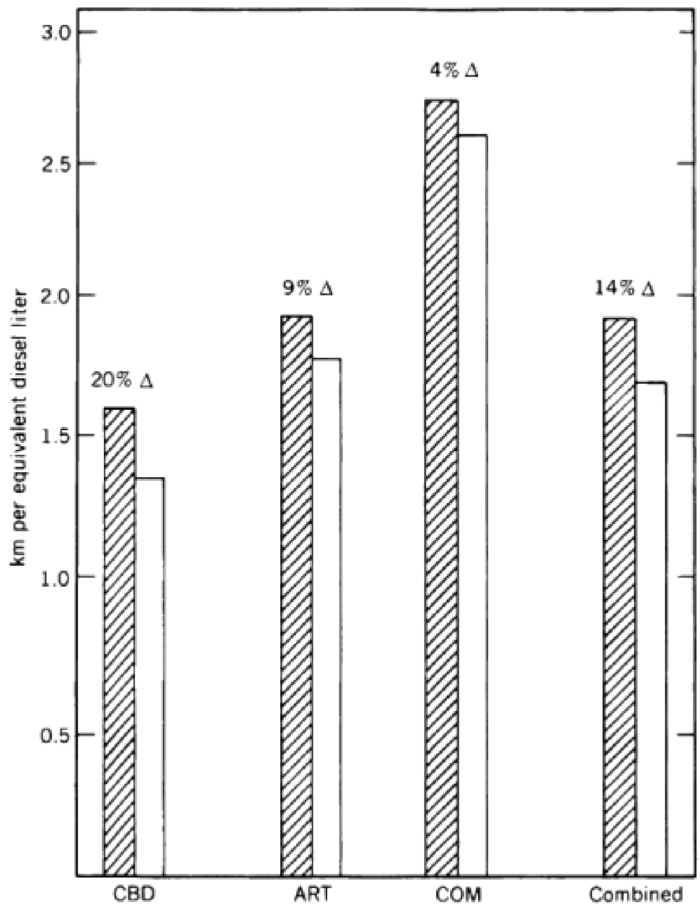

Fig. 9. GM RTS coaches transient fuel consumption for ▯ diesel and ▯ methanol. SAE type road test, UMTA ADB duty cycle. Differences in fuel consumption are indicated by the symbol Δ. CBD (Central Business District), 4.3 stops per km, maximum speed 32 km/h, 18 m deceleration, 7 s dwell time, 19.3 km; ART (arterial), 1.24 stops per km, maximum speed 64 km/h, 61 m deceleration, 7 s dwell time, 13 km; COM (commuter), one stop every 6.4 km, maximum speed of 88.5 km/h, 150 m deceleration, 20 s dwell time, 13 km. To convert km/L to mpg, multiply by 2.35.

the improver depends on the method of the additive modifying the ignition delay over the entire speed and load range. Ideally ethanol should match the same ignition delay behavior as diesel.

Four buses converted to ethanol started operation in 1979 and the engine used was an OM 352, 6 cylinder, direct injection engine rated at 96,200 watt (129 hp). The ignition improver was *n*-hexyl nitrate [20633-11-8] which was later changed to triethylene glycol dinitrate [111-22-8] (TEGDN). TEGDN was mixed with ethanol at 5% or less by volume (60). The test fleet was further expanded to a variety of trucks manufactured and marketed by Mercedes-Benz in Brazil. 1,700 heavy-duty trucks were converted to ethanol for use in the more gruelling sugar cane industry. Engines converted included the OM 352 O (5.7 L, 96,200 watt) and OM 355/5 O (9.7 L, 141,000 watt). Modifications to the engines to use ignition improved ethanol included increasing the fuel delivery capacity of the fuel injection pump, changing the fuel injection nozzles, and making material compatible with the TEGDN/ethanol fuel. The engines provided equal or better power and torque than the unmodified models. Some durability problems, which arose because of lack of lubrication or fuel material

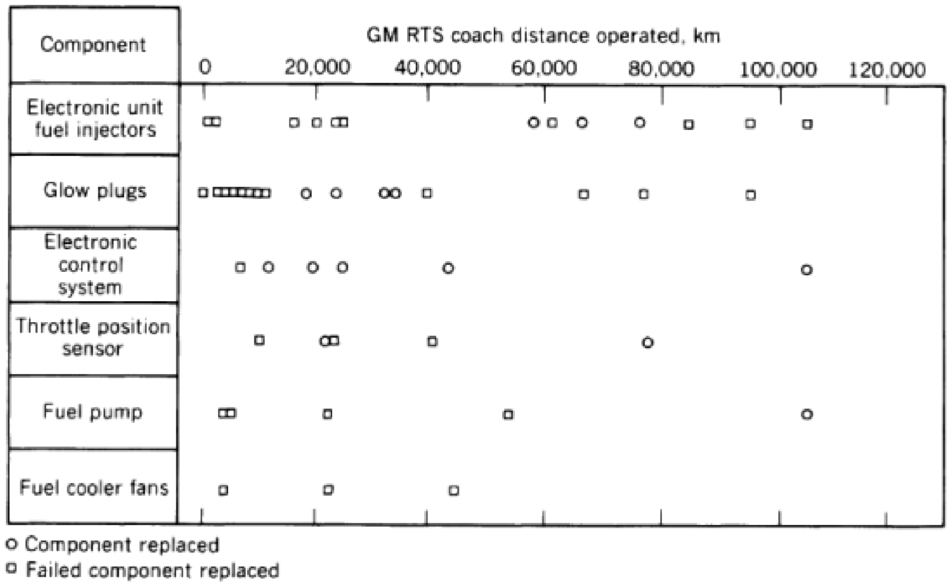

Fig. 10. Components of GM RTS methanol-powered coach replaced, ○, and replaced because of component failure, □, as a function of distance operated.

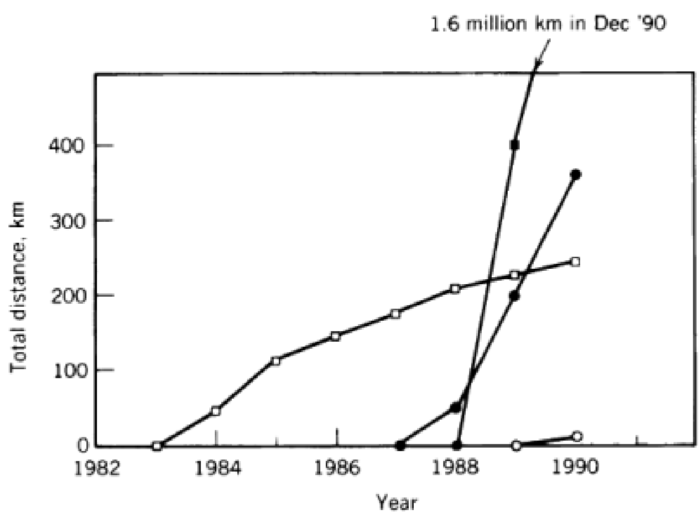

Fig. 11. Distance methanol-fueled transit coaches traveled per year of operation in the □ Golden Gate Transit District (GGTD); • Riverside Transit Agency (RTA), ■ Southern California Rapid Transit District (SCRTD); and ○ Orange County Transit District (OCTD).

incompatibilities, were solved by adding lubricants to the injection pump plungers or by changing materials. Emissions were also generally lower than those from the equivalent diesel engine. Even NO_x was lower because of the lower flame temperatures compared to diesel (62).

The biggest drawback was the cost of ethanol compared to diesel fuel and the cost of the TEGDN and ethanol mixture compared to diesel. Unlike in the United States, diesel fuel in Brazil is considerably less

Table 4. Distribution of California's Heavy-Duty Alternative Fuel Demonstration Vehicles

Transit district	No. of vehicles	Fuel	OEM/engine
South Coast Area Transit	1	methanol	DDC 6V-92TA
Riverside Transit District	3	methanol	DDC 6V-92TA
Southern California RTD	30	methanol	DDC 6V-92TA
Southern California RTD	12	methanol/Avocet[a]	DDC 6V-92TA
Southern California RTD	1	methanol	MAN D2566 MUH
Orange County Transit District	2	methanol/Avocet[a]	Cummins L10
Orange County Transit District	2	CNG[b]	Cummins L10
Orange County Transit District	2	LPG[b]	Cummins L10
		School bus demo	
various fleets	50	methanol	DDC 6V-92TA
various fleets	10	CNG	Bluebird/Teogen GM 454
		Trucking applications	
City of Los Angeles	1	methanol	GMC DDC 6V-92TA
City of Los Angeles	1	methanol/Avocet[a]	Peterbuilt Cummins L10
City of Glendale	1	methanol	Peterbuilt Caterpillar 3306
Golden State Foods	1	methanol	Freightliner DDC 6V-92TA
Federal Express	1	methanol	Freightliner DDC 6-71TA
Arrowhead	1	methanol	Ford/Ford 6.61
SCE	1	methanol	Volvo/DDC 6V-92TA
South Lake Tahoe	1	methanol	International/Navistar DTG-460
Waste Management	2	methanol	Volvo/DDC 6-71TA

[a]Avocet is a cetane improver.
[b]CNG, compressed natural gas, and LPG, liquefied petroleum gas, are also used as alternative fuels.

Table 5. Exhaust Emissions and California 1991 Bus Standards, g / kW.h[a]

	1991 California standards		DC 6V-92TA (catalyst)	
Exhaust component	g/(bhp·h)[a]	g/(kW·h)	g/(bhp·h)[a]	g/(kW·h)
OMHCE	1.3	1.8	0.10	0.14
CO	15.5	21.1	0.22	0.3
NO_x	5.0	6.8	2.3	3.1
particulates	0.10	0.14	0.05	0.07
aldehydes	0.10/0.05[b]	0.14/0.07[b]	0.04	0.05

[a]bhp = brake horsepower; 1bhp = 0.735 kW.
[b]The 0.10 and 0.14 values apply from 1993 to 1995; the 0.05 and 0.07 values apply beginning in 1996.

expensive on an energy basis than gasoline, because gasoline is taxed at a higher rate. This is generally the case in Europe as well. So, although technically feasible, the costs were too high for Brazil to convert many heavy-duty vehicles to ethanol.

Additional research for both ethanol and methanol showed that the amount of ignition improver could be reduced by systems increasing engine compression (63). Going from 17:1 to 21:1 reduced the amount of TEGDN required for methanol from 5% by volume to 3%. Ignition-improved methanol exhibited very low exhaust emissions compared to diesels: particulate emissions were eliminated except for small amounts associated with engine oil, NO_x was even lower with increased compression, and CO and hydrocarbons were also below diesel levels.

Auckland Regional Authority converted two M.A.N. buses to use a cetane improver and methanol and South Africa investigated the use of methanol with a proprietary cetane improver. Four Renault buses were converted in Tours, France to operate on ethanol and a cetane improver, Avocet, manufactured by Imperial Chemical Industries (ICI). The results of these demonstrations were also technically successful; slightly better

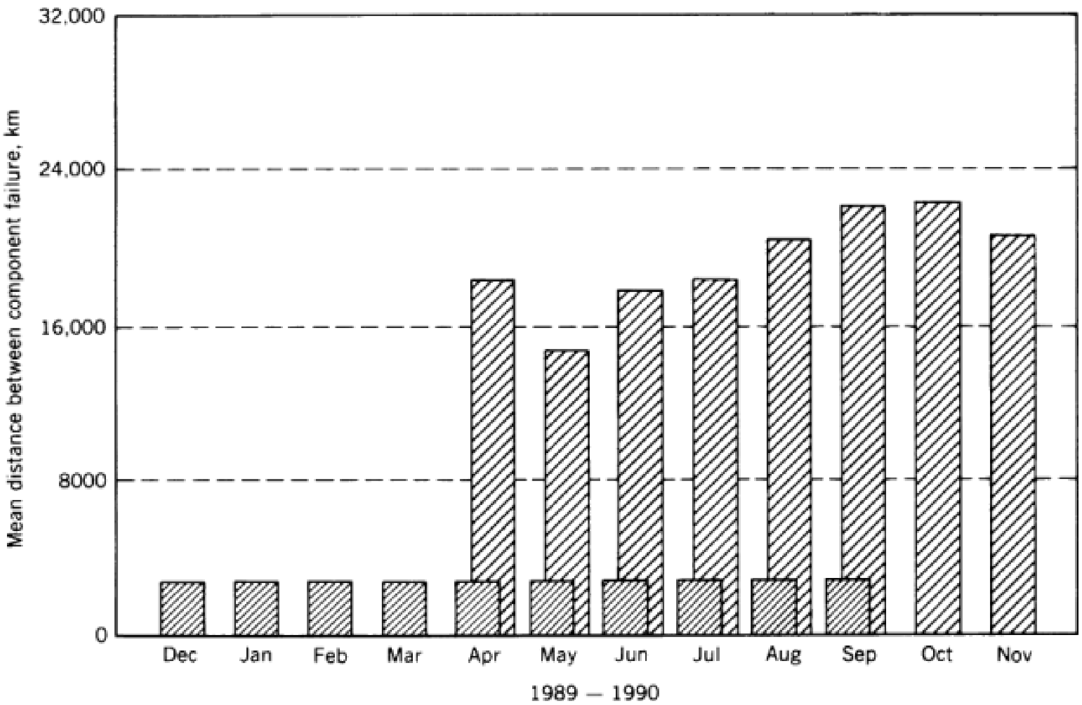

Fig. 12. Methanol and coach fleet cumulative distance driven before fuel injector failure, where represents operation without, and represents operation with fuel additive.

fuel economy was obtained on an energy basis and durability issues were much less than the earlier tests using dedicated engines.

Cetane improvers were first investigated in the U.S. as part of a demonstration project to retrofit DDC 6V-71 two stroke engines to methanol for three transit buses operating in Jacksonville, Florida. This project started out using hardware conversion where the engine was modified to control air flow and a glow plug was added to the system. Although this was basically the same approach as used in the dedicated 6V-92TA methanol engine, the 6V-71 employed mechanical injectors as opposed to electronic injectors. These mechanical injectors were failing even with 1% castor oil [8001-79-4] added to the methanol. Jacksonville thus decided to use a nitrate based cetane improver containing a lubrication additive and a corrosion inhibitor and the project proved the viability of cetane-improved methanol.

The first U.S. engine manufacturer to evaluate the use of cetane improvers was Cummins Engine Company. Their methanol designed L10 engines were converted based on the knowledge gained in Brazil with ethanol and 4.5% TEGDN in their 14-L engine (64). They increased the fuel capacity of their injection pumps, for instance, and modified the combustion process to match the diesel start of combustion by increasing the compression ratio from 15.8 to 16.1:1 and adding turbocharging (both increased in-cylinder temperatures). For the methanol L10 development Avocet at 5% by volume mixed with 100% methanol was selected (65). Engine modifications were only made to the fuel system. These included fuel pump changes for increased capacity, a different camshaft to change injection timing, and larger injectors. Changes were also made in various materials to make them compatible with methanol. The resultant L10 matched diesel power and torque, but emissions results were mixed. Data showed low emissions of particulates, but higher HC, CO, and NO_x at low speed, low load operation. These data suggest that additional optimization may be necessary for the L10 methanol engine.

The L10 methanol engines are currently being used in several demonstration fleets in California. The first use was in the city of Los Angeles Peterbilt dump truck (58), a part of the CEC truck demonstration project. Methanol L10s are also being used in the OCTD comparative alternative fuel demonstration project. In this project methanol, CNG, and LPG L10 engines are being compared to each other in a transit bus application. In the Canadian methanol in large engines (MILE) project, two L10 methanol engines were operated for several years in refuse haulers in Vancouver, British Columbia.

The largest retrofit demonstration project in the United States is under way at SCRTD where 12 vehicles using DDC 6V-92 with mechanical injectors are being modified to use methanol with Avocet (66). This project has evaluated the changes necessary to optimize the conversions for both fuel economy and emissions. Using the two stroke engine changes had to be made to reduce the air into the engine, increase compression from 17 to 23:1, and use better ring packages. These changes gave both good fuel economy and reduced emissions of NO_x by 50%, considerably lowered particulates, and maintained levels of CO and hydrocarbon. New York has also modified a 8V-71 for use on Avocet-improved methanol and had similar results (67).

The success of these tests indicate that cetane-improved alcohol is technically feasible. Engines can be designed to provide equal diesel power and torque characteristics having lower NO_x and particulate emissions than diesel. However, if it is not necessary to achieve lowest possible emissions, only changes in fuel rate are required, rather than engine changes, and the commercial application of this approach depends mostly on the cost of the cetane improvers. The price of Avocet is about $4/L in small quantities and adding 3.0% in methanol nearly doubles the cost of methanol from $0.13 to $0.22/L. If Avocet were produced in larger quantities its price would drop considerably.

The biggest potential use of the cetane-improver approach may be in vehicle retrofits where for environmental reasons bus and truck fleets may be required to convert to cleaner burning fuels.

7. Air Quality Benefits of Alcohol Fuels

In the 1970s evaluations of alcohol fuel programs always considered environmental impacts and objectives even though the main thrust of the programs was toward energy security and diversification benefits. Assessments of performance identified these fuels as consistent with environmental goals and by the mid 1980s, the environmental benefits of the alcohol fuels had become the chief driving force for their further consideration. Detailed assessments were made of photochemical smog and air toxics reductions that might be obtained from the wide use of alcohol fuels in light-duty vehicles. Methanol received the most evaluation, because it appeared to be far more cost competitive than ethanol. The potential benefits of alcohols used in heavy-duty diesel-type engines were also studied.

The most comprehensive air quality study, supported by the California ARB and the South Coast Air Quality Management District (68), showed that if gasoline and methanol cars emitted the same amounts of carbon, an assumption that seemed reasonable based on emissions test data taken throughout the 1980s, and if methanol cars had formaldehyde emissions controlled to 9.3 mg/km (equal to the current California formaldehyde emissions standard for methanol automobiles), then substituting M85 for gasoline would produce a 9% reduction in the peak summer-day afternoon ozone level and a 19% reduction in exposure to ozone levels above the Federal standard of 0.12 ppm. These reductions constituted a substantial fraction of the reductions that would be obtained by eliminating all the emissions from vehicles. Additional assumptions were that exhaust carbon emissions were at the level of 0.15 g/km, equal to the planned certification standard for new vehicles in California beginning in 1993 (but not really expected to be characteristic of in-use vehicles) and that the distribution of hydrocarbon species in the exhaust resembled that of cars tested in the 1980s.

The results of the study, conducted at Carnegie Mellon University, are now generally accepted as the best available guides for the smog-reducing benefits of a methanol substitution strategy, at least for the conditions prevailing in the Los Angeles basin. Overall, replacement of a conventional gasoline vehicle by an equivalent M85 vehicle should provide about a 30% reduction in smog-forming potential. A 100% result would be earned by eliminating the vehicle entirely. Vehicles using M100 would provide substantially greater benefits than M85 vehicles.

Benefits depend upon location. There is reason to believe that the ratio of hydrocarbon emissions to NO_x has an influence on the degree of benefit from methanol substitution in reducing the formation of photochemical smog (69). Additionally, continued testing on methanol vehicles, particularly on vehicles which have accumulated a considerable number of miles, may show that some of the assumptions made in the Carnegie Mellon assessment are not valid. Air quality benefits of methanol also depend on good catalyst performance, especially in controlling formaldehyde, over the entire useful life of the vehicle.

Methanol substitution strategies do not appear to cause an increase in exposure to ambient formaldehyde even though the direct emissions of formaldehyde have been somewhat higher than those of comparable gasoline cars. Most ambient formaldehyde is in fact secondary formaldehyde formed by photochemical reactions of hydrocarbons emitted from gasoline vehicles and other sources. The effects of slightly higher direct formaldehyde emissions from methanol cars are offset by reduced hydrocarbon emissions (68).

Methanol use would also reduce public exposure to toxic hydrocarbons associated with gasoline and diesel fuel, including benzene, 1,3-butadiene, diesel particulates, and polynuclear aromatic hydrocarbons. Although public formaldehyde exposures might increase from methanol use in garages and tunnels, methanol use is expected to reduce overall public exposure to toxic air contaminants.

8. Alcohol Fuels Usage as an Air Quality Strategy

The cost-effectiveness of methanol substitution as an air quality strategy has been studied in some detail. Air quality planners usually rate cost-effectiveness in terms of dollars per ton of reactive hydrocarbons controlled (or removed from the inventory of emissions). Typical costs for controlling reactive hydrocarbon emissions in the United States are in the range of several hundreds of dollars per ton. In the Los Angeles area, the average costs of future hydrocarbon control measures average about $500 per metric ton, although some individual measures have cost-effectiveness figures above $10,000 per ton. Methanol substitution appears to be a viable and competitive control strategy. Cost-effectiveness is linked to the price of oil. Methanol appears to have a cost-effectiveness ranging from a few thousand dollars to several tens of thousands of dollars per ton (18, 70–73). In heavy-duty engines, the alcohols may offer cost-effective reductions of particulates and NO_x emissions. A recent study indicates that the use of methanol was competitive with the use of cleaner diesel fuels and diesel particulate traps under some circumstances (74).

The potential air quality impacts of ethanol use have not yet been studied in detail.

8.1. Global Warming Impacts

Several studies have been made of the global warming impacts of alcohol fuels. The most useful assessments cover the entire life cycle from raw material feedstock production through processing, distribution, and fuel usage. They also consider global gases in addition to carbon dioxide (75, 76). Results reflect the influence of assumptions but methanol is expected to provide slight reductions in global warming impacts compared to gasoline. Ethanol evaluations are less certain.

9. Public Safety Issues

Several investigators have assessed the comparative safety of methanol and conventional hydrocarbon fuels (14, 77–79). The ingestion toxicity of methanol has been of some concern because of the number of gasoline ingestions associated with siphoning and in-home accidental ingestions. The use of gasoline in small engines such as those used for lawnmowers, leafblowers, and other small utility applications results in most of the siphoning ingestions and in-home accidental ingestions of gasoline. This potential problem is addressed by discouraging methanol use in small engines, by labelling and public education, and by positive siphoning prevention screens in the fill pipes of vehicles. These screens have been required in recent purchases of methanol vehicles by California agencies.

Skin contact with methanol may present a greater health threat than skin contact with gasoline and diesel fuel and is being evaluated.

The fire hazard of methanol appears to be substantially smaller than the fire hazard of gasoline, although considerably greater than the fire hazard of diesel fuel. The lack of luminosity of a methanol flame is still a concern to some, and M85 (or some other methanol fuel with an additive for flame luminosity) may become the standard fuel for this reason.

In reviewing the full range of health and safety issues associated with all alternative fuels, the California Advisory Board determined that there were no roadblocks that would prevent the near term deployment of either methanol or ethanol, assuming that adequate safety practices were followed appropriate to the specific nature of each fuel (14).

10. The Future of Alcohol Fuels

In the late 1980s attempts were made in California to shift fuel use to methanol in order to capture the air quality benefits of the reduced photochemical reactivity of the emissions from methanol-fueled vehicles. Proposed legislation would mandate that some fraction of the sales of each vehicle manufacturer be capable of using methanol, and that fuel suppliers ensure that methanol was used in these vehicles. The legislation became a study of the California Advisory Board on Air Quality and Fuels. The report of the study recommended a broader approach to fuel quality and fuel choice that would define environmental objectives and allow the marketplace to determine which vehicle and fuel technologies were adequate to meet environmental objectives at lowest cost and maximum value to consumers. The report directed the California ARB to develop a regulatory approach that would preserve environmental objectives by using emissions standards that reflected the best potential of the cleanest fuels.

The ARB adopted a regulatory package for light-duty vehicles in 1990 that modifies the historically uniform approach to vehicle emissions, in which each and every vehicle in a regulated class must meet the same emissions standard. The new approach adopts emissions standards that apply on the average to the entire sales mix of vehicles sold by each manufacturer in each of several broad weight classes of vehicles. Thus vehicles that use fuels such as methanol and ethanol having air quality benefits in the form of lower levels of photochemical reactivity have the emissions adjusted to reflect the lower smog forming tendency of these fuels. This regulatory approach provides a powerful incentive for vehicle manufacturers to certify at least some of the sales mix of vehicles on fuels such as methanol and ethanol.

The future market response to the new form of emissions regulation is unknown. For the purpose of meeting new vehicle emissions standards, however, it is still not clear whether some combination of new emissions control approaches and reformulated gasolines can provide benefits equal to those of methanol and ethanol. It is possible that the new emissions standards will simply result in improved gasoline technologies, and that, despite the prospective air quality advantages of the alcohol fuels, the market result of the new standards will simply be cleaner gasolines. However, in 1990 the U.S. Alternative Fuels Council agreed on a goal of a 25% share of nonpetroleum transportation fuels by 2005. Although this goal may not become part of a national energy plan, it represents the first official statement of a specific goal to substitute for the use of petroleum in transportation. Alcohol fuels could capture a large part of this 25% share of nonpetroleum fuels, although vehicles powered by natural gas and electric energy will no doubt win some acceptance. For the ordinary passenger car, alcohol fuels may offer the most gasolinelike alternative in terms of range, comparable costs, and compatibility with the current gasoline/diesel storage and distribution infrastructure.

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