ON THE ROAD WITH METHANOL: THE PRESENT AND FUTURE BENEFITS OF METHANOL FUEL

Prepared for

American Methanol Institute
Canadian Oxygenated Fuels Association
Natural Resources Canada

By

Gregory P. Nowell

Acurex Environmental
CORPORATION

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Preface

This report presents the case for methanol as a motor fuel. In recent years, a number of concerns about the environment and the reliability of current energy supplies have increased interest in a policy of oil displacement that would entail a major change from the petroleum dependency of past decades. Methanol is a liquid fuel with handling characteristics similar to gasoline. For many years methanol fuel has enjoyed a small but highly visible role as a premier racing fuel, used at the Indianapolis 500 and other professional races because of its high performance and safety characteristics.

Methanol also has advantageous emissions characteristics. Spurred by dual concerns about the environment and the magnitude of economic disruptions caused by instability in the petroleum market, the state of California began work in the late 1970s to perfect methanol vehicle technology in light-duty passenger car use, and also in heavy-duty public transit and trucking fleets. Today in North America there are 10,000 passenger cars and 500 buses running regularly on methanol fuel. These vehicles are made by the leading automotive and engine manufacturers of North America. They meet regular commercial as well as personal transportation needs. There are over 60 refueling sites, and this number is growing. Methanol's suitability as a widely distributed public fuel has been amply demonstrated.

Methanol is the technological front-runner in the high stakes contest to become a major commercial transportation fuel. It meets virtually all light and heavy-duty market needs. However, being front-runner is not without disadvantages. It means being subjected to intense scrutiny. Methanol ranks favorably in comparison to conventional and alternative fuels if it is evaluated within the total context of its advantages and disadvantages.

Acurex Environmental has prepared this report on the role of methanol fuel. The report clarifies the complex world of emissions characteristics, costs, transportation technology, environmental impacts, health effects, and other aspects of fuel use. This report provides a balanced assessment of methanol in comparison to petroleum-derived gasoline and diesel fuel. If adopted generally, methanol would significantly improve the quality of life in the United States, Canada, and elsewhere.

Now and in the future, methanol can help society meet significant environmental and economic goals. When all comparisons are made, methanol is an environmentally practical fuel.

Acknowledgements

Acurex Environmental prepared this report. Sponsorship and funding assistance was provided by the American Methanol Institute (AMI), the Canadian Oxygenated Fuels Association (COFA), and Natural Resources Canada (NRCAN).

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0.0 EXECUTIVE SUMMARY

0.1 METHANOL AS A MEANS TO IMPROVE THE TRANSPORTATION FUTURE

Methanol offers a wide range of economic, environmental, social, and health benefits to society. Its potential benefits as a transportation fuel are most effectively realized when it is deployed in light and heavy-duty uses. It is also an essential part of a long-term agenda for the development of fuel cells.

Methanol offers a ready-to-implement transportation alternative. Methanol is not a panacea for all the problems associated with a transportation network powered by internal combustion engines. But it is a cost-effective, technically attainable great step forward. If we ask ourselves whether we are we better off if we develop and deploy methanol in transportation sector, the answer is undoubtedly "yes."

This report reviews methanol's benefits in the following areas:

Volatile Organic Compounds, Nitrogen Oxides, Ozone. Methanol fuel use in light- and heavy-duty applications is a complementary strategy. In light-duty use, there is a large reactivity benefit with regard to hydrocarbon control, and some improvement in NO_x emissions. In heavy-duty use, where VOC emissions are generally small, methanol cuts NO_x emissions up to 66 percent. NO_x and VOC reductions are necessary to control ozone, which harms human health, agriculture, and forests, and is also a global warming gas.

Further Technological Progress. As methanol is marketed in larger quantities, further improvements will be made. In light-duty, a near-term transition from M85 to M100 is potentially achievable, which will allow even greater emissions reductions. As methanol fuel volumes increase, delivery costs can be substantially reduced, enabling methanol to compete more effectively with conventional fuels. This will allow for faster deployment in the heavy-duty sector, where the NO_x reductions would be large. Building a methanol fueling infrastructure will also increase the potential for successfully developing fuel cells that could reduce emissions to zero.

Greenhouse Benefits. Although studies have indicated that the net greenhouse warming benefit of methanol fuel is only 0 to 8 percent relative to a gasoline baseline, these studies have ignored the possible development of a methanol fuel infrastructure that will permit other kinds of methanol fuel producers to "feed into" the methanol fuel network. These other sources would include a number of biomass and co-production facilities. Waste treatment and manufacturing sectors that could co-produce methanol include municipal solid waste, sewage, steel, and agricultural biomass. Municipalities and farmers would be able to enhance their income by processing wastes and byproducts that are otherwise burdensome "solid waste" pollution problems. At the same time, the highly favorable biomass greenhouse emissions profile would lower the net greenhouse gas contribution of methanol fuels below the natural gas-only scenario found in many greenhouse gas studies.

Toxic and Particulate Control Strategy. Methanol fuel use will permit the reduction or elimination of many toxics known to be present in petroleum fuels and in their emissions. The reduction of ambient carcinogens and other health threats would be a step forward for the public health. Diesel fuel exhaust is now believed to be a major health threat. Methanol's simple molecular structure ensures favorable characteristics as a particulate emissions control strategy and makes it an attractive public health measure.

Oil Displacement. The twentieth century has seen a number of oil shocks and embargoes that have brought considerable instability to world petroleum markets. The advanced industrial economies of the world have repeatedly had to face economic disruption as a result of these events. Interference with normal market pricing mechanisms has imposed a high penalty on industrial economies and contributed to the endemic trade deficits and "stagflation" that have characterized the post-1974 North American economy. By offering a fuel choice, methanol could diminish some of the negative impacts of single-fuel dependency. There is large potential for growth in North American methanol production, both from natural gas and other sources.

Safety Issues. Methanol's low volatility and low radiant energy make it a proven safety fuel in professional racing, in spite of drawbacks such as low flame visibility in daylight hours. In general use methanol would improve fuel safety, reducing the danger of explosions and fires following accidents where a tank rupture occurs.

Methanol Technology Status. The technology available for methanol use is in an advanced stage of development. Over 10,000 methanol vehicles are on the road, and over 500 buses. Over 60 methanol fueling stations are in place. Methanol-powered passenger vehicles are for sale with the 300-mile range between refueling to which consumers are accustomed.

With appropriate government support that ensures a level playing field for all alternative fuels, methanol use can be expanded. The initial barriers to entry into the transportation fuel market, though large, are less than for other alternative fuels. Investor interest in methanol fuel and the vehicles that use it will best be provided by policies that promote the demand for the fuel and which guarantee that it will be widely available to commercial and private consumers. The payoff to society for these policy commitments will be the improved quality of life that will result from the reduction of pollution, reduction of greenhouse gases, improved economic security, and improved safety that will come with methanol use.

1.0 METHANOL'S BENEFITS TO THE ENVIRONMENT AND SOCIETY

1.1 THE MAJOR RECOGNIZED URBAN AIR POLLUTANTS

In the twenty-first century, methanol could replace oil in many transportation applications because of its environmental benefits. The replacement of oil with methanol will reduce three major urban air quality problem: vehicle emissions of hydrocarbons, NOx, and particulate matter.

Oil's dominance in twentieth century transportation helped the environment by ridding the cities of the black particulate grime, acidic deposits, and other pollutants associated with the coal age. As our population has grown and our knowledge of atmospheric chemistry improved, it has become clear that oil is not the environmentally preferable fuel for the next century. Methanol fuel use will sharply reduce widely recognized problems associated with petroleum dependency. At the same time, methanol infrastructure built today and in the future will be compatible with the next generation of methanol power: fuel cells. The major urban air pollution problems that methanol will reduce are pictured in Figure 1-1 and are described below:

Nitrogen Oxides. Methanol use can sharply reduce vehicle nitrogen oxide emissions, especially from heavy-duty trucks and transit buses. Seventy percent of the air is composed of inert nitrogen. When this nitrogen-containing air passes into diesel and gasoline engines, it combines at high temperatures with oxygen to form nitrogen oxides, or NO_x. Automobiles and trucks are major sources of NO_x. NO_x combines with hydrocarbons to form ozone, a recognized threat to human health. NO_x is also an eye and lung irritant, and a contributor to acid rain. It leads to the formation of peroxacetyl nitrate, which also is a threat to human health. Peroxacetyl nitrate can travel significant distances downwind from its point of origin. In the right conditions, it breaks down again into NO_x, which can then combine with natural or manmade hydrocarbons to produce ozone. (See Section 4.0 on nitrogen oxides.)

Hydrocarbon Airborne Emissions. Methanol fuel significantly reduces the reactivity of hydrocarbon emissions from automobiles. Hydrocarbons form ozone (smog) when they react with nitrogen oxides. They are a major part of the urban pollution problem. Hydrocarbon emissions are passed from vehicle tailpipes and also evaporate directly from gasoline: from automobile fuel lines and tanks, during refueling at the gasoline station, and from the production and distribution of the fuel "upstream" at refineries and oil wells. (See Section 5.0 on hydrocarbons.)

Air Toxics. Methanol eliminates most air toxics associated with traditional gasoline and diesel fuels. "Toxics" refer generally to cancer-causing substances, such as benzene, which are emitted by automotive fuels. There are literally hundreds of chemicals in gasoline and diesel fuel. Only a very few have undergone the rigorous testing needed to establish their cancer-causing properties. (See Section 8.0 on Air Toxics.)

Particulate Matter. Methanol dramatically reduces diesel exhaust particulate matter, or PM_{10}. PM_{10} has recently been shown to be a major health threat. The "10" refers to particles of ten microns or less in diameter, which means they can lodge deep within the tissues of the lung. One form of PM_{10} is the black soot from diesel engines, often seen coming out of buses and trucks. Recent statistical analyses have shown very high mortality rates in major metropolitan areas following elevated levels of PM_{10}. Other work underway is demonstrating that diesel-related particulates either directly cause, or else carry chemicals that cause, human cancers. Long ignored, PM_{10} is now under increasing scrutiny as a threat to public health. (See Section 9.0 on PM_{10}.)

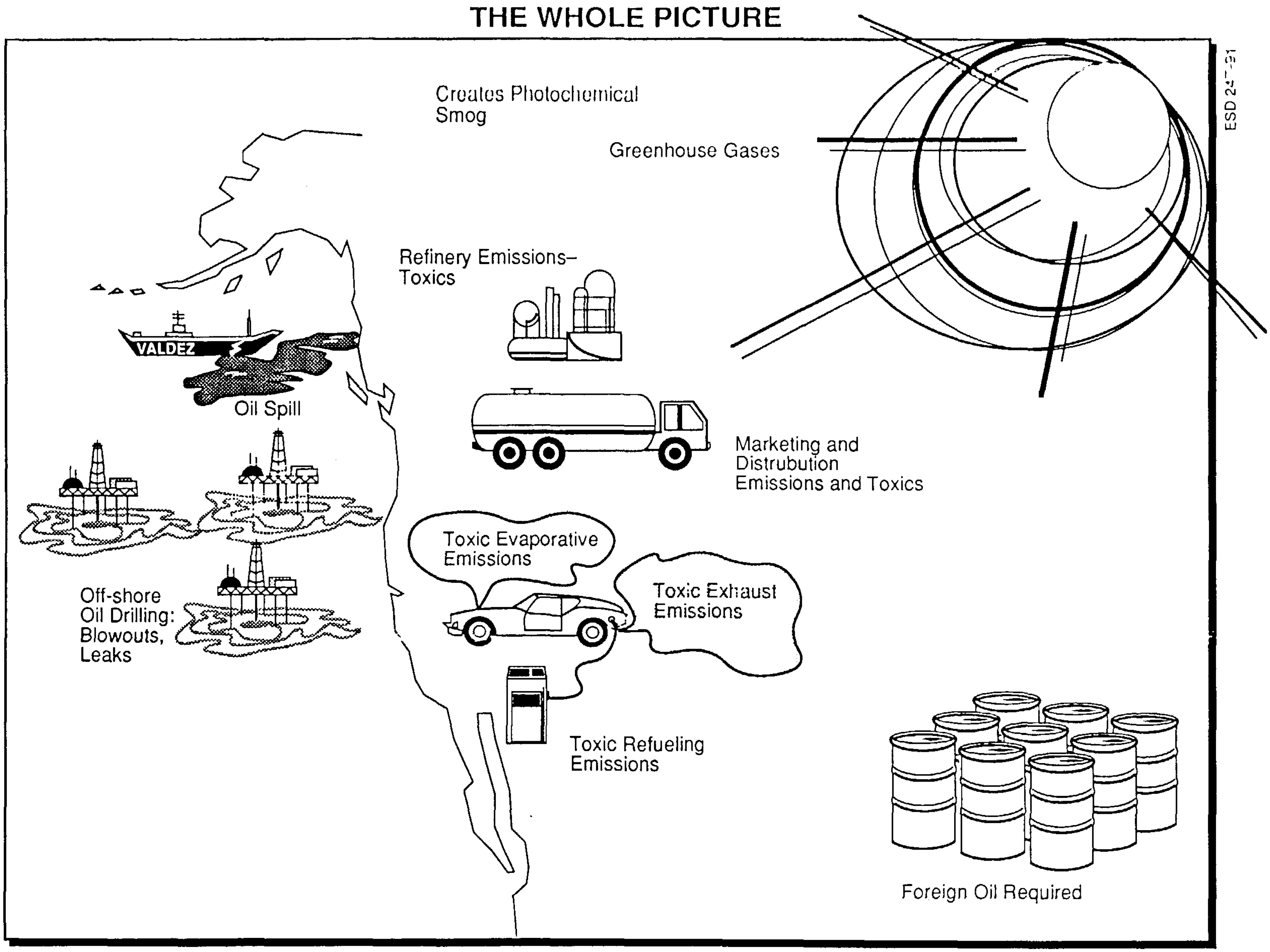


Figure 1.1-1. Gasoline and diesel fuel: the whole picture (Source: Acurex Environmental)

1.0 METHANOL'S BENEFITS TO THE ENVIRONMENT AND SOCIETY

1.2 REDUCING GLOBAL POLLUTION THREATS, ADVANCING OIL DISPLACEMENT, REDUCING SAFETY HAZARDS

Methanol fuel will displace reliance on oil. This will cause a modest reduction in greenhouse gases and eliminate ecologically harmful crude petroleum spills. Oil displacement will also help insulate the North American economy from price shocks caused by politically unstable producing regions. Methanol can also reduce fuel-related injury.

As can be seen in Figure 1.2-1, methanol offers additional benefits in addition to urban pollution control. It is a "balanced" fuel, offering possibilities for enhancing the environment and the economy in the short and long-term.

Global Warming and Other Global Pollution. Methanol offers long-term possibilities for reducing greenhouse gases. Today's transportation uses of fuel contribute to the inventory of "greenhouse gases" that trap solar radiation in the atmosphere and contribute to global warming. The measurable build-up of carbon dioxide and other gases is a good reason to find fuels that reduce or eliminate the possibility of long-term changes in the planetary environment. Methanol offers modest greenhouse gas reductions today. More importantly, it offers a chance to build a more greenhouse-friendly transportation network in conjunction with biomass methanol (See Section 7.0), and transportation powered by fuel cells.

Methanol biodegrades rapidly and offers a safer alternative to crude oil, gasoline, and diesel fuel. The toxic contamination of underground aquifers by gasoline is an expensive and frequent environmental problem. Major scenic and commercial resources of the world have been damaged by accidental oil spills. In the last twenty-five years the coasts of Santa Barbara, the Gulf of Mexico, France, Turkey, Scotland, Canada, and Alaska have all been the sites of major oil spills with durable ecological consequences and detrimental impacts on tourism and commercial fishing. The Persian Gulf oil spill of 1990 was a deliberate act of war.

Safety Hazards. Methanol's low rate of evaporation and low radiant heat energy make it a safer fuel: less likely to ignite in accidents, and less harmful to people when it does. Vehicle fires occur often in mechanical breakdowns and accidents, and also when fuel is misused in a number of home uses. In general use, gasoline is often used and abused as an "accelerant," to light fires, and as a household solvent for mechanical and other purposes. The ease with which gasoline evaporates into fumes that find their way to various ignition sources — in a house or at the scene of an accident — makes it a major source of burn-related hospitalization. (See Section 10.0 on safety issues.)

Oil Displacement. By increasing North America's margin of independence from overseas oil, methanol can contribute to economic stabilization in the energy sector. The world's fuel network has repeatedly been subjected to military and economic upheavals. Revolution shook major producing oil fields in Mexico from 1911 to 1917, in Russia in 1905, 1917, 1990-1994, and in Iran in 1979. War disrupted oil supplies during World Wars I and II, and also during the Suez crisis of 1956. Oil supplies to major industrial powers were embargoed by producers in 1973-1974. From 1979 through 1989 two major oil producers, Iran and Iraq, were locked in one of the most bitter military conflicts of the century. In 1991 the allied powers of the Middle East and the West, led by the United States, waged war to prevent Iraqi expansion in the Persian Gulf. Such disruptions have taken a heavy toll on the economic stability of oil-consuming nations. Methanol use will reduce reliance on unstable producing areas. (See Section 11.0 on oil displacement.)

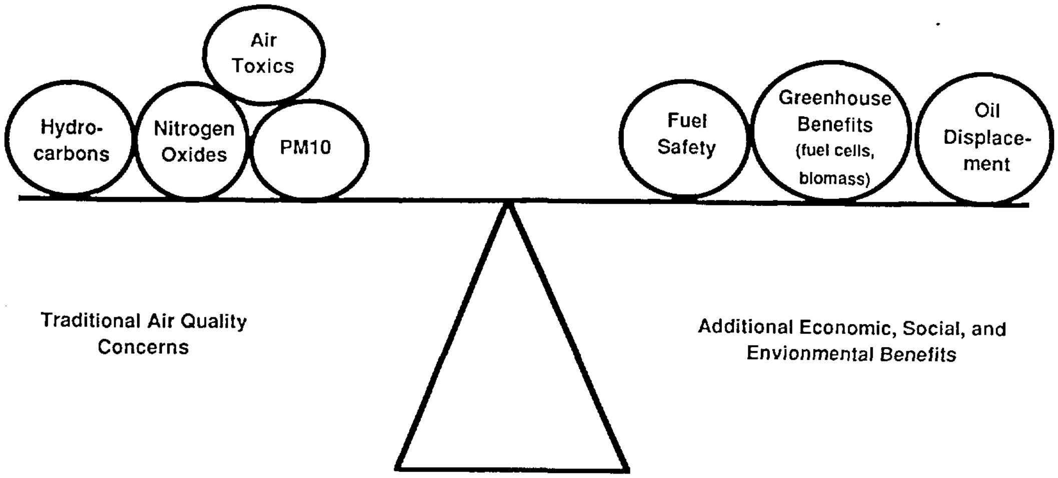


Figure 1.2-1. Methanol fuel use is a way to balance concern about the control of traditional air pollutants with the desire to promote additional environmental, economic, and safety goals. (Source: Acurex Environmental)

2.0 METHANOL: THE TECHNOLOGY

2.1 THE FUEL-FLEXIBLE VEHICLE (FFV) AS THE FIRST STEP TO DEDICATED VEHICLES AND FUEL CELLS

The transportation technology for the employment of methanol fuel is fundamentally similar to gasoline. This similarity means that methanol is the "fuel of choice" for original equipment manufacturers. It also means that off-the-shelf technology allows us to begin the transition to methanol fuels today. Today's methanol technology will pave the way for future transportation technology advances.

The racing cars competing at the Indianapolis 500 and other professional races use M100 fuel in vehicles designed for its use: these are "dedicated" vehicles. Most passenger cars today can only use gasoline as a fuel, and are "dedicated" gasoline vehicles. In the early 1980s, California fleet experiments with dedicated M85 vehicles (at that time, ordinary cars that had been converted to use only a specific mix of methanol and gasoline) indicated widespread driver dissatisfaction with the difficulty in finding fuel. There were only a few methanol-equipped gasoline stations participating in the program. It became clear that the "chicken-egg" problem was a formidable obstacle in introducing methanol fuel: people would not buy methanol-powered cars unless the fuel was widely available, and the fuel would not be widely available until and unless consumer demand was large enough to pay for the distribution costs.

Detroit automakers developed cars that can burn any combination of methanol or gasoline. Equipped with a computerized sensor in the fuel line, these cars can automatically make the adjustments to the engine needed to compensate for the different fuel mixes. With these cars, a driver can fill up on methanol fuel when possible and, when refueling where there is no methanol, use gasoline instead. Additional modifications to FFV vehicles include fuel lines and tanks that are compatible with methanol and gasoline fuels, as well as safety features such as anti-siphoning devices on the fill stem of the gasoline tank.

These fuel-flexible vehicles, depicted in Figure 2.1-1, are now the only methanol-powered passenger cars produced for general use. They overcome the "chicken-egg" obstacle but do not have the same, extremely high emissions benefits expected from an M100 "dedicated" vehicle. Methanol combustion is more efficient than gasoline combustion, even in current engine designs still heavily influenced by gasoline fuel. A smaller, lighter engine block, reduced cooling requirements, still lower emissions, better acceleration and mileage are to be expected from methanol-optimized engines in the future.

So long as gasoline is used in methanol-capable vehicles, the emissions benefits of methanol fuel use will be only partially, not fully, realized. Methanol fuel advocates see the "fuel-flexible" vehicle as a way to build up a general demand for methanol fuel. The fuel-flexible vehicles will make the later transition to dedicated methanol fuel vehicles possible by generating the demand for methanol fuel infrastructure.

Some day, the internal combustion engine will itself be superseded by electric-based technologies such as fuel cells. Fuel cells need a molecular hydrogen carrier in order to make power for a vehicle. Methanol is a prime candidate hydrogen carrier. The fuel-flexible vehicle is part of a strategy that begins with cars that can operate on gasoline and methanol, in order to build gradually the demand for methanol. As the demand for methanol leads to more widespread methanol infrastructure, dedicated M100 vehicles will be possible. The methanol fueling structure will remain compatible with the next generation of fuel cell technology that will shift the transportation market away from the internal combustion engine.

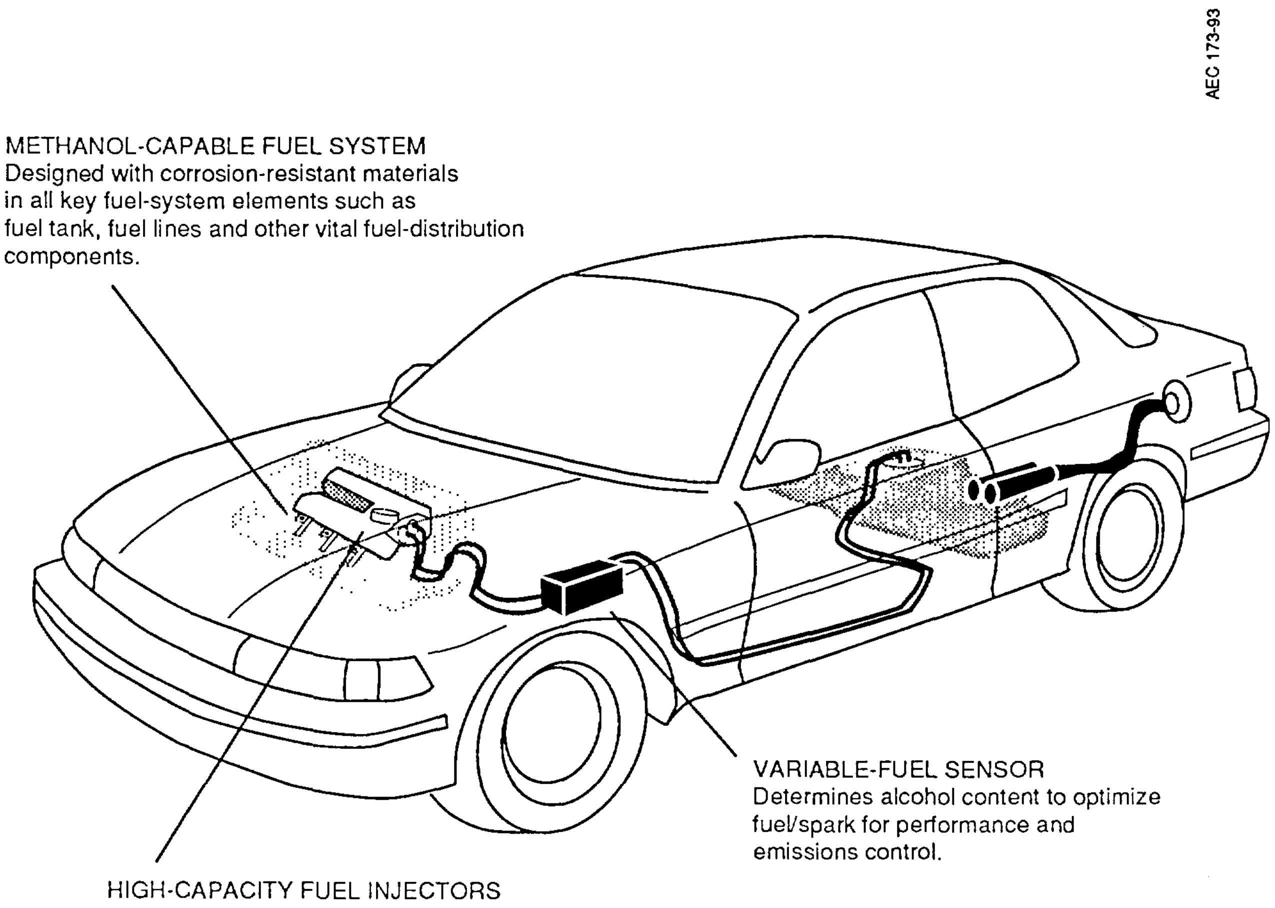


Figure 2.1-1. Fuel-flexible vehicles require very few modifications from conventional gasoline technology. Many thousands of these FFVs are on the road in the United States and Canada. (Source: Acurex Environmental)

2.0 METHANOL: THE TECHNOLOGY
2.2 THE METHANOL HEAVY-DUTY (DIESEL REPLACEMENT) ENGINE; FUELING INFRASTRUCTURE FOR ALL METHANOL VEHICLES

In heavy-duty as well as light-duty applications, methanol is the fuel most similar to petroleum fuel, though much less polluting. Few infrastructure changes are needed to get methanol vehicles on the road.

The Dedicated Methanol Heavy-Duty Engine. Heavy-duty diesel engines are, with modifications, able to use methanol fuel. Typical modifications for heavy-duty engines include higher compression, air system changes, and the addition of an ignition system (glowplugs) to assist with detonation of the fuel (traditional diesel fuel designs are compression-ignited). A catalytic converter is added to control hydrocarbon and formaldehyde emissions. The existence of a large heavy-duty engine market with centrally fueled facilities means that the "chicken-egg" problem is not as much of an obstacle as it is with light-duty vehicles. Currently most of the heavy-duty engines in use are in urban transit buses, although some experimental deployment with truck fleets has occurred. Since most of the fleets using methanol have been centrally fueled, little focus has been given to "fuel-flexible" concepts for heavy-duty applications. One manufacturer, however, is currently evaluating the concept for line-haul trucking applications which may need to use a clean fuel in cities but not on the open road.

A typical methanol heavy-duty engine is shown in Figure 2.2-1, with the principal engine modifications identified.

Fueling Infrastructure. The development of methanol technology means that more than just fuels must be changed. Some modifications must be made to the fueling facilities. At most gasoline stations, double-walled steel tanks are installed. These tanks are in increasing use generally not just because of methanol, but also because they effectively reduce groundwater contamination from gasoline fuels. Filling pumps, nozzles, and hoses also must be made methanol compatible. This means using polymers, metals, and other materials which do not deteriorate in the presence of methanol. Nonetheless, a methanol fueling station looks very much like the gasoline stations already in use, and costs are about the same. Very little disruption to consumer habits would occur with the development of a methanol market, but the environmental and other benefits would be large.

A typical methanol fueling pump design is shown in Figure 2.2-2.

Methanol Technology Costs. The switch to methanol technology therefore implies some additional costs in comparison to traditional gasoline and diesel fuel engine technologies. The projected incremental cost of a fuel-flexible vehicle is in the range of $150 to $300 more than their current costs, although fuel-flexible vehicles on the market today often are priced the same as their dedicated gasoline counterparts. Retrofitting gasoline stations to accommodate methanol varies greatly in cost, depending on when the underground tanks would need replacing due to ordinary use, the specifics of the gasoline station terrain and tank site, how many filling pumps are changed, and other factors. Figures for these costs range from U.S. $12,000 to $40,000. The first-time adoption of M100 in a centrally fueled site, such as an urban bus transit agency, involves significant one-time conversion costs. Methanol heavy-duty engines are more expensive due to their smaller production runs, higher maintenance costs (because of the novelty of the technology), and the need for the fleet mechanics to acquire experience. With time, these costs will decline.

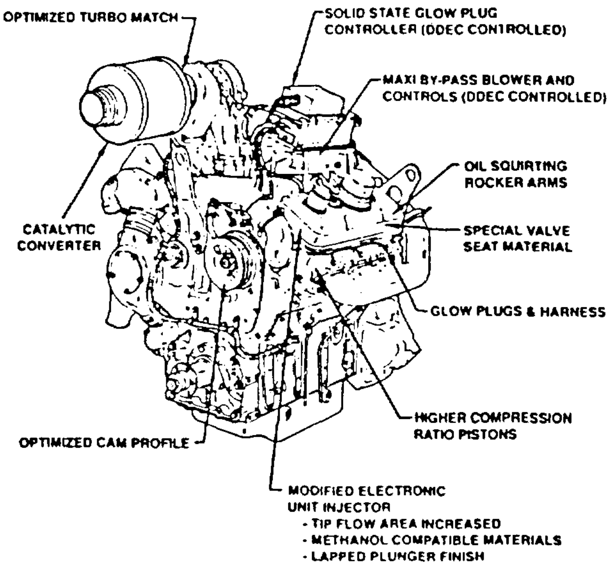


Figure 2-2.1. Methanol truck engine versus diesel: hardware modifications. (Source: Detroit Diesel Corporation)

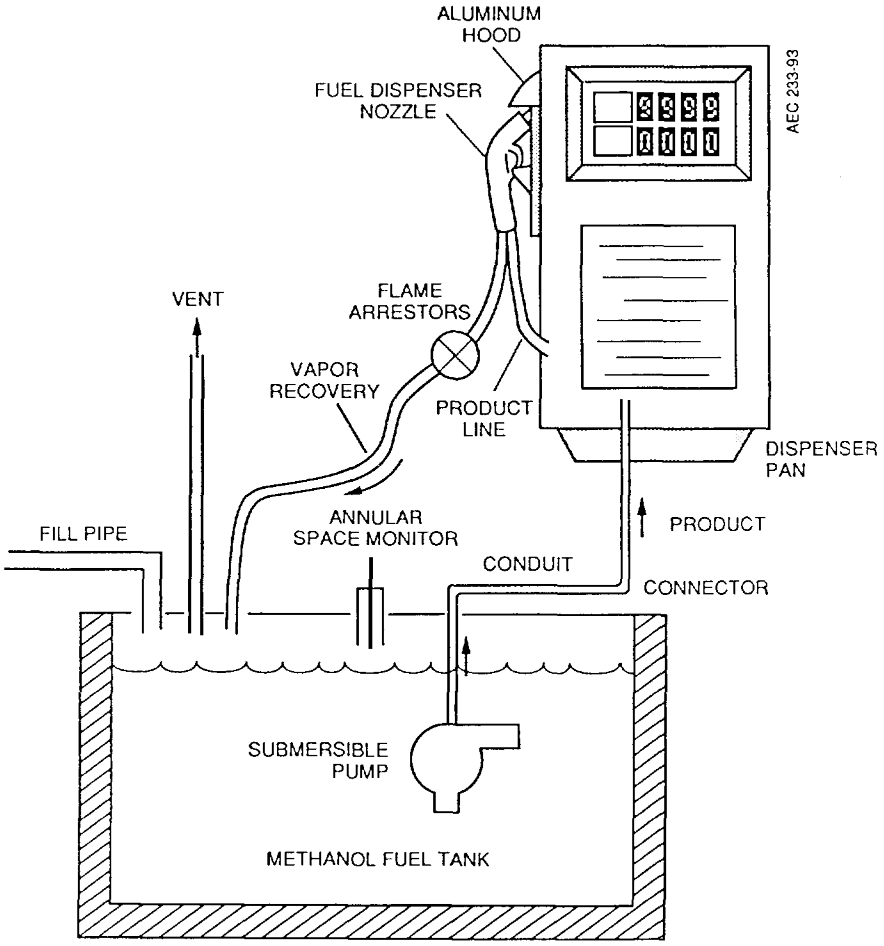


Figure 2-2.2. Schematic of a typical methanol fuel pump. (Source: Acurex Environmental)

3.0 METHANOL FUELS
3.1 METHANOL FUEL TYPES

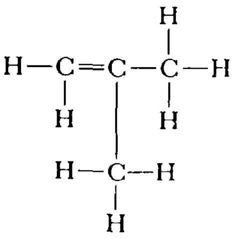
Methanol fuel is currently marketed in two basic forms. The first is pure methanol, or M100. The second is a mixture of 85 percent methanol and 15 percent gasoline, called M85.

M100 is an attractive fuel because of the simplicity of its molecular structure (see Figures 3.1-1 and 3.1-2 for examples of hydrocarbon and methanol molecules). The methanol molecule is simple and low in reactivity. Gasoline contains over one hundred different chemicals, many complex and highly reactive. Whether burned as a fuel or released through simple evaporation, these chemicals create many different "species" of emissions, many of which are harmful to human health. The hydrocarbons emitted by gasoline evaporation (in automobile tanks and during the manufacturing and distribution process) make the fuel a potent ozone source when combined with nitrogen oxides. By contrast, M100's simple molecular structure means that very few "species" are emitted after combustion. Methanol substantially cuts ozone formation relative to both conventional gasoline and the new "reformulated" or "California Phase II" gasolines, because methanol is less reactive than gasoline hydrocarbon species.

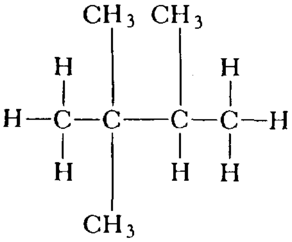
In heavy duty engines (diesel trucks) M100 is an effective means to control NO_x emissions to levels far below today's diesel engines. Today, M100 is in use primarily in heavy-duty applications such as urban transit buses and fleet trucks. (See Section 4.0 on NO_x.)

M85 was formulated during the course of methanol engine development work in the mid-1980s. M85 addressed two problems. First, automobile manufacturers, particularly Ford Motor Company, were worried about the public's lack of familiarity with M100's properties: methanol flames are nearly invisible in daylight. Although there are substantial reasons to think that methanol is a safer fuel than gasoline in spite of the daytime problem with flame visibility (see Section 10.0 on safety), the company believed that liability problems were best addressed by adding enough gasoline to methanol to guarantee visibility in case of a daytime accident followed by fuel ignition. M85 flames are easier to see. Unfortunately, the addition of gasoline makes the fuel more likely to ignite in case of an accident, and cuts the ozone-reducing potential of M100 by half. The second issue was starting the car engine when it was cold. Methanol's lower volatility makes cold-starting an engine more difficult. The addition of 15 percent gasoline alleviated this difficulty. There are ways that passenger cars could be equipped to cold-start using M100 fuel, but the gasoline additive simultaneously solved the visibility and the cold-start problem.

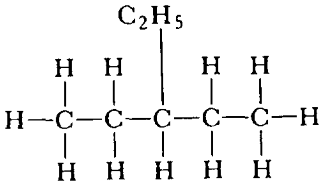
M85 is the only methanol fuel currently used in commercially sold passenger cars, but methanol advocates believe it is a transitional form of methanol, due to the greater environmental benefits of M100 use. M85 fuel infrastructure is fully compatible with M100, which eventually could replace M85. Though not as effective as M100, M85 still cuts ozone formation 50 percent relative to conventional gasoline and 35 percent relative to the best low-emission reformulated gasolines. Methanol fuel in all its forms allows for progress today with off-the-shelf technology, and progress tomorrow with technology under development. M85 and M100 both reduce human exposure to toxic carcinogens (See Section 8.0).



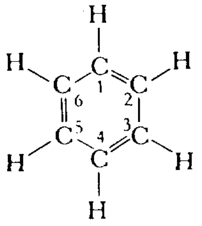
C_4H_8 isobutene



2,2,3 trimethyl butane
or triptane

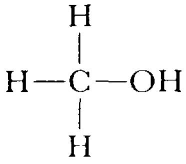


3 ethyl pentane



C_6H_6 or benzene

Figure 3.1-1. **Gasoline is composed of over one hundred complex molecules, of which these are a few examples. The molecular complexity of petroleum constituents makes petroleum a valuable chemical feedstock, but when used as a fuel the highly chemically reactive constituent elements form ozone, a major public health hazard. Many of the chemicals that form gasoline are also highly carcinogenic. (Source: E.F. Obert, Internal Combustion Engines and Air Pollution, N.Y.: Harper Row, 1973)**



$$H-\overset{\displaystyle H}{\underset{\displaystyle H}{C}}-OH$$

Figure 3.1-2. **By contrast, the methanol molecule is simple and stable. It has a lower ozone-forming capacity, and the many carcinogenic compounds in gasoline are simply not present. (Source: E.F. Obert, Internal Combustion Engines and Air Pollution, N.Y.: Harper Row, 1973)**

3.0 METHANOL FUELS

3.2 METHANOL FUEL COST

Methanol is a price-competitive fuel for light-duty automobiles, providing superior performance and great emissions benefits at a price roughly equivalent to premium gasoline. As a heavy-duty fuel methanol is valuable where NO_x reductions are a priority, but its price-competitiveness varies with regional taxation policies. Current methanol prices reflect the specialized demand of the chemical market, not the potential economies of scale and lower prices possible in a continental fuel market.

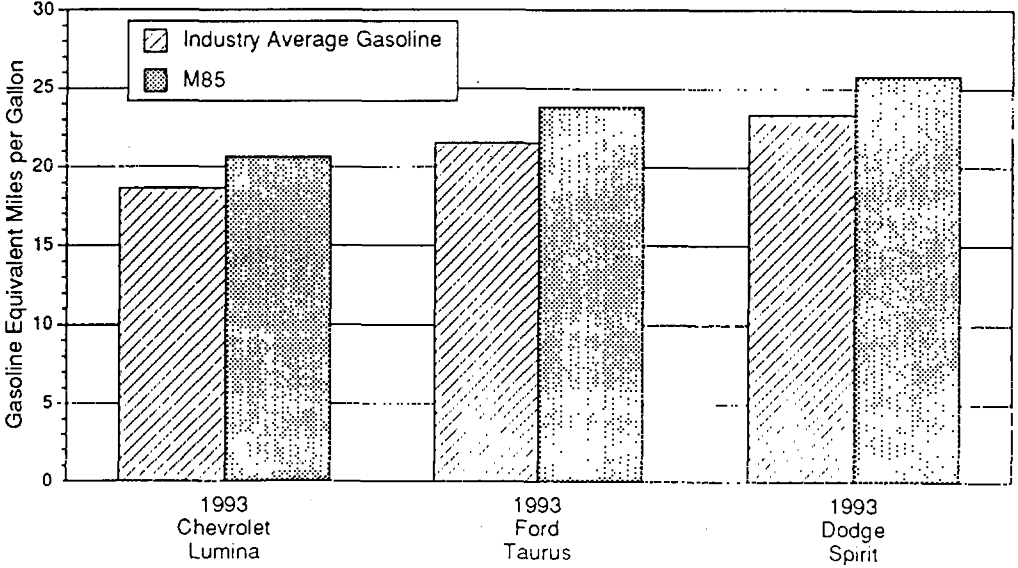
Estimating the cost of using methanol must take into account a number of factors. The energy content of both M85 and M100 is lower — by about 50 percent — than gasoline (for passenger cars) and diesel fuel (for heavy-duty trucks), but methanol fuel obtains better engine efficiency. To make a meaningful price comparison, we need to know the "energy equivalent basis per gallon": for the same number of BTUs of energy, which fuel will make the car go further? This is part of the information which, factored with cost, allows consumers to know how far they can travel on a dollar's worth of fuel. Figure 3.2-1 expresses the "fuel equivalent basis per gallon." Even though methanol's energy content is lower, its octane rating is higher: methanol fuel provides better engine performance and better acceleration. This is true even for today's engines, which are not designed to benefit fully from methanol's properties. Methanol-optimized engines in the future will provide even better fuel economy.

In a 1992 survey of California retail stations, methanol sold at U.S. 78.9 cents per gallon, which, adjusted for the miles-per-gallon difference, would be equivalent to U.S. $1.30 per gallon of gasoline. More recently, the cost of gasoline has declined and the cost of methanol has increased, as prices in the two markets are not linked. The cost advantage now favors gasoline. Taking fuel energy content and engine efficiency into account, M85 price equivalency per gallon with gasoline can be calculated by multiplying the M85 price by 1.64. Methanol is price competitive with diesel fuel in the United States only if the value of the emissions reductions are taken into account. M100 price equivalency with diesel fuel can be calculated by multiplying the M100 price by 2.3.

M85 is used in light-duty passenger vehicles, whereas M100 is used in heavy-duty buses and trucks. Fuel-equivalent M85 prices should be compared to gasoline prices, and fuel-equivalent M100 prices should be compared to prices of "clean" diesel fuels. The methanol fuels should be considered against the cost of the "best" low-emission petroleum equivalents, because methanol's natural fuel market is in those areas where the decision has been made to use cleaner fuels of all kinds.

Unlike the United States, methanol in Canada enjoys some of the tax relief that is available to other alternative fuels such as compressed natural gas. As a result, M85 is available at Canadian fueling sites at a price that is competitive with regular gasoline. Similarly M100 for heavy-duty applications is being supplied at a diesel equivalent price.

These fuel price "rules of thumb" exclude the acquisition cost of the vehicles and the infrastructure. In paying a price premium for methanol fuel one is purchasing superior engine performance, dramatically improved emissions profiles, and a number of other environmental and economic benefits. With the development of sufficient demand, world-scale methanol production facilities dedicated to supplying the methanol fuel market would lower prices. Today's prices are set largely by demand for methanol in specialized chemical markets. The decision to go ahead now with methanol fuel deployment is a means to invest in lower prices for the future — which will lower the cost of purchasing methanol's environmental, social, and economic benefits.



Industry Average Gasoline
M85
Gasoline Equivalent Miles per Gallon
30
25
20
15
10
5
0
1993 Chevrolet Lumina
1993 Ford Taurus
1993 Dodge Spirit

4.0 NITROGEN OXIDE EMISSIONS

4.1 METHANOL ENGINE REDUCTIONS OF NITROGEN OXIDES

Nitrogen oxide (NO_x) emissions is a major precursor to ozone formation. They also play a role in the formation of acid rain. Atmospheric NO_x plays a role in the formation of particulates, which are eye and lung irritants. Methanol fuel cuts NO_x formation in light-duty and heavy-duty use.

NO_x is a major element of urban pollution. One of the largest contributors to NO_x formation are transportation related sources, which in 1990 contributed 38 percent of the total NO_x inventory in the United States. The large number of light-duty automobiles make them collectively a significant source of nitrogen oxides, but heavy-duty diesel trucks have a disproportionate effect. In California, for example, heavy-duty engines contribute 31 percent of the total on-road NO_x inventory.

NO_x emissions are crucial to the formation of ozone, but the extent to which NO_x reductions translate into reductions of ozone are not constant from one region to another. Sometimes a reservoir of NO_x which has helped to create ozone can then scavenge it and break it down, but often at the expense of producing more ozone downwind. In other regions limiting NO_x emissions puts an absolute limit on the rate of ozone formation. The circumstances vary with the particularities of individual air basins. Worldwide, most NO_x is man made, but some is produced by natural causes such as lightning. Were there no man-made NO_x, there would be no urban ozone problem. NO_x also can undergo chemical reactions which turn it into relatively stable forms, such as peroxyacetyl nitrate, that can travel long distances. In the right conditions, the peroxyacetyl nitrate breaks down and in the presence of sunlight combines with other hydrocarbons to form ozone. The complex chemistry of NO_x is not fully understood, but it is clear that NO_x plays a role in the long-range distribution of ozone in downwind areas, as well as in urban areas. NO_x can also contribute to the formation of acid rain. The reduction of man-made NO_x is therefore a major objective of air quality regulators.

The state of California has the most advanced emissions standards in the world. Over the next decade, three new categories of low-emission vehicles are to be phased in: "Transitional Low-Emission Vehicles" or TLEVs, "Low-Emission Vehicles," or LEVs, and "Ultra-Low Emission Vehicles," or ULEVs. A fourth category is reserved for "Zero Emission Vehicles," which, if battery operated, are expensive, severely range-limited, and remain a speculative technology for practical applications. Methanol vehicles, on the other hand, are already on the road. Equipped with larger fuel tanks that give them the 300-mile range to which consumers are accustomed, they have *already* tested well below required future standards for NO_x control for internal combustion engines. The NO_x emissions levels of several 1991 and 1993 vehicles are shown in Figure 4.1-1.

In heavy-duty uses methanol's NO_x-control effectiveness is even more pronounced. A methanol powered transit bus, in comparison to conventional diesel technology, may cut emissions over the vehicle lifetime by *8 tons*. Figure 4.1-2 shows how commercially available methanol engine technology is already reducing NO_x to a fraction of the U.S. Environmental Protection Agency's 1998 standard. The methanol engine produces NO_x at levels so far below conventional technologies that both the U.S. Environmental Protection Agency and the California Air Resources Board have issued guidance documents on how these reductions might be certified for sale as credits to utilities and other businesses. In heavy duty applications, methanol has set the "standard to beat" for environmentally beneficial heavy-duty technologies.

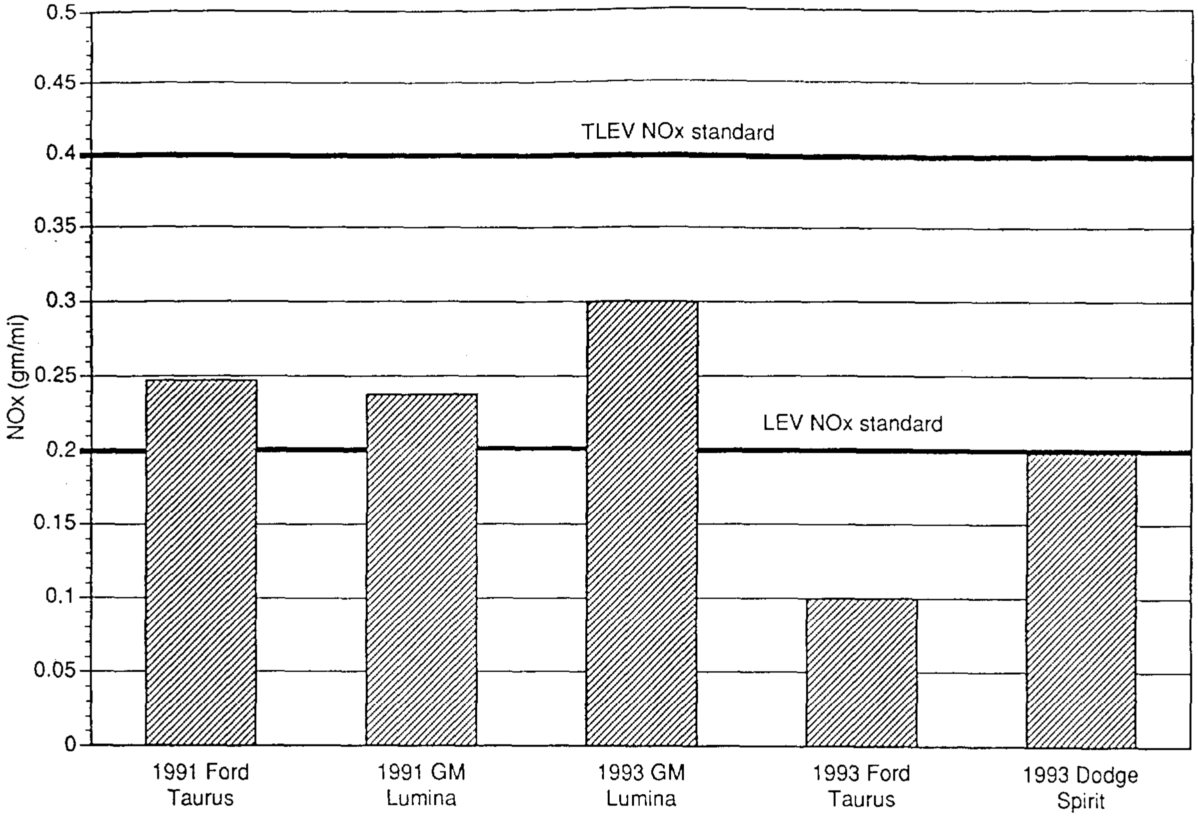


Figure 4.1-1. NO_x levels of selected 1991 and 1993 fuel-flexible vehicles. Note that two of the 1993 vehicles are already in early compliance with California's advanced "Low Emission Vehicle" standard. (Source: Browning and McCormack, 1993)

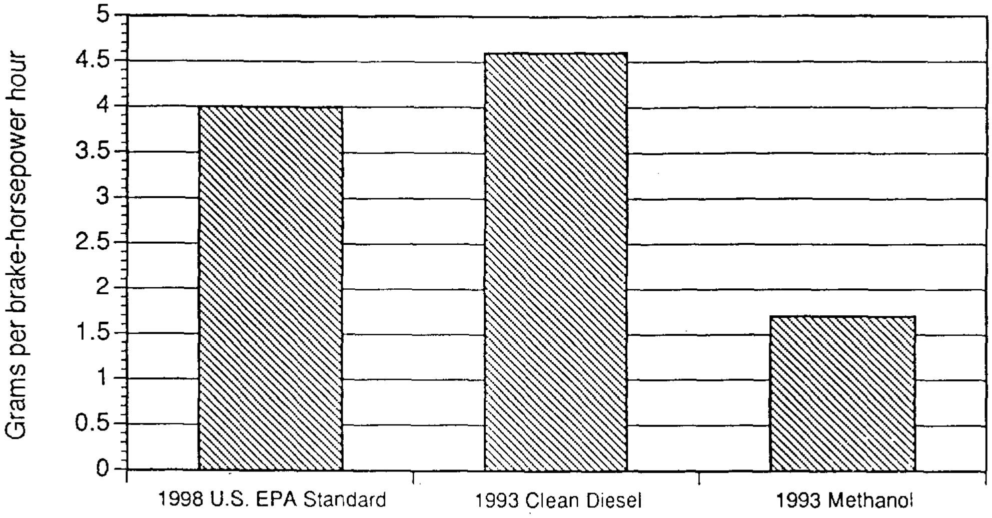


Figure 4.1-2. Methanol heavy-duty engines are among the lowest NO_x heavy-duty engines available. This graph shows 1993 certification test results for Detroit Diesel Corporation's "Clean Diesel" and M100 engines. The methanol engine, today is less than half the 1998 standard. Methanol is one of the most effective NO_x control strategies. (Source: California Air Resource Board)

5.0 VOLATILE ORGANIC COMPOUNDS (VOCS)

5.1 THE VOC POLLUTION CYCLE

VOCs accelerate the production of ozone from atmospheric NO_x. The full cycle of VOC emissions sources runs from the oil well through the tailpipe of the automobile.

VOCs, often called hydrocarbons, are one of gasoline's major pollutants. VOC compounds are the different "species" of chemicals which result from the combustion of gasoline. As was seen in Section 3.0, the number and complexity of these molecules is very large. In the presence of sunlight, NO_x forms ozone through a series of reactions accelerated by hydrocarbons. Some of these hydrocarbons are also highly toxic carcinogens. Hydrocarbon control strategies are both an anti-ozone and anti-cancer policy for air quality, and therefore beneficial to human health.

Hydrocarbon emissions are of two basic kinds: tailpipe and evaporative. Tailpipe emissions are well known to drivers: the pungent smell of a car that has cold-started is largely unburned components of gasoline that have passed through the engine and come out the exhaust. Though the quantity of these emissions drops sharply as the engine warms up, and may no longer be detectable to the nose, they remain a constant output of an automobile's operations. Since the 1970s, hydrocarbon emissions have been controlled through the use of catalytic converters on automobiles, but catalytic converters do not do their job perfectly. A large part of a car's total hydrocarbon emissions occurs before the catalyst has warmed up and become fully functional. With many millions of vehicles in operation, enough hydrocarbon emissions escape to form ozone, even though catalytic converters are required by law.

Evaporative emissions are another source of hydrocarbon pollution. Such emissions come from the fuel system during vehicle operation (running losses). "Hot soak" emissions occur when a car in use is shut off and cools down. During this time the fuel system emits hydrocarbons at an increased rate.

Other emissions are associated with the manufacture and distribution of the fuel. From the pump, to the refinery, from the refinery to the delivery truck, from the delivery truck into the gas station, and from the gasoline pump into the vehicle, gasoline fuel evaporates wherever there are minor spills and leaks. Fugitive emissions occur when tanks are opened and hoses connected. Emissions even come from parked cars when the engine is not running (diurnal losses). Hydrocarbons evaporate from the fuel system when the vehicle is not in use, as ambient air temperatures fluctuate during the day. These evaporative losses are a major component of the total contribution of petroleum to the hydrocarbon inventory. Figure 5.1-1 shows where some of these emissions occur. At each step, they contribute to ozone formation and to the reservoir of carcinogens in the environment. Methanol's lower reactivity and lower evaporation rate offer a chance to slash hydrocarbon emissions from all of these sources.

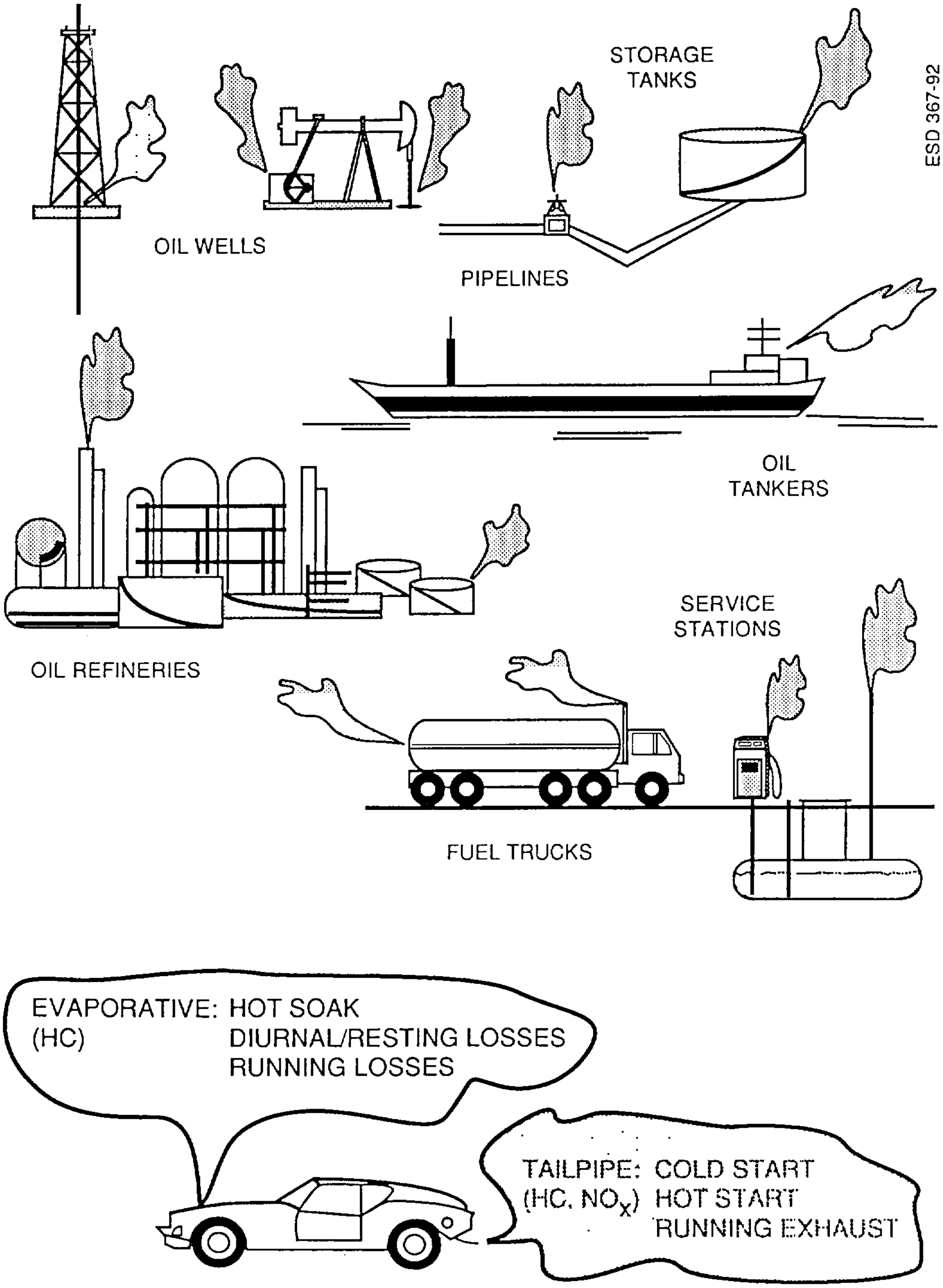


Figure 5.1-1. Methanol use will cut VOC emissions not just from the automobile tailpipe, but from the entire cycle of fuel production, refining, and distribution. (Source: Acurex Environmental)

5.2 METHANOL'S LOWER REACTIVITY (OZONE-FORMING POTENTIAL)

Methanol greatly reduces tailpipe and evaporative emissions of ozone-forming hydrocarbons and carcinogenic substances.

Methanol is much less reactive than gasoline in the atmosphere. It is much less prone to evaporate during refueling or when spilled. Even though methanol emissions may be the same *quantity* (mass) as gasoline emissions from a car's tailpipe, the chemical "liveliness" (reactivity) of the emissions in the atmosphere is much less. Thus, for a given amount of emissions, less ozone is formed. This is called the marginal incremental reactivity, sometimes also called the Carter reactivity factors. Even when methanol is diluted with gasoline, the reduction in total emissions reactivity is dramatic. Figures 5.2-1 and 5.2-2 show the difference between a 1990 Dodge Spirit, using M85, and 1991 Ford Tempo on industry average gasoline. These figures break down the VOC emissions into categories and then look at the total reactivity-adjusted ozone: M85 fuel is less than half.

In Figure 5.2-1 the ozone-forming components of M85 come largely from the 15 percent gasoline present in the fuel. M100 emissions would be lower still, by about half. In the M85 category, one can see that for the alcohols the ozone formation is substantially less than the mass of the emissions. For the aromatics, olefins, and paraffins in gasoline, the reactivity and ozone formation are much higher relative to the mass emissions. Methanol's reactivity is dominated by the "aldehydes" category, principally formaldehyde. Formaldehyde is a highly reactive component of methanol emissions. It is classified as a probable carcinogen. The risk from this one component of methanol engine emissions, which is controlled with a catalytic converter, must be measured against the dozens of known and suspected carcinogens in gasoline and diesel fuels. It should also be remembered that formaldehyde is a component of gasoline emissions, and that secondary formation of formaldehyde from other elements of gasoline exhaust leads to a total as much as five times greater than is shown in the "aldehydes" section for the gasoline fuel in Figure 5.2-2.

Some members of the petroleum industry have argued that "reformulated" gasoline can be made to be "as good as methanol." So far, the reformulated gasolines have shown themselves to be significantly better than the gasoline shown here, but still not as good as M85. In Figure 5.2-1, the 15 percent gasoline component is the industry average gasoline. If that 15 percent gasoline component had been reformulated gasoline, the emissions profile would have been cleaner. Reformulated gasoline, unlike M85, does not pave the way for M100 (which no gasoline will match) and fuel cells. Reformulated gasoline therefore is not as "good as methanol": not as good as M100, not as good as M85 as sold today, and not as good as M85 as it could be sold, made with reformulated gasoline instead of industry average gasoline. Furthermore, the comparison should not be narrowly targeted at emissions reactivity. Methanol also offers a decline in carcinogenic emissions. Light-duty use of methanol fuel will cut many vehicle and upstream toxics. Heavy-duty use will cut toxic diesel exhaust particulates.

Methanol is a "full strategy" public health fuel for light- and heavy-duty vehicle applications. Methanol's ozone-generating emissions, including formaldehyde, are a cause for concern. Catalytic converters are now controlling these emissions. With widespread use of methanol, there would be an overall reduction in secondary formaldehyde formation due to lower hydrocarbon emissions. It is good, sound public policy to begin the journey to the alternative transportation technology of the future with a practical fuel that offers solid public health benefits with off-the-shelf technology.

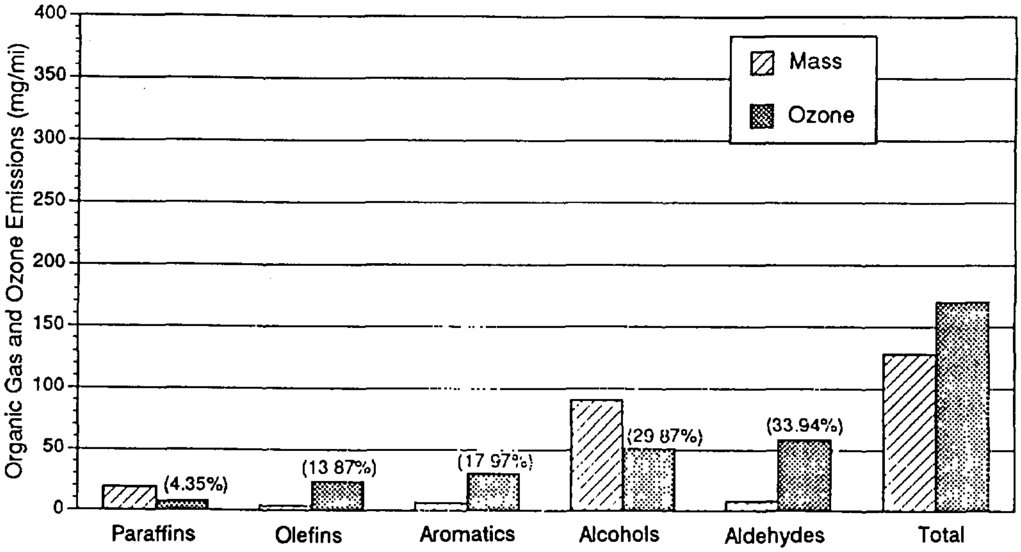


Figure 5.2-1. Breakdown of emissions reactivity for a 1990 Dodge Spirit FFV on M85. (Source: Louis Browning and Michael McCormack, "A Technology Assessment of Light-duty Methanol Vehicles," 10th International Symposium on Alcohol Fuels, Colorado Springs, Colorado, 1993)

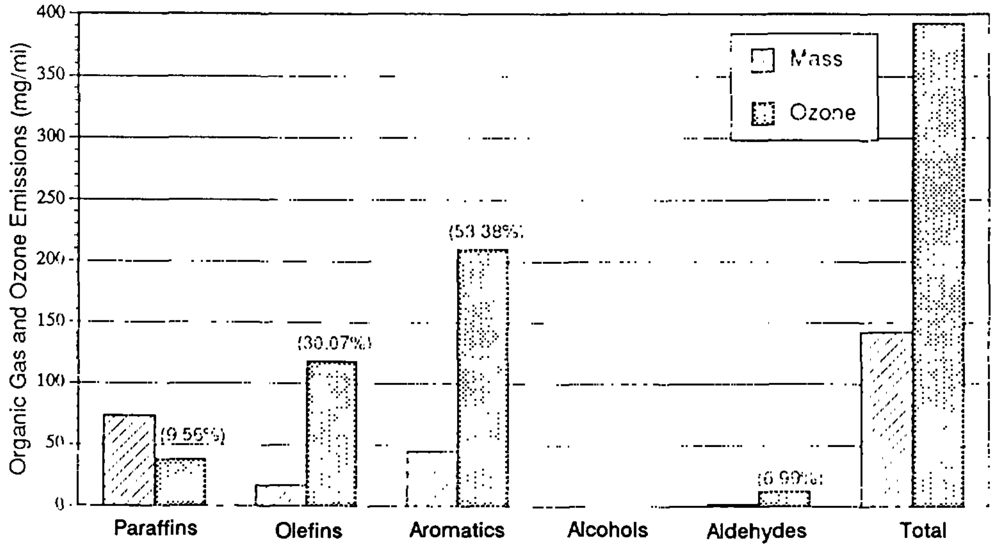


Figure 5.2-2. Breakdown of emissions reactivity for a 1991 Ford Tempo on industry average gasoline. (Source: Louis Browning and Michael McCormack, "A Technology Assessment of Light-duty Methanol Vehicles," 10th International Symposium on Alcohol Fuels, Colorado Springs, Colorado, 1993)

6.0 OZONE

6.1 OZONE AS AN URBAN AND A GLOBAL PROBLEM

Ozone has been recognized as a threat to urban public health for several decades. More recent studies have shown that it is harmful to agriculture and to forests. Ozone at ground level--tropospheric ozone--is gaining increasing attention as a global health threat.

The stratospheric layer of ozone above the earth is essential to life. In recent years, "ozone holes" above the north and south poles have gained international attention and been the subject of international treaties. Perhaps because of the scale of the problem and the high-level diplomatic negotiations needed to cope with it, stratospheric ozone depletion has been the "glamour environmental concern." Down below, ozone is known as smog, and though not as glamorous as stratospheric ozone depletion, it is a threat to the public health. This ground-level, tropospheric ozone is largely but not entirely generated by human activities.

Human-caused hydrocarbons combined with human-caused nitrogen oxides are the usual cause of urban ozone pollution. However, some nitrogen oxides can occur naturally: lightning is a major source. More surprisingly, much of the available hydrocarbon inventory comes from natural "biogenic" sources such as trees. In some areas, controlling the production of peak ozone levels requires reducing hydrocarbons; in others, reducing NO_x, and often, a combined reduction strategy is needed.

Human-caused NO_x can travel long distances and then combine with local biogenic sources of hydrocarbons. This can contribute to the problem of ozone transport which can cause substantial damage to forests and agriculture. In California, for example, the forests of the whole Sierra Nevada mountain range are threatened by transport ozone from the coastal areas. Ozone from the heavily populated U.S. east coast has been detected off the coast of Iceland. Figure 6.1-1 shows the true dimensions of the global ozone problem: the hemispheric ambient levels of ozone now typically range from 40 to 80 ppb. An exceedance of the U.S. federal standard is set at 120 ppb; the lower California limit is 90 ppb. Canada's official attainment goal is 82 ppb. The two lower values are justified by medical studies of ozone's effects on human health. "Transport ozone" is an increasingly intractable problem and nearly impossible to control with local strategies; ambient continental levels as measured by satellites are approaching established minimum health protection levels.

Forest and crop damage can occur at levels of 40 ppb. Figure 6.1-1 suggests that urban-centered control strategies for ozone may simply not be enough to control the global growth of the tropospheric ozone problem. Typically ozone control strategies have been oriented towards urban air basins: a high-NO_x emitting truck was "not a problem" after it left Los Angeles and went out into the desert. But the truck contributes its emissions to the "ozone plume" drifting away from the city. If we value our forests and agriculture we may need to develop a broader view.

Ozone has also been implicated as a greenhouse gas agent. A recent scientific study has suggested that tropospheric ozone has increased between 100 percent and 200 percent in this century. A strong absorber of infrared radiation, ozone's contribution to global warming may be about 23 percent that of carbon dioxide. It is thus a significant control objective from the greenhouse gas perspective.

Methanol could be broadly introduced into the transportation network. Its reductions of hydrocarbons and NO_x should be part of a broader strategy that envisions continental adoption of low-NO_x and low-hydrocarbon fuels.

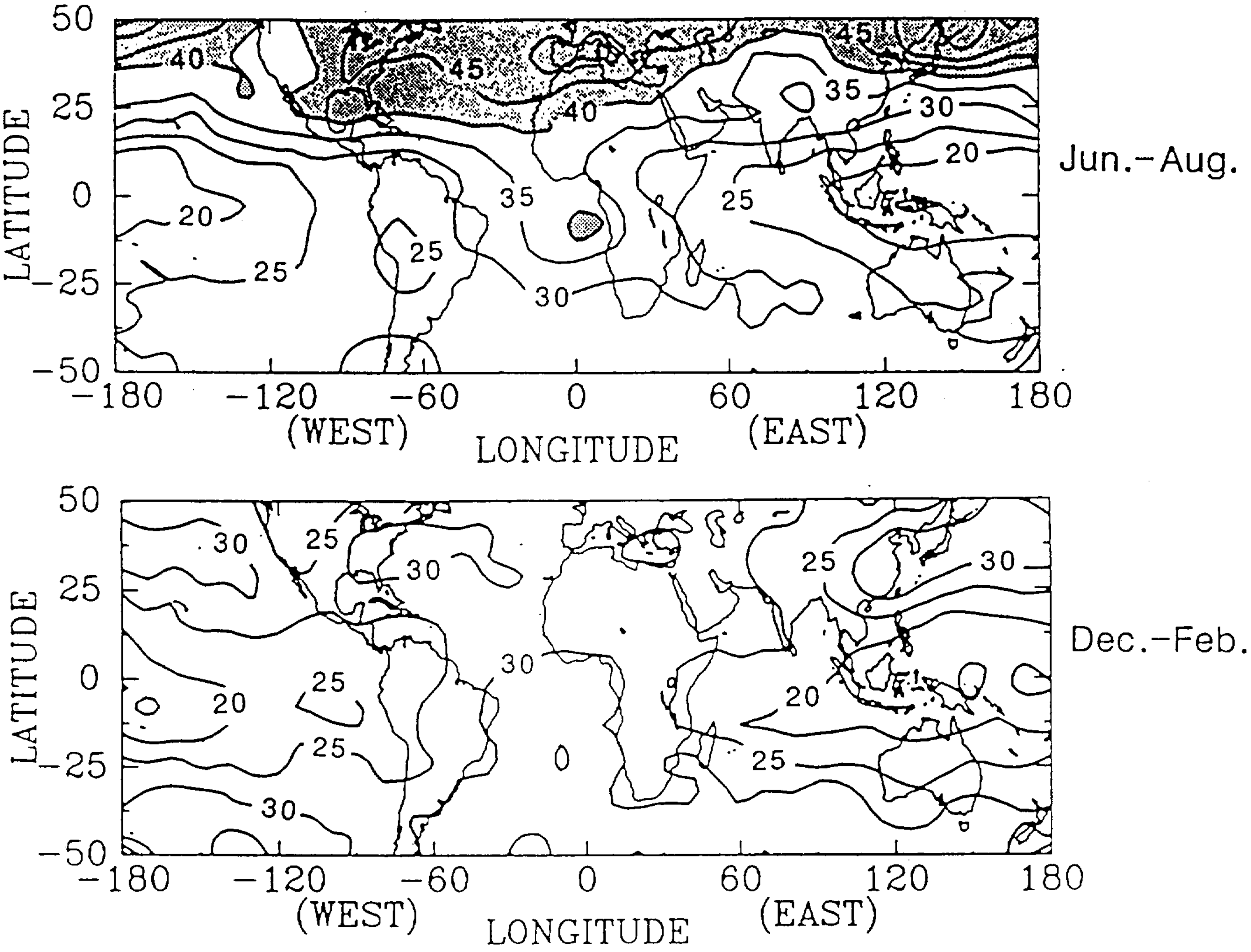


Figure 6.1-1. Global tropospheric ozone distribution derived from satellite data. Isobar values are in Dobson units: multiply by 1.6 for parts-per-billion equivalent. Through much of the year, ambient ozone levels are more than sufficient to damage forests and agriculture in North America over wide areas. Tropospheric ozone is also a strong absorber of infrared energy and is a contributor to global warming. (Source: Jack Fishman, "Global Smog: A New Environmental Threat," in Tropospheric Ozone and the Environment, eds. R.L. Berglund, D.R. Lawson, David J. McKee. Pittsburgh, PA.: Air and Waste Management Association, 1991)

7.0 GLOBAL WARMING (THE GREENHOUSE EFFECT)

7.1 METHANOL AND THE GLOBAL WARMING PROBLEM

The greenhouse effect is not easily solvable with known technologies. Transportation emissions are only a small part of the global inventory. Methanol could nonetheless play a role in the reduction of greenhouse gases from the transportation sector.

Global warming, or the greenhouse effect, is simple in its underlying idea although highly controversial in its details. In theory, human production of gases such as carbon dioxide (and many other gases, such as methane, chlorofluorocarbons, ozone, etc.) trap infrared heat. These "unnatural" additions to the global atmosphere may force a climatic change of considerable magnitude. In the earth's past, such changes have occurred even without the human presence. The threat of global warming is that it may provoke the fastest change in climate in the geologic record, forever altering the world as we know it.

To control global warming, the production of "greenhouse gases" must be kept in approximate balance. Fuels which maintain this balance come from "renewable sources." Burning the fuel releases carbon dioxide, but the process of making the fuel involves growing new feedstocks which remove carbon dioxide from the air.

Since global warming became a major focus of study in the 1980s, the entire inventory of potential greenhouse gases has been studied. Estimates vary greatly. Generally speaking, methanol from natural gas has been found to reduce potential greenhouse gas emissions relative to gasoline from 0 to 8 percent.

It is wrong, however, to evaluate methanol solely on the basis of its "natural gas profile." The development of an infrastructure to use and distribute methanol fuel will open up an attractive market for others. Some agencies or businesses would see revenue from methanol as an "added bonus" to mandatory waste processing, allowing some money to be made where before there was no such possibility. Municipal sewage treatment, municipal garbage, and agricultural byproducts and biomass are all good renewable candidates for the production of methanol at local facilities, which could then be sold into local distribution facilities as fuel. The process would be analogous to the co-generation of electricity. Steel facilities would still be net contributors to global warming. But with co-produced methanol from the coal-fired furnaces, they would at least be compensating for their greenhouse gas emissions somewhat by displacing petroleum fuels that would otherwise continue to make a net contribution to the global inventory. Greater energy use efficiency is a good way to combat global warming. Figure 7.1-1 illustrates these ideas. Note that it is not possible to estimate accurately the extent of greenhouse gas reduction through renewable methanol feedstocks because this will depend on the many potential fuel sources, market incentives, and legislation put in place to encourage them.

But agricultural biomass, municipal sewage and waste, and co-produced methanol from steel will not be able to build a transportation market by themselves. Methanol from natural gas is the most cost-effective production process today, and it must lead the way. Greenhouse benefits will come when the basic infrastructure is widespread.

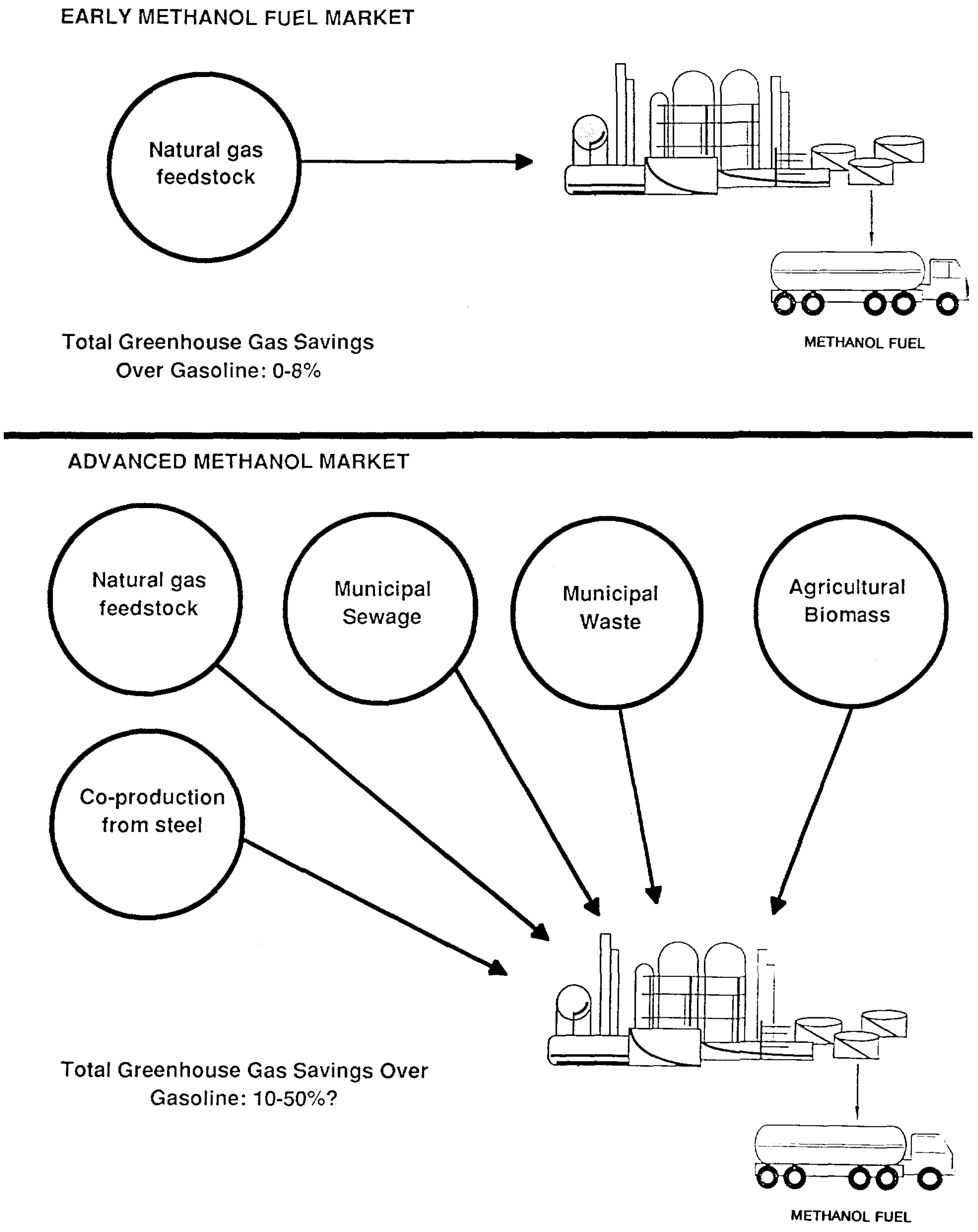


Figure 7.1-1. Greenhouse gas emissions from transportation are only 8 percent of the total world inventory. The small reductions possible with methanol from natural gas could be greatly augmented with methanol from other sources. (Source: Acurex Environmental Corporation)

8.0 TOXIC RISKS

8.1 IDENTIFIED TOXICS IN METHANOL AND GASOLINE

The use of methanol fuel will also reduce the exposure of drivers and the public to known and probable carcinogens.

Gasoline is a widespread source of environmental exposure to toxic, cancer causing substances. These substances include benzene, formaldehyde, 1,3 butadiene, and acetaldehyde. Benzene is a proven carcinogen based on human exposure studies. Formaldehyde, acetaldehyde, and 1,3 butadiene are classified as probable carcinogens and may also have mutagenic properties (i.e., cause reproductive harm). There are many other chemicals in gasoline which may or may not be hazardous to human health. The risk estimates presented here represent only those four substances for which substantial laboratory testing has been carried out.

The toxic pathways of gasoline exposure include inhaling tailpipe exhaust, fumes in the air, and drinking contaminated water. The data presented here include toxic risk exposure estimates for tailpipe emissions and evaporative losses from the automobile as well as exposure to fumes during refueling. However, data from water contamination and from the upstream release of gasoline-related toxic substances during refining and delivery of the product have not yet been integrated into the risk factors discussed here: quantification of these risks is still underway. Therefore the toxic risk assessments in this section contain two "conservative" biases which may make gasoline appear safer than it in fact is: only four substances are included out of many dozens of potential carcinogens, and the full fuel cycle of upstream emissions has not been included.

Figure 8.1-1 lists the most toxic substances associated with gasoline and diesel fuel that are not present in M100, though of course they are present to a lesser degree in M85, which contains 15 percent gasoline.

Overall, the toxic risk from the use of methanol as a fuel is lower than gasoline. The exhaust of vehicles powered by pure methanol fuel contains many fewer toxic contaminants than gasoline-powered vehicles. When methanol fuel is used steps must be taken, through appropriate use of catalytic converters, to minimize the formation of formaldehyde as a combustion byproduct. These emissions were a concern with earlier methanol vehicles. Even now methanol-powered light-duty vehicles emit more formaldehyde, directly out of the tailpipe, than equivalent gasoline powered vehicles. However, gasoline exhaust does contain formaldehyde. Moreover, gasoline exhaust leads to the formation of secondary formaldehyde as a result of photo-oxidation of gasoline's volatile organic compounds. When primary and secondary formation of formaldehyde are considered, gasoline emissions are roughly equivalent to methanol fuel. Some airshed models, such as for the Los Angeles basin, have indicated that because of secondary formation, gasoline leads to higher formaldehyde levels than if M100 were the sole fuel in use.

In spite of its containing 15 percent gasoline, M85 represents a significant diminution of toxic risk factors in comparison to industry average gasoline and also in comparison to the newer reformulated gasolines (two different reformulated gasolines are shown in Figure 8.1-2). Figure 8.1-2 shows a quantification of the relative risks, assuming catalytic emissions control of both gasoline and methanol vehicles.

Toxic risk in heavy-duty use is also greatly reduced by methanol fuel. This is discussed in Section 9.0 on particulates (PM_{10}).

Toxic	Gasoline	Diesel	Methanol
Benzene	X	X	
Xylenes	X	X	
1,3 Butadiene	X	X	
Chromium	X	X	
Manganese	X	X	
Nickel	X	X	
Mercury	X	X	
Arsenic		X	
Lead	X	X	
Cadmium	X	X	
Formaldehyde	X	X	X
Acetaldehyde	X	X	X
Acrolein	X	X	X
Phenol	X	X	X[a]
Cresols	X	X	X[a]
Polynuclear Aromatic Hydrocarbons	X	X	X[a]
Dioxins	X	X	
Nitrosomorpholine	X	X	
Nitrosamine	X	X	
Nitrobenzene	X	X	
Chloroform	X	X	
Ethylene Dibromide	X		
Ethylene Dichloride	X		
Ethyl Bromide	X		

[a]Engine oil emissions not from methanol or CNG.

Figure 8.1-1. Toxics present in gasoline, diesel and methanol vehicle exhaust

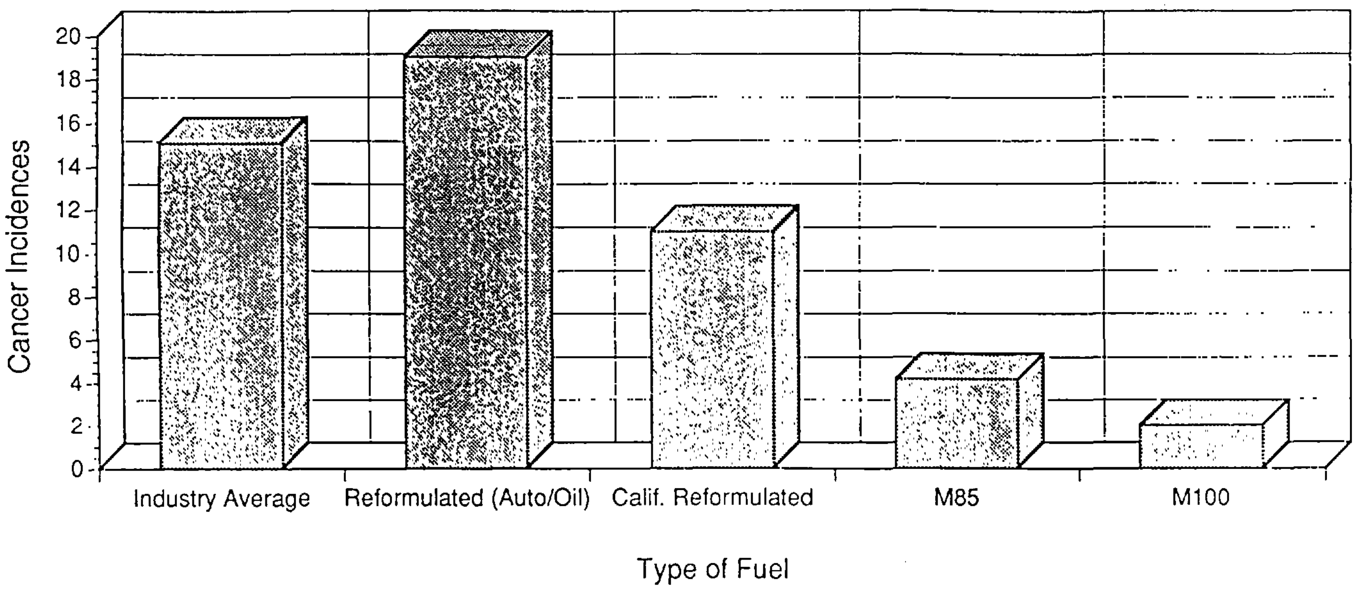


Figure 8.1-2. Toxic risks associated with different fuels. Assumptions are lifetime exposure per 1,000 people exposed to one microgram per cubic meter. Fuel types: industry average, typical industry gasoline; auto/oil reformulated, blend used in testing in Detroit; California Reformulated, gasoline designed to meet California Phase II standards. (Source: Browning and McCormack, 1993)

9.0 PARTICULATE EMISSIONS CONTROL

9.1 PARTICULATE EFFECTS AND CONTROL TECHNIQUES

Particulate emissions — black soot from diesel fuel heavy-duty engines — are under increasing scrutiny for their potential threat to human health. Methanol in heavy-duty applications sharply decreases particulate emissions.

For decades motorists who have followed buses and large trucks have been offended by their heavy black exhaust soot. Until very recently, however, diesel particulate emissions, or PM10, were not considered a major threat to human health. This was due in part to the fact that diesel particulates were classed in the same category as other sources of PM_{10} — agricultural dust, for example, and particles from tire wear. Some diesel engines have been measured as producing as much as a cup per mile of black soot.

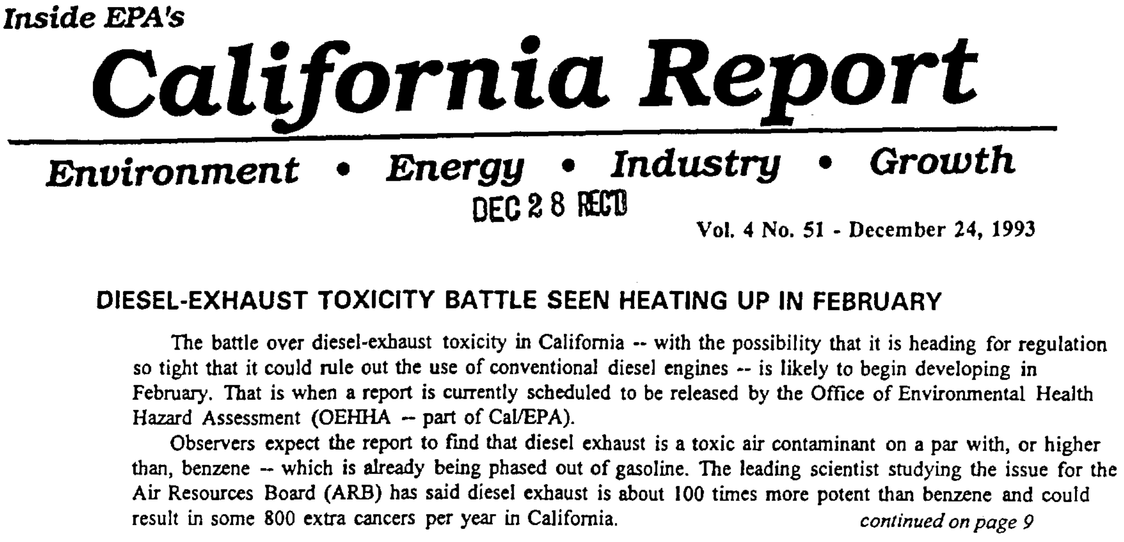
Recent studies are changing this picture. The U.S. Environmental Protection Agency has conducted several epidemiological studies which have shown that mortality rates in urban cities rise sharply after episodes of elevated PM_{10}. The rise in mortality is lagged and happens after the episode itself but is statistically consistent. Deaths from this source have been estimated at the thousands per year in major cities. The studies have not identified the specific physiologic causes of increased mortality, but the mortality spikes occur too soon to be attributable to cancer.

The general conclusion of this work is that PM_{10} of all kinds is a major health threat. This work has not disaggregated the different kinds of PM_{10}. Since diesel particulate's contribution to the total PM_{10} inventory is typically very small — on the order of 3 to 6 percent — it would be easy to conclude that it is not a major part of the health threat.

Nonetheless, this small fraction does not take into account human exposure, or the relative potency of different types of particles. Due to the "street canyon effect" — the tendency of emissions to have long residence times in protected streets and areas between buildings — the exposure of people in urban areas to diesel particulates is in fact much higher than the total inventory count would lead one to conclude. People on sidewalks, waiting at bus stops, and traveling behind heavy-duty vehicles are getting much higher exposures to diesel particulates.

Another area of research, which is currently being surveyed by the California Air Resources Board, concentrates on the specific health effects of diesel particulates. This research indicates that particulates are far deadlier than hitherto believed. The exact mechanisms are not understood — toxic petroleum carcinogens may cling to the diesel particulates, for example, or may be released in gaseous form by the diesel combustion process and expelled along with the particulates. However, the picture that is now emerging is that diesel particulates are one of the most toxic substances to be considered for control by the California Air Resources Board in the agency's entire history. It is as bad, and may even be 100 times as bad, as benzene, one of the most carcinogenic chemicals in widespread use (see Figure 9.1-1).

Fortunately, public health officials and air quality regulators have appropriate tools to reduce these emissions. Methanol heavy-duty engines emit particulates at lower rates than petroleum fuel heavy-duty technology. Figure 9.1-2 shows that the methanol engine, as of 1993, was already certifying at levels 40 percent lower than the 1998 standard. For the reasons described above, such a reduction may soon be demonstrated to have substantial public health benefits.



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DIESEL-EXHAUST TOXICITY BATTLE SEEN HEATING UP IN FEBRUARY

The battle over diesel-exhaust toxicity in California -- with the possibility that it is heading for regulation so tight that it could rule out the use of conventional diesel engines -- is likely to begin developing in February. That is when a report is currently scheduled to be released by the Office of Environmental Health Hazard Assessment (OEHHA -- part of Cal/EPA).

Observers expect the report to find that diesel exhaust is a toxic air contaminant on a par with, or higher than, benzene -- which is already being phased out of gasoline. The leading scientist studying the issue for the Air Resources Board (ARB) has said diesel exhaust is about 100 times more potent than benzene and could result in some 800 extra cancers per year in California.

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Figure 9.1-1. The toxicity of diesel exhaust is a developing area of regulation that may have far-reaching effects on the transportation market. (Source: as shown.)

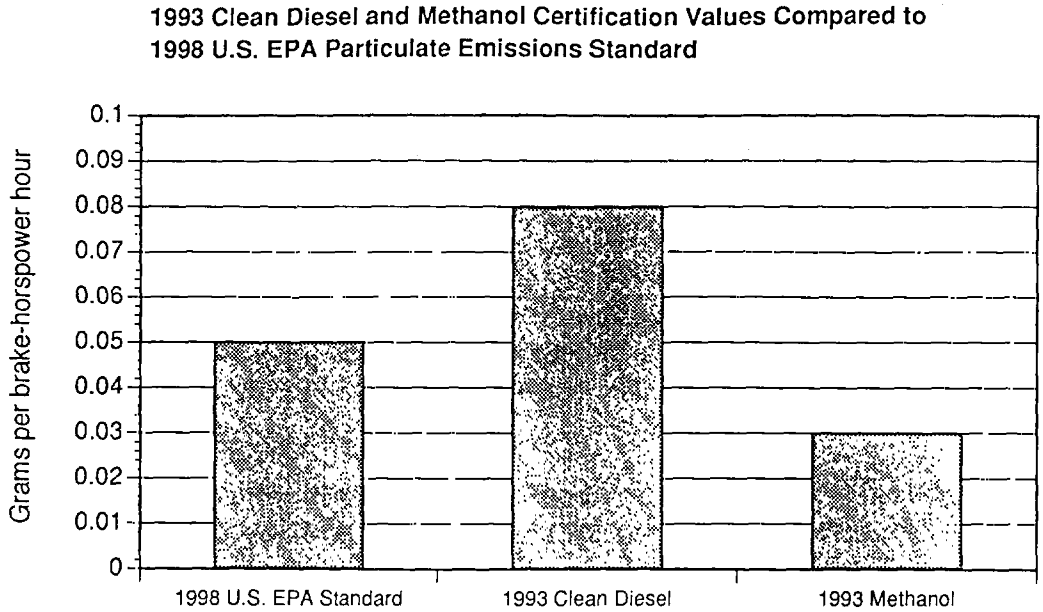

Figure 9.1-2. Methanol in 1993 was already below the U.S. particulate standard of 1998. As more is learned about the need to control particulate emissions, it is clear that methanol provides an excellent public health value. This graph shows the verification results of two 1993 DDC engines: the 6V92TA methanol engine, and the Series 50 "Clean Diesel" engine that was developed partly in response to the competitive edge of methanol in providing environmental benefits. Older diesel engines would be off the scale of this graph. (Source: California Air Resource Board)

10.0 SAFETY ISSUES

10.1 GENERAL INTRODUCTION

Mass marketed fuels are used and abused in many aspects of ordinary life. A full consideration of safety must not focus on any single characteristic of a fuel, but look at the broad spectrum of avoidable and unavoidable accidents.

When a product is mass marketed, it becomes part of the human environment and therefore subject to the full range of appropriate and inappropriate human behaviors. Many of the concerns about gasoline and methanol fuel can be partially addressed through safety-conscious hardware and facility design. Nonetheless, it is very difficult to design products to compensate for ignorance or carelessness. And unfortunately, even where reasonable precautions are taken, unforeseen circumstances will occur. Billions of people use gasoline, or use a service which has drawn upon gasoline power, every day. If a North American methanol economy develops, tens of millions of consumers will directly or indirectly use the fuel every day.

Under these circumstances, what is needed to make a fair fuel evaluation is a full-cycle estimate of the likely uses and abuses of a fuel in use. For example, in an accident followed by a fire, a methanol flame is nearly invisible in broad daylight, which poses one kind of safety hazard. A gasoline flame is visible but its higher radiant energy means it can inflict bodily harm at a greater distance and do more burn damage, more quickly, than an equivalent quantity of methanol. Thus an unconscious person near a crash site with burning methanol fuel may have greater chance of survival than someone in a similar accident involving gasoline fuel. This advantage may well compensate the possibility of accidental burn due to contact with an invisible flame.

Similarly, it is true that methanol ingestion poses a danger to people that siphon fuel. That is why all methanol vehicles in public use are equipped with anti-siphoning devices. However, many accidents with gasoline occur when fuel is siphoned and used as an accelerant — perhaps to start a barbecue when no lighter fluid is convenient, or to pour through the butterfly valve of a carburetor-equipped car that is not starting. These gasoline-related fire hazards have put many people into the hospital, and it is regrettable that measures such as anti-siphoning devices are used to stop one kind of siphoning hazard — accidental swallowing — but not another, accidental explosive ignition.

Some immigrants come from areas of the world where gasoline is used as a household cleaner for floors and other surfaces. Often glass-paned windows and pilot lights are luxuries in these parts of the world. Fuel uses that did not result in fires — though unadvisable from the point of view of toxic exposure — in the home country are not safe in colder climates where windows and pilot lights are more frequent. But recent immigrants are not alone in misusing fuel as a solvent: many accidents occur in home garages and workshops. It is possible, since methanol fuel is less satisfactory as an oil solvent and lower in overall volatility, that when misused it will be less prone to result in accidental fires, and that these kinds of fires will burn people less severely when they do occur.

Gasoline is also abused as an intoxicant: fume overexposure, whether deliberate or accidental, is gasoline's most toxic human pathway and can result in multiple organ failure and death. Methanol can also be abused as an intoxicant, and can result in blindness or death.

Figure 10.1-1 suggests that fuels must be evaluated in terms of their total social risks, not focusing on any one aspect.

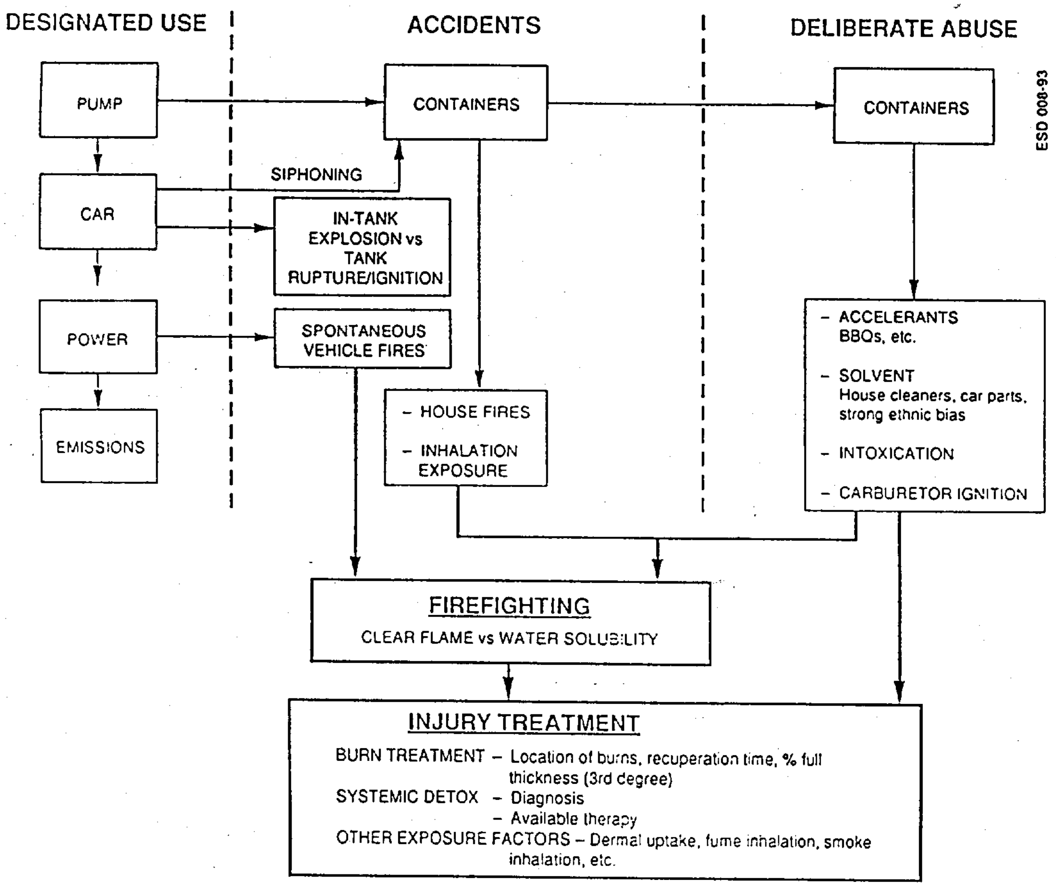

Figure 10.1-1. **A meaningful comparison of fuel safety must take into account the complete cycle of use, misuse, and abuse. (Source: Based on Gregory P. Nowell, "Epidemiological Effects of Methanol and Gasoline Use," Clean Fuels Program, Sacramento Metropolitan Air Quality Management District, 1992)**

10.0 SAFETY ISSUES
10.2 RISK OF FIRE AND EXPLOSION

All fuels designed to power an internal combustion engine, by definition, are flammable and have a propensity to explode: this is the source of an engine's power. Nonetheless, many characteristics such as volatility, radiant energy, and flame visibility affect the overall hazard profile of a fuel in an accident. Methanol is one of the safest liquid fuels.

Explosions in Automobile Accidents. Gasoline is almost incapable of exploding inside a car's closed gasoline tank at temperatures above freezing. At temperatures below freezing, the theoretical possibility of "in-tank ignition" increases, but the experience of millions of motorists in the winters of Canada, the U.S. Northeast, and the Midwest have shown this danger to be vanishingly small. Methanol's theoretical danger of exploding in a closed tank at warmer temperatures is comparable to gasoline at very cold temperatures.

In some serious automobile accidents the fuel tank ruptures and spills fuel. The chemistry of fuel behavior in the open air is very different from in a closed tank. Gasoline emits more fumes, which travel farther, than methanol fumes. This makes gasoline more likely to find an ignition source and catch fire or explode. Figure 10.2-1 makes a rough comparison of the hazard levels of methanol and petroleum fuels.

Fire Hazards. In an accident where the fuel has caught fire, methanol has a disadvantage but also advantages relative to gasoline. The single disadvantage is that because it is clean burning, the methanol flame, in broad daylight, is nearly invisible. The advantages are that methanol flames have much lower heat intensity, and flame height is sharply reduced. Given equal exposure and distance from the fire, the methanol flame will do less harm to a person than a gasoline flame. This "safety feature," combined with methanol's lower propensity to explode, is why methanol is a preferred fuel in much professional racing.

A fuel's vapor pressure affects the probability that leaks from the fuel system may result in fires. Figure 10.2-2 shows an EPA estimate that methanol's lower vapor pressure would reduce fire incidence in light-duty use from about 8 per thousand accidents for gasoline to 6 per thousand accidents for M85, and 3 per thousand for M100. A reduction in fire-related deaths might be M100's biggest single contribution to safety and welfare, bigger even than reduction of exposure to air toxics and particulates.

Special Properties of M85. M85 is a mixture of 15 percent gasoline and 85 percent methanol. The gasoline evaporates out of the fuel mixture more quickly than the methanol. M85's gasoline fumes are more likely than pure methanol (M100) to make contact with a distant ignition source in the event of a spill. The 15 percent gasoline raises the heat content of the flames, making them somewhat more harmful to people but more readily visible in daylight.

Probability of Explosion				
	Gasoline	**Diesel**	**Methanol**	**M85**
Explosion in closed, sealed tank	Extremely Low	Extremely Low	Very Low	Extremely Low
Explosion following accident with rupture of tank	High	Very Low	Low	Moderately High

Figure 10.2-1. Methanol fuels compare favorably to gasoline in terms of explosion risk, but are more volatile than diesel. (Source: Acurex Environmental Corporation)

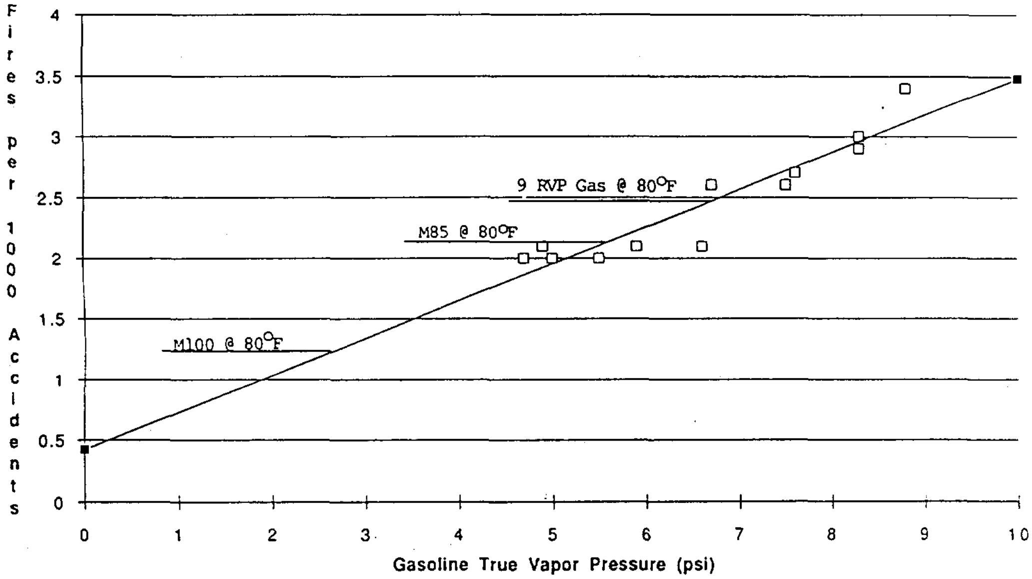

Figure 10.2-2. As fuel vapor pressure declines, the risk of automobile fires also falls. M100 offers significant advantages over conventional gasoline and M85. M85 is nonetheless an improvement over conventional gasoline. (Source: Paul Machiele, "Methanol Fuel Safety: A Comparative Study," U.S. Environmental Protection Agency, 1990)

10.0 SAFETY ISSUES
10.3 METHANOL AND GASOLINE COMPARED: ASSORTED HEALTH ISSUES

Methanol has many safety advantages over gasoline fuels. However, the fuels are not strictly comparable. Statistical data on gasoline-related accidents is poor; methanol has never been used on a scale comparable to gasoline. Only a qualitative judgment is possible at this time.

A brief discussion of major issues relating to methanol and gasoline use follows, and are summarized in the table in Figure 10.3-1. Methanol is a safe fuel — as safe or safer than gasoline — but does pose some risks.

Dermal Absorption. Methanol and gasoline can be absorbed through human skin. Neither fuel is particularly dangerous to motorists who refuel their cars, but care is advisable. In cases of prolonged skin contact with gasoline, chemical skin burns and multiple organ failure leading to death are possible. Dermal absorption fatalities are rare with gasoline but do occur; the same would most likely be true if methanol were in widespread fuel use.

Ingestion. Methanol is most deadly when swallowed. Siphoning accidents and mistaken ingestion by people who do not understand the difference between methanol (wood alcohol) and ethanol (drinking alcohol) are the most likely problem. Medical attention is necessary following methanol and gasoline ingestion. But ingested gasoline, unlike methanol, is not easily absorbed by the digestive tract.

Inhalation. Gasoline is most deadly when inhaled. The most frequent problems are car accidents leading to fume exposure and deliberate inhalation to become intoxicated. In the worst cases multiple organ failure (heart, liver, kidneys) can lead to death; damage to lung tissue by inhaled and exhaled hydrocarbons is also a problem. Low-level exposure over long periods is another kind of inhalation exposure scenario. Gasoline has many documented toxic and carcinogenic effects. Methanol studies have not shown equivalent health threats. Methanol's toxicity is well documented and understood, and there is no evidence for any carcinogenicity in humans.

Non-fuel uses. Many accidents and fatalities with gasoline occur in non-fuel uses. People use gasoline to clean car parts; it is also used as an accelerant to start a barbecue or other fire. Some immigrants from less-developed countries with warm climates, where glass-paned windows and appliances with pilot lights are rare, use gasoline to clean their floors. In their adopted countries, severe fires and explosions have resulted from these kinds of non-fuel uses. No one knows how people might choose to use methanol in non-fuel uses. Anti-siphoning devices will make it next to impossible to siphon the fuel from a car, but it still may be difficult to prevent non-fuel uses of methanol. Not easily soluble with oil, methanol may not become popular as a solvent for car parts. Whether methanol will be used to clean floors is hard to predict, but it would undoubtedly serve as a barbecue fire starter. In theory, the lower evaporation of methanol and lower energy content of the flames should make accidents from non-fuel uses both less frequent and less severe.

Intoxication. Gasoline has been, and is, deliberately abused ("sniffed") by several millions of North Americans. Methanol has been both deliberately and mistakenly ingested by alcoholics who were either unaware of or indifferent to the threat to their health. This can be discouraged through the use of additives to impart an unpleasant odor and smell to methanol.

<table>
<tr><th colspan="2">Brief Summary of Fuel Exposure Scenarios and Possible Effects
(Gasoline and Methanol)</th></tr>
<tr><td>Dermal contact, methanol, small refueling splash</td><td>No harm likely</td></tr>
<tr><td>Dermal contact, gasoline, small refueling splash</td><td>No harm likely</td></tr>
<tr><td>Dermal contact, methanol, extensive and prolonged</td><td>Blindness or death possible with no treatment</td></tr>
<tr><td>Dermal contact, gasoline, extensive and prolonged</td><td>Chemical skin burns, multiple organ failure (heart, liver, kidneys), damage to lungs, death possible (systemic hydrocarbon poisoning)</td></tr>
<tr><td>Ingestion, gasoline</td><td>No lasting harm likely; induces vomiting which purges system</td></tr>
<tr><td>Ingestion, methanol</td><td>Possible blindness or death if swallowed in sufficient quantity, with no medical treatment</td></tr>
<tr><td>Inhalation, gasoline short-term high exposure</td><td>Intoxication, and possible systemic failure in high doses, possible lung damage, organ failure, death</td></tr>
<tr><td>Inhalation, methanol short-term high exposure</td><td>Very difficult to achieve toxic levels through fume inhalation</td></tr>
<tr><td>Inhalation, gasoline, long-term low exposure</td><td>Multiple documented carcinogenic and toxic effects</td></tr>
<tr><td>Inhalation, methanol, long-term low exposure</td><td>Ambiguous carcinogenic data, some evidence of reproductive toxicity</td></tr>
<tr><td>Non-fuel uses and misuses, gasoline</td><td>Fires and explosions frequently associated with use as an accelerant and/or parts solvent, household cleaning solvent</td></tr>
<tr><td>Non-fuel uses and misuses, methanol</td><td>Unclear what effects would be in general use. Possible decrease in frequency and severity of fire-related injuries. Possible increase in ingestion accidents.</td></tr>
</table>

Figure 10.3-1. Source: Based on Gregory P. Nowell, "Epidemiological Effects of Gasoline and Methanol Use," Clean Fuels Program, Sacramento Metropolitan Air Quality Management District, 1992.

11.0 OIL DISPLACEMENT AND ENERGY DIVERSIFICATION
11.1 ECONOMIC BENEFITS OF METHANOL FUEL

An oil displacement policy is the transportation energy equivalent of not putting "all the eggs in the same basket." A diversified fuel portfolio for North America would mean that businesses and consumers could have fuel choices.

Very little methanol is imported into the United States, and most imports are from Canadian suppliers. The development of a methanol fuel market in North America would draw the interests of many indigenous producers. Ninety percent of the methanol sold in North America is made in North America from domestic natural gas. This production could expand. Moreover, the development of a methanol market in North America will attract the interest of biomass fuel suppliers and of potential methanol co-producers, including utilities, municipal sewage plants, municipal dumps, and steel companies. Methanol use would increase the energy independence of the North American economy.

Although today inflation-adjusted oil prices are near record lows for the post-1974 period, this situation will be temporary. World oil cartels have intervened in normal market mechanisms from 1905-1914, 1928-1940, 1948-1968, and 1973-1986. Even at low prices of $10 to $15 a barrel, billion-dollar investments in the Middle East earn enough income to pay themselves off in two or three years. But the influence of monopolistic actors on the world oil market, such as OPEC, does not mean stabilized prices: it means predatory behavior in times of crisis (such as the Iranian revolution, 1979-1980, and the Allied war against Iraq in 1990), and a world in which prices never really fall to competitive levels.

The result of single-fuel dependency has been massive disruption of industrial economies. Figure 11.1-1 shows one estimate of some of these disruptions: loss of wealth due to capital outflow, loss of gross national product growth due to the foregone investment lost by this capital outflow, and the toll exacted by price shocks which interfere with economic planning and investment by firms, leading to inflation and layoffs as firms raise prices to cover higher production costs and reduce investment because overall demand is falling. A competitive transportation fuel market, in which consumers had a choice of fuels, is one way to dampen the effect of price shocks and to lessen the high costs of oil dependency.

The costs of dependency are in the hundreds of billions of dollars a year. The Canadian economy, tightly linked to the United States, is also affected. And, of course, the world-class United States and Canadian methanol industry would profit from the opportunity to replace U.S. petroleum imports with environmentally beneficial methanol fuel. Figure 11.1-1 shows only the economic impact of relying on uncertain foreign petroleum supplies. There are also environmental, health, and direct military expenditures that are not shown. The additional environmental and military expenditures are a deadweight loss to the United States economy, and lost U.S. purchasing power that might otherwise result in purchases from Canada.

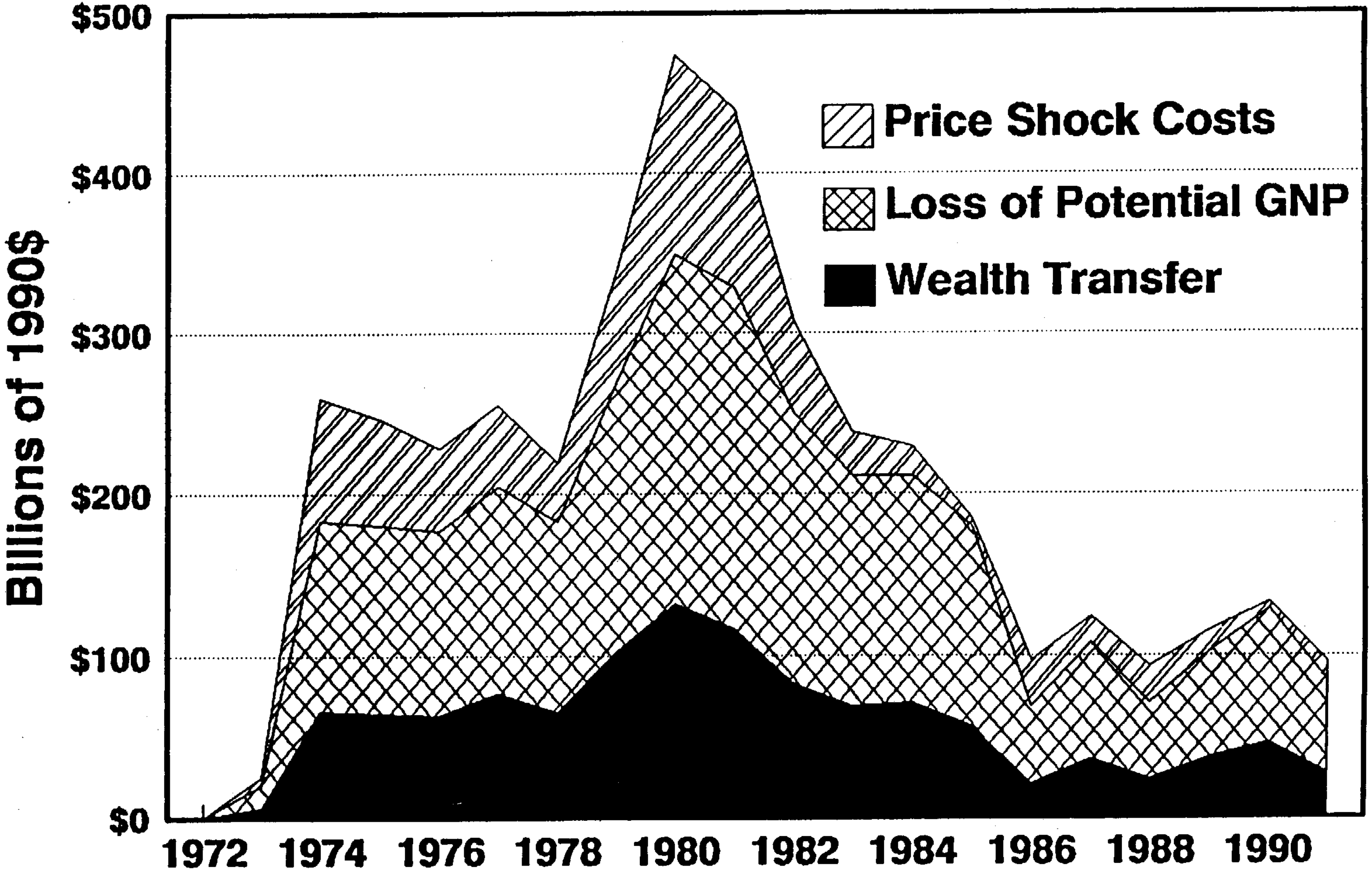

Figure 11.1-1. Losses to the U.S. economy from monopoly pricing of oil, 1972-1991. (Source: David L. Green and Paul N. Leiby, "The Social Costs to the U.S. of Monopolization of the World Oil Market," Oak Ridge National Laboratories No. 6744, January 1993)

12.0 THE NEED FOR INCENTIVES TO BUILD A METHANOL MARKET

12.1 METHANOL AND THE PROBLEM OF MARKET BARRIERS TO ENTRY

The history of the development of the gasoline and diesel fuel markets cannot be duplicated. Formidable market barriers to entry must be overcome before the methanol market can achieve the economies of scale needed for large scale market penetration.

Why does a methanol fuel market need incentives to compete? Because the situation which led to the development of the gasoline market cannot be duplicated. Ninety years ago gasoline fuel was a luxury product for "Sunday drivers." The pioneers of gasoline use bought their fuel in 5-gallon tin cans sold at general stores. As volumes increased, the stores installed pumps. Eventually it became possible to set up retail outlets devoted exclusively to the needs of refueling automobiles: gasoline stations. Today, automobiles are a necessity, not a luxury. Production lines for automobiles do not become profitable until they reach hundreds of thousands of units. Automobile manufacturers do not want to mass-produce cars for methanol if there is no network for the distribution of the fuel. Fuel producers do not want to invest in retail outlets unless there are hundreds of thousands of methanol car owners to serve as customers. Luxury market demand, combined with the general store distribution system, allowed the modern petroleum industry to grow. The costs of building a petroleum distribution network were subsidized by the profits from other goods sold in general stores. Additional investments in higher volume facilities were made in small increments on an as-needed basis. Today's methanol pioneers use their cars every day, not just on Sundays, and cannot refuel at the local general store. They want a mass market retail system that covers wide areas. Private investors cannot risk providing the retail distribution system, and building the cars that will buy from it, unless a coordinated effort is made for the simultaneous introduction of fuels and vehicles. An explicit government policy commitment, based on a careful examination of costs and benefits of moving towards the new fuel era, is essential.

The fuel-flexible vehicle offers a partial solution to the absence of infrastructure in light-duty uses, but a vehicle designed to run on two fuels cannot be "emissions optimized" for either, and some compromise is made in environmental benefits. In heavy-duty use, methanol has thus far been confined to centrally fueled fleets which do not need to buy from retailers on streets and highways. Methanol fueling infrastructure has yet to reach the "critical mass" needed to make the fuel more visible to investors and to the public.

Some significant incentives are in place, but more will be needed for the first decade or two of the methanol fuel industry's growth. In Canada, there is no excise tax on methanol fuel and no provincial road taxes for it in Alberta, British Columbia, and Ontario: these provinces include 60 percent of Canada's population. The United States has two major incentives: the first is the Alternative Motor Fuels Act, which allows alternative fuel vehicles to help manufacturers meet their average mileage standards as required under the Corporate Average Fuel Economy Act. The second is the National Energy Policy Act, which mandates the introduction of alternative fuel vehicles into light-duty federal, state, and local fleets (see Figure 12.1-1). These incentives are helpful, but they do not address the issue of getting methanol vehicles out of fleets and into general use. The economies of scale needed to lower methanol's price — especially necessary to compete in the heavy-duty market – will probably not be realized without larger scale vehicle deployment. As methanol becomes a fully available fuel, it will be possible to phase out many incentives which are essential to prepare for the industry's initial growth. A sustained commitment to methanol's environmental and social benefits is needed if methanol fuel is to overcome the significant barriers to entry caused by the sheer scale of the modern transportation and fuel network.

Year	Federal Fleets	State Fleets	Fuel Provider Fleets	Private & Municipal Fleets
1993	7,500			
1994	11,250			
1995	15,000			
1996	25%	10%	20%	
1997	33%	15%	50%	
1998	50%	25%	70%	
1999	75%	50%	90%	20%
2000	75%	75%	90%	20%
2001	75%	75%	90%	20%
2002	75%	75%	90%	30%
2003	75%	75%	90%	40%
2004	75%	75%	90%	50%
2005	75%	75%	90%	60%
2006+	75%	75%	90%	70%

Figure 12.1-1. **U.S. National Energy Policy Act (EPACT) Fleet Purchase Requirements for New and Replacement Light-Duty Vehicles: Required Numbers and Percent Purchase of Alternative Fuel Vehicles. Significant numbers of alternative fuel vehicles will be required by EPACT, but the impact will be confined to fleet uses, except for eventual resale of some vehicles. Fuel provider fleets are fleets of participants in the fuel market. A methanol fuel provider, for example, would have to purchase new and replacement vehicles in the percentages indicated. EPACT is "fuel blind." An electric utility might purchase methanol vehicles, for example, if it is dissatisfied with the range of electric vehicles available beginning in 1996. (Source: Acurex Environmental Corporation)**

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